March 2017

Humanity and Space

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Humanity and Space
Design and implementation of a theoretical Martian outpost

An Interactive Qualifying Project
submitted to the faculty of
Worcester Polytechnic Institute
In partial fulfillment of the requirements for a
Degree of Bachelor Science
By

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Abstract

Over the next century, humanity will be faced with the challenge of journeying to and inhabiting the solar system. This endeavor carries many complications not yet addressed such as shielding from radiation, generating power, obtaining water, creating oxygen, and cultivating food. Still, practical solutions can be implemented and missions accomplished utilizing futuristic technology. With resources transported from Earth or gathered from Space, a semi-permanent facility can realistically be established on Mars.
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Chapter 1

Executive Summary

Outer space has fascinated humans since the dawn of their existence. Now that, in the year 2017, humans have had the technological capacity to access it for just over half a century, one can clearly see how outer space has inspired and continues to inspire the creation of various space programs, laws, policies, inventions, and even companies. What is not as clear to many people is how humans are even capable of navigating space or why humans do so at all.

In particular, in the last decade or so, people, governments, companies, and other organizations have wondered how to send humans to Mars and why such a task would be worth its tremendous cost and risk. Concerns about a manned Mars mission, including but definitely not limited to the means of propelling the spaceship, the time frame for launching the spaceship and the payload, providing food, water, and waste management for the astronauts, cosmic radiation, and assigning the astronauts to appropriate duties, force the entities designing space technologies to take their time analyzing every single detail of their projects to ensure that their labors do not turn out to be in vain when the time comes to initiate the manned Mars mission.

The initial goal of the IQP team was to explore the growing connection between
humanity and space as technology allowed humans to reach progressively further into the depths of space. This goal evolved into a vision of contributing to the great cause of bringing humanity to Mars, of bringing humanity ever closer to space. To offer ideas on how to pragmatically address the issues behind a manned Mars mission and successfully complete such a mission, the members of the team have collaborated to roughly draft a potential future mission to Mars which will task astronauts with establishing a permanent outpost on Mars. The team believes this mission, though difficult, is entirely possible solely using technologies that currently exist or will very soon exist on Earth. The success of this mission will set the physical and metaphorical foundation for the continuation of advanced human space activity and programs. Much like the International Space Station (ISS), the Mars outpost would mainly serve as a distant, extraterrestrial shelter and research facility shared by multiple Earth nations that would allow for further experiments in non-Earth environments and, by extension, a further understanding of how humans can learn to survive in and adapt to such environments.

In this IQP, the team first briefly reviews personal (of each member of the team) and national (of the U.S., Russia, and China as they are only nations to achieve human spaceflight as of the start of 2017) reasons for the patronage of space programs and expected outcomes. Then, the team overviews possible solutions to the major complications of a Mars colonization mission, such as the duration of a round-trip from Earth to Mars, the total mass and cost of all the physical components of the mission, food and water, the physical and psychological health of the astronauts chosen to go and how to choose them, the initial set up of the outpost, and resource scarcity. Finally, the team decides which of the various solutions are optimal to implement and details how to logistically implement them, e.g., through careful physics calculations, one can determine the best time to launch humans into space so as to minimize the duration of the trip to Mars and the eventual trip back to Earth. Through this process, the IQP team elaborately outlines a creative and unique approach to settling humans on Mars.
Chapter 2

Introduction

For 60 Years, humanity has been traveling into the final frontier of space, pushing the boundaries of technology and science. NASA’s space policy has greatly changed in recent years, and it is currently gearing towards the exploration of Mars, with the rest of the world following suit.

Additionally, space activity is becoming increasingly globalized as nations such as China, Japan, India, and even the European Union as a whole have established their own space agencies to increase their presence beyond Earth. Private companies including but not limited to Boeing and SpaceX are also devoting much of their research and development toward improving human space capabilities for commercial reasons.

This heightened interest in bringing humanity further into space will allow for international cooperation and improved diplomacy. Mankind will find it impossible to expand its reach and dominion deep into the cosmos if individual nations try to achieve the feat alone. Global cooperation will be essential in the coming years, as the feats become increasingly challenging.
2.1 Kenneth Fong

Humans have spent virtually all of their existence on the speck in the seemingly infinite universe that English-speakers call planet Earth. All humans consider Earth their home planet, the only known planet that can naturally sustain human lives, livelihoods, and civilizations.

This fact is very concerning; if anything at all happens to this fragile speck, everything that the Earth’s human nations and societies have done or created could be annihilated in an instant by some catastrophe. What is worse is that in recent and modern times, humanity itself has acquired the technological capabilities to destroy Earth. Thus, continued human existence currently hinges on the probability that not a single cosmic object or entity will cross paths with Earth and that all current and future world leaders will have the decency and sanity to not employ nuclear arms in warfare.

The primary reason I chose to complete this IQP was to explore the plausibility of expanding human civilization into the cosmos lest disaster strike, ideally with current or near-future technologies because the sooner humans can create a extra-terrestrial settlement, the better their odds against the unknown and unforeseen circumstances of the future. The project connects with me and my career goals personally because as a physics major, I wish to apply what I can learn in a physical laboratory to the prospect of permanently establishing the presence and spirit of humanity in and throughout the universe. Though I have neither a specific concentration in mind nor much experience in a laboratory yet, I can certainly say that whichever concentration I choose, I can contribute, even if only a small part, to an audacious space mission through my future research.

The purpose of this IQP in general was to decide how humanity would initially tackle a transition into space; in particular the IQP team decided to tackle the design of a Mars colonization mission. This IQP was indeed interactive in that the group not only got a glimpse into the ambition held by many national space agencies to send humans deeper and deeper into space, but also got a chance to offer diverse ideas on how to make this ambition
an actuality.
2.2 Andrew Kelly

For as long as I can remember I have been interested in science and technology, more specifically, I have always been fascinated by the far reaches of space and mankind’s attempts to explore them. When applying for IQP’s, I wanted to work on a project that would give me an opportunity to apply my engineering experience on a topic I was thoroughly interested in. The Humanity and Space IQP has given me an opportunity to focus my engineering education towards a topic that was the cornerstone of why I decided to become an engineer.

My goal during this project was to assess mankind’s technological capabilities and determine the feasibility of a manned mission to Mars, with the hopes of establishing a permanent and self-reliant colony over time. As a mechanical engineer I have been able to apply my knowledge of physics, design analysis, materials science, thermodynamics, and CAD towards completing this project. Solving the problems presented by this project has required me to use my knowledge in applications I otherwise would never have had to consider. Topics such as base design, base construction, resource utilization, and energy requirements were all considered with current technology in mind in order to show the possibility of our mission using both well established and cutting edge technology.

The advances made in science and technology that will come from exploration in space over the next several decades will have a massive impact on many fields of engineering. Various technological organizations should be looking for progress in space to lead innovation now more than ever. This IQP has allowed me to grow as an engineer by giving me the vital project experience that WPI prides itself on. While attending WPI I have learned many important skills that will aid me in my career as a Mechanical Engineer; I believe that the technical knowledge that I have learned here is what will qualify me for a career, but the curiosity and problem solving abilities that I have fostered during the Humanity and Space IQP will be the qualities that will distinguish me from my peers as I try to benefit the world through engineering.
Throughout all of time humans have been exploring. From Leif Ericsson discovering North America in 1001 AD, to Ferdinand Magellan circumnavigating the globe in 1519, all the way to Neil Armstrong and Buzz Aldrin landing on the moon in 1969, Humans have constantly pushed the boundary of the unknown. At our point in time, we as a species have discovered just about everything worth discovering about Earth, so our next step in exploration is space. So why should we explore, Earth is a wonderful place right? Humans as of right now do not have a backup plan. What if some unforeseen event happened either due to an occurrence in space or our own doings as a species (such as pollution, nuclear war, etc.) happens. Elon Musk, CEO of Space-X said There’s a fundamental difference, if you look into the future, between a humanity that is a space-faring civilization, that’s out there exploring the stars compared with one where we are forever confined to Earth until some eventual extinction event. Exploration of space is necessary for the survival of our species.

The idea of saving humanity is what has drawn me to taking on the challenge of this project. I hope to show that settlement on Mars is within humanity’s technological grasp, and that humans as a species have a reasonable backup plan if extinction is near. I also hope that I can contribute to an incredible feat in exploration and science in my generation that will change the course of humanity forever. This project will complement my studies and career in Aerospace Engineering well, as the most innovation of all other fields needs to occur in this specific field in order to make interplanetary settlement possible. Ultimately I hope this project can make people grasp how close civilization is to achieving a Mars settlement.
2.4 Kenneth Quartuccio

People who were born near the end of the 1990’s have grown up in two very different worlds. We can recall a time when pagers were prominent and cell phones were exotic, yet as teenagers every person we knew had a device in their pockets containing all of the information humanity has ever produced. It isn’t a stretch to say that we are the last children of the old world and the first born into the new one. In a few short years, our generation will be the one in charge of fixing all of the worlds issues. Over population, global warming, and the energy crisis are all things that will destroy humanity if we don’t find a solution. All of the problems that humans have caused over the course of their existence seem to be coming to a boiling point, and that is the exact reason why we need brilliant engineers and scientists.

I chose this IQP because it addresses a very important step in our evolution. Humans can only live on Earth for so long, and we are quickly running out of time. Within our lifetime, people must begin to stretch out across the stars. This will lead to problems, both technological and philosophical. Even if a manned mission to another world is years away, we as a people need to start thinking about it now, because humanity and space are two forces that are destined to be intertwined. My goal for this IQP is to learn about the challenges that face today’s scientists and to think about how we can address them. Lots of problems will be solved in new and exciting ways and it could be anyone with an idea who figures out the best possible solution.
I grew up in a family full of aerospace engineers with my great grandfather running a bomber factory in World War II and my grandfather working on the Apollo missions. Air and space have always been a part of my life and this became a stronger tenet as I grew older and became involved in science, technology, and engineering myself. The path I took carried me away from that of my family members and into the realm of electrical and electronics engineering, by my love of space never entirely subsided. Of course, there was always the speculation of what my life may have been had I taken the same path they did, but exploring on my own was always the winning factor; it’s far less fun to do something if someone else has already done it.

When choosing an IQP, traveling to another country just to do schoolwork wasn’t particularly enticing. However, the idea of humans traveling to Mars or beyond certainly was. As an engineer, one is often lost in the details and the realistic limitations of any idea or plan, but this project let me explore a venture without being bounded by what is currently possible but only by what my peers will be able to realize in the future. Of course, this didn’t entirely free me or my partners from the mindset and we often found ourselves evaluating ideas based on their practicality, which is not an entirely bad thing if any of this plan is ever to come to fruition. Perhaps our efforts paired with advancements in other fields will make an IQP on Mars a possibility in a few decades’ time.
Chapter 3

Research
3.1 Current Space Policy

3.1.1 US Space Policy

Since its inception in 1958 and especially through the space race of the sixties, the United States’ space program has been a great source of national pride. This has continued into more modern times with the exploration of Mars and has followed the program into the private sector, with SpaceX experiencing, albeit to a lesser degree, a similar outpouring of support at launch events.

Similarly, the program has been responsible for advancing the boundary of possibility through its entire life. Beginning with the first man-made satellites and the first men in space, impossible has been a fleeting concept. This sense of continual innovation is carried into the private sector with the recent advent of rockets that can land as well as the lives of the general public with numerous day-to-day products that have been introduced as the product of NASA research, such as memory foam and cordless vacuums to name a few in a field of many.

As more nations have seen the benefits of space programs, they have followed suit and created their own. While fostering scientific and technological development on a global scale, this also creates a whirlwind of geopolitical pitfalls as nations are forced to interact outside the realm of concepts such as air space or sovereign territory. Perhaps the most notable incident regard this concept was China’s destruction of the Fengyun-1C satellite. This single event generated more space debris than any other, with 2,317 pieces of golf ball-size or larger, an estimated 30% of which will still be in orbit in 2035. Additionally, the event demonstrated the ability of a nation to forcibly remove a satellite from orbit, and while in this case it was one of their own, it would apply equally to the satellites of other nations. This had the potential of starting a sort of arms race in space, though this seems to have
been avoided, at least as far as the public is concerned.

On a more positive note, the Senate has laid out a set of goals for the future of the US space program. These goals largely revolve around the establishment of a human presence beyond low Earth orbit and eventually on Mars. Such an endeavor would require a follow-up to the recently-decommissioned space shuttle that would be capable of taking 70 – 100 tons of cargo into low Earth orbit and beyond while also filling the former role of the space shuttle in regard to the ISS. This new vehicle, in combination with bases in low Earth orbit or beyond would enable human exploration deeper into space. The bases’ contribution to such voyages would be the opportunity to resupply – just as fighter jets can refuel in the air, the new vehicle would be able to dock with bases in space to refuel, replenish life support systems, and refill stocks of rations. This capability may also be extended to other nations or commercial craft as other groups also seek to enter deeper space.

3.1.2 Russian Space Policy

The Russian space policy is based heavily on the space policy from the Soviet Union. Although a lot has changed and Russia has faced ups and downs, the Russian Federal Space Agency has managed to keep the program running by focusing much of their efforts on commercial satellite launches. Currently, Russia has focused on updating its rockets, as well as its Global Navigation satellites and its communication network.

3.1.3 Chinese Space Policy

Historically, the Chinese space program has had its ups and downs. It took them until 1970 to launch their first satellite, and even though their space program was founded in 1967, they put their first astronaut into orbit in 2003. The Peoples Republic of China has revealed that they intend to create a permanent space station by 2020, and want to put Chinese on the
Moon in the near future. Their long term goals include using near earth space for industrial purposes, and they were one of the first countries to propose harvesting resources from the moon. Recently, The National Space Bureau has spent a lot of resources on a Solar Satellite power grid.

The United States and China have an interesting conflict in terms of space policy. The United States Congress has made it illegal for NASA to spend any money on Chinese visitors to NASA. All Chinese citizens are required to get a waiver from NASA before they are allowed to enter any facility run by them. In addition, any employees of a Chinese Government owned company are not allowed to work on NASA projects, and are viewed as a security risk. This policy extends as far as the ISS, which is maintained by several space fairing nations, but does not allow the Chinese astronauts on-board.
3.2 Propulsion Methods

3.2.1 Launch Loops

A rather novel approach to launching cargo and passengers into orbit is the launch loop. First proposed by an electrical engineer by the name of Keith Lofstrom, the structure would be a roughly 2,000km long and 80 km high arc near the equator. The main piece of the structure would be the cable which is shown in red in figure 4.12. This cable, or rotor, would be magnetically levitated within a protective sheath. This sheath would then be anchored to the ground by numerous steel cables. This is rather peculiar as the cables in fact hold the loop down instead of up. This is because the rotor, which is traveling at 14 km/s, follows a parabolic path if left unchecked. This path would extend far higher than 80km, but is limited in order to keep a large section at a constant altitude. At each end of the structure, the rotor is turned around in a teardrop-shaped loop and then follows the same path back to the other station.

In order to launch a payload, it is first lifted via cable up to the western station, which is where the cable first reaches its full height after rising up from a turnaround section. Then, a permanent magnet that is attached to the payload is placed around the rotor. This magnet will induce eddy currents within the rotor which will in turn pull the payload along in the direction of the rotor. Thanks to this coupling method, the acceleration is mild at only 3G. Compared to other methods, this is minuscule and is entirely compatible with the limits of the human body, which makes it viable for transporting humans. Once the payload is up to the required velocity, it is released from the cable and begins flying of its own accord. However, a closed orbit at 80km isn’t particularly useful, so a small kick motor, likely a rocket, is necessary to put the payload into a different orbit. Without a kick motor, the launch loop would still be capable of putting payload into non-closed orbits, such as escape
orbits, gravity-assist trajectories, or injection into Lagrangian points. Since each payload launch requires only a permanent magnet, possibly a kick motor, and, of course, the energy to keep the loop running, launches are extremely economical. With a full scale launch loop constructed, it may cost as little as $3/kg to launch cargo into orbit. This would allow for frequent launches – up to 80 per day – that would make large-scale commercial space travel feasible.

However, this low per-kg cost is balanced in part by a large up-front cost. Building a full-scale launch loop would cost in the neighborhood of $30 billion, which is more than NASA’s annual budget in its entirety. For this reason, it will likely be an international undertaking, much like the ISS. Even with international support, a smaller pilot model would be more likely as the first launch loop. This model would cost about $10 billion, but at the cost of annual payload capacity as well as a higher cost per-kg – approximately $300/kg – to launch payloads.
In the case of either loop, no new high-tensile strength materials would be necessary, which are currently the limiting factor behind space elevators. At 80 km high, the loop is above most weather, making it possible to launch cargo all day every day regardless of weather conditions. However, this altitude is still low enough that the loop is largely protected from space debris, which would make maintenance much easier and increase the lifespan of the structure as a whole. This sets it apart from space elevators yet again, which are prone to being wiped out by space debris. The launch loop can also mitigate the effects of radiation by using strategic open orbits that travel through radiation belts as fast as possible. In this manner, exposure time is limited, unlike other methods that may leave passengers in the belts for days.

Despite all the benefits of the launch loop, there are a few detriments. For one, too many launches may overheat the rotor. Overheating would cause the rotor to lose ferromagnetic properties, so its containment would be lost. The massive amount of kinetic energy contained in the loop – nearly that of an atomic bomb – would then have to be dumped at deliberate failure points. The risk of such an event is why the loop is proposed to be built over an ocean far, far away from habitation. Furthermore, every piece of the loop from the rotor temperature, rotor levitation, turnaround containment, etc would need to be carefully monitored as a failure in any system could cause a catastrophic failure. For this reason, all systems would need to be highly redundant in order to allow for many individual components to fail while the system remains operational. Then, of course, there’s the biggest problem of all, which is how to turn the loop off. As soon as it loses power and begins to lose energy, the rotor and sheathe will begin to descend back to Earth. Protecting these components as they come down to Earth is no small undertaking and as of yet is unsolved, meaning that the loop would have to undergo extensive repairs each time it was taken off line.
3.2.2 Solar Sails

The main benefit to solar sails is their simplicity. Essentially, they are massive and extremely thin sheets that are deployed from a spacecraft. They use no electricity, fuel, and can be folded up to take minimal storage space. A metallic and reflective alloy film is used for the sail. They produce thrust from the reflection of photons coming off the sun. While they do not produce the same amount of thrust as a rocket or ION thruster, the acceleration is a lot more consistent and is applied over a much larger time. An ideal and perfectly efficient solar sail would produce an acceleration of $0.117m/s^2$ using a sail size of $0.82km^2$. The main disadvantage of solar sails is their short lifespan. Because they are large solid structures, space objects will puncture and warp the sails until they are no longer functional. While it is hard to predict, it is very likely that sails would have a lifespan of only a couple trips. It is also worth mentioning that vessels operating within peak solar winds like solar sails do would be exposed to larger levels of radiation than spacecraft that do not rely on those forces.

