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The Future of Construction as it Applies to the Colonization of the Moon and Mars

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THE FUTURE OF CONSTRUCTION AS IT APPLIES TO THE COLONIZATION OF THE MOON AND MARS

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Abstract

The goals of this research are:

1. To compile a comprehensive list of all the viable known solutions (and early stage potential solutions) to the issues related to constructing permanent, sustainable, and safe structures for human colonies on our moon and Mars,
2. Determine the most effective potential solutions, and
3. Further develop these ideas as to assist in further space endeavors.

This proposed paper will assist space experts in determining the best next steps in the development of deep-space travel and colonization technologies. Preliminary research has identified several key problems associated with establishing space colonies. They are as follows: (1) damaging effects of cosmic radiation, (2) the need to generate and maintain a breathable atmosphere, (3) the time it takes to reach other celestial bodies, and (4) scarcity of conventional construction materials and life-supporting supplies/systems. Each of these four problems has many components that must be solved for humans to successfully colonize our planetary neighbors.

Many promising construction technologies are being developed and used by several large-scale space operation organizations. Some of these solutions are being used to directly solve the problems while others are smaller parts of a larger solution. For example, there have been recent material advancements with respect to 3D printing; sintering technology may also prove to be a viable solution for construction materials. Some current solutions from NASA involve modularized space station units.

The findings summarized in this paper incorporate several cutting-edge and innovative technologies related to constructing an extraterrestrial base for humans. There are several proposed solutions for overcoming the four primary issues, though a few solutions demand the attention of further development as they are more feasible than others. When overcoming cosmic radiation, the most feasible solution is the use of Hydrogenated Boron Nitride Nanotubes which are able to block both primary and secondary radiation particles making it an ideal shielding material. In order to overcome the lack of an atmosphere on the moon or Mars, a technology called MOXIE, developed by the Massachusetts Institute of Technology, is able to develop and harvest breathable oxygen with the assistance of microbial life.

Overcoming the issues related to time can be the most difficult as no current technology exists that speeds up time or reduces trip duration between worlds. However, preliminary developments in hibernation technologies may very well be the future of long-term interstellar missions. Finally, when overcoming material-related problems on other planets, the advanced applications of additive manufacturing processes appear to be the solution for building habitats as well as creating tools, spare parts, and inadvertently solving some of the other problems. These solutions and more will be discussed in greater detail throughout the solutions and results portion of this paper.

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Background

Space is a vast and constantly expanding, scattered with trillions of stars and planets; some would call it the final frontier of human exploration. Mankind has wondered about space and its mysteries for millennia, but it was only in the last 50 years that we as a species have been able to travel into space and land on another celestial body, the moon. While humans have only recently begun exploring the cosmos, the interest and fascination regarding space has existed since our ancestors first looked to the stars for guidance. Many aboriginal and Native American tribes hold firm beliefs that their ancestors and gods came from the sky.

Whether or not their assumptions are correct remains to be seen; however, it is worth mentioning that these tribes and communities have always felt a unique connection with the universe beyond the Earth. That strong yearning may have been briefly quelled by the technological advancements over the last few centuries, however, we still come back to space as the next step for our future. Going forward, we will find our way to the Mars and beyond.

Landing on the moon in 1969 has since altered our view of space from an unattainable desolate expanse devoid of life to the future of human civilization. While there still exist many unknowns about what will be out there when we go looking, the fact of the matter is that we are going. With the ability to send unmanned spacecrafts into space, we have been able to learn more about our universe than the ancient physicists could have ever hoped to learn. With the addition of a human element on these missions, we would be able to learn about our planetary neighbors at a much quicker rate than relying on rovers for collection and analyses.

Introduction

Despite the many issues and concerns associated with space travel and colonization, there is strong desire by our species to break through the atmosphere and travel into the cosmos to stretch the reach of the human race across the universe. Regardless of the motivation for wanting to achieve such a goal, it is going to be accomplished one way or another. In order for this goal to be completed successfully, the many problems faced when leaving the Earth must be solved in an effective, safe, and sustainable manner. Therein lies the issue, there are many problems faced when leaving the Earth. While technology has come quite a long way since first launching humans to the moon, we still have not been able to achieve manned missions beyond the moon due to the lack of available sophisticated technology. The technology required for such a mission would need to support human life on long duration interplanetary missions or for long duration habitations on other rocky planets, moons and asteroids.

NASA, SpaceX, Mars City Design and a plethora of other companies, organizations, and government entities are developing ideas and technologies to reach Mars more quickly and to set up a permanent, sustainable colony. There are several technologies and developments that are on the cusp of solving the problems experienced when traveling into space. However, given the vast number of unknowns about the logistics of leaving Earth, traveling to Mars, and setting up permanent sustainable structures, we may still be several years away from sending humans to Mars. Gathering space travel and colonization information from the vast variety of companies and organizations available will be the first step in determining the best choices we have going forward to achieve the goals we have set for ourselves.

It is expected that the information resulting from this paper will prove to be useful for groups looking to travel to the moon and Mars. It is anticipated that this research will assist in continued development of technologies and create new ideas for aerospace professionals going forward as to increase the options available to those striving to achieve these goals. While Mars is millions of miles away from Earth, it is not quite out of reach. Once we have developed the appropriate technologies for traveling to, colonizing, and sustaining life on extraterrestrial worlds we will be able establish a human colony on Mars. Utilization of these technologies may also allow us to colonize other planets in our solar system and beyond provided the conditions are appropriate for such systems.

Research Objectives

There are three primary objectives or goals for this research:

1. Compile a comprehensive list of all the viable solutions, and early stage potential solutions, to the issues related to constructing permanent, sustainable, and safe structures for human colonies on the moon and Mars.
2. Determine the most effective potential solutions through literature review and the attendance of lectures.
3. Further develop these ideas as to assist in further space endeavors both from colonization and deep space exploration purposes.

These research objectives will be met through literature review, lecture attendance, scientific deductive reasoning and the comparing and contrasting of all source data to determine the most effective and efficient methods of enduring the goal of colonizing the moon and Mars.

Speculative and theoretical ideas may also be included, within reason, if potential for real world application exists.

Research Beneficiaries

The expected beneficiaries from this research will first and foremost the astronauts. The focus of this research will be to find solutions to problems experienced by astronauts and space professionals as they leave the Earth's atmosphere and magnetic field on their way to constructing long-term, safe and sustainable human colony housing units on our neighboring planetoids. Other beneficiaries include professionals in the aerospace industries, who will be conducting the technical planning, design and construction of the spacecrafts and habitations the astronauts will use themselves. This document will also benefit those eager to learn about space and how the human race may survive the cosmos.

The information compiled in this research summarizes the current state-of-the-art technologies being used to address the colonization issues. Finally, remaining beneficiaries shall include any and all members of academia that will reference this information in the future or who may be inspired to conduct their own research to follow a lead on a topic discussed or mentioned in the bulk of this research.

Methodology

Research for this paper was conducted in two ways; the first being a literature review which consisted of combing through articles, journals, books, websites, papers, booklets, brochures, and other forms of data to find useful information on the problems and solutions related to human colonization of the moon and Mars. The second means of research was through the attendance of academic, informative lecture events held by the National Atomic Testing Museum in which professionals in academia and industries someway related to radiation come to discuss topics pertaining to the relevant topic. The following sections address specific information developed during this research.

Literature Review

The literature review portion of this research came from the media referenced above, ranging from publications and information from NASA to construction specifics in national engineering journals and just about everything in between. The information collected and used in this paper provides a comprehensive look into the many problems associated with space travel as well as the current and potential solutions to said problems so that we as a species may achieve our dreams of colonizing the moon, Mars, and beyond.

Lecture Attendance

In addition to literature review, the author attended several distinguished series lectures on the topic of space and/or space radiation in some form. These lectures were given by professionals in the aerospace fields, professors from esteemed universities, and experts on the topics of discussion. Several of the ideas learned about during these lectures will be discussed and utilized throughout this paper.

Problems

There is a myriad of issues associated with space travel, many of which deal with human health concerns. The number of things that could go wrong while on a space mission is absolutely staggering; however, some issues are quantifiably more problematic than others. Regarding the scope of research for this paper, there are four main problems with space travel and colonization that need to be addressed before manned missions to Mars and beyond can be established. Cosmic radiation is one of the biggest threats to organic life beyond the Earth and its protective magnetic field and atmosphere. Cosmic radiation is emitted from all stars in the universe, and long-term or high amounts of exposure can result in deleterious effects on the human body in the form of diseases and abnormalities such as cancers and sterility.

Another great concern for future colonists is the lack of an atmosphere on the moon and the lack of a breathable atmosphere on Mars. While protective shelters may be the immediate answer, the long-term idea is to create a breathable and functional atmosphere on the planets we colonize in order to thrive for future generations. Until an atmosphere can be conjured up, the colonies will have to rely on fully enclosed housing units to provide breathable air and a comfortable environment.

Human beings are always at the mercy of time; there is never enough time in the day to complete all of our tasks, the older we get the less mobile we become, and as we age our bodies begins to break down and become more difficult to maintain. There is not much that can be done to counteract time, though some options exist for greatly slowing the effects. This type of technology would be useful for long-term space missions such as seven-month trips to Mars or a decade long journey to Pluto and beyond.

Finally, the lack of readily available materials is a huge problem for colonists; without materials to build settlements, colonization is not possible. There exist two real viable options for creating structures on far away worlds; either bring everything you need with you or bring technology to terraform the existing landscape into something useable and livable. Both ideas are incredible undertakings that would require billions of dollars and years of time, but one of them is the only option at this point. The hope is that once colonies have been established, humans can develop the things they need using the natural resources of the planet as we did all those years ago on Earth; getting to this point will take several generations of humans.

To fully grasp the magnitude of these problems, much more information is needed. The following sections will discuss the aforementioned space colonization problems in depth for a better picture of why these issues matter and illustrate the kind of effort required to overcome these problems.

Cosmic Radiation

Any form of radiation can prove to be problematic with enough exposure; though cosmic radiation is in a weight class by itself in terms or destructive ability and unique origins. While these cosmic rays are undetectable by the human eye, they can pack quite a wallop when colliding with other energetic particles or organic tissues. Cosmic radiation or space radiation is comprised of three types of ionizing radiation: particles trapped in the Earth's magnetic field; particles shot into space during solar flares (solar particle events); and galactic cosmic rays, which are high-energy protons and heavy ions from outside our solar system (Wall, 2009). It is important to note that cosmic radiation is an ionizing type of radiation which means that, with a great deal of exposure, is has the potential to mutate and alter genes and DNA in living organisms which could result in evolutionary implications (Caros, 2013). While this type of mutation is highly unlikely on the ground due to the lack of high energy particles which are deflected by the Earth's magnetic field; astronauts risk this occurrence each time they leave the Earth's atmosphere. In addition to cosmic rays there are gamma rays, alpha rays and x-rays all of which are different from cosmic rays with respect to their charges as well as their average air penetration depth (Caros, 2013).

Space radiation is very different from any form of radiation we experience on Earth; this form of radiation is comprised of atomic nuclei in which electrons have been stripped away as the atoms are accelerated in interstellar space to speeds approaching the speed of light - eventually, only the nucleus of the atom remains (Gushanas, 2017). Between the three types of cosmic rays mentioned, they are all comprised of the same particles though, galactic cosmic rays (GCRs) are the biggest threat to the future of space travel due to the fact that they can come from any direction given that their origin is from exploding super novae across the universe. They also require the greatest amount of shielding, requiring at least ten meters of shielding material, typically an aluminum alloy, to be effective in protecting astronauts (Cucinotta, 2017).

While the Earth has trapped bands of radiation clinging to its magnetic field, known as the Van Allen radiation belts; it is unlikely that the moon or Mars would have any trapped cosmic rays considering their magnetic fields are either incredibly weak or nonexistent. Solar particle events could prove to be problematic for colonists if they are to develop colonies along the polar regions of these worlds. Cosmic rays have free access over the Earth's Polar Regions where magnetic field lines are open to interplanetary space (Beville, 2014). However, radiation coming from solar particle events that did not make it through to the poles would likely be trapped within the radiation belts encompassing the magnetic field, if a stronger magnetic field has been developed by the colonists. Below, Figure 1 shows what happens when the radiation is able to infiltrate through the magnetic field to the planet's Polar Regions.

Figure 1: Aurora Borealis - Solar Radiation Entering the Atmosphere (NASA, 2011)

How are we protected on Earth?

According to Gushanas, 2017 "Life on Earth is protected from the full impact of solar and cosmic radiation by the magnetic fields that surround the Earth and by the Earth's atmosphere; as we travel farther from Earth's protective shields, we are exposed to the full radiation spectrum and its dangerous effects". Lower energy particles are typically broken up by our layers of atmosphere; larger or higher energy particles are often deflected or trapped by our magnetic field and the Van Allen belts (Cucinotta, 2017). Though sometimes they can penetrate through our atmosphere and reach the ground depending on the path of travel of the particle, the amount of energy the particle has, and the composition of the particle. However, for all intents and purposes, the Earth's atmosphere and magnetic field are the sources of protection from incoming cosmic rays blasting through our solar system ranging from solar particle events and coronal mass ejections to supernovae explosions and gamma ray bursts. Figure 2 below illustrates how the magnetic field system surrounds the Earth.