NASA and The Planetary Society have built working examples that have been tested in space. The light sail 2 is a small cubesat, developed by the Planetary Society. It is 10cm by 10cm by 30cm and contains a 32 square meter sail that is 4.5 microns thick. Its predecessor was launched in 2015 as a proof of concept. In the future, solar sails can be used to make trips to the inner three planets much more efficiently. This would be its ideal use, because it is a region of low debris and high solar energy. Another possibility would be to shoot the sails with a powerful laser. This would produce much greater thrust than sunlight, and such a laser could be positioned on the moon or in orbit and could use solar power to charge the laser.
As more nations have seen the benefits of space programs, they have followed suit and created their own. While fostering scientific and technological development on a global scale, this also creates a whirlwind of geopolitical pitfalls as nations are forced to interact outside the realm of concepts such as air space or sovereign territory. Perhaps the most notable incident regard this concept was China’s destruction of the Fengyun-1C satellite. This single event generated more space debris than any other, with 2,317 pieces of golf ball-size or larger, an estimated 30% of which will still be in orbit in 2035. Additionally, the event demonstrated the ability of a nation to forcibly remove a satellite from orbit, and while in this case it was one of their own, it would apply equally to the satellites of other nations. This had the potential of starting a sort of arms race in space, though this seems to have been avoided, at least as far as the public is concerned.
3.2.3 Ionic Propulsion

Ionic Propulsion, though promisingly fuel efficient will not be viable for a Mars mission. Ion thrusters are engines that ionize gas particles with electron bombardment and electrostatically exhaust them to produce thrust. Advantageously, ion thrusters use low weight propellant, and have a very high specific impulse, while they can be powered by the use of solar panels. However, this technology has not come a long way considering that it can only provide a relatively small thrust and can not be used in launch stages. Ion thrust is certainly more palpable for Deep Space missions that do not hinge on time requirements, high weight requirements, and more. Therefore an ion propulsive thruster will not be taken into consideration for Mars Colonization.

![Diagram of a Typical Ion Thruster](image)

Figure 3.3: Diagram of a Typical Ion Thruster
3.2.4 Space Elevator

While the current preferred method of space travel relies on chemically powered rockets taking off from Earth’s surface, a space elevator could prove to be the most effective way of reaching space in future generations. A space elevator is an earthbound transportation system that utilizes extremely strong material in geostationary orbit to lift cargo into space. Geostationary orbit occurs at about 35000 kilometers in the air, at this point the centrifugal force outwards equals the gravitational force inwards, the space elevator will extend beyond this point until reaching anchor point several more kilometers out where a counterweight will be placed. If constructed a space elevator would use slow moving lifters to gradually lift cargo and astronauts into space without the need for powerful yet inefficient rockets.

The main limiting factor to the plausibility of a space elevator are currently the materials needed to build it. Unfortunately, a space elevator would be under an extreme amount of stress due to its massive size, and as of yet current man made materials are not able to withstand such forces. Once the material science breakthroughs necessary to support a space elevator are achieved, a lifter will be able to transport objects of various shapes and sizes into space without the conventional limitations of rocket powered shuttles. The most important benefit of a space elevator would be the reduction in cost required to send material into space. This advancement would make sending objects into low Earth orbit an order of magnitude cheaper per kilogram. The lack of high velocity takeoffs involving thousands of liters of chemical explosives inherent with rocket powered shuttles would put less strain on cargo and make sending materials into space much safer and more reliable.
3.2.5 Chemical Propulsion

Chemical rockets use thrust produced by the expansion of hot gas created by combustion. For methods of this type to work, two types of propellant must be present: a fuel and an oxidizer. All current rockets designed to launch from Earth into space use some sort of chemical propulsion system. The most common of these methods is the multi stage solid fuel rockets that use solid fuel. Solid fuel is created by mixing a fuel and an oxidizer into a solid mass, called a Grain. There are 2 main types of grain:
• Double-Base, which is mostly made up of nitroglycerin and nitrocellulose and resembles smokeless gunpowder

• Composite (now predominant), consists of an oxidizing agent such as ammonium nitrate or ammonium perchlorate mixed an organic or metallic fuel.

There are also two main types of engines that use liquid fuel. The first type, liquid bipropellant engines, use two different chemicals, a liquid fuel and a liquid oxidizer, and combines them in a combustion chamber to create thrust. Usually either high power pumps or pressurized tanks are used to feed the fluids into the combustion chamber. The second type, liquid monopropellant engines, use chemicals that can be turned into hot gas through decomposition in a rocket chamber. The most common application of this is passing hydrogen peroxide through a platinum catalyst mesh. This causes it to decompose into hot steam and oxygen, which can be expelled for propulsion. These engines have relatively low thrust, but only require one tank, and can easily be turned on and off, making them useful in situations where efficiency of fluid is not important.
Figure 3.5: Common Rocket Using a Chemical Propellant
3.3 Colonization

3.3.1 Farming

Farming is the only realistic way of providing the astronauts enough food for their stay on Mars since establishing a continuous supply chain of food to Mars is incredibly expensive and impractical. Hydroponics, aquaponics, and aeroponics are all promising forms of crop farming on Mars since fertile soil for crop growing would be hard to find. In hydroponics, aqueous solutions would provide nutrients and water to the plants instead while some solid objects keep the plants stable. Aquaponics is similar to hydroponics, except that the aqueous solution is provided by the water in a connected habitat for aquatic organisms. The plants and aquatic organisms essentially exist in symbiosis as they continually share and recycle the water and dissolved nutrients. Aeroponics is also similar to hydroponics, except that the aqueous solution doesn’t sit at the plants’ roots. Instead, the solution is occasionally delivered to the plant in a sprayed mist. All these forms of farming will probably not work in a zero-gravity environment without extreme and careful control and consideration, but on the surface of Mars, it offers an excellent substitute to conventional soil farming.

Vertical farming is another option for efficient farming, as it does not require wide open flatlands but rather a box-shaped volume of space to grow crops; plus, general plant growing in a cramped, zero-gravity environment was and still is regularly occurring, especially on the ISS, so crop growing isn’t too far-fetched [18][20][38]. So far, based on experiments on plant growth in space and the fact that resources are very limited in space, the crops most suited for sustaining an initial space colonization mission are lettuce, radishes, snap peas, tomatoes, and possibly even potatoes and sweet potatoes [20]. Additionally, any form of crop farming can be accompanied by insect or small animal farming for the same reasons of limited space and resources; closed ecological system experiments by Japan, Mexico, and
Russia have shown that bugs and certain animals like goats, quails, and perhaps rabbits show potential to be food sources in space \cite{20,50}.

![Aquaponics System Diagram](image)

Figure 3.6: Diagram of a Standard Aquaponics Setup

### 3.3.2 Sustainable Habitats

Orbital colonies and surface outposts seem to be the simplest and most cost-effective habitats for sustaining human life in space, and quite frankly, they would not be very different in concept or structure from currently existing space habitats like satellite space stations. The major difference, and drawback, is that these habitats will not be close to Earth to benefit from Earth’s natural radiation shielding or from practical resupply missions as with
the currently orbiting stations. The issue of radiation protection still requires considerable research and development to fully address, though some plausible solutions to this issue exist (see Sections 4.1.4 and 4.11). The issue of supplies on Mars, at least the minimum to support human life, is more or less already solved: creating an artificial ecosystem where the substances that maintain life continually recycle themselves should be enough. The real issue of supplies is ensuring that there is a backup for everything, in case any part of the habitat or ecosystem should fail, but with the right technologies (e.g. robots, 3D printers, drillers, transport rovers, etc.) on board the ship to Mars, it should be somewhat feasible to harvest the elements of Mars to replenish resources lost to unforeseen circumstances.

![Figure 3.7: Earth Testing of Martian Habitat](image)

Habitats based underground or in caves would be significantly more expensive to construct than those in orbit or on the bare surface simply because they involve the arduous
processes of digging, burying, and providing structural support throughout the digging and burying. While still prone to accidents as any space habitat, radiation becomes nullified under the mass of all the Martian soil on top of the habitat. Plus, despite the costs of digging without causing cave-ins, more Martian land is inevitably unearthed as digging continues, thus allowing the astronauts to explore and learn about Mars like never before since most rovers are restricted to surface scouting; said unearthed territory should be available immediately whenever expansion is desired with little worry for radiation and the climate on the surface.

3.3.3 Sustainability

Even without any major technological breakthroughs, the construction of a sustainable base on Mars is very possible in the near future, and the initial Martian colonization process could be completed within a single generation. If humans were preparing to travel to Mars, a large portion of the construction necessary for their survival could be performed by autonomous robots. Robots could ensure that any humans arriving on Mars would be able to immediately begin the long term planning and preparation necessary for expanding into a thriving colony. Robots could also aid humans in performing time consuming tasks that would drain the outpost of unnecessary resources such as exploration and collecting resources. Simple tasks that would prove too difficult and/or dangerous for humans could be performed by robots with little risk to human life involved. It is critical that resources such as oxygen, water, and nutrients are recycled to their fullest on the colony, these resources will be difficult to procure on Mars, although it is feasible in the long run, and saving as much as possible will be crucial for the early outpost’s survival. One key to a sustainable outpost setting the stage for colonization would be the ability to expand and improve on the existing habitat. Developments such as adding farmable areas to grow a sustainable food source, collecting resources such as water and oxygen allowing for the survival of a growing population, and
extracting resources such as iron that could be used to help bolster the construction process of new habitable areas.

Unfortunately for future colonists, even with excellent planning and ideal conditions there is still the possibility that an equipment failure will occur. The failure of vital systems is a real and dangerous threat facing astronauts, and they may need to be able to recover from said failures without receiving aid from Earth. A system in which replacement parts can be built from scratch will prove vital to the success of the colonization effort. Technological advancements like 3d printers will prove exceptionally useful in situations such as this, and if these processes can take place on a large enough scale then the construction of additional living space can be achieved. One of the most important developments that needs to take place for a sustainable colony to exist on Mars will involve the development of a safe and precise system of manufacturing that can be performed on site.

### 3.3.4 Social Issues

The socioeconomic concerns of a Mars Colonization are absolutely not to be overlooked. There are a few different ways to go about setting up a governmental structure. Mars colonization could be set up as a government agency in which people are hired by governments on earth to inhabit, and employees are assigned with specific tasks. On the other hand, providing business incentive for colonization might make the colony self sustaining on its own, and an isolated government may need to be set up on that planet. Since the ultimate goal is population growth, test tube babies might be the most advantageous option. Human pregnancy on Mars is something that must be studied because it cannot be assumed that it will work from a biological standpoint. As the population grows on Mars, infrastructure must be set in place to expand as the population grows, with proper support. It is also important to note that proper medical and mental health facilities should be in place, as they are essential to human life.
3.3.5 Terraforming

Terraforming is the process of altering the magnetic field, atmosphere, and other traits of a planet in order to make it more habitable for humans. This is a long term process but would eventually result in a fully inhabitable second world, which many argue is the best reason for space exploration and development. The process varies based on the needs of each world, but are all considered theoretical because of the scale required. Another fact that should be considered is that outside of certain methods, terraforming is a very long process. Humans have terraformed Earth over the course of our existence, so it is not a short process.

![Figure 3.8: Expected Transformation of Mars from Ideal Terraform](image)

Out of all planets we can visit, Mars is the current best option. In order to terraform it, we need to produce a magnetic field, and an atmosphere. This would allow water to stay
in its liquid form. The process of terraforming can be accelerated by nuking the poles of Mars, sending robot factories to pump CO2 into the environment, or by using rockets to push Mars closer to the sun. If humanity wanted to produce noticeable changes in a human lifetime, it would likely require a combination of all these methods. Unfortunately, we do not have an effective and feasible plan to create a magnetic field across the entire planet. The ideal way of doing it would be to restart the Martian planet’s core, but that is about as far as that plan has gotten. Some notable scientists think meteors might work, or using thermonuclear devices on the planet’s now cooled outer core. If resources were not an issue, it would also be possible to create a large electromagnet that loops around the equator. For now humans will be able to live on Mars using biodomes and closed environments, but one day humans will be able to live and breathe unhindered on the red planet.

3.3.6 Harvesting Water from Mars

One of the biggest barrier to life on Mars is the apparent lack of liquid water. Any organisms that might have once lived on the planet no doubt depended on H2O, in the same way that we do on Earth. If humans want to go to Mars, they need to have a source of water, be it taken from earth or some other means. While it is possible to extract water from the soil using a complicated chemical procedure, finding a source of it on Mars would be the best possible solution. By looking at geographic features on Mars, it is clear that liquids once flowed across the planets surface. River beds and basins have led scientists to believe that the Red planet was once blue. Water was recently discovered in a 375,000 square kilometer region of Utopia Planitia, in the North Eastern Hemisphere of Mars. If this is true, it would mean that Future Martians will be able to extract water ice right from the planet, and would significantly reduce the amount of water that will need to be brought along. If all of the identified Ice on Mars were returned to water, it is expected that it would be equal to nearly five million cubic kilometers, or enough to cover the whole planet in 35 Meters of water.
However, because the planet does not have an atmosphere, any liquids on the surface would quickly be lost into space.

Figure 3.9: Color Map of Possible Water on Mars
3.4 Realistic Plan for Mars

3.4.1 Preparations

Funding from various organizations across the public and private sectors will be very important to the success of a mission of this nature. While state owned organizations such as NASA have historically led the world in space exploration, a new generation of corporations are preparing to take the lead in securing a foothold on Mars in the near future. Companies such as Boeing and SpaceX have recently stated goals of designing the rockets that will bring astronauts to the moon. If these organizations can cooperate on common goals, the goal of establishing a Mars outpost can become an affordable reality. Another vital stage of preparation is choosing a landing site; Mars is covered in craters and ancient volcanoes that could provide a suitable home for Martian colonists. The location choice will depend if colonists are going to try to build on open plain type areas or seek shelter in the ancient cave systems found on Mars. After the funding and location have been chosen all of the cargo and technology needed to complete the mission can be designed, built, and prepared for the long journey to Mars. Things like autonomous robots will have to be designed if any of the habitat is going to be constructed or assembled while the astronauts are on route to Mars. The exact amount of equipment sent is also a crucial part of the planning process when every kilogram sent up costs up to $20000 dollars in fuel. The most important part of preparing for a mission such as this is almost certainly the crew selection and the training that they will receive before leaving to establish an outpost on Mars. Everything hinges on the crew being able to make the important decisions and reacting to real time situations that may unfold at any point after they leave the surface, as well as holding up to the pressure of spending extended amounts of time in a hostile environment such as space or the surface of Mars.
3.4.2 Space Travel

One of the most important parts of the planning process is having several smaller launches before the manned mission. In order to keep a crew of six alive in space for a nine month plus transit stay on Mars, approximately 3 million pounds of resources will be required. This number is even larger because a manned trip to Mars would most likely not have a return trip unless an emergency situation occurred. In order to get all of these supplies into orbit using current technology, NASA and other space organizations would need to collaborate at least sixty launches. Some of these launches would be sent to Mars before humans, such as the ones containing the ground structures and surplus resources.

Figure 3.10: Representation of SpaceX heavy rocket

The shuttle that would launch with the astronauts would contain all of the supplies
that the space travelers need to survive the trip, as well as any last minute additions. This is possible because the ideal window to send a ship to Mars is once every 26 months. During this time, the elliptical orbits of the Earth and the Red Planet line up in such a way that would ensure a relatively short voyage of 260 days. The resources that need to be set up for our arrival would be sent ahead of the astronauts, and then 26 months later would be followed by humans. If any changes are made in the period, or any issues are occurred during setup of base, the plan could be adjusted with ease. The crew of 6-10 astronauts would be put into hibernation for the majority of the flight, with 2 of them out of hibernation for 2 week intervals. This is so that if any emergency occurs aboard the vessel, such as loss of communications or system failure, there is a person who can step in immediately while the rest of the crew is woken up. While almost every possible event can be planned for, there are quite a few things that will be challenging for a flight. Extended time in higher radiation environments, the risk of solar flares, and micrometeor impacts are all threats that need to be prepared for. Once people arrive on Mars, things will become much safer, though definitively not to the same degree as Earth.

3.4.3 Assembling the Base

The outpost will initially consist of six lander modules connected side by side and two elongated inflatables attached to the center two modules. The inflatables will serve as the main living quarters for the colonists. They will have a total floor space of about 200 square meters and will include sleeping quarters, farm land, project workspaces, and whatever else is needed for the colonists to survive. The two center modules contain the airlocks needed to enter and exit the base. The other four contain life support systems to sustain the base and the equipment used to extract water from the soil on Mars.
The modules will all be launched separately along with a robot designed to prepare the base before the astronauts arrive. It will move all of the modules to the desired location. It can then attach the inflatables and start the water and oxygen collection processes.

### 3.4.4 Humans on Mars

As the humans move into their new martian home, they will be given time to become adjusted to their new world. After acclimating to the gravity, they will ease into their new way of life. Each member of the team will have specific assignments that are given based on their background experience. Lots of lower level life functions, such as basic farming and maintenance, will be handled by the vast array of robots that will coexist with humans in the outpost. Higher order functions, such as robot repairs and drone based scouting can be done by humans. In addition to carrying out experiments of all sorts, the most important task
will be improving the quality of life for the humans that come after. The biggest and most prolific task that is thrust upon these young men and women is that they will be the first of many future martians. Everything they do should be aimed at bringing more people to the Red Planet. Tasks like building roads between the outpost and resources will be done mostly by machines, but under the command of humans. As brilliant and powerful as NASA is, they don’t have experience living on Mars. After a year of living out in space, the astronauts will know what they want to change to improve the quality of life. As it goes from being a cramped outpost to a more established settlement, hopefully it will attract more and more people to make the journey. Exponential growth will take effect and in only a few decades Mars will go from being a barren wasteland to a barren wasteland with a bustling settlement nestled on its surface. Those first humans will be in charge of guiding this transition, and as they experience life on Mars, they will know better than anyone what needs to be done to move forward.

3.4.5 Food and Water

Various farming possibilities have been discussed in detail in Section 3.3.1. Based on that discussion, the team has decided that the ideal method of feeding the astronauts on the ship is not farming but simply storing a year’s supply of food aboard the space vessel, nine months of food for the trip as planned and three months of food as emergency rations.

The ideal method of feeding the astronauts on the Martian surface would a combination of aquaponics and animal farming supplemented by a compost system as a backup or reserve for emergency purposes. The aquaponics system would be an independently functioning and self-sustaining ecosystem that regularly provides and replenishes food. Much like the astronauts themselves, the animal farming system would depend on some proportion of the crops grown in the aquaponics system and would simultaneously provide organic waste to be recycled through the compost system. The compost system would simply turn
the organic waste into fertile soil for potential conventional farming should the aquaponics system malfunction or the crops receive insufficient nutrients.