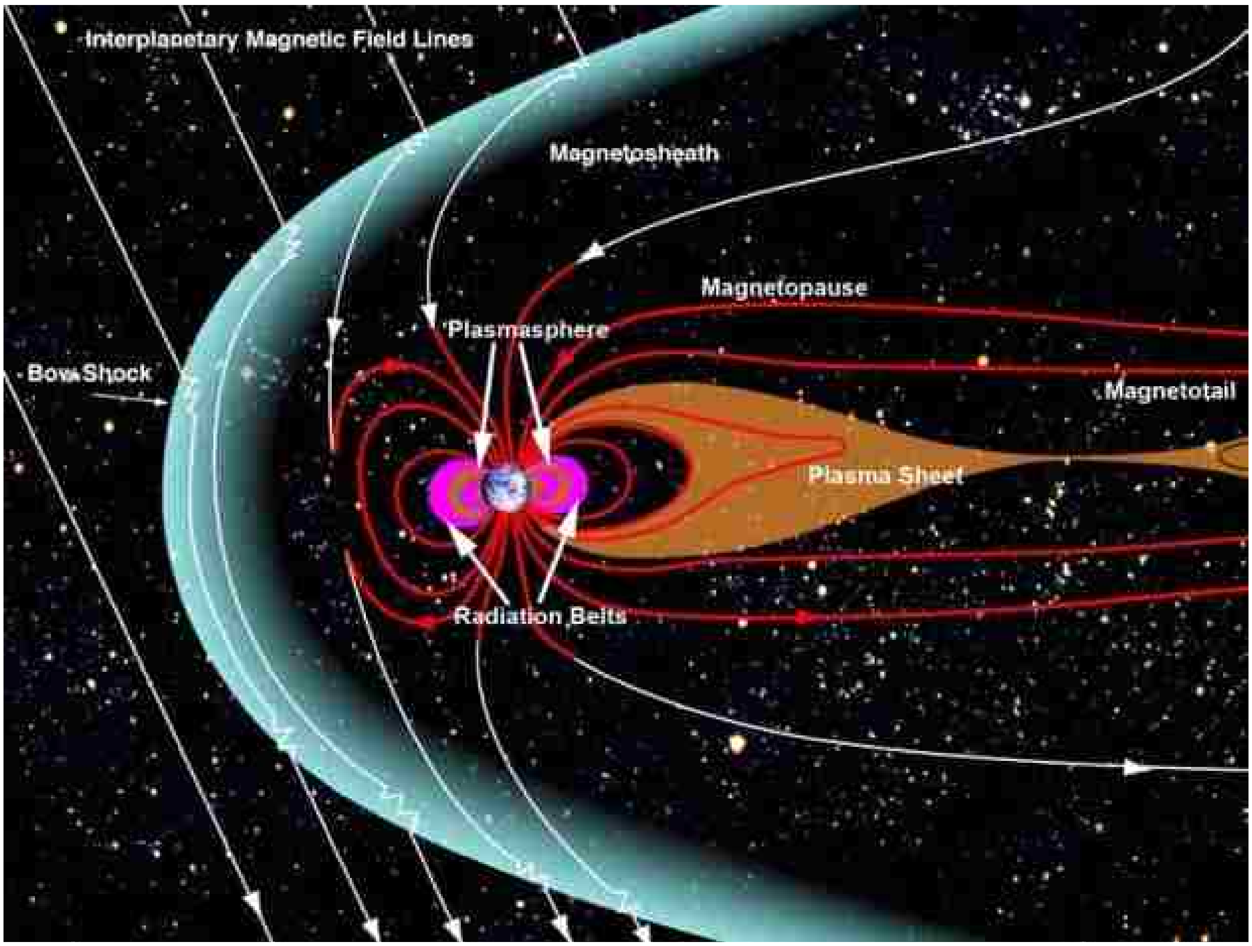


Figure 2: Illustration and Labeling of Earth's Magnetosphere System (Zell, 2013)

Health problems associated with exposure.

Exposure to cosmic radiation, or any radiation for that matter, can result in detrimental effects to the human body and brain. The longer and more concentrated the exposure the greater and more severe the health risk. Astronauts are not the only ones risking exposure to cosmic rays. Airlines workers are also at risk on a daily basis as well as frequent travelers, people living at high elevations, and people living near the poles. NASA has determined four main factors that help to determine the amount of radiation an astronaut is exposed to while in orbit around the Earth. First, orbital inclination with relation to the distance from Earth's poles i.e. where Earth's magnetic field concentrates ionizing particles; the closer to the poles the higher the radiation. Second, altitude above the Earth, at higher altitudes Earth's magnetic field is weaker which means there is less protection from ionizing particle. Third, solar cycle, the sun operates on an 11-year cycle and during this cycle there is intense fluctuation in solar flare activity. Finally, an individual's susceptibility, which is basically how each person is able to handle the radiation dosage they are being exposed to (Wall, 2009).

With respect to pilots, stewards and stewardesses, according Johnson-Groh, 2017 "because of their time spent in Earth's upper atmosphere, aircrew in the aviation industry are exposed to nearly double the radiation levels of ground-based individuals". Even those in a non-flight related industry (either aerospace or aviation), living in certain cities can be exposed to higher radiation levels simply by living at a higher altitude. For example, Denver is more than 5,000 feet above sea level and Miami is only about 40 feet above sea level; this means that people living in Denver are exposed to more cosmic radiation than people living in Miami (L'Annunziata, 2016).

The Earth's magnetic field and atmosphere protect the planet from nearly all of the incoming radiation from space; however, for people outside the Earth's protection, cosmic radiation becomes a serious concern. According to Howell, 2016 "An instrument aboard the Curiosity Mars rover during its 253-day cruise to Mars revealed that the radiation dose received by an astronaut on even the shortest Earth-Mars round trip would be about 0.66 sievert; this amount is like receiving a whole-body CT scan every five or six days". Howell, 2016 goes on to say, "A dose of 1 sievert is associated with a 5.5 percent increase in the risk of fatal cancers; the normal daily radiation dose received by the average person living on Earth is 10 microsieverts (0.00001 sievert)".

According to Cucinotta& Durante, 2006 "Epidemiology studies on Earth have shown that exposure to moderate high doses of ionizing radiation increases the risk of cancer in most organs; leukemia and cancers of the breast, thyroid, colon, and lung are particularly sensitive to induction by radiation". Not only is cancer a result of long-term or high dosage exposure to ionizing radiations, but a slew of other deleterious health issues and diseases can come from radiation exposure including acute radiation poisoning, central nervous system and brain diseases, and cataracts which can occur even after low doses of galactic cosmic radiation (Cucinotta, 2017). Vision impairment, as well as many of the other outcomes, could lead to potential problems down the road for colonists as vision (and other functions) deteriorates without proper care or repair.

Due to the ionization of these high energy particles, not only is the risk of cancer increased, but it is also possible that the cell functions in the brain, reproductive organs, and other tissues may change (Schimmerling et. al., 2003).This could result in the inability to function properly or even procreate which would be the biggest problem when trying to colonize a lunar or Martian outpost. The central nervous system (CNS) risks are categorized as mission risks and late risks, mission risks indicating issues that may be faced during interstellar missions and late risk indicating the long-term effects of such a mission. Possible CNS risks during a mission are altered cognitive function, including detriments in short-term memory, reduced motor function, and behavioral changes, which may affect performance and human health; the late CNS risks are possible neurological disorders such as premature aging, and Alzheimer's disease (AD) or other dementia (Cucinotta et.al., 2014). These cognitive function changes would result in much less work being done as well as people behaving differently under severe exposure, especially during multi-year trips to Mars and back.

A study was conducted by UC Irvine that measured the long-term effects of space-like levels of radiation in six laboratory mice using two different species. While their results are those of rodents, the scientists note that due to the similar results from each species of rodent, the effects on the brain would likely be similar across all mammal species including humans. After six months of radiation exposure, Khan, 2016 states "the rodents still were suffering from brain inflammation and neural damage; neurons sported fewer dendrites and spines, which meant their neural networks were less interconnected than in a healthy brain". If these same issues were to be experienced by human astronauts on missions, they may develop impairments that could directly affect mission performance and decision-making functions. Pair that with poor memory and heightened stress or anxiety and it could result in mission failure or death. Without proper protection these effects from cosmic radiation are all but guaranteed for those who travel beyond the safety of the Earth and its atmosphere and magnetic field.

Effects of radiation on electronics.

In addition to causing terrible problems in organic life, radiation is also bad for inorganic life, specifically electronics and equipment, which are a very important part of traveling to and sustaining life on other planets and moons. While machines can't develop cancer, they can easily malfunction and break down, which on Earth is no issue because you are able to call someone to fix the problem. On Mars, or on the moon, unless you packed a highly knowledgeable maintenance technician with all of the necessary tools and spare parts, when something malfunctions it can be the end of the mission or even worse, the end of life.

The main reason for why space bound technology malfunctions is due to the infiltration of charged high-energy energetic particles or ionizing cosmic radiation into the components, namely the semiconductors. As high-energy energetic particles enter, the materials and interactions of such devices will undergo a certain percentage of charge coming from outside; this will entail a sudden memory error and cause various malfunctions (Maki, 2009). The more radiation experienced by electronics, the higher the current flowing through the system; this can result in components malfunctioning much sooner than expected as well as continuous charge. Continuity on parts that should be insulated may result in a phenomenon where current continues to flow (latch-up); if burning occurs due to this continuous flow of current, permanent breakdown may result (Maki, 2009). In other words, high-energy energetic particles can cause communication errors in equipment and potentially cause fires leading to permanent malfunction. More studies need to be done on satellites and other space bound electronics in order to help solve the issues experienced from space radiation exposure.

Lack of Atmosphere

Having a breathable atmosphere that functions as well as the one on Earth does is very important for sustaining life on another world. Not only do colonists need air to breath, but an atmosphere also provides the benefits of precipitation cycles (giving the planet water and life) as well as shielding from incoming cosmic rays and space debris. On Earth, one might take our atmosphere for granted, but those colonizing a new world would likely appreciate the atmosphere that they are leaving behind much more than would have before. The moon does not have an atmosphere in the traditional sense, and the one on Mars is too thin to support life at its current state which is cause for concern if colonists plan to survive on these rocky planetoids in the millennia to come.

No oxygen rich air &potentially toxic gases.

Without a breathable atmosphere available, life on a Martian planet becomes much more difficult. Though the moon and Mars do not have breathable atmospheres, other worlds have atmospheres that contain poisonous gases that could cause death within seconds of exposure. For years, people have always accepted that the moon does not have an atmosphere; however, upon further review, the moon does have an atmosphere referred to as an exosphere. This is a much smaller version of an atmosphere where the gases are so sparse and spread out they rarely collide with one another. This thin layer allows the surface of the moon to be very cold, especially on the side of the planet that does not receive any light.

Although there were initial reports of additional detections, the Apollo studies of the lunar atmosphere made firm identifications of only three elements, Ar, He, and Rn (Morgan & Killen, 1997) which are Argon, Helium and Radon respectively. Recent studies confirm that our moon does indeed have an atmosphere consisting of some unusual gases, including sodium and potassium, which are not found in the atmospheres of Earth, Mars or Venus (NASA, 2013). Solar particle events are the cause for the moon's exosphere. Solar wind plasma impinges directly on the lunar surface, the plasma is then neutralized, thermalized, and reemitted from the surface to build up the major constituents of the atmosphere (Daily et.al., 1977). Breathing these gases would not be possible for colonists, they would require some form of clean breathable air at all times and a filtration system to keep the toxic gases from infiltrating their living space.

The composition of the atmosphere is not the only difference between the moon and Earth; the atmospheric density of the moon varies greatly with Earth's atmosphere. At sea level on Earth, we breathe in an atmosphere where each cubic centimeter contains 10,000,000,000,000,000,000 (ten quintillion) molecules; by comparison the lunar atmosphere has less than 1,000,000 (one million) molecules in the same volume (NASA, 2013). This would indicate that there are 10,000,000,000,000 (ten trillion) times the number of molecules per cubic centimeter of atmosphere on Earth than there are on the moon suggesting that even if the elemental composition was ideal, the air would be too thin to breathe. This thin exosphere would also leave colonists exposed to the ravages of cosmic radiation as there are significantly fewer molecules for the incoming radiation to break apart in.

Like the moon, the atmosphere on Mars is not breathable to humans and other Carbon based life forms. The composition for the Martian atmosphere at the surface of the planet is as follows: Carbon dioxide comprises 95.32 percent of the atmosphere, followed by Nitrogen at 2.7 percent, Argon at 1.6 percent, Oxygen at 0.13 percent, Carbon monoxide at 0.07 percent, water vapor at 0.03 percent and Neon, Krypton, Xenon & Ozone measuring in the parts per million or ppm (Owen et. al., 1977). Many theories and findings suggest that Mars was a thriving planet millions (or billions) of years ago with oceans and rivers and a thicker atmosphere; however, the conditions on Mars are less than ideal for life in its current form.

There are many theories that try to explain the mysteries behind the significant planetary change experienced by Mars, though according to Brown et. al., 2015 "NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission has identified the process that appears to have played a key role in the transition of the Martian climate from an early, warm and wet environment that might have supported life to the cold, arid planet Mars is today". According to new results, solar wind and radiation are responsible for stripping the Martian atmosphere away through sputtering. This phenomenon is when ions are slammed against the top of the atmosphere by solar winds which knocks other atoms loose into space (Brown, 2017), over time this can lead to significant atmospheric degradation.

While the conditions may be alien to us, there very well could be microscopic life hiding within the Martian surface, waiting for a chance to thrive and evolve. However, it is important to point out that if microorganisms are or were present on Mars, the sub permafrost region is their most likely abode because the presence of hydrogen peroxide, intense ultraviolet (UV) radiation, and the low temperature and low pressure at the surface of Mars would render the surface hostile to life as we know it (Formisano et. al., 2004). Mars has a much thinner atmosphere than ours and is much farther from the sun than we are, this causes the Martian planet to be much colder than it is on Earth. The average temperature on Mars is roughly negative 80 degrees Fahrenheit (F), but it can range from negative 195 F near the poles during winter to as much as a comfortable 70 F at midday near the equator (Sharp, 2017).

Figure 3: Martian Surface Before and During a Large Dust Storm (NASA, 2002)

In addition to the extreme cold, Mars is also host to the largest dust storms in the solar system. Illustrated on the previous page in Figure 3, some are large enough to encompass the planet in a shroud of red dust for months at a time. The important thing is to learn how to survive through one of these world swallowing dust events and to be able to make any repairs to damaged equipment and habitats afterwards. Mars can also experience snow, though the snowflakes on Mars are made of Carbon dioxide and look more like a shroud of fog rather than the typical snowfall we see on Earth (Sharp, 2017). While the Martian world is one of violence and isolation, the atmosphere is only one thing that future colonists need to worry about, even with sophisticated breathing apparatuses there are other things the Martian planet is currently without.

No liquid water on the surface.

Preliminary findings have shown that the moon and Mars are devoid of any flowing liquid water on the surface. While there is evidence to suggest that water may have flown across these surfaces millions of years ago, that does not help humans attempting to live on these planets today. While recent reports have shown that ice is present near the poles on both Mars and the moon, the undertaking required for harvesting the ice and converting it to useable, drinkable water, would be immense. Once colonists are able to create a rich and breathable atmosphere, water will no longer be an issue, though that would be many generations down the line.

Until recently no one knew if there was water on the moon. In 1998 there was speculation that the moon was home to plenty of water for sustaining life, though in the form of ice, thanks to a lunar probe. Data returned by the Lunar Prospector spacecraft indicated that water ice might be present at both the north and south lunar poles; the estimated total mass of ice is 6 trillion kg (6.6 billion tons) (Williams, 2012). Though it is worth mentioning that this initial estimate could be significantly lower due to the ranges of the ice patches assumed by the results. On October 9th, 2009 NASA's LCROSS probe discovered beds of water ice at the lunar South Pole when it impacted the moon (Thompson, 2009). While ice may exist on the moon, there still remains an uphill battle for harvesting the ice and converting it to drinkable water, burnable Hydrogen fuel, and breathable Oxygen rich air. Figure 4 shows large deposits of hydrogen at the lunar poles which leads scientists to believe that these are large deposits of water ice below the surface.