Water will be extracted from small particles of ice in the martian soil. This will be accomplished by grinding the surrounding rocks into fine dust, then superheating the dust in order to evaporate the water particles out. Each of the four modules will be able to produce 1500 liters of water and 365 kg of oxygen with this method, so that they will be able to support six colonists all together.

### 3.4.6 Projects

Once the initial outpost is fully constructed and safe for the astronauts to live in, there are various projects for expansion, exploration, and research that can be put into motion. One of the most important jobs the early colonists will have will be to scout the surrounding areas in search for important resources and valuable strategic locations. The possibility of finding resources such as frozen or liquid water underneath the Martian surface is vital for improving the efficiency of large scale colony expansion on Mars. Locating expansive cave systems that provide geothermal energy and radiation shielding could be another important development that can help to facilitate the expansion of a Martian colony beneath the surface.
Aside from searching the martian planet for valuable locations and resources, scientists and engineers can look for novel ways to improve the colony from a technological perspective while working to expand the outpost. Another important project that colonists can undertake is the construction of laboratories specializing in indoor and outdoor experiments similar to those found on the ISS; the early research conducted on Mars may prove invaluable to the long term success of the colony. A key project to expanding the Mars colony will be the construction of a manufacturing facility that can mass produce materials necessary for expanding the colonies without the need for expensive equipment to be sent from Earth. All of these projects will help to make Mars more independent from the supplies that will be sent from earth over the years.
Chapter 4

Application
4.1 Proposed Plan for Martian Outpost

4.1.1 Astronauts for Outpost and Colony

While none of this would be possible without the advanced technology found in today’s society, one of the most important factors of a successful colonization will undoubtedly be the men and women selected to undertake this grand scheme of colonizing Mars in the name of humanity. A young group a diverse and well prepared engineers and scientists will be in charge of making this dream possible, and with the help of countries and companies across the world they will have all the tools necessary for the task that lies before them on Mars. These brave astronauts will be the backbone of the entire mission, without them there can be no colonization effort on Mars, they will be the pioneers that take the world onwards towards the final frontier of mankind.

The screening process for both outpost and colonization stages must be extremely thorough, this mission will be incredibly difficult and will require every astronaut to perform their duty to the best of their abilities while on board the shuttle and on Mars itself. Astronaut candidates must display many traits that will make them suitable for space travel and colonization on Mars. They must be resilient, adaptable, curious, trustworthy and trusting, resourceful, above the age of 18, physically fit and healthy, and social. Once selected these astronauts will undergo a year-long test in a space-like environment to examine how well they are able to work together while coping with relative isolation and claustrophobia. After the training process is complete the astronauts will begin the mission of establishing a permanent outpost on the Martian Surface.

The outpost astronauts will be responsible for the most perilous and difficult part of the colonization process, they will need to be able to set up a sustainable outpost and take the first steps towards colonizing Mars. While some of the setup can be done by robots that
will be sent along with cargo headed for Mars, in the end it will be the astronauts who make sure that the artificial habitats are properly constructed and ready to sustain life. Once on Mars, they will address any failures that occurred during robotic setup and complete any stages that could not be handled prior to landing. Once the final phases of securing a sustainable base on Mars are complete, the astronauts can begin focusing on studying their new surroundings and expanding the outpost in preparation for the coming colonists.

While the colonists may not have the honor of being the first inhabitants of Mars, their task is one of even greater impact on the future of the human race. Upon arrival, the colonists will take over the task of expanding the outpost left to them by their predecessors. Their main focus will be to maintain and improve the base while making sure maximum sustainability is achieved. At this point large scale projects such as underground shelters and cave based outposts can be built separately from the initial outpost. The first generation of the Mars Colony should consist of at least 160 people. According to genetic research, this number is the minimum number of inhabitants conducive for a genetically stable colony that can assure genetic diversity for up to 10 generations. This will give the initial colonists plenty of time to expand the colony and better adapt to life on Mars. The Initial outpost inhabitants can be married or single due to the fact that they will return to Earth after the outpost is completed. However, colonists must either be single or married to a fellow colonist in order to insure maximum genetic diversity, and while colonists will be able to return, it is expected of them to be willing to live on Mars permanently.

While sending fully-grown adults from Earth to Mars seems to be the most reasonable option for colonization, a more effective strategy could include sending the material needed to create humans to the Mars colony in order to improve the colonization process. The colonists could bring genetic material such as embryos and “test tube babies” in order to assure genetic diversity and genetic health of future generations. Qualified donors can send their DNA to Mars in order to help bolster the genetic diversity of such a small group of inhabitants. This technology may prove crucial to fulfilling one of the colony’s main goals
of allowing more humans to live on Mars.

4.1.2 Spacecraft Propulsion

The spacecraft will, for all intents and purposes, be a replacement for the space shuttle, albeit with greatly increased capabilities. Like the space shuttle, it will require boosters to exit Earth’s atmosphere and these will likely be something akin to the reusable Falcon IX from SpaceX. Having reusable boosters greatly decreases the cost of launch, though fuel is still fairly expensive in and of itself. Once in space, propulsion will come from variable specific impulse magnetoplasma rockets, or VASIMR’s. These engines ionize gas then guide and accelerate it out of the engine to create thrust. A variety of gases may be used, with the more common choices being argon and hydrogen. Hydrogen would be preferable in this scenario as it is much easier to obtain while on other planets, making off-Earth refueling much easier. As an added bonus, hydrogen is a fantastic barrier to neutron radiation. This is especially useful since the only viable way of powering VASIMR’s, which consume large amounts of power, in space is by the use of a nuclear reactor. While fusion would be preferable, fission is far more likely. Both emit neutron radiation, which may be conveniently blocked by strategic placement of fuel containers. The rest of the radiation produced would be blocked in the same manner as that coming from outside the vessel as will be discussed in section 4.1.4.

4.1.3 Life Support

Space and, for the most part, other planets are inherently hostile to human life. This has always been a problem faced by astronauts, so thankfully much of it has been solved by people with much more expertise than the IQP team. To begin, humans exhale carbon dioxide and water. The water is extracted and while some of it is reserved for crew use, the
rest is split into oxygen to breathe and hydrogen. A Sabatier reaction utilizing a ruthenium-on-aluminum catalyst can then react carbon dioxide and hydrogen to form methane, water, and energy in the form of heat. The product methane can then be used as a fuel source that is – at least marginally – more stable than the raw hydrogen produced by oxygen generation. Combusting methane will yield water and carbon dioxide, which can then be fed back into the life support system for recycling as well as large amounts of energy, which may be used to provide power when other methods are out of commission in some manner. As a backup, the vehicle as well as the cargo initially delivered to Mars will include lithium perchlorate canisters. At 400°C, this chemical will decompose to form solid lithium chloride, which is a salt, as well pure oxygen. Each of these canisters produces enough oxygen for one crew member for one day, making them an extremely effective backup plan.

As for water, cues will be taken from the ISS. All waste water, whether it be from the showers, sweat, or urine of crew members or lab animals alike will be captured. Capturing it is fairly straightforward with gravity, but during the journey some of it may float away, leaving it to be captured by the cabin air recycling system. Once captured, the wastewater is heavily filtered by a mix of chemical processes as well as physical filters until it is once again pure and ready for use.

4.1.4 Radiation Protection

Radiation is a problem that must be combated in order to take a successful trip to Mars. A Mars shuttle is always subjected to galactic cosmic rays, as well as solar energy particles, especially when there are solar flares. Solar flares can be expected to happen at least twice in a sixty day trip aboard a Mars Shuttle. Polyethylene, with an areal density of 40 g/cm² coated on a sheet of aluminum, would reduce the current amount of radiation dosage that people on the shuttle would experience by two thirds. On top of this, a shell filled with water should be onboard, so that when solar flares are detected by Geiger counters, people on the
shuttle will go into the water shell and avoid the radiation submitted effectively.

4.1.5 Location

One of the most-discussed topics with the plan to Mars is the location. As any good realtor will tell you, location is everything. With this being the first step of humanity onto another celestial body, that phrase is even more applicable. Some places that are considered are right near the equator, and on one of the poles. They each have their own benefits. The equator is warmer, offers more ideal geography, and would be much simpler to accomplish. The poles offer easy-to-obtain water (and oxygen, by extension), and have a small magnetic field to protect against radiation. However they are much much colder. A first settlement would most likely be established in the equator, because of the more hospitable temperament. One vista that is being looked at in particular is the region of Arsia Mons. It is part of the 3 volcanic calderas that neighbor each other, with coordinates 8.35 degrees south and 120.09 degrees west. It is an interesting area because satellites have identified seven separate cave systems around the walls of the extinct volcano. In the first outpost, parts of it could be constructed inside these caves, such as the water reservoirs and farms. Underground, they would be safe from radiation, and the temperature is much more stable. While a large amount of the initial outpost will be structures that are man made and buried, it is important to use your environment to your advantage.
4.1.6 Water Production

Much like on the spaceship, the water on Mars will be heavily recycled to conserve energy and resources required to make more. However, new water will need to be produced in order replenish losses and to be converted to oxygen. This new water will be created in a process that uses the carbon dioxide in the atmosphere to extract Hydrogen from martian rocks. This process requires equipment that can turn carbon dioxide into a supercritical fluid by heating it to about 31°C and a pressure of 73 atm. In this state, carbon dioxide becomes a strong solvent that can extract useful materials from martian rocks. When rocks containing Hydrogen are submerged in this supercritical fluid, carbon dioxide’s carbon atom becomes fixed in the rock, and leaves the oxygen free to bond with the hydrogen to create water.
The advantage of this process is that it used materials that are abundant all over Mars and very little effort needs to be used to collect them, as well as the fact that there is no need to worry about running out of them or needing to find a new location to collect from. The atmosphere on Mars is 95% carbon dioxide and hydrogen is present all over in the soil on Mars’s surface.

However, this process will only be necessary if a source of readily-available water cannot be found. Recent data suggests large deposits of water exist under the Martian surface either in the form of ice or liquid water. If this proves to be the case and there is a deposit near the base, a simple well would be adequate. Water would first be inspected for microbes or harmful substances, such as heavy metals. If given the "all-clear," this water would be added to the system where it would be purified and act to replace the water lost to inefficiencies in the system or the astronauts themselves.
4.2 Candidate Selection

After everything is said and done in terms of funding, designing, and developing the mission, the process of finding a proper crew will prove to be the most important factor in deciding whether or not this groundbreaking venture into space will prove to be one of mankind’s greatest achievements. Despite the painstaking effort of some of the best minds on earth, anything could go fatally wrong while in space or on the Martian surface. It will be largely up to the outpost crew to handle any problems that will arise during the 9 month flight to Mars, as well as during the years of preparation leading up to the expansion of the colony. Due to this responsibility, it is of the utmost importance that these crew members are able to solve a host of issues that can render life saving equipment nonfunctioning, and do so without the backup of organizations here on earth. This project has determined that sending 6 astronauts to build the outpost will assure an acceptable level of diversity while also maintaining maximum efficiency of resources and cargo required. Due to the scientific nature of the operation each of the candidates selected will be required to have an extensive background in an engineering discipline vital to the completion of the mission.

4.2.1 Engineering Qualifications and Applications

One of the most important tasks of the outpost crew will be to expand the outpost and construct living spaces for the future colonists of Mars. Due to the highly specialized nature of the habitats and the extremely low margin for error it is vital that every stage of development is closely monitored by a trained engineer who is capable of ensuring the structural integrity of the colony. The architectural/civil engineer will be in charge of development of the colony through the implementation and understanding of the physical structures that will be built and assembled on site.
One of the most pressing concerns about the wellbeing of members of a long term space mission is the biological effect that space will have on organic material, most importantly humans. A biomedical engineer will be in charge of studying the long term effects of space travel on the crew and keeping the crew fit and healthy. They will also be in charge of studying the long term effects of life on Mars and how to alleviate the issues that stem from these effects.

Many of the chemicals that will be sent with the astronauts to Mars will not be found on site, therefore it is imperative that a member of the team can understand the chemicals and chemical reactions that will sustain the crew and outpost over the course of the mission. A chemical engineer will be responsible for observing and maintaining chemicals that are vital for food, fuel, and fluid management.

An incredible amount of technology will accompany the astronauts on their mission to Mars, as well as during their mission on Mars. It is necessary to have a crew member that understands the control system and is able to fix any technological issues that arise with hardware and software during the mission. A computer/electrical engineer will be in charge of maintaining computer and electrical systems aboard spacecraft and on the outpost.

Every mechanical system on-board the ship and located on the outpost will experience wear and tear from the demanding environments that they have been placed in, things will inevitably need to be fixed, built, and replaced. Someone with extensive knowledge of machines must be present to carry out these duties while the colony is constructed. A mechanical engineer will be responsible for maintaining the equipment and machines aboard the ship as well as on the outpost. In many cases they will work together with other crew members to maintain the vital systems to ensure the success of the mission.

With recent advances in technology, it is clear that a majority of the physical work will be carried out by robots or highly autonomous machine elements that will assist the crew in developing the outpost for colonization. The robotics engineer will be responsible for maintaining and optimizing the robots that are involved with the design, assembly, and
expansion phases of outpost construction. In order for the mission to be a success the robots must be able to perform many of the base expansion operations.

Almost all of the equipment sent to Mars will be used at some point or another will experience fatigue, and it will be the job of these brave astronaut to maintain the equipment and keep things running smoothly so that the colony can be made operational as quickly as possible. With a combination of specialists in a variety of fields the chances of failure are severely diminished, and almost any problems can be addressed without the need for additional crews to be sent to continue the work that must be done to set up the Mars colony.

### 4.2.2 Other Qualifications and Applications

Aside from just the engineering requirements of the mission, a multi-year mission to Mars and back will require many other tasks to be completed before colonists will be ready to begin life on Mars. These astronauts should have a range of skills necessary for survival and advancement on Mars. On top of extensive knowledge in their chosen field of engineering, each astronaut will specialize in one of the following areas in order to completely cover any challenges that may arise during the mission. These skills do not fall into the same skill set of engineering but will still cover vital areas of the mission that will need to be filled out.

One of the most important factors to consider when sending a group of humans on a perilous and challenging mission such as this is who will make quick, important decisions while operating on site with the crew. The need for a leader to make decisions using first hand information when Earth cannot is imperative to the overall success of the mission. The leader must be able to keep the crew motivated and on task but not strain the relationship of the small and isolated group. The leader must command respect while also addressing the needs of the crew. If the mission is to be a success then any and all issues between members must be adequately handled by someone on site. The commander will serve as the leader of
the crew who will make decisions and ensure all other members of the crew are performing optimally and working together without issues.

Despite a massive amount of navigational oversight from organizations such as NASA that will plot the shuttles course as it approaches Mars, the need for a human pilot will be critical at certain stages of the Mission. As the shuttle gets further and further away from Earth, the latency of information sent back and forth between the shuttle and Earth will become a big concern for the crew. As the latency reaches approximately 20 minutes it becomes vital that a members of the crew can be responsible for quick maneuvers that cannot be handled by mission control. Operations such as docking, avoidance of space debris, and other course reconfigurations will be the difference between life and death for the crew. The pilot will also be able to fly the craft if contact with Earth ceases to function. Overall, the pilot will control the spaceship maneuvers to and from Earth in order to help maximize independence from the command center on Earth.

While engineering can solve many of the technical problems that might arise during the mission, a crew member with extensive medical knowledge must be on board to help diagnose and treat any of the medical issues the crew might face while off planet. Despite all crew members being fit and healthy at the beginning of the mission, they are not guaranteed to remain so over the course of the mission, especially after several years while their mission nears its end. Stress, illness, or injury can all lead to disaster if not properly treated by the crew’s medical expert. The long term effects of space travel and lowered gravity are well understood, and resisting their degenerative effects are vital to the completion of the mission and the wellbeing of the crew. For the most part, the mission medical expert will make sure all members of the crew are fit and healthy. They will also address any health issues that may arise on route or while on the outpost.

Navigating such immense distances requires a complete understanding of astrophysics that will allow someone to understand the motion, direction, and coordinates of an object in space. In the event of the shuttle needing to make course alterations, it is important
that someone onboard can ascertain the changes that need to be made in order to assure that the corrections needed to reach the proper destination can be made. Space is incredibly hard to navigate, three dimensional travel as well as relative speed over an extended period of time become incredibly important during space travel. The Astrophysicist/Navigator will be in charge of calculating any course alterations that will occur as well as observing any necessary changes to the flight that may occur. This person will make sure that the shuttle reaches an extremely precise location moving at just the right speed.

Despite decades of observation and exploration carried out by machines, the ability for a human to be able to observe the Martian surface and collect samples in person will be a truly groundbreaking opportunity for the scientific community. What lies beneath certain areas of the Martian surface still remains largely unknown, and further research could yield vital information on the composition of Mars’s surface and what lies below. A geologist can study samples collected by robots as well as explore the geological properties and features that surround the outpost. They will use their knowledge to find suitable locations for expansion and development, and maybe even discover the existence of water just below the rocky surface.

One of the most important factors that will determine if the colony will be able to survive and provide for itself is if a stable supply of crops can be formed in order to feed the future colonists. A large scale system that can support extended amounts of food production will be constructed and maintained for the duration of the colony, an expert who can efficiently and effectively care for crops will be essential for developing sustainable life on Mars. A hydroponic system will most likely be utilized for this mission, which allows for more efficiency while also requiring much more specified care. With the proper knowledge and application the colony can achieve extremely high yields that are otherwise unattainable on conventional Earth farms. The effects of Martian soil, gravity, and sunlight can also be thoroughly observed over the course of several years while the crew develops the colony. This Botanist will use their knowledge to grow and develop crops as well as maintain the crops
for the maximum level of efficiency and crop health.
4.3 Meal Plan for Trip from Earth to Mars

4.3.1 Nutritional Needs

With current technology, the astronauts will likely have a nine-month journey, during which all astronauts will be fully active and thus must be fully fed.

"Caloric requirements are determined by the National Research Council formula for basal energy expenditure (BEE). For women, $BEE = 655 + (9.6 \times W) + (1.7 \times H) - (4.7 \times A)$, and for men, $BEE = 66 + (13.7 \times W) + (5 \times H) - (6.8 \times A)$, where $W =$ weight in kilograms, $H =$ height in centimeters, and $A =$ age in years." [15].