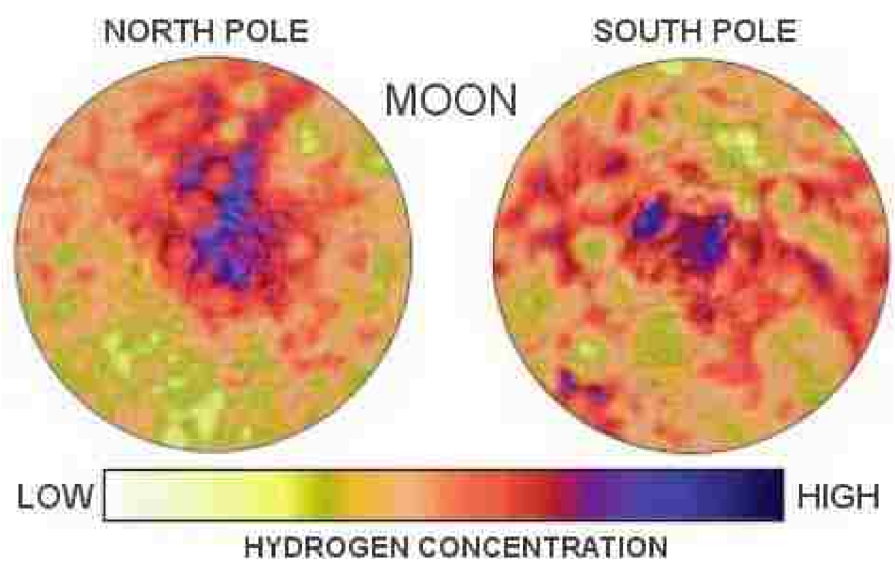


Figure 4: Hydrogen Deposits Measured by Lunar Prospect (Science, 2005)

Much like the moon, no one believed there was water on the Martian planet; however, recent missions have proven otherwise. According to Greshko, 2018 "In 2002, the NASA Odyssey mission scanned the planet from orbit and detected signs of shallow ground ice at high latitudes. In 2008, the NASA Phoenix mission dug up water ice at its landing site near the Martian North Pole. And in late 2016, scientists using the Mars Reconnaissance Orbiter (MRO) found a buried ice sheet at Mars's mid-latitudes that holds about as much water as

Lake Superior". The amount of ice discovered thus far is compelling, though there are other options for a water source on Mars.

Using an imaging spectrometer on MRO, researchers detected signatures of hydrated minerals on slopes where mysterious streaks are seen on the Red Planet (Anderson, 2015), these streaks are shown below in Figure 5. Anderson goes on to explain that these streaks are known as recurring slope lineae (RSL) and appear to grow darker and thicker during the warmer season on Mars and fade away in the colder season. Often times people associate these RSL with the possibility of liquid water in the vicinity; and in 2015, spectral analysis of RSL led scientists to conclude they are caused by salty liquid water (Redd, 2017). While this may prove that water does flow on the red planet, there is not enough for a colony to survive on. Another concern is the fact that it is contaminated with salts and other minerals indigenous to the makeup of Mars which would not be desirable as a potable water source. A water treatment/desalination facility would be required for colonists to survive for long-term habitations on Mars.

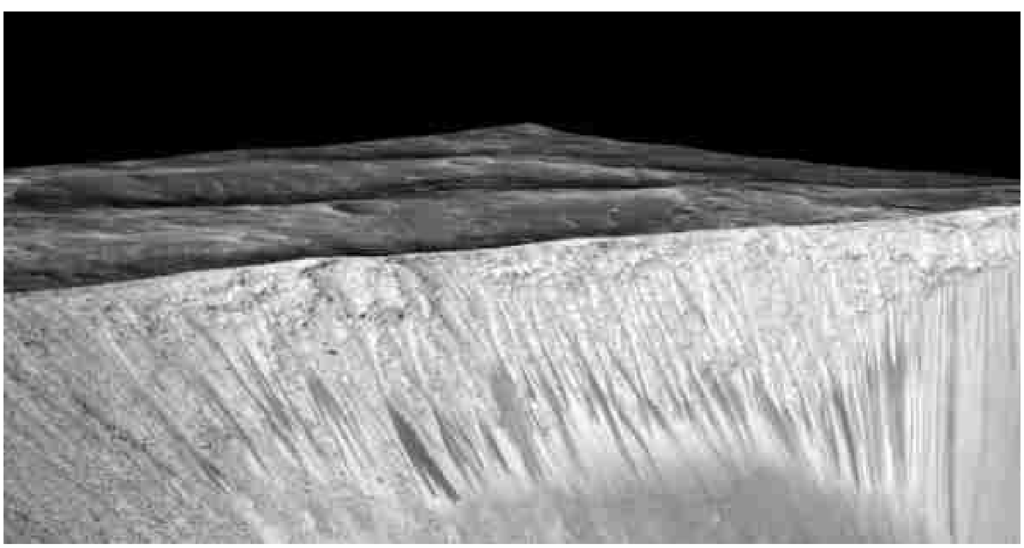


Figure 5: Recurring Slope Lineae Emanating out of the Walls of the GarniCrater on Mars (Anderson, 2015)

Space debris.

While the issues of radiation, atmosphere, and water are a primary focus in the space communities, not many people appear overly concerned with space debris. Space debris includes both natural and manmade particles and these particles can travel at speeds of up to 17,500 mph, fast enough for a relatively small piece of orbital debris to damage a satellite (Garcia, 2016). Space debris becomes a concern when the planet you live on does not have an atmosphere or when one is working in planetary orbit, such as performing repair work on the International Space Station (ISS). On Earth we have the luxury of our atmosphere breaking up space debris upon entry keeping us safe from death and destruction. However, on Mars, the moon or in orbit colonists and space travelers would be susceptible to man-made or naturally occurring space debris.

Some space debris is so small that it evades detection yet can still pack a wallop. According to Garcia, 2016 "even tiny paint flecks can damage a spacecraft when traveling at these velocities; in fact, a number of space shuttle windows have been replaced because of damage caused by material that was analyzed and shown to be paint flecks". These paint fleck sized particles are potentially the deadliest as they can arrive with enough force to break glass yet remain undetectable to the naked eye as well as to sophisticated tracking technologies. To put the force of these tiny particles into perspective, a collision with a metallic particle of debris with a 1 cm (0.4 in) radius is energetically equivalent to a collision with a car moving at a speed of 100 km per hour (62 mph) (Smirnov, 2002). For spacecrafts and astronauts moving through and roaming around planetary or lunar orbit, these particles could prove to be deadly if they strike the right location on the hull of the shuttle or on the astronaut's spacesuit.

Time

Time is always in motion, continually ticking along for as long as humans have understood the concept of time and will continue along well after we have left the Earth. The more time that passes, the longer something is affected by it, this can be a difficult issue when planning manned missions for planets that are light years away from our planet. Before setting our sights on missions to other solar systems, knowing the amount of time needed to travel those distances is very important. Leaving the Earth's surface and arriving in space only takes about eight minutes; however, making it to the ISS takes almost three full days (Dyson, 2017). While the ISS is closer to Earth than the moon is, it also takes about three days to make it to the moon on average. NASA sent eight crewed Apollo missions to the moon, six of which landed successfully on the surface; each spent about three days traveling through space (Sharp, 2017). Three days may not seem like a great undertaking, but the moon is the closest celestial body to our planet, reaching the next one takes quite a bit longer.

The next planetoid on the list for colonization is Mars and a trip to Mars depends on several different variables to determine the most appropriate answer. According to Loff, 2012 "It depends on how you go, what kind of rocket is used and what technologies are available; with current technology, our robotic missions usually take about 8 months to travel to Mars". This complicates things for space missions; not only do the astronauts need to remain healthy and alive during the entire trip, but the equipment must be maintained. Even a light malfunction could lead to death for all those aboard a mission to Mars. Including the return trip and a mission phase, trips to Mars could last anywhere from 16 months to three years depending on the type of mission and flight path. The human body is not equipped to handle living in space for long periods of time, even after moon missions astronauts need to go through physical therapy to return to full strength.

United States' astronaut Scott Kelly and Russian cosmonaut Mikhail Kornienko spent nearly a year aboard the ISS to perform experiments, but the main goal was to see what happens to the human body after a long duration in a microgravity environment. During their 340 mission, the two experienced several effects from being in space for such a long time, many of the issues experienced were due to the lack of gravity. When astronauts first experience weightlessness, their sensorimotor system becomes immediately disrupted (Koren, 2016); in layman's terms your eyes and your inner ear are sending completely contradictory messages to your brain. It takes time for astronauts to adjust to their new environment, they typically experience motion sickness for the first day or so in space as well as once they return to the gravitational grip of the Earth; it's like coming off a ship and not having your land legs under you (Wei-Haas, 2016).

Without gravity, circulation of liquids and gases becomes a problem; for instance, the carbon dioxide an astronaut exhales can form an invisible cloud around their head causing headaches (Koren, 2016). The fluids in the human body float upward and clog the sinuses, making astronauts' heads feel congested and their faces appear puffy (Koren, 2016). The astronauts wore thigh straps to help keep the blood and other fluids from pooling in their heads. According to NASA, over the course of his year in space, the amount of fluid shifting into Scott Kelly's head could fill a two-liter soda bottle (Wei-Haas, 2016). While some of these fluid issues can be avoided, fluidic drift also causes more serious conditions, including pressure on the optic nerve, which can affect vision (Wei-Haas, 2016). Typically, these eye problems subside once back on Earth, though some astronauts have experienced long-term vision damage from venturing into space.

Muscle atrophy is a common and fairly well-known side effect of space travel but even bones can atrophy the same way that muscles do. Without gravity bones do not need to support the muscles so they begin to lose minerals and fibers; astronauts can lose one percent of their bone density per month (Koren, 2016). After 340 days in orbit, these astronauts could have lost up to 12 percent of their bone density. Losing calcium in your bones creates higher calcium levels in your blood (Wei-Haas, 2016) which, if not for the incredible amount of exercise performed by these astronauts, would likely lead to kidney stones. In addition, they are constantly being exposed to cosmic radiation while in orbit. The Earth's magnetic field provides some shelter from the harsh rays though they receive 10 times the usual amount of radiation (Koren, 2016), which greatly increase their risk of dying from cancer; farther out, exposure would be more severe.

Another significant ailment experienced by astronauts is sleep deprivation, which can start to set in after two weeks or so in space. Sleep deprivation is one of the most prevalent problems as astronauts' circadian rhythms and dark-light cycles are thrown out of whack, without sleep the human brain does not function well for very long. Hollingham, 2014 states "This is a particular issue in orbit where, with a new dawn every 90 minutes, astronauts struggle to adapt to artificial night times; on top of this, they arrive in space overexcited, work shifts and have to adjust to sleeping strapped to the wall in a sleeping bag". The ISS is equipped with countermeasures for these issues, but they still occur and with a longer trip these issues only become a greater hindrance.

After a full year in space astronauts become much more susceptible to diseases, both physical and mental. There is evidence to suggest that being in space for long periods of time can significantly reduce the effectiveness of the immune system. This should make sense considering the increased exposure to radiation; radiation is used on Earth to suppress the human immune system for cancer treatments. The immune system can also be weakened simply by living in close quarters with other people, closed environments can increase stress levels and alter the immune system which increases the susceptibility to allergies or other illnesses and disease (Abadie et. al., 2017).

According to Hollingham, 2014 "A NASA study found that the white blood cells of fruit flies flown in orbit were less effective at engulfing invading microorganisms and fighting infection than those of genetically identical flies on the ground". Depression can also become a concern for very long missions. Having a mentally unsound astronaut would be a worst-case scenario for any deep space crew as someone not thinking clearly may do something to jeopardize the mission or the safety of the crew. NASA has learned that behavioral issues among groups of people crammed in a small space over a long time, no matter how well trained they are, are inevitable (Abadie et. al., 2017).The more confined and isolated humans are, the more likely they are to develop behavioral or cognitive conditions, and psychiatric disorders.

Materials

The biggest problem regarding materials for colonists is the fact that there are none available on the moon or Mars. In order to successfully create a sustainable and safe colony for future humans, one must bring either the materials, the technology, or both from Earth for developing and creating long-term housing units for the lunar and Martian astronauts. While the composition of the moon and Mars are different than the Earth in some ways, they also share some similarities. Most importantly the natural regolith, or rocky soils, of these planetoids can potentially be used to create the necessary building materials for housing and other buildings and structures.

The moon's crust has a thickness of about 43 miles on the moon's near-side hemisphere and 93 miles on the far-side; it is made up of Oxygen, Silicon, Magnesium, Iron, Calcium and Aluminum, with small amounts of Titanium, Uranium, Thorium, Potassium and Hydrogen (Davis, n.d.). Because of the volcanic activity on the ancient lunar surface, basaltic rock comprises much of the surface; the basaltic samples from different lunar sites exhibit a range of compositions (Pieters et. al., 1993) indicating that there are several different types of basalts across the surfaces suggesting that certain areas would be better for building than others.

A study was conducted in 1974 where the seismic data from the four stations of the Apollo passive seismic network had been analyzed to obtain a velocity structure of the moon (Toksoz et. al., 1974). A velocity structure is essentially a model that helps scientists analyze the different layers and regions of soil in a planet's crust using assumed seismic information to assist in earthquake related studies. To a depth of 20 km (12.4 miles) a basaltic composition is consistent with, but not uniquely specified by, the observed velocities in the Mare Cognitum region (Toksoz et.al., 1974). What this result indicates is that the layers of lunar basalt reach depths of over 12 miles in some areas of the moon's crust, potentially even deeper on the moon's far side where the crust is more than twice as thick as the near side.

The soil of the moon's crust is plenty thick for anything colonists would use it for and the soil has many of the same minerals and elements as the Earth's soil so the potential for creating bricks or other types of building units out of the lunar material is rather high. The major drawback is the logistics of sending excavation and building equipment all the way to the moon from Earth. The cost for such an undertaking would be staggering so determining the absolute best practices for this part of colonization would be a major key to the long-term success of the missions.

With respect to the red planet, the reason for it appearing so distinctly red is due to the rusted Iron dust particles in the soil. The Martian crust and surface is mostly Iron-rich basaltic rock similar to Earth's thin crust (NASA, n.d.) as well as to the lunar crust. In addition to the Iron-rich portion of the crust, it also contains Magnesium, Aluminum, Calcium and Potassium; this crust is between 6 and 30 miles deep (Dunfordet.al., 2017). The rocks on the plains are mostly typical basalts (such as olivine and pyroxene) with only thin alteration (or weathering) rinds high in Sulfur, Chlorine, and other volatile elements. Soils consisting almost entirely of sulfates or silica are also present (Malin et.al., 1998) which shows the diversity of the Martian soils.

It is also worth noting that the crust can be thinner in some places than the estimated depth of the basalt on the moon. Choosing the right location to build a permanent settlement will be key prior to arrival. Unlike the Earth, Mars has no tectonic plates that ride on the mantle to reshape the terrain (Sharp, 2017); Mars' crust is thought to be one solid piece. While Earthquakes are no threat on Mars, that doesn't mean the crust sits quietly; new research has found that powerful landslides may speed down Martian slopes at up to 450 mph (Sharp, 2017). Scientists believe that ice on Mars may play a large role in providing the lubrication necessary to facilitate these deadly landslides.

While yes, there is soil available for developing building materials on the moon and Mars, it will not be easy or cheap to provide the astronauts with everything they would need to create bricks or whatever other type of materials necessary for such a project. There is a myriad of logistics involved with sending people, equipment and shuttles into space; however, most logistical efforts are driven by cost. Today, it costs $10,000 to put a pound of payload in Earth orbit (Dunbar, 2008); the cost of transporting a single brick to the moon can cost up to $2 million (Leach, 2014). According to Dunbar, 2008 "NASA's goal is to reduce the cost of getting to space to hundreds of dollars per pound within 25 years and tens of dollars per pound within 40 years".