These are the minimum caloric requirements for non-active (i.e. physically active) humans. In reality, astronauts will be responsible performing very many activities for months in unusual conditions of a spaceship in zero gravity. So with regards to calorie consumption, all astronauts should meet their BEE plus 50-100% of that value daily.
4.3.2 Options

<table>
<thead>
<tr>
<th>Beef, Diced (IM)</th>
<th>Fruit</th>
<th>Tortillas (FF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beef Goulash (T)</td>
<td>Apple, Granny Smith (FF)</td>
<td>Tuna</td>
</tr>
<tr>
<td>Beef Pattie (R)</td>
<td>Apple, Red Delicious (FF)</td>
<td>Tuna Creole (T)</td>
</tr>
<tr>
<td>Beef Steak (T)</td>
<td>Apple sauce (T)</td>
<td>Tuna Salad Spread</td>
</tr>
<tr>
<td>Beef Stroganoff w/Noodles (R)</td>
<td>Apricots, Dried (IM)</td>
<td>Turkey</td>
</tr>
<tr>
<td>Beef Tips w/Mushrooms (T)</td>
<td>Banana (FF)</td>
<td>Turkey Salad Spread (T)</td>
</tr>
<tr>
<td>Bread (FF)</td>
<td>Cocktail (T)</td>
<td>Turkey Tetrazzini (R)</td>
</tr>
<tr>
<td>Breakfast Roll (FF)</td>
<td>Orange (FF)</td>
<td></td>
</tr>
<tr>
<td>Brownies (NF)</td>
<td>Peach Ambrosia (R)</td>
<td></td>
</tr>
<tr>
<td>Candy</td>
<td>Peaches, Diced (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pears, Diced (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pineapple (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strawberries (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trail Mix (IM)</td>
<td></td>
</tr>
<tr>
<td>Cereal</td>
<td>Granola Bar (NF)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ham (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ham Salad Spread (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jelly</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Apple (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grape (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Macaroni and Cheese (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Meatballs in Spicy Tomato Sauce (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Noodles and Chicken (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nuts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Almonds (NF)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cashews (NF)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Macadamia (NF)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peanuts (NF)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trail Mix (IM)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peanut Butter (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Potatoes au Gratin (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Puddings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Banana (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Butterscotch (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chocolate (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tapioca (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vanilla (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rice and Chicken (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rice Pilaf (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Salmon (T)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sausage Patty (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shrimp Cocktail (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soups</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chicken Consoom (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mushroom (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rice and Chicken (R)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spaghetti w/Meat Sauce (R)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: A large sampling of the menu used on a NASA Space Shuttle [15]
(FF) Fresh Food  Item underwent no special preparation and thus, must either be eaten within the first few days of the flight or stored in a refrigerator to prevent spoilage.

(IM) Intermediate Moisture  Item was drained of all but around 15-30% of its original moisture (water) content. The item must contain a substance that readily chemically binds to water, specifically salt or sugar, so that the item does not readily spoil; packaged in a clear flexible pouch and ready to eat.

(I) Irradiated  Item was preserved, or rather, sterilized by exposing it to ionization radiation; beef steak is the only product on this list produced this way; packaged in a flexible foil-laminated pouch.

(NF) Natural Form  Item was specially packaged to delay spoilage but otherwise unchanged; like Fresh Food, except it is not urgent to consume the item early in the trip; packaged in a clear flexible pouch and ready to eat.

(R) Rehydratable  Item was freeze-dried to remove nearly all its moisture, reduce its mass, and preserve it for at least a year. Simply adding water, or rehydrating, the item will make it suitable for consumption by astronauts.

(T) Thermostabilized  Item was heated to destroy microorganisms, the only major threat to the item’s long-term quality; packaged in aluminum or bimetallic cans, plastic cups, or retort pouches and ready to eat.

Table 4.2: Abbreviations in in table 4.1

Of course, many foods will need to be processed so that they can last the journey through space. For example, fresh produce, unless refrigerated, lasts only two days, hence the need for special preparation procedures; note that most vegetables on the list are labeled R. The abbreviations above indicate the methods of preparation each individual food item would undergo on Earth before their storage on the spaceship. Once they go through the manufacturing or packaging processes on Earth, most space foods can be eaten straight out of their containers (FF and NF) or prepared simply by adding water or heat (R and T) [15].

Foods would be various to provide a wide variety of nutrients (beef, cereals, chicken, bananas, etc.). Even luxury items that many people may take for granted on Earth can be brought onto the ship like condiments and espresso coffee. Given the great menu of space
foods above, giving astronauts variety and luxuries in their space dining experience should be relatively straightforward.

An aside to this topic is the possibility of international cuisine options so that all members of the (ideally) internationally diverse spaceship crew may enjoy or share the cuisine of their cultures throughout the arduous journey, provided that such foods are also prepared using one of the listed methods as appropriate.

4.3.3 Expected Payload for Food

Each astronaut should have no more than roughly 3.8 lb (of which about 1 lb is packaging) worth of food daily to minimize the spaceship’s payload; this was a standard used and established by the space shuttles. Additionally, the astronauts should have predetermined emergency rations expected to have a two-year shelf life when stored at ambient temperature (60-85°F) in case the journey to Mars or the building of a sustainable Martian farm takes longer than expected [15]. To account for this, it is assumed that the astronauts will need food for 12 months. If it is also assumed the crew will consist of 6 astronauts:

\[ 3.8 \text{ lb/astronaut/day} \times 6 \text{ astronauts} \times 365 \text{ days} = 8322 \text{ lb} = 3775 \text{ kg} \]

Cost to launch food (assuming SpaceX Dragon is used at $9,100/lb[13]): $75,730,200
### 4.3.4 Example Meal Plan for the Trip

<table>
<thead>
<tr>
<th>Meal</th>
<th>Sunday</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakfast</td>
<td>Choice of cereal and fruit; cocoa</td>
<td>Food bar; coffee; orange juice</td>
<td>Food bar; coffee; orange juice</td>
<td>Choice of eggs; bread or breakfast roll; cocoa</td>
<td>Food bar; coffee; orange juice</td>
<td>Food bar; coffee; orange juice</td>
<td>Choice of cereal and fruit; cocoa</td>
</tr>
<tr>
<td>Lunch</td>
<td>Choice of beef and vegetable; fruit-flavored drink</td>
<td>Choice of granola bar and nut; fruit-flavored drink</td>
<td>Choice of turkey and vegetable; fruit-flavored drink</td>
<td>Choice of soup, cracker, and spread; fruit-flavored drink</td>
<td>Choice of chicken and vegetable; fruit-flavored drink</td>
<td>Choice of chicken and vegetable; fruit-flavored drink</td>
<td>Spaghetti, mac and cheese, noodles with chicken, or meatballs; fruit-flavored drink</td>
</tr>
<tr>
<td>Dinner and dessert/snack</td>
<td>Ham, salmon or sausage; choice of candy; tea or apple cider</td>
<td>Potatoes; bread with peanut butter; tea or apple cider</td>
<td>Shrimp cocktail; choice of vegetable and fruit; tea or apple cider</td>
<td>Rice with chicken; bread with spread or jelly; tea or apple cider</td>
<td>Rice pilaf; choice of pudding; tea or apple cider</td>
<td>Bread with choice of meat and condiment; brownies; tea or apple cider</td>
<td>Tortilla with choice of meat and condiment; choice of cookie; tea or apple cider</td>
</tr>
</tbody>
</table>

Table 4.3: Example meal plan for the trip
4.4 Long Term Food Production on Mars

4.4.1 Initial Considerations

The BEE for men and women are still assumed to be true on the surface of Mars. Surplus food will be needed for strenuous individual activity, morale-boosting celebrations, and population growth. This surplus will be achieved through agriculture. Since the base will be built underground to minimize radiation exposure, all food must be grown in a somewhat cramped, underground, and indoor environment. By minimizing the crops’ radiation exposure, however, their access to natural sunlight are also limited, so the options for agriculture are limited to indoor methods – this fact is not much of hindrance. Such indoor methods actually produce significantly higher food yields, though at a higher cost than conventional methods. Recall from Section [3.4.5] that the agricultural options chosen to be ideal are:

- Animal Farming, in which the astronauts would bring along chicken and quail to Mars and raise them as livestock to reproduce and provide natural meat. Experiments on quail as potential space livestock have been promising, as they have already been successfully hatched with minimal complications in zero gravity, even though the same cannot be said of chickens yet.

- Aquaponics, a form of soil-free farming. It would take up less volume than and also function more efficiently than classical farming. Aquaponics in particular allows for the growth of a miniature ecosystem that can yield both edible crops and edible fish.
4.4.2 Livestock on Mars

The top animals of choice for initial Martian agriculture should be animals small enough to store in a compartment or box on the ship but large enough to provide meaningful nutrients and be easily accounted for. Plus, these animals should reproduce quickly and have relatively short life cycles.

Chickens and quails best meet these specifications. Additionally, the eggs of this birds can be sent to Mars and incubated during the journey; this would be preferable to sending up the heavier payload of fully grown birds. Maintaining these birds should be a relatively straightforward task as all they really need are water, poultry feed, and coops.

Fish are perfect for establishing an aquaponic system and farm; for simplicity, our hydroponic system will include with tilapia and catfish. A tilapia is resilient to many water conditions; it is a warm-water fish that eats algae. A catfish is a bottom-feeder; it eats (and therefore recycles) waste products in the system or practically anything that other fish would eat. The exact species of fish the crew would bring would be the channel catfish (Ictalurus punctatus) and the blue tilapia (Oreochromis aureus) [5]. Much like the Mars outpost itself, this aquaponic system would recycle all expended resources with great efficiency.
## 4.4.3 Nutritional Comparison of Viable Livestock and Crops

<table>
<thead>
<tr>
<th>Livestock and Crops (yields per 100 g)</th>
<th>Energy (kcal)</th>
<th>Water (g)</th>
<th>Protein (g)</th>
<th>Total lipid (g)</th>
<th>Fiber (g)</th>
<th>Calcium (mg)</th>
<th>Iron (mg)</th>
<th>Potassium (mg)</th>
<th>Sodium (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lettuce</td>
<td>15</td>
<td>94.98</td>
<td>1.36</td>
<td>0.15</td>
<td>1.3</td>
<td>36</td>
<td>0.86</td>
<td>194</td>
<td>28</td>
</tr>
<tr>
<td>Peas (in a pod)</td>
<td>42</td>
<td>88.89</td>
<td>2.80</td>
<td>0.20</td>
<td>2.6</td>
<td>43</td>
<td>2.06</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>Radishes</td>
<td>16</td>
<td>95.25</td>
<td>0.68</td>
<td>0.10</td>
<td>1.6</td>
<td>25</td>
<td>0.34</td>
<td>233</td>
<td>39</td>
</tr>
<tr>
<td>Potatoes</td>
<td>77</td>
<td>79.25</td>
<td>2.05</td>
<td>0.09</td>
<td>2.1</td>
<td>12</td>
<td>0.81</td>
<td>425</td>
<td>6</td>
</tr>
<tr>
<td>Sweet Potatoes</td>
<td>86</td>
<td>77.28</td>
<td>1.57</td>
<td>0.05</td>
<td>3.0</td>
<td>30</td>
<td>0.61</td>
<td>337</td>
<td>55</td>
</tr>
<tr>
<td>Chicken</td>
<td>239</td>
<td>59.45</td>
<td>27.30</td>
<td>13.60</td>
<td>0</td>
<td>15</td>
<td>1.26</td>
<td>223</td>
<td>82</td>
</tr>
<tr>
<td>Chicken eggs</td>
<td>154</td>
<td>76.13</td>
<td>10.57</td>
<td>11.66</td>
<td>0</td>
<td>48</td>
<td>1.48</td>
<td>117</td>
<td>155</td>
</tr>
<tr>
<td>Quail</td>
<td>227</td>
<td>60.00</td>
<td>25.10</td>
<td>14.10</td>
<td>0</td>
<td>15</td>
<td>4.43</td>
<td>216</td>
<td>52</td>
</tr>
<tr>
<td>Quail eggs</td>
<td>158</td>
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<td>11.09</td>
<td>0</td>
<td>64</td>
<td>3.65</td>
<td>132</td>
<td>141</td>
</tr>
<tr>
<td>Catfish</td>
<td>144</td>
<td>74.65</td>
<td>18.44</td>
<td>7.19</td>
<td>0</td>
<td>9</td>
<td>0.28</td>
<td>366</td>
<td>119</td>
</tr>
<tr>
<td>Tilapia</td>
<td>128</td>
<td>71.59</td>
<td>26.15</td>
<td>2.65</td>
<td>0</td>
<td>14</td>
<td>0.69</td>
<td>380</td>
<td>56</td>
</tr>
</tbody>
</table>

Table 4.4: Nutritional comparisons of viable food sources [14]

The recommended daily amount of the trace elements shown are roughly 1000 mg for calcium, 8 mg (for males) or 18 mg (for females) for iron, 4700 mg for potassium, and no more than 1500 mg for sodium [26]. Because it can be tricky to supply these nutrients along with all other recommended nutrients with such limited farming capabilities, the astronauts will bring dietary supplements to meet these recommendations. In the future as the Mars outpost grows into a full colony and advanced farming techniques and manufacturing equipment become available, ensuring that the inhabitants receive all the recommended nutrients should become less difficult.
### Meal Plan on Mars

<table>
<thead>
<tr>
<th>Meal</th>
<th>Sunday</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakfast</td>
<td>Chicken Eggs</td>
<td>Potato</td>
<td>Sweet Potato</td>
<td>Potato</td>
<td>Sweet Potato</td>
<td>Potato</td>
<td>Quail Eggs</td>
</tr>
<tr>
<td>Lunch</td>
<td>Catfish and Lettuce</td>
<td>Chicken and Peas</td>
<td>Quail and Radish</td>
<td>Chicken and Radish</td>
<td>Quail and Radish</td>
<td>Chicken and Peas</td>
<td>Tilapia and Lettuce</td>
</tr>
<tr>
<td>Dinner and dessert/snack</td>
<td>Potato and Radish</td>
<td>Sweet Potato and Lettuce</td>
<td>Potato and Peas</td>
<td>Sweet Potato and Lettuce</td>
<td>Potato and Peas</td>
<td>Sweet Potato and Lettuce</td>
<td>Potato and Radish</td>
</tr>
</tbody>
</table>

Table 4.5: Example meal plan for the stay on Mars
4.5 Space Allocation

4.5.1 Overview

While much of the focus of this report is on the immediate setup of a Martian outpost, eventually we hope to achieve a fully functioning society on the Martian surface that offers a unique and enjoyable experience for the colonists. For a developed colony with a population of under 1000, the basic requirements for everyday life will need to be met either through trade with Earth or on site production. The long term goal of the colony is to become independent from Earth in every way possible, this means that many everyday facets of life must be developed in the colony itself. Some developments will be critical for survival, but others may be more trivial things that help add to the diversity of life on Mars. Here we have decided on some of the basic allocations of space in the colony that will be able to simulate the diversity of day to day life on Earth. The long term health of colonists will depend on their ability to adapt to the new environment of Mars, but that does not rule out the construction of a colony that supports lifestyles similar to that on Earth. Each one of the following buildings will, once constructed, help colonists enjoy and take part in a full and fulfilling life. These additions to the colony may also help them deal with the stress that may come with being a colonist on Mars.

4.5.2 Proposed Construction Projects

Residential spaces are a very important part of how the colonists will live their personal lives, if each colonist has a small space to personalize and call their own it will help boost their morale and foster a spirit of individuality and privacy that will nurture the long term psychological health of each and every member of the colony. These private spaces will
also serve to help build a sense of community, with neighboring colonists spending extended amounts of time with other groups of colonists within the colony as careers, interests, and locations within the colony begin to take shape. Family units can be connected using the individual pod based system utilized in the colony’s construction, helping to create the next generations of colonists as well as the first native Martians.

One of the most important things that will developed once a fully developed colony emerges is a small economy based on the specializations of members within the colony itself. Space will be allocated for commercial business such as shops and offices. Basic materials and services will be provided to all colonists while in the colony, but colonists who wish to provide unique services will also be allowed to do so once construction allows for such expansions. Colonist with marketable skills and interests can provide services to other colonist, setting up the basis for a small Martian economy to develop.

Public and semi-public enclosed spaces will eventually be constructed within the colony to provide for many important elements of modern life. Government offices that help maintain order and leadership within the colony will eventually need to be set up. Hospitals will need to care for citizens as the population and duration of colonial stays increase. Schools to educate the future Martian workforce will be vital for the long term success of the colony as a whole. Community centers, recreational centers, and entertainment

Public open spaces are another important development that will add to the diversity of life on Mars. Construction projects for things like parks and other outdoor recreational centers such as swimming pools and playgrounds will add to the full lifestyles that the colonists will want to experience. These types of spaces will be much larger than the usual pods that are developed and therefore will require extensive planning and design before they are added to the existing colonial structure.

Later expansion of Martian society will eventually lead to a Light service industry, where people will be able to acquire an assortment of goods that are created on Mars for Martians. Colonists will be able to purchase things such personal goods, furniture, and
handicrafts (just to name a few) made by other colonists.

An important development for the colony is sets of pods dedicating to storing large amounts of materials that may not need to be used immediately. Storage pod areas will be set up once the colony is able to create resources in bulk and save surplus resources for future use or repurposing. This way if production on a resource falls behind the loss can be mitigated through the implementation of surplus resources.

Mechanical subsystems will be brought with the initial outpost in order to keep early colonists alive, but as more and more colonists arrive the need for larger systems will lead to the construction of more advanced and industrial infrastructural systems. Systems such as electrical distribution and transformer substations, communication and telephone distribution, oxygen treatment (air movement and distribution), water treatment (supply, return, recycling), and sewage treatment to name a few of the vital infrastructure systems that will keep the colony functioning over the years.

Once the colony becomes large enough colonists may not want to travel by foot to get from place to place, a form of transportation will need to be developed in order to make travel faster, easier, and more efficient. A separate pod system dedicated to transportation will help to achieve this goal while also not disrupting the established pod system that will have already been put into place.

Despite a wide variety of pods that will be set aside for the use of colonists in their day to day life, the majority of space will still be dedicated to the agricultural needs of the colony. Hydroponic crops will take up a large part of the colony, while sections that raise animals will also take up a considerable amount of space within the colony. Agricultural needs are the main consideration for sustaining the population, and agriculture areas will need to constantly be expanded in order to provide for a growing colonial population.
4.6 Space Allocation for Colony Farming Area

4.6.1 Overview

In order to sustain large numbers of people on Mars an advanced system of farming must be constructed and maintained on a very large scale. One of the best crops to grow on Mars is arguably sweet potatoes, the team has decided to use sweet potatoes as one of our staple crops due to its versatility and viability as a primary crop for Martian colonists. Sweet potatoes have about 180 calories per kilogram, which makes them one of the most calorie dense food items on Earth (or Mars). Sweet potatoes are also very nutrient dense, providing a multitude of vitamins and antioxidants that will help to support the long term health of colonists. Recent testing on Mars-like soil has also proved that sweet potatoes could easily be grown in Martian soil as well.