In addition to directly reducing costs, there are ideas of indirectly reducing costs through the use of reusable launch vehicles (RLV) which are space vehicles that can be used and reused for multiple launches versus the traditional one-and-done models currently being used. Stanley, 2000 believes that the RLV "will provide NASA and other customers with unprecedented reductions in cost and improvements in reliability, safety, and performance". Other launch programs such as NASA's Space Launch System Program (SLSP) are being developed to, in essence, achieve our space-related goals while reducing mission costs and increasing efficiency. The SLSP is expected to provide the same benefits of increased operational availability for a lowered cost of ownership (Neeley et. al., 2014).

Prior to traveling into space there were a multitude of hurdles for NASA to overcome before they were able to send people to the moon in 1969. Similarly, effort is being made to overcome these hurdles today; however, NASA is not the only group developing viable solutions. The following section will cover many existing and potential technologies that are being used and can be used to solve some of the problems discussed in this section. Many of the solutions do come from or are funded by NASA, though there are several promising ideas that come from other agencies such as SpaceX, Mars City Design and other cutting-edge organization sand programs.

Solutions

While there exist many obstacles for colonists, there are many solutions currently being used, currently being developed, and currently being invented to combat these dangers and problematic logistical issues. Many of the technologies coming out of the aerospace industries are focusing more on traveling into space and reaching far away worlds, specifically Mars. Several of these advancements are incredibly unique and seem like science fiction whereas others are simple adjustments to age old technologies. Certain ideas appear to ready for commercial application while others are still in incubatory stages. Regardless of the stage of development it appears clear that we as a species are going to achieve the goal of permanently sending humans to Mars, as well as back to the moon and beyond.

Material Advancements

In the world of materials science, new materials are developed and put into practice constantly. In addition to new types of materials and compounds, the methods for creating materials is also evolving. There are several cutting-edge technologies that are already being used in the STEM (Science, Technology, Engineering and Mathematics) fields, including aerospace. While these advancements are important and necessary for the future of space travel, one must also be aware of current material needs for housing structures on far away planets. Building insulation is one of the most important aspects of a building or a home, one small mistake can lead to significant water damage, insect and pest infestations, temperature related damage and fluctuation, increased energy costs, and on the moon or Mars, radiation infiltration or loss of breathable air.

Using the correct materials is more important than using the newest ones; understanding how a material is going to behave is a very important aspect of developing sustainable colonies on these other worlds. Since the elemental makeup of the Martian and lunar soils is known, NASA has identified potential uses for this natural regolith material on the moon and Mars including: construction of shelters and other structures, radiation shielding, life support systems (oxygen extraction), propulsion systems (oxygen extraction), solar array systems (silicon extraction), and fabrication of machine parts and hardware (Howell et. al., 2007).If these were developed quick enough colonists could even create processing plants and manufacturing facilities. These newer materials and technologies make it possible for us as a species to further our reach into space and achieve the goals of developing long-term settlements on the moon, Mars and beyond.

Many of these material advancements are not specifically related to the aerospace industries; however, the applications for these materials can be utilized in some form for space travel and colonization. Some of these advanced technologies related to materials and material development could be crucial for future space travel with respect to shipping logistics and cost. Such technologies are explained in this section as well as how each technology may be used to combat one or more of the four main problems discussed in the Problems section. Of all the advanced building material technologies, the two most appropriate solutions appear to be 3D printing and sintering.

3D printing advancements.

Printing technologies have been around since Johannes Gutenberg first developed the printing press in 1440 for mass production of the bible. Since then, printing has gone beyond the scope of mass producing written accounts, stories and information. 3D printing technology is an automated, additive manufacturing (AM) process for producing 3D solid objects from a digital (i.e. CAD) model (Bogue, 2013). What that means is a 3D CAD (or other program) file is sliced up into two-dimensional sections that are set by the printer, one at a time, one above the other, until the full object has been created. According to Lipson & Kurman, 2013 "In the not-so-distant future, people will 3D print living tissue, nutritionally calibrated food, and ready-made, fully assembled electronic components"; some of these things are already being printed in different countries across the globe.

3D printing first grabbed the public's attention in 2013 when plans for a plastic gun that would not set off metal detectors went viral; however, since then the uses and advancements for this technology have been unparalleled. In the five short years since its introduction, 3D printing has become a huge research market as people are constantly developing new printing media for different results and applications such geo-polymer or wood-based materials. Many believe that 3D printing will revolutionize the construction industry once these technologies become commercially available on a grand scale.

ProMetal, a division of Extrude Hone Corps has made breakthroughs in metal solid free form (SFF) technology that are going to provide a multitude of benefits over current tool manufacturing methods including: waste reduction, inventory diversification, labor reduction, higher quality control, and easy set-up (Bak, 2008). Advancements from ProMetal allow them to create parts for rapid production while making parts that are quality and resistant to malfunction. Another fascinating new technology called faBrickation integrates 3D printing with Lego building. The way that this happens is through three basic steps which are shown on the following page in Figure 6. First, the user loads their digital model into faBrickator and selects the legofy-button which breaks the model into the smallest size of Lego building blocks; the user then selects the layout button and the program begins grouping the smallest Legos into larger pieces in order to minimize the number of bricks (Mueller et. al., 2014). Second, the user then decides which sections, if any, require full 3D printing; the user brushes the desired region with the high-res brush in the program and this tells faBrickator to print those areas in full detail and

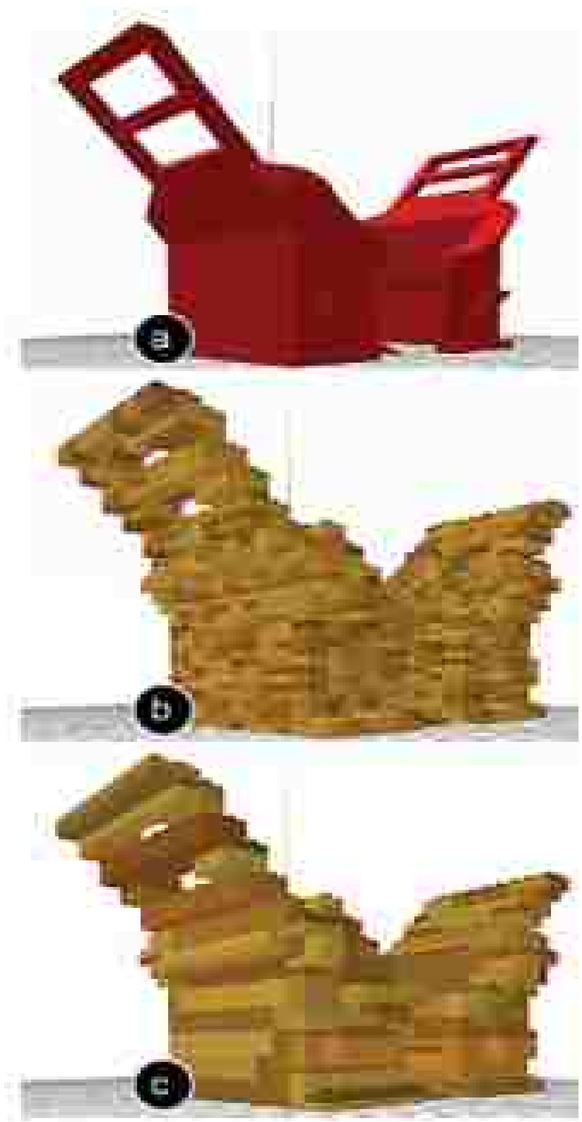


Figure 6: (a) Model Loaded into faBrickator, (b) Legofied into 1x1 Lego Pieces, (c) Layout Model (Mueller et. al., 2014)

provides an updated rendering (Mueller et. al., 2014). Third, and finally, the user exports the file to the printer and begins building the Lego portion using the detailed layer-by-layer instructions provided by the program. While the final product may not be finish quality, this method significantly reduces total fabrication time by several factors going from an overnight process to performing several fabrications per day (Mueller et. al., 2014).