4.6.2 Conventional Farming Requirements

Conventional farming is the basis by which we will test the efficiency and effectiveness of farming viability on Mars. In order to figure out how much dedicated farming space will be required per person is a complicated endeavor, but in order to simplify that matter we are going to assume that the diet of our colonists is supported by artificial protein and multivitamins that provide the colonists with everything except for the actual calories they must consume to stay healthy. The Average yield of sweet potatoes on 4000 square meters of land in average Earth conditions using conventional modern farming techniques comes out to about 2750 kilograms/year. Sweet potatoes provide about 860 calories per kilogram according to the USDA, which means that under these conditions a harvest of solely sweet potatoes will create about 2.25 million calories per year. The average male requires 2500
calories per day, which comes out to about 1 million calories per year. This means that under nominal conditions an average male would be able to subsist on 1500 square meters of land on a Martian colony.

4.6.3 Hydroponic Farming Requirements

While the use of conventional farming makes sense here on Earth due to the high costs related to hydroponic farming, the need for efficient use of space and resources on Mars will play a much bigger role in the allocation of resources. Hydroponic farming or an equivalent technique will need to be utilized in order to reduce the amount of material that is sent up with the initial colonists. In terms of time, space, and resources, hydroponic farming has several key advantages over conventional farming that will prove essential to the Mars colony. The exact quantity of improvement from conventional to hydroponic farming techniques vary, but many techniques state a conservative estimate of 10 times the yield of produce per square meter. In addition to huge boosts in special efficiency, using hydroponics provides a 90 percent reduction in water requirements compared to conventional farming. On top of that, due to the precise and consistent nature of hydroponic operations, hydroponic crops grow 50 percent faster than conventional crops. Hydroponic crops also utilize exact quantities of nutrients which serves to increase the growing capacity per kilogram of cargo significantly. Combining these factors makes farming on Mars an order of magnitude more efficient in terms of space and raw materials required for the long term survival of the colony. Combining these statistics and extrapolating from the conventional farming techniques section, a harvest of solely sweet potatoes would be able to sustain the caloric intake for the average male for a year using only 80 square meters of land. This type of efficiency would make growing crops on site not only efficient, but extremely reasonable despite the massive limitations of space allocation that would be present in a space colony.
4.6.4 Rooms and Basic Requirements

Much like the rest of the outpost, all the food production rooms should be Earth-like in atmosphere and utilities. The rooms should be about 18.33°C (i.e. room temperature) and the artificial atmosphere should be about 78% nitrogen and 21% oxygen at 1 atm pressure. As briefly discussed in Section 3.4.5 and Section 4.4, it has been decided that the optimal forms of farming to have on the Mars base would be the animal farming of chicken and quail and the aquaponic system of fish and crops growing in a symbiotic environment. Additionally, although it would be burdensome and even unnecessary to bring fertile soil to Mars for farming purposes, redundancy in mission planning and emergency preparation cannot be dismissed.

There would be three types of rooms in the complex, one for compost, one for the birds, and one for the fish and crops. The compost room would serve to store the compost, continuously processed by earthworms in a composting chamber, as a backup medium for crop growth in case some part of aquaponic system should fail, but it could also be used to support the growth of high demand crops like potatoes. The room would be designed such that human waste from toilets and other organic waste could be pumped or otherwise easily disposed into the composting chamber and recycled as potential soil for the crops. The chicken and quail room would simply consist of holding pens for birds, as well as incubators kept at 37.5°C for hatching laid eggs. The aquaponic room would be the most complex and large of the room types, housing the fish tanks for the catfish and tilapia, the containers into which the crops will be grown, the lighting system that would allow crops to grow underground, and the pumps and pipes circulating water throughout the system. Catfish can grow well in water from 18-30°C, and tilapia can grow well in water from 16-27°C, but since plants grow better in water around 22.7°C, the temperature for water in the aquaponic system will be set to 22.7°C. Also for the sake of the plants, the artificial lighting systems under which crops will
grow should emit light of a wavelength of 400-500 nm, or ideally a combination of lights with middle wavelength values from 425-475 nm, to maximize the absorption of light by both the chlorophyll and carotenoids in the plants, and, by extension, the rate and extent of crop growth.

4.6.5 Expected Dimensions for Farm

A few scientifically and mathematically sound assumptions can be used to estimate some of requirements about the aquaponic room. First of all an ideal ratio of the total mass of fish in a fish tank to the volume of water available in said fish tank is about 0.04 kg to 1 L. The average mass of channel catfish is hard to pin down since they can grow to be anywhere from 1 to 50 lbs. However, many commercially grown catfish are harvested as food when there are about 1.5 lbs, or 0.7 kg so this mass is assumed to be the average. The average mass of a blue tilapia can be better estimated as it has a smaller range of masses; an adult tilapia is typically between 5 and 6 lbs, or 2.2 and 2.7 kg. The average mass is estimated to be on the lower end of the range at 2.3 kg because Mars could complicate fish growth and the tilapia will be harvested more often and sooner than the catfish since catfish grow much more slowly.

At least 1600 m² of aquaponic ”field” will be needed to grow enough crops to sustain one colonist, assuming the colonists eats only the crops grown in the system, i.e. no animals. The plants will demand a significantly greatly portion of nutrients in the system; low-maintenance fish were chosen to simplify the matter of making sure all organisms receive the right amount of everything they need to grow. Since the fish chosen will eat practically anything, the challenge is ensuring that there is enough fish producing enough waste in the tanks to supply enough nutrients to the plants via the water; this fish waste turned to plant nutrients will mostly be nitrogen.

Additionally, fish waste is initially fish food, so the growth of the crops depends
on the maximum of mass of food that the fish can consume daily. In other words, the food web in the aquaponics system will require that the fish eat a certain amount of food daily so that in turn the plants can "eat" just enough fish waste to grow, and some portion of the crops will return to the system to feed the fish. In prior research by Dr. Wilson Lennard, this amount is called the aquaponic feeding rate ratio; mathematically, it is the number of grams of food that should be given to the fish per square meter of crops per day \[32\]. There will be plants that demand very many nutrients, particularly tomatoes, potatoes and sweet potatoes, and according to Doctor Lennard’s research, such high-maintenance plants would need to eat fish food at least at a rate of 100 \(g/m^2/day\); it is assumed that all plants will require this amount so as to cover potential nutrient deficit.

Recall that a 1600 \(m^2\) field is needed in an aquaponic system to feed a colonist, so to supply enough nutrients to the plants through fish waste, all the fish must eat:

\[
1600 \ m^2 \times 100 \ g \ food/m^2/day = 16,000 \ g \ food = 16 \ kg \ food/day
\]

Fish need to about to eat 2% of their total body mass daily to survive, so total mass of fish needed to consume 16 kg food daily would be:

\[
16 \ kg \ food/day \times (1 \ kg \ fish ÷ 0.02 \ kg \ food/day) = 800 \ kg \ fish
\]

Now applying the fish mass to water volume ratio from earlier, the required volume of water is:

\[
800 \ kg \ fish ÷ (0.04 \ kg \ fish/1 \ L \ water) = 20,000 \ L \ water = 20 \ m^3
\]

A 20 \(m^3\) fish tank will be split into two parts, one for all the tilapia and one for all the catfish, though water could still flow freely between both parts. The split will be based on their average mass so that there are roughly equal numbers of tilapia and catfish:

\[
0.7 \ kg \ catfish + 2.3 \ kg \ tilapia = 3.0 \ kg \ (total \ mass \ of \ 1 \ catfish \ and \ 1 \ tilapia)
\]

69
800 kg fish ÷ 3 kg fish ≈ 267 catfish and 267 tilapia

20 m³ × (0.7 kg catfish/3.0 kg) fish ≈ 4.7 m³ space for catfish

20 m³ × (2.3 kg tilapia/3.0 kg) fish ≈ 15.3 m³ space for tilapia

With these volumes in mind, catfish will be housed in a volume of dimensions 1 m × 4.7 m × 1 m and the tilapia in a volume of dimensions 1 m × 15.3 m × 1 m for a tank of dimensions 1 m × 20 m × 1 m.

The volume of the aquaponics room where all the crops grow and the colonists can walk around will be 3200 m³ (that is, 40 m × 40 m × 2 m). Plus the volume of the fish tank brings the total amount of space needed to construct a sustainable aquaponic farm to 3220 m³. Since this room could only feed one colonist hypothetically, six rooms are needed to feed all six colonists, bringing the grand total volume of the aquaponics complex that could feed the Mars crew to 19,920 m³.

As far as the chicken and quail room is concerned, too many chickens and quail in the early outpost will be a disadvantage because they should not consume too much of the food from the aquaponic system that the astronauts will depend on for survival. Hence, a single 4 m × 2 m × 2 m room (volume 16 m³) with a 0.9 m × 1.2 m × 1.8 m incubator and a 1.2 m × 1.8 m × 1.8 m coop for the chickens and quail should suffice. As was the case with the fish, the coop the shall be divided by species, with the special rules that each chicken gets its own private section of a set volume while a group of quails, on account of their much smaller size, occupies a section of similar volume. A single chicken needs 0.108 m³ of space and a single quail needs only about 0.00472 m³ or equivalently, 20 quails require 0.0945 m³ of space [8] [21]. The space needed for 20 quails is brought up to 0.108 m³ so that all the sections of the coop can be of equal dimensions 1.2 m × 0.3 m × 0.3 m. Thus there will be 36 sections that can each house one chicken or 20 quails; there will be 30 sections housed by 30 chickens and 6 sections housed by 120 quails.
4.7 Health of the Crew

4.7.1 Sanitation

Since the astronauts, by basic biological necessity, will live in a enclosed, controlled habitat on the spaceship and on Mars, all matter, from particles in food packaging to soil from planets, or from human sweat to computer parts, has the potential to move to any location within the habitat. While some such recirculation of matter is good, such as the recycling of urine for water, most recirculation poses high risk to the astronauts, such as the spread of pathogens.

Although microbes like bacteria and fungi first come to mind with regards to contamination, seemingly harmless household items like tape, plastics, and even food can cause problems for an closed internal environment because of their potential to off-gas vapors that can’t naturally dissipate into the outside environment. Plus, since all matter recirculates in these habitats, all contaminants, if left unchecked, threaten the astronauts’ health. Advanced monitoring systems and sensors will be equipped on the spaceship and the Mars outpost to notify the crew about increased contamination levels; thus, the crew could take informed, appropriate measures to reduce the contamination, such as regularly replacing or cleaning air filters, treating water, and disinfecting surfaces [27].

A couple contamination-monitor devices, the volatile organic analyzer (VOA) and the Vehicle Cabin Atmosphere Monitor (VCAM), use a gas chromatograph a spectrometer to detect, identify, and quantify a wide variety of particulate substances, especially volatile gases like ethanol and methanol. Also used is the POTOK, an air filtration device by Roscosmos, which disinfects microbes with electrostatic pulses and charged ions. Another sanitation device is the Heat Melt Compactor (HMC) that, as its name suggests, uses heat to melt trash then promptly compacts and safely contains the trash mass [27].
In the particular case of space “sewage”, all human waste and wastewater collected through toilets and drains (powered by vacuum pumps to work in zero-gravity) are automatically and immediately processed through devices like the POTOK to filter out odors and disinfect microbes. Additionally, the HMC removes water from the melted trash to deter microbial growth and potentially yields two useful end products as a result, water, obviously, which can be treated and recycled, and desiccated organic matter (assuming that only organic trash goes into the HMC), which could be pumped into the compost chamber in the compost room [27].

4.7.2 Fitness

On the spacecraft, the astronauts will stay fit for the time they will spend between Earth and Mars using three types of exercise machines that are present on the ISS. Each machine is essentially a redesign of a classical exercise machine seen on Earth in fitness clubs.

The Advanced Resistive Exercise Device (ARED) is a weightlifting machine that
uses piston-driven canisters and a flywheel to function in zero-gravity environments. The Treadmill 2 (T2), also known as the COLBERT, is a zero-gravity treadmill with harnesses to secure the astronauts to the machine; it is mounted on top of a vibration isolation system to protect delicate nearby laboratories and experiments from vibrations. The Cycle Ergometer with Vibration Isolations and Stabilization System (CEVIS) is a zero-gravity stationary bicycle that possesses a harness and a vibration isolation system for the same purpose as those of the COLBERT; it also has foot straps to secure feet to the pedals [40].
Figure 4.3: The Advanced Resistive Exercise Device (ARED)
Figure 4.4: The Treadmill 2 (T2/COLBERT)
On Mars, yoga mats and resistance bands would provide the easiest, most cost-effective way to ensure that the astronauts stay physically healthy inside the outpost. With these simple equipment, the payload for transporting exercise equipment would be low, and the astronauts could perform a wide variety of exercises. With yoga mats, they could do exercises such as push-ups, crunches, and planking. With resistance bands, they could do exercises such as leg extensions, pull aparts, and standing bicep curls.

Since Mars has intermediate gravity (less than Earth gravity but not zero gravity; specifically, 38% of Earth’s gravity), it would be worthwhile to bring the ARED, the COLBERT, and the CEVIS to the Martian surface to minimize the negative effects of decreased gravitational force on human anatomy and physiology. These machines could be modified to
function in a alternate-gravity rather than zero-gravity environment. Also, these machines can be designed with easy disassembly and reassembly in mind for simple transfer of the exercise equipment between the outpost and the spacecraft.

4.7.3 Physiology

The effects of microgravity on human physiology are various and adverse; bone loss, muscle atrophy, and weakened immune system are just a few of the prolonged effects on the human body caused by extended stays outside of Earth’s gravity. Thus far, despite extensive research on the effects of microgravity themselves, there is very little that astronauts can do to combat long-term exposure to microgravity except constantly condition and exercise before and during their missions in space (a preventative measure for possible physical trauma) and equip medical devices like monitors and resuscitation and other medical equipment on their spaceship (should physical trauma actually occur).

The Crew Health Care System (CHeCS)/Integrated Medical System is a hardware suite used on the ISS to provide through several means the medical support that astronauts need for extended missions. A manned mission to Mars would be unreasonably perilous without a CHeCS, that is, without the set of technologies needed to ensure good health to a person in microgravity. The CHeCS is so comprehensive in fact that it is subdivided into three smaller systems, the Countermeasures System (CMS), the Environmental Health System (EHS), and the Health Maintenance System (HMS) \[28\].

The CMS includes all the equipment, from the specialized machines mentioned in 4.7.2 to data collecting computers, needed to provide not only an appropriate exercise regimen for counteracting microgravity but also feedback during the workouts and regular evaluations. The EHS consists of monitoring devices which measure the artificial atmosphere inside a space habitat for contaminants, water quality, radiation levels, and even acoustics;
the POTOK mentioned in 4.7.1 is one such device. The HMS, in short, provides emergency medical services should an astronaut experience physical trauma; it includes a medical kit (with several components such as a medical checklist and a defibrillator), and a computer with electronic medical data (with several software-based capabilities such medical training and physiological monitoring) [28].
4.8 Artificial Intelligence

In science, artificial intelligence is the concept of a computer that has such a powerful and well developed code, that it is considered to be on par with, or above human intellect. There are many different types of AI, but the two primary ones are Strong and Weak intelligence. Strong AI, or true AI, is a machine that can perform any intellectual task a human can. An AI that is considered strong would be indistinguishable from people, containing the ability to learn and observe social cues, access memories and communicate with flawless dialog. General Intelligence is still several years away, but soft intelligence has become much more prevalent in the past decade. A Soft, or weak intelligence is one that can do one task at human level or better. Skills can vary from chess playing to giving directions based on traffic and road hazards. While it might not be as impressive, weak AI has revolutionized the world and is paving the way to a future where humans and robots will exist in symbiosis.

4.8.1 Need for Intelligence

If people want to live hundreds of millions of kilometers away from civilization, they need a to be able to keep track of everything that is happening around them. No risks can be taken and every possible scenario needs to be planned for. A Martian outpost will contain dozens of robots and life support systems, and managing them is a task that should not be left in human hands. By diverting much of the day to day functions, the people living on Mars will be able to spend more of their time working on progressing their cause. Additionally, putting a computer in control will make it easier for NASA and Astronauts to communicate with each other, as well as with all of the robots that are involved. A computer can react faster and more efficiently than most people, and they do not get stressed out like people would.
4.8.2 Current AI and its role

While not ideal, it is theoretically possible for current AI to be implemented in any Mars missions. If people go to Mars in the next 15 years, it will most likely be with the assistance of an extremely advanced weak AI. With modern technology, it would be possible to control all of the robots 99 percent autonomously, as well as monitor current outpost conditions and report to both NASA and the Astronauts themselves. The controller would also be able to do basic psychological testing in order to determine the mental soundness of the people in the outpost. Using advanced planning protocols, AI would be able to optimize the power and life support systems of the base, and would be able to respond to disaster much more quickly and efficiently than humans.

Building a system that could accomplish all of this is no small feat, and it would incur great expenses. SIRI, which is the soft AI behind every modern Apple device, cost over 100 million dollars to create, and hundreds of millions more to keep on the cutting edge of technology. It would not be difficult for a similar software developed by a space fairing organization to cost the same amount. While it would need to have much greater functionality than other examples, this functionality would be much more targeted and specific, versus Siri’s wide variety of skills.

4.8.3 Barriers to Strong Artificial Intelligence

In the early days of computer science, circa 1960, when Artificial Intelligence was all the rage, it was proposed that the challenges of Artificial Intelligence would be solved within 10 years. Since that time, AI has come in and out of favor several times, usually alongside the arrival of a new groundbreaking technology. The most recent revival of AI has come in recent years, due to the advent of Cloud Computing and simulated neural networks. Every
time AI comes back into favor people believe that it is only a few short years away, but the truth is even today there are still several technological barriers standing between humanity and advanced artificial intelligence.

There are several fields of study that make up Computer Intelligence, and science has made various levels of progress on each one. One of the fields of study that we have a pretty strong grasp of is Planning. This involves a computer determining the best way to break down complex tasks into smaller simpler ones. Currently, AI are very able to do this as long as they are the only entity to have control over an outcome. Once other actors are introduced into the system, the process becomes much more complicated. In coming years, advances in processing power will make it easier for systems to plan with multiple influences.

Another field where humans have made headway is in computer learning. In its simplest sense, this is the process where a program will rewrite itself in order to improve efficiency. Several computer systems nowadays do this. True "learning" is the process of acquiring new knowledge, and this has little to do with computational power and more to do with understanding how information is contained in language and text. This is part of the field of computer knowledge. That subset is focused on organizing information in a way that allows efficient access and natural connections between related data. A lot of it is focused on the way the human brain works. Our brain is the standard for simulated intelligence because it is one of the few that we know of that possesses all of the traits of intelligence. The human brain contains an average of 100 billion neurons and 230 trillion synapses, or connections between neurons. In order to model this accurately, in 2005 it took a supercomputer 50 days to simulate 1 second of brain processing. While a human brain model is several years away, science has already made accurate working models of a worms, rats, and cats brain. They use artificial neurons, which are equations that simulate the way an actual neuron works. In order to accurately simulate a brain requires immense processing power. If we ever hope to efficiently achieve a human level of simulation, technology needs to move beyond transistors
and onto the next layer of technology.

Figure 4.6: Estimated Progression of Neural Network Simulation

With the right advances in processing power, we will also be able to complete many of the required building blocks. One such process is reasoning, which is decision making based on a weighted decision matrix. While we can currently solve simple problems, complicated real world reasoning requires more processing power than we have access to at this time. Perception is another important asset for robots and AI that will be improved by more processing power. A truly advanced AI will be able to interpret thousands of different camera feeds and sensors at the same time.

At the far end of the spectrum, there are several essential parts of Artificial Intelligence that we do not fully understand yet. While we have the primitive ability to read social cues from single actors, a lot of work must still be done in order to react to them. The way
an AI decides to react to micro-expressions and emotions will be massively complicated and relates back to the reasoning area.

Once all of these challenges are figured out, there is still one massive task left. One of the most important and defining characteristics of human existence is the element of creativity. While some debate whether it truly exists, almost all of human civilization was born from creativity. Conceptually it is a very challenging thing to define, because its very purpose is to go against set notions. There are a few ways of "simulating" creativity, but they aren’t very well developed, and often reflect the creativity of the programmer. If we ever hope to create truly creative machines, work needs to be done to further our understanding of human creativity and where it comes from.

It is safe to say that one day, machines will exist among men, as equals or superiors. If that day comes within our lifetime, we can expect the world to change vastly overnight. It will pave the way for the last expansion of the human race, and raise many questions about our future. In the meantime, our weak AI will become more and more capable. For focused tasks, such as optimizing and protecting a Martian outpost, soft intelligence will be more than sufficient.
4.9 Robots Required for Martian Outpost

4.9.1 Level 1: Controller

At the top of the outpost would be the central controller. This device would house the AI running the base. In its most primitive form, it can be viewed as an advanced computer terminal, but a more accurate representation of its existence would be the base itself. All of the robots would be controlled by and report to it, and it would also be in control of all the sensors and cameras throughout the base, in addition to having control of the Thorium Reactor and Life Support systems. While there would be fail safes in place, this device would be the most over engineered and well tested equipment brought to Mars, on par with other survival essentials. While similar controllers don’t exist currently, this device’s power consumption can be based on other devices. A computer strong enough to perform all of the tasks would have a rough power consumption of 1kW.

4.9.2 Level 2: Observer

The next step up from the central AI is another primitive robot design. Observer robots would be very simple analytic robots, designed to move about the base effectively and make sure everything is running fine. Thermal camera observers could be used to make sure all the electronics are properly functioning, as well as locate any potential leaks in the structure or in other containers. Similarly, X Ray and ultrasonic equipped observers would be able to evaluate the structural integrity of the outpost as well as serving a medicinal property. LIDAR equipped drones would be able to map the outpost. All of the observer robots would transmit directly to the Controller, and would receive instructions from it as well. Based on the technology used, this robot would have a power consumption of anywhere from 200W.
to 500W. This would rely heavily on optimizing the way they travel around the base.

Figure 4.7: a Summit XL robot with 360 degree camera array.

4.9.3 Level 3: Caretaker

Keeping a human outpost in deep space will require patience and attention to detail, both traits that robots excel at. Some of the tasks that Caretaker robots will be in charge of include tending to the farms, cleaning, and helping out with some of the more tedious aspects of human life such as moving large objects. Robots that fall under the Caretaker category have a pretty versatile range of manipulators, designed for as many applications of
their particular skill sets. For the most part, these robots will run autonomously. Caretaker robots will in general consume 1kW of power, with heavy lifting machines consuming more and light work machines consuming much less.

![Image](image.jpg)

Figure 4.8: Robot will be able to tend to the hydroponics system full time

### 4.9.4 Level 4: Construction

Construction robots are clearly identified by their complex forms and simple coding. In order to design the Martian outpost, we will need a vast array of diverse mechanisms all aimed at fulfilling as many tasks as possible. By combining as many features into each robot as we can, we can reduce the number of bots overall and ideally, improve the reliability and adaptability of each one. One of the disadvantages of this is that these robots will consume a large amount of power. Construction robots will be semi autonomous, meaning they will be given simple instructions and complete their assigned tasks to the best of their ability. An approximate power consumption would be 20kW, which is based on what current industrial machines of a similar nature require.
The Leveler robot is designed to flatten layer of concrete as they are poured. It features two driving wheels, both attached to the main body by linear actuators. The purpose of these actuators is that the main body will remain level with respect to the surface it is flattening. The body can expand and shorten as needed. The tires would be developed to not stick to concrete, and would need a friction coefficient high enough to push wet concrete.
- Wire Pulling Robot

Figure 4.10: First draft of a Wire Pulling Robot in travel mode

Figure 4.11: First draft of a Wire Pulling Robot in pulling mode
Another simple robot that will be needed for assembling a base is a robot that is capable of pulling wires through a pipe. In order to make the robot work, the dimensions of the pipe need to be clearly defined. The back of the robot has an eyelet that can attach to the wire, and once the robot gets to the other end of a line, it will adjust to a position offering maximum traction and begin to ratchet the wire through.

- General Construction Bot

![Diagram of General Construction Robot](image)

Figure 4.12: First draft of a General Construction Robot

The most important robot for constructing the base, the General Construction
Robot contains all of the tools required to complete a majority of the build itself. It has two separate arms, one for maneuvering pipes and other resources and tools, and the other specially designed to move large sheets of polymer and to tighten them into the airlocks. The body also contains a cement mixer, and it can accurately pour the cement. For a drive train, the GCB will feature a very sturdy tank drive, and deploying legs for additional stability.

4.9.5 Level 5: Excavation

The first robot to be deployed and the most robust in design will be the robots meant to move the Martian Dirt. Excavation robots will be in charge of leveling the construction site, moving pay-dirt into the General Construction Robot’s cement mixer, and afterwards burying the base in several inches of sand.

![Figure 4.13: A Brokk 330 Excavator Robot](image)
4.10 Mars Base Plans

4.10.1 Outpost Location

Mars is a large planet, and has a very diverse geography. For as long as humans have looked at the red planet, they have wondered where they could settle on it. The first robots that landed on Mars touched down in Utopia Planitia, a large plain that has gentle terrain. This was essential for the rovers because challenging terrain would put a stop to the mission. However, a manned trip has very different criteria. The ideal location for a human settlement would be near the equator, where the climate is the most hospitable. It would be located in extreme proximity to sources of water, so that less water would need to be transported from Earth and the society could eventually be self sustaining. Another thing to consider is the rest of the benefits that the location has to offer. Mankind is going through a lot of effort to send people onto a different world, it would be ideal if they had some reason for being there.

The Tharsis Bulge is an interesting region of Mars in the western hemisphere near the equator. It is home to the largest Volcano in the solar system, Olympus Mons, as well as several large shield calderas. This region has been of particular interest to scientists in recent years because of the cave systems that are present in and around the volcanoes. One particular landmark, Arsia Mons, has seven large cave entrances in and around the summit. NASA has been fascinated by these caves because they are massive and could hold any number of significant scientific discoveries.

Arsia Mons is the location we picked for a Martian Outpost because it has the perfect combination of key features. The region has been scanned and the soil is known to contain elements that indicate water is present. This is crucial to the survival of the base. It is located reasonable close to Utopia Planitia, where large swathes of water ice have been discovered beneath the ground. The proximity would make it reasonable to transport water
from Utopia if it was necessary. The region is very close to the equator, which means it will have the warmest climate of any potential landing zones. This will reduce the energy needed to heat the base, as well as making the design constraints a little easier to control. Finally, the caves will provide Human Martians with a possible shelter, as they go deep enough below the surface to nullify radiation and to protect against all but the largest meteors. The caves will provide humans and robots something to explore, and are significant enough to justify a trip to Mars.

The construction of the first outpost on Mars will be one of the most impressive accomplishments of humanity. It will be done completely with robots, using technology developed specifically for this purpose and mostly autonomously. This is a huge risk, which is why several years of earth testing would need to be done before any soil is moved on Mars.

4.10.2 Outpost Construction Preparation

When robots do go to Mars to begin construction, it will be years before humans are sent. By leading with robots, there will be plenty of time for the base to be built and any unforeseen challenges to be tackled. While a tighter window between robot and human launches might be possible, this gap can be considered a factor of safety for the project. Any issues that arise during construction will be hurdles, but if that issue were to occur while humans were there it would be disastrous.

Before any construction can be done, an exact location needs to be selected. Several dozen probes will be sent down to the planet, where they can take samples of the soil and weather and report them back to HQ. Ideally, a location will be found that has water in direct proximity. All locations will be evaluated and a final decision will be made based on the proximity to water, ease of construction, and ease of access. After the decision is made, the construction can commence.

All robots that are needed for construction will be sent together. The first launch
will contain the robots that can dig and move Martian rocks, the robots that can take soil and convert it into MarsCrete, as well as a robot that can level concrete and a robot that can place structural re-bar and pipes. The landing pod that contains all of the robots will also provide them shelter from harsh weather such as sandstorms and power, in the form of an on-board thorium reactor. It will contain all of the equipment for communication from the Mars robots to earth humans, and act as the main martian antenna for all future expansions, including when humans move in.

Once they are safely touched down on the red planet, the hard work begins. The environment needs to be surveyed, the ground leveled, and the perimeters of the base established. This will be done both mostly by humans at HQ, who will make decisions and give commands to the construction team. The robots will be able to carry out the functions autonomously.

### 4.10.2.1 Construction Robots

On earth, robots are used in every aspect of daily life. They make day to day living much more convenient for the majority of people. In the past 50 years, technology has allowed robots to replace humans in several industries, especially manufacturing and exploration. One of the areas that hasn’t seen the machine takeover is construction. This is due to a number of reasons, but the primary one is how cheap general laborers are. However, as the wage goes up and the cost of human workers rises with it, Robots will no doubt become more prevalent. This was demonstrated when the minimum wage increased, and to balance costs, fast food locations replaced human cashiers with robotic ones. It is not a stretch to assume this same shift will happen with construction, and we are already beginning to see the rise of automated construction programs.

In order to fully automate the development of a Red Planet Outpost, there are several robots that need to be built. They range from relatively simple to very advanced,
but none of them are so advanced that they are outside the realm of possibility.

The most important robot will be a large general construction device. It will have two manipulators on it, both of them being sturdy multi link arms that allow freedom of motion while at the same time providing accurate control. They will allow the robot to place re-bar into drying marscrete, as well as piping and moving the blocks required to shape the concrete.

A robot that is able to landscape will also be essential. Being able to level terrain, as well as dig trenches and holes will be crucial to burying the base in the sand, where it is safe from the hazards of an atmosphere-less world. These will do a majority of the grunt work, and a full scale operation will require several of them.

This mission will also require a special system that is able to convert Martian dirt into a concrete like substance that can be poured and formed. This machine needs to be mobile, with a large storage capacity and the ability to pour accurately.

The final robot that is needed is a simple one. It serves to level the concrete as it is poured, to ensure an even distribution across the desired zone. Two of these robots in unison will be used to deposit the polymer sheets, but this won’t be needed until phase two of construction.

4.10.3 Base Construction

The plan for robotic base construction is as follows:

1. Scout robots find a proper cave and determine a suitable area for building (specifications for these caves and areas are discussed in 4.14)

2. Excavation robots dig sufficient soil from inside the cave to begin underground building, matching the shape of the foundation on the bottom surface of the hole

3. Soil is brought to the mixer robot and is combined with the sulfur brought from Earth
in order to create the Martian concrete fill.

4. Robots place blocks to serve as boundaries for the concrete foundation

5. Concrete is filled into the foundation by robots.

6. Polymer Rebar is placed in the concrete fill for the foundation by robots as specified in drawings.

7. Concrete is left to dry

8. Steps 4, 5, 6, and 7 are repeated for the walls

9. Interior and exterior doors are placed as well as the stars to the exit

10. Anything that is too large to fit through airlock doors are lowered into the base by robots. This may include Oxygen Generation interfaces, Water Pumps, furniture, and workspaces.

11. Structural Columns are placed inside the base

12. Steps 4, 5, and 6, and 7 are repeated for Ceiling with concrete decks instead of blocks

13. Excavation fill top of the underground section of the base with six inches of soil

14. The rest of the base infrastructure is brought in and setup inside of the base.

4.10.4 Cave Exploration

The team plans to use a simple, mobile robot to explore the caves to determine their potential benefits. This robot will have to be able to traverse difficult terrain, sustain impacts from falls and collisions, and transmit signals back to the command post. NASA has spent $500,000 to develop a working prototype of a robot for this exact purpose. It is a spherical rolling robot with all its sensors protected by its outer shell. With a high coefficient of
friction, it will be able to climb most inclines, and it will be capable of jumping so that it can traverse ledges. The low rolling resistance of this design helps ensure a long battery life.

One of the biggest challenges of a cave exploration mission is transmitting video and data back to Earth and to the colony. Our solution is to use a multi-antenna relay system to get the signal out of the caves before transmitting it:

(ANT) An antenna will be deployed directly outside of the cave system that is being explored, which will use long wave radio transmission to send signal back to the colony, which can be a repeater to send the signal back to earth.

(SLAVE) Inside the cave, another antenna would be set up, and would function as a transceiver between the robot itself and the antenna outside. Also a charging station for the robot.

(BOT) Inside the cave, the robot can communicate with the SLAVE using Through-the-Earth Ultra Low Frequency Communication (300-3000Hz) (TTE)

The purpose of this robot is to explore the unknown subterranean underworld of Mars. With a better picture of what exists down there, it will be easier to decide what to do with that space. It could very easily be the most valuable land on Mars. It could contain water, essential resource deposits, or even primitive life forms. Because the location of the initial colony is right there, the caves of Arsia Mons could serve as anything from a storage location to a future expansion of the colony. The only way we will know is to explore.
4.11 Radiation Protection

4.11.1 Onboard During Trip

One of the major health concerns for planetary space travel and planet settlement is radiation from deep space and from the sun. Galactic Cosmic Rays (GCR’s) are emitted from other stars in the Milky Way and pass through the sun’s solar system. On Earth, this is not a concern due to the strong planetary magnetic field, electrostatically reflecting charged radiated particles back into space, however this does not exist in interplanetary space and on Mars. The other major form of radiation are called Solar Energy Particles and are emitted by the sun. Fortunately radiation dosage was recorded with both a silicon chip Geiger counter and a plastic chip Geiger counter aboard the Mars Science Laboratory (MSL) mission from NASA in 2010-2011. This mission is most known for deploying the Mars Curiosity rover. The data obtained allows a better understanding of the general radiation dosage passengers would experience on a trip to Mars.
The total radiation dosage a passenger would receive based on the data in Figure 1 would be 0.66 .16 Sieverts per day for a round trip mission. The radiation shielding used on this mission was a 4.5 g/cm2 areal density aluminum shell on the ship. Considering NASA’s recommended radiation dosage guidelines for astronauts in Figure 4.15, minimization of total dosage for a round trip mission is necessary.
Another study performed by NASA shows that materials rich in Hydrogen and Carbon are best at shielding against GCR’s. Out of all materials tested in this study, Polyethylene (C2H4)n contained the highest Hydrogen amount per mass and volume, and consistently performed the best at protecting against radiation generated to emulate GCR’s in a laboratory. Using this study, a Polyethylene coating of 40 g/cm² areal density on the Aluminum shell of 4.5 g/cm² areal density (for structural purposes) would diminish onboard radiation dosage by a factor of . This will allow much more round trips for passengers in their lifetime to avoid radiation diseases.

The spikes on the chart in Figure 1 represent Solar Electron Particles emitted from the sun during Solar Flares. The Polyethylene coating placed on the spacecraft is not strong enough to protect against these large bursts of radiation from the sun. Considering that Hydrogen based materials are strong at protecting against radiation, it is recommended that a sufficient shell of liquid water exist on board for passengers to take shelter in during Solar Flare passthrough. It is also required that electronic notification of incoming solar flares be implemented through the spacecraft’s Geiger counters, so passengers know when to take radiation shelter.

It is also expected that onboard electronics have proper magnetic shielding for anti-interference from the small amount of onboard radiation that will be experienced. This carries over to processors, boards and etc.

4.11.2 Mars Surface Radiation Shielding

The goal for Radiation Shielding on Mars’ surface is to provide a magnetic shield simulating that of Earth’s on small areas of Mars surface where inhabitants need to be. The solution to this problem is actually quite simple. Earth’s magnetic field is about .5 T - .6 T and sufficiently protects Earth against radiation. Rare Earth magnets are lightweight and known to provide magnetic fields similar to Earth’s in strength. By keeping an N52 Neodymium mag-
net attached to a person navigating the surface, the magnet’s field is sufficiently distributed outside the human body so that it emulates Earth’s magnetic field and prevents radiation dosage from entering the human body.
4.12 Comet and Asteroid Collision on Mars

4.12.1 Introduction

Using standard angular momentum mechanics as well as light physics and thermodynamics, equations can be derived to determine the temperature change as Mars’ radius decreases, due to being bombarded by many floating objects in space, ideally comets or near-earth asteroids. For this study we consider Mars being bombarded by an estimated average comet size, and a well-known near-earth asteroid called 1023 Ganymede. Values used for the lab are located below.

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<tr>
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<td>0.250</td>
</tr>
<tr>
<td>\sigma (Boltzmann Constant)</td>
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</tr>
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</tr>
<tr>
<td>Comet Velocity</td>
<td>33.109 ms^{-1}</td>
</tr>
</tbody>
</table>

Table 4.6: Properties of Space Projectiles, Planets and the Sun used

4.12.2 Derivations

\[ E_{\text{radiated}} = E_{\text{absorbed}} \] (4.1)

\[ 0.25 R_{Mars}^2 L_{sun} (1 - a) = 4\pi R_{Mars}^2 \sigma T^4 \] (4.2)

\[ \frac{1}{\sqrt{d}} \sqrt[4]{\frac{L_{sun} (1 - a)}{16\sigma \pi}} = T \] (4.3)
Where \( d \) = Distance from the Sun and \( T \) = Surface Temperature

Plugging in the values of the equation derived gives you the simplified equation:

\[
T = \frac{88.2734}{\sqrt{d}}
\]  

(4.4)

Now an equation to relate the comet collision to the radius of the planet must be determined.

Figure 4.16: Collision of Comet/Asteroid with Mars in orbit
Using the following assumptions:

*Angular Momentum is conserved*\( (L_1 = L_2) \) \( (4.5) \)

*Collisions Occur Tangentially* \( (4.6) \)

*Mars is in circular orbit* \( (4.7) \)

And derive the following:

\[ \omega_1 = \frac{v}{r} \] \( (4.8) \)

\[ m_c v_c + m_m v_m = MV \] \( (4.9) \)

\[ \omega_2 = \frac{V}{r} \] \( (4.10) \)

\[ \omega_2 = \frac{m_c v_c + m_m v_m}{Mr} \] \( (4.11) \)

*Where m and c refer to Mars and the comet* \( (4.12) \)

*And M and V refer to the post collision mass and velocity* \( (4.13) \)

Both the new radius and the new angular velocity can be determined with these equations and the angular momentum assumption. These equations can help us create graphs to determine temperatures and masses visually.

\[ L_1 = L_2 \] \( (4.14) \)

\[ m_1 \omega_1 r_1^2 = m_2 \omega_2 r_2^2 \] \( (4.15) \)

\[ r_2 = \sqrt{\frac{m_1 \omega_1 r_1^2}{m_2 \omega_2}} \] \( (4.16) \)

\[ r_2 = \sqrt{\frac{m_c}{m_c + m_m} \omega_1 r_1^3 \frac{m_c + m_m}{m_c v_c + m_m \omega_1 r_1}} \] \( (4.17) \)
\[ \omega_2 = \frac{m_m \omega_1 r_1^2}{(m_m + m_c) r_2^2} \]  \hspace{1cm} (4.18)

These functions change for each collision, so each next collision depends on the previous radius and angular velocity calculated. Entering this into Excel recursively for five thousand collisions, we can determine an equation using a log fit, and use that equation to come up with a better graph for collisions vs distance.

4.12.3 Results

![Distance From the Sun vs Temperature for Mars](image)

Figure 4.17: Distance from the sun vs. Surface Temperature of Mars
Figure 4.18: Number of Comet Collisions vs. Mars Orbital Radius

Figure 4.19: Number of Asteroid Collisions vs Mars Orbital Radius
4.12.4 Discussion

Though near Earth asteroid collisions show significantly better results than comets, both appear to require an unreasonable number of collisions in order to make a significant change on the surface temperature of Mars. If this project were to be undertaken, it would likely last a millennium to complete, and technology will likely advance to the point where this method would be outdated by that date.
4.13 Using an Asteroid as a Martian Moon

4.13.1 Overview

One of the most significant attributes of Earth that allows human inhabitation is its magnetic field. Earth’s magnetic field repels radiation discussed in [4.11] that is toxic to humans. It also creates an ozone layer in our atmosphere, essentially containing our atmosphere and allowing us to breathe. The magnetic field of Mars however, is nearly nonexistent.

Figure 4.20: Diagram of the Magnetic Field Generated by Dynamos in the Earth’s Core
The dynamo theory was first hypothesized by a 17th century astronomer named William Gilbert. It states that rotating, convecting, and electrically conducting fluids can create a consistent magnetic field. The molten liquid core of the Earth is thought to satisfy these requirements. Earth’s core is made of an iron/nickel alloy, a metal, which is electrically conductive. Though unknown, its reasonable to believe that these fluids flow convectively through itself and in rotational motion.

An unanswered question here is what makes these molten fluids in Earth’s core flow. Just like how Earth’s oceans flow, the fluids in Earth’s core flow due to the gravitational forces from the moon. These tidal forces on a flowing liquid in a spherical container also contribute to the dynamo effect.

4.13.2 Dynamo Effect on Mars

It may seem possible to create the dynamo effect on the Martian core. A terraformed Martian magnetic field would reap many benefits such as radiation protection, and the ability to create an Earth-like atmosphere on the planet. The state of Mars’ core is unknown and is highly disputed by current astronomers. Since Mars has two moons of considerable mass, we can assume from the dynamo theory that the Martian core does not at a sufficient state to create a magnetic field. Thus in order to create a magnetic field, the planet’s core must be melted further. Once the core is melted, the Martian moons should do the job of creating dynamos in the liquid core and thus creating a stronger magnetic field.

4.13.3 Melting Acceleration of Mars’ core

Elon Musk has always brought up the idea of launching thermonuclear weapons to Mars. He claims that it would increase the climate on the planet and make it more habitable for humans. In this case the team suggests that thermonuclear bombs be placed in the mantle
of the planet and detonated. This would require an incredible feat in excavation, one of which has not been seen before on Earth, and is not within the current realm of technology. But success in liquefying the Martian core would likely bring results of less radiation on the planet and the origins of an atmosphere would appear.
4.14 Base Design

4.14.1 Overview

One of the most important assets of a Mars landing is a facility to provide shelter, workspace, and a farm for the inhabitants. Constructing a building on another planet poses a variety of issues that need to be addressed. Firstly the issue of materials. The weight of materials brought from Earth to Mars needs to be minimized. This poses a significant challenge as construction on Earth is not nearly as weight dependent. Another issue is radiation. A Mars base will need to prevent the permeation of radiation for the safety of those humans living inside of it. Oxygen will also be an issue. The base will require a lining such that oxygen can be contained. To prevent radiation, the base will be built underground, submerged in 6 inches of the martian soil. This will effectively nullify the radiation concern inside of the base. Structural designs are based off of the International Code Council (ICC) 2009 International Building Codes.

4.14.2 Location

A major concern of construction will be the location to choose. Mars is hit very frequently with space debris (almost 200 impacts per year) and an area stricken with large space debris typical of Mars impacts submerged 6 inches underground will not be safe. Unfortunately building the base even deeper will not resolve the issue. Some of these impacts can make craters up to 150 meters in diameter. Inserting a base 75 meters underground is unreasonable.

A volcanic caldera on the planet called Arsia Mons is said to have seven cave entrances on it. These caves could provide sufficient defense against space debris, as well as area for the base to be built. This area is also said to possibly have water, and has the
warmest climates on the planet. Scouting robots will help determine which cave is most suitable for base construction, and construction will begin in one of these caves. The base will still be built underground inside the cave as that base still will require sufficient radiation protection.

4.14.3 Materials

On Earth, concrete is commonly used for underground construction. Most homes that have basements are built with a concrete foundation and concrete walls. Concrete would be perfect for a Mars base as well because it is very easy to prepare and is easily transportable. Geologists at Northwestern University did research and into a concrete that can be developed using a half and half mix Martian soil and sulfur. Sulfur based concretes have become increasingly more common building tool on Earth, as it has a much higher compressive strength than standard stone and gravel based concretes that are typically used. The Martian concrete is created by hot-mixing the Sulfur and Martian Soil at 120 °C, filled, then cooled. This process can be done very simply by the Martian robots that will be sent to perform construction. Martian concrete was tested to have a compressive strength of 50 Megapascals (MPa) and has an elastic modulus of 6.5 Gigapascals (GPa).

The ACI Codes state that concrete must have rebar in regular intervals inside concrete based on a variety of dimensional and environmental factors that will be looked into in the structural calculations section. Standard rebar on earth is usually around a 1 in. diameter steel rod. Steel can be incredibly dense, and therefore there needs to be a better option than transporting steel rods to the planet. There are two options, iron is mined from the Martian surface and smelted into steel, or a Composite rebar using a Fiberglass Reinforced Polymer (FRP) is transferred from Earth, which has the density of steel rebar. Considering that the mining and smelting facilities required for steel production are far too complicated and massive for something as insignificant as rebar, the FRP rebar option is
The best lightweight materials known to prevent air escape are known as barrier polymers. Barrier Polymers have tightly knit molecules that block the ability of air to pass through them. They are typically used for food packaging, and tend to have comparably low densities to other materials sufficient as containers, such as glass. Polyethylene is one of the lightest barrier polymers, as well as one of the cheaper barrier polymers in abundance on Earth. An interior lining of 1 in. thick Polyethylene inside the Mars base will be a sufficient lining for preventing oxygen escape.

4.14.4 Structural Calculations

ACI 318 states that an 8 foot wall with 4500 psi needs the concrete to be 6 in thick in sand. Sand is the most comparable Earth soil to Martian soil. They are both dry and very fine in particle size. This requires No. 4 rebar spaced out by 48 inches, with a soil pressure of 1250 lb. Using these ratios we can determine the soil pressure from Martian soil, considering the gravity difference on Mars.

\[
1250 \frac{lb}{ft} = 5560.277 \frac{N}{ft} \times \frac{3.711 m/s^2}{9.8 m/s^2} = 2105 \frac{N}{ft} = 473.33 \frac{lb}{ft}
\] (4.19)

As a safety factor we will consider the soil pressure on Mars to be half of the sand soil pressure on Earth (625 lb/ft). Using that Compressive Strength and wall thickness are directly proportional, we can determine the proper Martian concrete thickness using the following:

\[
50 MPa \times \frac{145.038 psi}{1 MPa} \times x = 4500 psi \times 6 in
\] (4.20)

\[
x = 6 in
\] (4.21)
As another safety factor we will round the 3.72 in thickness up to 4 in. ICC 2009 also recommends that slab on grade foundations be used for sandy environments. These foundations have trapezoidal footings. ICC 2009 also states that we need 4 in. diameter columns for every square 144 ft² area. That means that every 12ft by 12ft grid needs a vertical column. The fact that the ceiling will have much more pressure on it, as it will be receiving a direct vertical load from the soil, needs to be considered. So we make a similar calculation as above and determine that rebar needs to be spaced out by 24 in. in both directions, which will have additional support from concrete decks in the ceiling for filling the concrete.

### 4.14.5 Emergency Procedure

As an extra precaution, the base needs to have a procedure for emergency situations that inhabitants must know and practice regularly. A red emergency button will be used to control airlock doors. These airlock doors will be set to be normally open, so that when power is cut to the doors they immediately open. The emergency button will cut power to the airlock doors which keeps them open and will allow an exit path. Also an alarm will trigger which inhabitants will know to apply their breathing devices and exit the base.

If structural failure occurs inside the base, the stairs are designed so that their structural support is not dependent on the structural support of the base. This means that the stairs will stay upright for escape permanently, as designed in buildings everywhere today
4.14.6 Bill of Materials

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Table 4.7: Material weights and cost for Mars base construction

4.14.7 Base Drawings

Figure 4.21: 3D View
Figure 4.22: Floor Plan
Figure 4.23: North Elevation View

Figure 4.24: East Elevation View
Figure 4.25: Electric Plan
4.14.8 Power Systems

Almost every aspect of the astronauts’ lives requires electricity, and on Mars, there is no convenient grid to tie into. Before the astronauts even arrive, the robots building the base need power, the life support systems in the base need power, the hydroponic system needs power, and once the astronauts are in the base, just keeping the lights on takes power. The ISS takes roughly 100kW, which is already a sizable draw, but the Mars base will be much larger and, most importantly, permanent. Taking this into account, a conservative estimate would bring the base to a requirement of 300kW. While this figure is certainly large for any household, its scale is relative to the power source being used and that scale varies drastically in reference to each possible technology.

4.14.8.1 Potential Technologies

As with any problem, there are a variety of ways to approach powering the base. In the past, solar panels have been the go-to method for objects on Mars, namely the myriad of rovers that have been sent to the Red Planet over the years. However, rovers have considerably lower power requirements than a full Martian base. Even in optimal conditions with an array placed at 25° north, which is the most-irradiated latitude, the array would need to be 30,000m$^2$, which is the area of a little over five-and-a-half football fields. While just installing such a massive structure would be a challenge, the maintenance requirements are major problem; Mars is a dusty place. As dust storms roll over the panels, they would be coated if not buried by thick layers of Martian soil that would significantly lower if not completely stop power generation. While wiping off the panels of a small robot, namely a rover, would be a trivial task, clearing a base-sized panel array would be more akin to plowing snow, except that even touching the ”pavement” with the plow would be catastrophic. As an example, figure 4.26 shows the panels of the Spirit rover after roughly two Earth years in
Another possible source of energy, wind power, would work with the dust storms to generate power. In fact, a few large wind turbines could easily supply enough power for the base. However, wind turbines are massive and require cranes to install, which puts them out of the question for Mars installation. Even if smaller, easily-constructed turbines were designed, constructing a wind farm would need large amounts of materials sent from Earth, cutting into valuable cargo space. Another novel approach would be solar panels in orbit that would then beam energy to the base via laser or microwave link. While experimental setups have been promising, with 20W transmitted 148km between islands in Hawaii, that figure is still four orders of magnitude short of the base’s target. Additionally, such systems require very accurate alignment, which is understandable when one considers the task as hitting a target from nearly 100 miles away. This would only get more difficult as a solar panel array in a stationary orbit above Mars would be roughly 11,000 miles above the surface, again upping the ante two additional orders of magnitude. The final nail in the coffin is the same one that did in solar panels – dust. During a dust storm, particles would be thrown into the atmosphere between the transmitter and receiver. Microwaves readily scatter in such
conditions, and this fact has been exploited for other applications, namely radar. The same issue would come into play if a laser transmission was used instead; the laser would scatter or be blocked entirely, resulting in large drop in transmission efficiency, resulting in a net power deficit. Furthermore, the ground-based receiver for either microwave or laser transmission would be buried in dust, requiring the same sort of upkeep as solar panels.

4.14.8.2 Nuclear Power

The most viable, and, notably, dust impervious solution would be a nuclear reactor. Reactors come in all sorts of varieties, distinguished, for the most part, by fuel, fission strategy, and cooling method.

4.14.8.2.1 Fuel

Nuclear reactors can run on a variety of fuels. The most well-known of these are plutonium and uranium and for good reason. These two elements are both fissile, which means that when hit by a neutron, they split and produce more neutrons. This behavior creates a chain reaction that can continually generate heat, which is then used to generate electricity. However, they have a darker side and largely came into use due to their weaponization potential. The same chain reaction that is carefully controlled in a nuclear reactor can be left uncontrolled, creating a nuclear bomb. This lead governments that were already creating or seeking nuclear material for use in weapons to select enriched uranium reactors. When creating enriched uranium, highly radioactive plutonium can be produced, which is a key portion of nuclear weapons. However, with nuclear weapons being phased out by treaties and human rights concerns, other fuels are being explored.

The most promising of these fuels, and the one that will be selected for the reactor on Mars, is thorium. In its natural state, thorium is barely radioactive, with a half-life on
the order of 14 billion years, which is about 200 million years longer than the current age of
the universe. In fact, thorium isn’t even fissile in this state. This is actually an advantage
over uranium or plutonium when it comes to early refueling of the base. Until thorium can
be mined and refined on Mars, it will need to be sent from earth. In the past, launching even
tiny amount of radioactive material in a rocket has resulted in widespread concern over the
possibility of the rocket exploding in Earth’s atmosphere and scattering nuclear fuel over a
large area. In contrast, if a rocket carrying thorium were to fail, the element is so marginally
radioactive that there would be no risk of a nuclear explosion and the particles spread would
be of little to no consequence.

Once the reactor was up and running on Mars, a steady fuel supply would be
needed. In the case of uranium or plutonium, this fuel would be exceedingly difficult to mine
and then need to be heavily processed and enriched. thorium, on the other hand, is plentiful
compared to other radioactive elements, as can be seen in figure 4.27 and has already been
surveyed from orbit by the 2001 Mars Odyssey Mission, which is shown in figure 4.28.

Refining thorium from the most-commonly-found minerals is fairly straightforward,
though there are multiple methods to do so. In one process, thorium pyrophosphate is
reacted with nitric acid in order to produce thorium nitrate. This thorium nitrate is then
treated with tributyl phosphate, with impurities separated by manipulating the pH of the
solution. In another method, the harvested minerals are decomposed in a heated sodium
hydroxide solution. The metal hydroxides are then removed by lowering the temperature of

Figure 4.27: Relative abundances of elements in the universe

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the solution, washed with water to remove excess sodium hydroxide, and then dissolved with hydrochloric acid. Next, the PH of the resulting solution is neutralized, yielding thorium hydroxide. This can then be dissolved in nitric acid to produce thorium nitrate, just as the first method did. In either case, the extraction is a purely chemical process. In contrast, the refinement steps for enriched uranium involve separating individual isotopes. Many of those methods require large amounts of energy for a relatively low fuel yield, making them impractical for use on Mars.

4.14.8.2.2 Reactor Style

Using thorium as a fuel presents specific challenges and demands specific reactor types in order to be effectively utilized. The first of these is that the reactor must be a breeder reactor, in which the fission of fuel releases enough neutrons to make more fuel fissile. In this way, breeder reactors generally produce more fuel than they consume, though the amount of fuel generated can be tuned to prevent excess being generated while still producing enough to sustain the reaction. Using a breeder reactor allows each element in the thorium series to
be generated and used for power generation, which greatly reduces the fuel requirements – up to a 100-fold decrease by some estimates – as compared to single-stage fission reactors.

Breeder reactors are a broad category which can be further narrowed. For maximum efficiency, reactors must be allowed to run at the highest temperature possible, which is usually limited by the melting point of containment materials and the vaporization temperature of the coolant being used. This need for a high-temperature coolant is best serviced by molten salt. While molten salt is conventionally thought of as being quite hot, in regard to the maximum temperature of a nuclear reactor, it’s actually quite cool at temperatures under 1000°C. While still cooler than the reactor, molten salt can operate at much higher temperatures than water-cooled reactors.

Fuel delivery in a thorium reactor is carried out almost exclusively by a liquid salt mixture. In this scheme, thorium and uranium, the latter of which arises after breeding, are dissolved into a liquid fluoride salt solution. This solution then travels to the reactor where it becomes critical, or able to sustain the chain reaction of fission. The fluid then travels out of the reactor and products can be removed for processing while others are added. In order to simplify fuel processing, two separate loops of fluid are often used; one that contains thorium to be bred in the reactor and another containing the uranium or further products that are to be burned. In such a design, the thorium is kept out of fuel that is being actively consumed, which keeps the thorium away from the chemically-similar and difficult-to-separate lanthanide elements further down the decay chain. Additionally, with the core fluid isolated, less fissile material is needed to start the reactor, which is especially useful since this seed material will likely need to brought from earth. Lastly, the two-fluid design is extremely efficient at breeding since the separate blanket fluid can capture nearly all of the free neutrons while itself not undergoing fission. Thus, a two-fluid liquid fluorine thorium reactor is the best fit for a Martian base.

Using a molten salt for the core, one for the blanket, and one for cooling brings the reactor’s loop count to three before power is even generated. Power generation will come
from a fourth loop that holds water or a similar fluid that vaporizes at a relatively low temperature. This fluid will exchange heat with the molten salt cooling loop and produce either steam or a high-pressure gas if another substance, such as carbon dioxide or nitrogen, is used in this loop. This high-temperature, high-pressure gas would then drive a turbine that would generate the power for the base. After exiting the turbine, the gas would need to be returned to its lower energy state by passing through a radiator that either interfaces with the Martian atmosphere or an underground lake, as the large body of water would be extremely effective at absorbing waste heat. While not as useful for cooling the fluid, passing it through radiators within the base would aid in heating, though would present the risk of taking power generation offline should the piping within the base break. On the same line, such a break would also present the hazard of superheated steam within the base, so this option should likely stay hypothetical unless more safety precautions can be taken. After the fluid is cooled, it reenters the molten-salt heat exchanger and restarts the cycle.

4.14.8.3 Power Transmission

Due to the inherent safety and self-regulation of thorium-based nuclear power, the reactor can be placed fairly close to the base. This relative proximity makes long-distance transmission unnecessary, though this could be easily solved by stepping up transmission voltages then stepping them down again at the base. Raising the voltage in this way lowers the current in the lines, which in turn lowers losses. Without the need for long-distance transmission, power can be transmitted at the voltage it will be used at, which will be 120V AC for use with consumer goods, such as off-the-shelf lighting from existing manufacturers. At this voltage, a peak draw of 300kW would translate to a current of 2,500A, which is an extreme figure. This can partially be mitigated by dividing power needs. By running separate lines to power robots, the farms and the rest of the base, each set of conductors would need to carry about 830A, which is still high, but more manageable. This current requirement can
be lowered even further by implementing a three-phase system. Such a system would not make generation any more difficult while providing more power, so it’s an obvious choice. Three-phase also has the additional benefit of lowering the current per conductor and would take it down to about 275A each. This ampacity is within reach of a single conductor and each would need to be 0.5” in diameter. With this taken into account, each section would need four half-inch conductors – one for each phase and one for ground – that would be run underground. Once inside the base or otherwise at their destination, these transmission cables would be connected to a distribution panel with individual circuit breakers for further division of power. Much like in houses on Earth, these circuits would have ampacities under 50A and would be serviced by appropriately-sized conductors which generally top out at 12 AWG for all but the highest-draw applications. These circuits would be fairly modular and configured and reconfigured by an electrically-inclined member of the crew.
4.15 Hydroponic Farm Design

4.15.1 Overview

As humanity looks to take its first steps towards securing a base on Mars many complex and multifaceted problems must be considered. One of the most important aspects of a base millions of miles from earth will be the ability of its inhabitants to survive without a constant supply of resources from earth. While information can be sent via satellites and energy can be secured on sight, there are several resources that are absolutely necessary to account for in order to assure the survival of any living creatures that will inhabit the base. The requirements for sustaining life are quite obvious, but meeting these requirements in such a hostile and remote environment will be a difficult task to accomplish even with the help of some of the smartest scientists on the planet. When the outpost is first established, life giving resources like food, water, and air will likely be sent with the astronauts in order to ensure their survival if they discover any problems involving the collection and harvesting resources on site. Overtime however, earth based assistance will hopefully draw down once on-site projects provide the colonists with the resources they need to survive on Mars. One of the biggest hurdles to self-sufficiency, other than adequate water supplies, is the implementation of a highly efficient hydroponic farming system that will provide the entirety of the requirements for the colonist’s food-based needs. This report will cover a range of topics focusing on providing food for the colonists using a hydroponic farming system. First and foremost this report includes an in depth analysis of the design, functionality, and requirements of a Martian hydroponic farming system. The food based requirements of each colonist will also be accounted for in detail with relation to the design of the farm. Food variety selection and subsequent nutrition capabilities will also be covered in detail. The various energy requirements necessary for maintaining and growing the farm will be covered,
including the justification behind the choices made for energy based decisions. In addition, this report will include a detailed analysis of the material and spatial requirements for the farm. The goal of this report is to create a feasible model for a hydroponic farming system that will be able to operate as efficiently as possible while also providing a robust and a reliable source of food for prospective Mars colonists.

4.15.2 Human Requirements

The most important consideration to take into account when deciding exactly how many resources will need to go into the hydroponic farming system is exactly how much food a human needs. Humans require a multitude of micro and macronutrients in order to remain healthy and active within the colony. While no one item of food can provide all of the requirements for a healthy life, there are several foods that can efficiently fulfill many of the food based requirements of a human being. After careful research and comparison among a
series of different plants in which we weighed the nutritional benefits of each vegetable against their projected efficiency in providing a balanced diet, we decided to use sweet potatoes as an example of our staple crop for the Martian base. This decision was made based on a combination of advantages that sweet potatoes provide, primarily their high calorie, protein, sugar, fiber, and vitamin content. For the sake of efficiency and optimal space reduction this report will analyze meeting the caloric requirements of a human using just sweet potatoes, when the hydroponic farm is implemented the diet of colonists will include many foods other than sweet potatoes. Based on research carried out by the USDA, we determined that the average male colonist would require 2500 calories per day, over the course of the year that brings the calorie count of a human to just over 1 million. A large sweet potato provides 180 calories, which means that while supplementing the necessary vitamin requirements with supplies brought from earth, it appears the equivalent of 14 sweet potatoes per day must be harvested on Mars in order to indefinitely ensure the survival of human colonists on Mars. On average, sweet potatoes take between 100 and 150 days to harvest, but combining ideal conditions (lighting, temperature, and nutrients) with hydroponic efficiency the time to harvest drops to about 75 days. Extrapolating that data brings us to the conclusion that each colonist will need just under 1000 sweet potato pods growing in a hydroponic farm to provide and even slightly exceed the entirety of their caloric, fiber, protein, and carbohydrate needs indefinitely. This demand can reasonably be met using indoor hydroponic growing facilities, both the energy and material requirements of this project will be covered in later sections.

4.15.3 Design

The design of the hydroponic farm is perhaps the cornerstone of long term human survival in the Martian colony. Not only will it represent self-reliance in one of the harshest conditions ever faced by mankind, it will also be an amazing stepping stone towards permanent human settlements outside of earth. The design will utilize compartmentalized farming bases that
will each house approximately the amount of plants needed to sustain one colonist. Based on earlier calculations the projected number of plant growth pods needed is about 1000 per colonist, using 32 columns of 32 plant rows the number of plant growth pods reaches 1024, which is more than enough to sustain the colonists indefinitely once each farm is up and running. The plants will be separated into rows of boxes containing four plant growth pods each. Each box will be connected to a pipe that will provide water and nutrients to each plant. The arrangement of four plant boxes was selected so that the amount of space and lighting required could be minimized while also keeping the farm highly compartmentalized and easy to assemble. Each box will be placed beneath a specialized LED that will provide the plants with the proper intensity of light to ensure fast and healthy plant growth. All of the lights in the farm will operate off of simple timers that will provide the plants with day and night cycles best suited to their native environments. The duration of light cycles will vary depending on the crop being grown, for example, sweet potatoes will optimally receive 12 hour light cycles per day in order to ensure healthy but accelerated growth. The pipes will run from a large tank of water in the center of the room into a system of pipes that will travel through each individual plant growth box. The tank will be responsible for harvesting and distributing nutrient filled water due to the utilization of a fish based nutrient replenishing system. Water will be delivered to each plant via hydraulic pumps that will also be set to timers designed to optimize the amount of nutrients each plant receives per day. Space heaters will also be utilized in order to keep the temperature inside the farming base at a temperature consistent with the optimal growth temperatures of a preferred crop. Based on the dimensions of the engineering model created to replicate the farm, a conservative model requires each farm to consist of a 40m by 40m room. Further downsizing can be achieved based on the design model. All of these elements will come together to form a highly resource efficient hydroponic farm that will allow colonists to survive without extensive resupplying from Earth.
4.15.4 Lighting Requirements

Sunlight is one of the key components to many of the crops that are grown here on earth, but unfortunately, due to several compounding factors of life on the Mars base, artificial lighting will have to be utilized. While it is theoretically possible to grow plants using Martian sunlight in Martian soil, the dangers of radiation still pose a threat to any living organism that spends prolonged periods of time exposed to the Martian environment. In order to prevent any damage caused by radiation, the farm will be buried underground along with the rest of the base. Instead of sunlight spurring plant growth, artificial lights will provide plants with the light based energy that they need to grow. The main drawback of this system of lighting will be the increased energy consumption the lights will create, this consumption will be accounted for and analyzed below. The underground hydroponic facility will use specialized LED grow lights optimized for growing plants as efficiently as possible. Despite its drawbacks there are several advantages that will benefit the farm when using LED grow lights. The LED’s will be able to optimize plant growth by using a specific wavelength selection based on the type of plant being grown. LED’s create less heat than most bulbs and can be placed closer to plants without causing heat based damage. LED’s are very durable and have a comparatively long lifetime for a lightbulb, this will allow later flights to focus on bringing other vital materials on resupply missions instead. In terms of Energy consumption, there are several important factors to consider when designing the hydroponic farming system. The amount of wattage required shifts due to the type of plant and stage of growth but on average 40 watts/foot (430 watts/meter) should suffice for the hydroponic operation. The hydroponic farm will implement 40 Watt LED’s that have been selected due to their relatively low energy consumption and longevity/durability. Different plants require different lighting cycles in order to reach optimal growth rates, but most plants will be given a constant 12 hour lighting cycle followed by a 12 hour unlit cycle. The design will account for the spread of lighting and utilize reflection and cross lighting between LED’s
to grow 4 plants per light, meaning 256 bulbs can power each colonist’s entire food source indefinitely. Based off this design for the hydroponic farm the total energy requirement of each farm’s LED system to about 11 kilowatts or 122 kWh per 24 hour day. As a note, cross lighting could be further utilized to increase the efficiency of lighting and reduce the number of lightbulbs needed with only a minor loss of plant growth rate.

4.15.5 Heating Requirements

One of the most important energy requirements that will need to be accounted for when building these hydroponic farms is the amount of energy that must be exerted in order to ensure the plants grow at the optimal rate. Near the equator, the surface of Mars experiences temperature swings between 70 and -70 degrees Celsius, so while the farms should be well insulated, the thermodynamic properties of the room will still need to be addressed. Fortunately being underground will help insulate the base from the harsher swings of weather, but maintaining and monitoring the temperature inside each base remains a high priority. The optimal temperature for growing most plants is around 30 degrees Celsius, which means that the room must utilize heaters to maintain a constant temperature within the farm. The size and material makeup of the room are the two most important factors to consider when deciding how much energy to use in order to keep the rooms at the proper temperature.

Using data obtained regarding temperature, size of the base, and the thermodynamic properties of the material used for insulation, the exact amount of heat loss that will occur in the base can be calculated. Currently, the farms are designed to be forty by forty meter rooms with heights of three meters, giving the base a surface area of 3680 square meters. The biggest layer of insulation surrounding the base will be a two meter thick wall of Martian concrete, which is estimated to closely match the thermodynamic properties of sulfur based concrete. The interior of the walls will be coated with a 1 centimeter thick layer of aerogel developed by NASA that will utilize extremely low thermal conductivity properties.
This material will be used to help efficiently insulate the base from outside temperatures. Temperature calculations will be based on the average temperature on the surface of Mars, which is -60 degrees Celsius, compared to the preferred temperature in the farm, which is 30 degrees Celsius. After reviewing this data, the energy required to negate heat loss per hydroponic farm will come out to about 25 kilowatts per farm.

![Figure 4.30: Close Up of Hydroponic Growth Pods and Water Transport Pipes](image)

### 4.15.6 Assembly and Material Requirements

Once the initial design phase is finished, determining how to construct the base on site and what the proper materials to use are important steps that need to be taken in order to properly implement the final system. Many factors were taken into account when designing
the base, understanding how it would be constructed, and researching what it should be made of. One of the biggest design goals for the base will be to create the entire hydroponic farming operation using as little material (and mass) as possible. Another important design feature was to make the entire system highly compartmentalized so volume used during the flight is minimalized. The farm is designed to be shipped in a completely disassembled state and then be completely assembled on site using simple and easy to assemble pieces. Most of the pieces used will be formed out of lightweight yet strong plastics, such as Low-Density Polyethylene (LDPE), that will resist corrosion and safely contain all of the plant material and nutrients needed for the system to operate.

Building materials:

- Growth Pods for holding individual plants.
- Boxes used for containing sets of four plant pods.
- Plastic Pipes connecting series of plants to water supply.
- Water Reservoir chamber to hold and distribute water.
- Water quality sensors to distribute water at the optimal nutrient level for each crop.
- Timer controlled pump to move nutrient filled water through the system when necessary.
- Timer controlled LED grow lights with adequate connections to electricity.
- Light reflectors to help utilize a more efficient cross pattern lighting system for the amount of lightbulbs used.
- Thermal sensor controlled space heaters that will keep the entire room at a consistent temperature.
Chapter 5

Conclusion

For as long as people have looked at the Red Planet and understood its significance, they have desired to visit its surface. Even before humans landed on the moon, NASA spent a great deal of time and money thinking about a trip to Mars. In the sixty years since then, Mars has been a primary focus of space programs around the world. In the past five months, this IQP team has investigated topics in sending humans to Mars ranging from propulsion methods to character trait selection and almost everything in between. The team has researched existing Martian plans and crafted its own, based on real science and real technology. If this plan was put into motion today, it is 100 percent fair to say we could have humans on Mars in the next decade.

When we set out on this project, our main goal was to explore the growing connection between humanity and outer space; we then chose to focus on humanity’s nascent interest in colonizing another planet. Within the scope of this project, the initial goal was accomplished with resounding success. As a team, we have vastly expanded our understanding of space technology, mission planning, and risk management.

It is also important to mention something that was not discussed much in the
paper. At any time during a Martian mission, there is a chance for man or machine to encounter alien lifeforms. If this happened, the whole mission would dramatically change. Alien lifeforms could exist in any state, from microbe to full sized organism. Because they developed outside of our world, they could present a biological risk to all astronauts. While aliens would open a window to an all new breakthrough in human science and era in human history, the mission priority would change from being about setting up an outpost to safely researching and coexisting with the alien life.
Chapter 6

Appendices
## 6.1 Authorship

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Table 6.1: Authorship
6.2 Plot and Figure Credits

Cite our figures here in the order they were used

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5. **Figure 3.5** Image from GeePee1, flickr.com [https://s-media-cache-ak0.pinimg.com/564x/31/d9/1d/31d91da79b1e287d5ef48183da23d91a.jpg](https://s-media-cache-ak0.pinimg.com/564x/31/d9/1d/31d91da79b1e287d5ef48183da23d91a.jpg)

6. **Figure 3.6** Image from GardeningandHoriculture.com [http://tc974.ediya.hop.clickbank.net/](http://tc974.ediya.hop.clickbank.net/)


8. **Figure 3.8** Rendering from Daein Ballard, 2006 [https://commons.wikimedia.org/wiki/File:MarsTransitionV.jpg](https://commons.wikimedia.org/wiki/File:MarsTransitionV.jpg)

9. **Figure 3.9** Map generated by Los Alamos Research Lab, 2003 [https://upload.wikimedia.org/wikipedia/commons/b/b0/Water_equivalent_hydrogen_abundance_](https://upload.wikimedia.org/wikipedia/commons/b/b0/Water_equivalent_hydrogen_abundance_)

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10. **Figure 3.10** Rendering from SpaceX presentation, 2016 [http://nerdytoday.com/wp-content/uploads/2016/05/14240353517_80ae718490_b_1199x800.jpg](http://nerdytoday.com/wp-content/uploads/2016/05/14240353517_80ae718490_b_1199x800.jpg)

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12. **Figure 3.12** Photograph from Jessica Orwig at Business Insider [http://static6.businessinsider.com/image/568ad506c08a801b008b6b25-1200/122917071010682664362337537jpg](http://static6.businessinsider.com/image/568ad506c08a801b008b6b25-1200/122917071010682664362337537.jpg)

13. **Figure 4.1** Map generated by Jet Propulsion Lab [http://planetfacts.org/wp-content/uploads/2010/05/Mars_daytime-temperature.jpg](http://planetfacts.org/wp-content/uploads/2010/05/Mars_daytime-temperature.jpg)

14. **Figure 4.2** Artist rendering of VCAM, Johnson space Center [https://www.nasa.gov/mission_pages/station/research/experiments/VCAM1.jpg](https://www.nasa.gov/mission_pages/station/research/experiments/VCAM1.jpg)

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17. **Figure 4.5** Photograph from Meredith Popolo, PCMAG 2013 [https://assets.pcmag.com/media/images/393370-cevis.jpg?thumb=y&width=630&height=473](https://assets.pcmag.com/media/images/393370-cevis.jpg?thumb=y&width=630&height=473)

18. **Figure 4.6** Graph generated by Tga.D for WikiMedia Commons [https://upload.wikimedia.org/wikipedia/commons/thumb/1/1e/Estimations_of_Human_Brain_Emulation_Required_Performance.svg/800px-Estimations_of_Human_Brain_Emulation_Required_Performance.svg.png?148941566905](https://upload.wikimedia.org/wikipedia/commons/thumb/1/1e/Estimations_of_Human_Brain_Emulation_Required_Performance.svg/800px-Estimations_of_Human_Brain_Emulation_Required_Performance.svg.png?148941566905)

19. **Figure 4.7** Image from Robotnik, company [http://robosklep.com/546-thickbox_default/robotnik-mobile-robot-summit-xl-hl.jpg](http://robosklep.com/546-thickbox_default/robotnik-mobile-robot-summit-xl-hl.jpg)
20. **Figure 4.8** Photograph from Erik Bland, 2009 [http://media2.s-nbcnews.com/j/MSNBC/Components/Photo/_new/robot-gardener-540x380.grid-6x2.jpg](http://media2.s-nbcnews.com/j/MSNBC/Components/Photo/_new/robot-gardener-540x380.grid-6x2.jpg)


22. **Figure 4.14** Chart generated by Cesar Martin [https://www.researchgate.net/profile/Scot_Rafkin/publication/236977793/figure/fig1/AS:299528596017156@1448424590788/Fig-1-Dose-rates-recorded-in-a-silicon-detector-black-circles-and-in-big.png](https://www.researchgate.net/profile/Scot_Rafkin/publication/236977793/figure/fig1/AS:299528596017156@1448424590788/Fig-1-Dose-rates-recorded-in-a-silicon-detector-black-circles-and-in-big.png)

23. **Figure 4.15** Table from NASA, 2008 [http://2.bp.blogspot.com/-1aMpQLYd84A/U4juViErsbI/AAAAAAADWI/Q-4dvePHQ8I/s1600/NASA+Astronaut+Career+Limits.PNG](http://2.bp.blogspot.com/-1aMpQLYd84A/U4juViErsbI/AAAAAAADWI/Q-4dvePHQ8I/s1600/NASA+Astronaut+Career+Limits.PNG)

24. **Figure 4.20** Diagram from United States Geological Survey [https://upload.wikimedia.org/wikipedia/commons/thumb/b/b4/Outer_core_convection_rolls.jpg/220px-Outer_core_convection_rolls.jpg](https://upload.wikimedia.org/wikipedia/commons/thumb/b/b4/Outer_core_convection_rolls.jpg/220px-Outer_core_convection_rolls.jpg)


26. **Figure 4.27** Chart created by Swift for WikiWand, 2016 [https://upload.wikimedia.org/wikipedia/commons/6/6a/Elements_abundance-bars.svg](https://upload.wikimedia.org/wikipedia/commons/6/6a/Elements_abundance-bars.svg)

27. **Figure 4.28** Map generated by JPL from survey data gathered in 2001 [http://photojournal.jpl.nasa.gov/jpeg/PIA04257.jpg](http://photojournal.jpl.nasa.gov/jpeg/PIA04257.jpg)
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