Even though 3D printing has only been popular for a few years, there are already developments for 4D printing; 4D printing is a new process that involves multi-material prints with the capability to transform over time, or a customized material system that can change from one shape to another, directly off the print bed (Tibbits, 2014). In laymen's terms, the printed object changes its shape over time to form a different shape; this technology could be incredibly useful for robotic missions to Mars and other planets. At this stage water is the only form of activation energy i.e. what causes the object to change shape, the key is using the right combination of active and rigid materials in order to achieve the desired effect. Given that 3D printing is still in the early stages of its usefulness this 4D technology likely will not been seen for some time though it has several applications for many industries including construction.

Concrete printing, shown on the following page in Figure 7, may be a very popular idea at the moment, but concrete is heavy. Sending the raw materials to space would be incredibly expensive, but if astronauts could develop concrete (or a concrete equivalent) out of the natural regolith, then 3D printing may be the most efficient way to develop habitats. While this technology may be more effective for terrestrial applications at the moment, the potential for space application is significant. According to Lim et. al., 2012 "The manufacturing process is similar to conventional additive processes including the component design, the conversion of this solid geometry to machine instructions, the printing of the component and finally post processing which includes removal of support structures and any required surface finishing".

Figure 7: The Concrete Printing Process (Lim et. al., 2012)

Though it has been around for just a short time, 3D printing is already being looking at for many space-related applications, including the development of buildings and structures on both the moon and Mars. Many AM technologies, including 3D printing, allow for the printing or creation of metal components and accessories. With respect to metals, NASA is interested in titanium and nickel-based alloys. Nickel based alloys are desirable in aerospace due to their tensile properties, damage tolerance, and corrosion/oxidation resistance (Joshi & Sheikh, 2015); however, using these alloys in AM processes typically results in cracking.

Titanium is desirable for similar reasons as Nickel, though the microstructure of titanium alloys vary depending on the type of AM process used. A few studies have shown that mechanical properties of AM titanium parts can be modified with heat treatment (Joshi & Sheikh, 2015). Given the exorbitant cost of sending things into space, Leach, 2014 states "the future of extraterrestrial construction rests on the development of technologies that are able to employ in-situ materials, such as lunar dust". Using natural regolith is not only a cost benefit, but it also increases safety by a significant margin as astronauts would not be directly involved in construction which also reduces their risk of exposure to the incoming radiation.

Recently, the concept of building a base on the moon was endorsed by the European Space Agency (ESA), in collaboration with a team of architects, to determine if the idea was feasible. ESA's team came up with a weight-bearing catenary dome design with a cellular structured wall that helps shield against space debris and radiation (Soderman, 2017); a schematic design of this catenary model is illustrated below in Figure 8. In order to develop this type of structure an array of printing nozzles on a frame sprays a binding solution onto a sand-like building material i.e. regolith, this material is mixed with magnesium oxide which turns it into the "paper" element and then the structural "ink" component, a binding salt, is applied to convert the material to a stone-like solid (Soderman, 2017). At the current rate of about 2 meters per hour, completing an entire building would take roughly a week, though that time could be reduced as printing speeds increase.

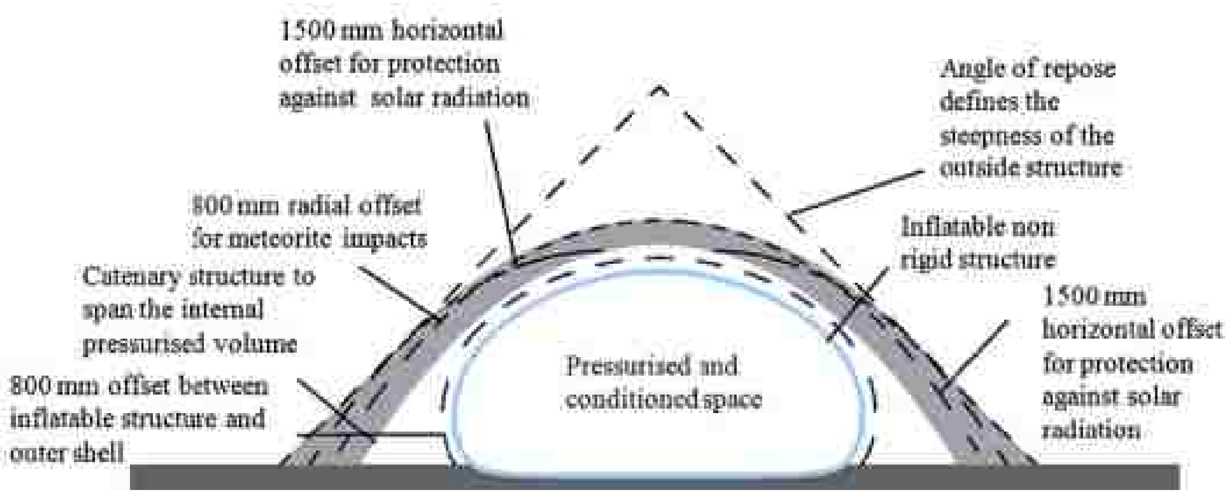


Figure 8: Schematic Description of Outpost Structure (Cesaretti et. al., 2014)

Building such a structure on the moon could provide temporary stay as well as provide more appropriate living accommodations for astronauts that may go back to the moon for additional missions. These outpost style structures could be supplemented by an interior inflatable compartment to provide additional support and have the potential to be linked together via an above ground tunnel system. A team of European researchers has studied the logistical side of a project such as this one in order to determine the type of internal structure necessary to provide the exterior regolith shell with suitable resistance and stability as well as to determine the amount of material required to be brought from Earth (Cesaretti et. al., 2014).

The design developed by this team encompassed three main requirements: need to keep the structure stable, protect from micrometeoroids or space debris, and protect from solar radiation (Cesaretti et. al., 2014), ideally from all forms of space radiation. They determined that the D-Shape, a patented 3D printing technology, is the closest to achieving full scale construction of buildings of all the existing rapid prototyping methods (Cesaretti et. al., 2014). A suitable simulated lunar regolith has been developed for testing and research purposes. Future research in this area can focus on developing more efficient D-Shape technologies.

Basalt is very abundant on Mars so developing a highly efficient printer capable of printing basaltic compounds would be a good first step. The process for using basalt as a printing material would require the basalt to be heated to a molten state, likely through the use of electric heating coils, and then extruded using a screw-style auger (Kading& Straub, 2015). Kading and Straub have set forth a fairly intuitive base design and manufacturing plan for the red planet using this basalt printing technique. Initially, upon arrival, autonomous robots will unload all of the necessary components for the deployment and erection of the base.

Inside the space craft a 3D printer will be set up to print with basalt that is to be collected by the robots; the basalt will be deposited into a hopper that is fed to a furnace that melts the basalt for printing purposes (Kading& Straub, 2015). A large dome will be the first structure to go up which is where the printer will be installed and print the subsequent smaller dome structures used for work, living, services, connections, sub-surface access, and command centers (Kading& Straub, 2015). The base will be connected through a system of above ground tunnels that connect each module creating a grid-like system.

There are many advantages to building on the moon or Mars where there is little to no gravity or atmosphere such as reduced buckling forces. Additionally, on the moon, there is a lack of wind loads, rain loads and weather delays as well as no potential for Earthquakes as the moon is also a seismically quiet environment (Leach, 2014). However, some technologies have significant negatives that need to be remedied prior to application. According to Joshi & Sheikh, 2015 if conditions are not ideal, "delamination and breakage under stress can be caused by weak bonding between layers; studies have shown that 3D printed products will cause anisotropic mechanical performance". Anisotropic means that an equal force would cause different reactions on each different face of a material, much like the way wood behaves. It is worth noting that with the addition of fibers to the matrix powder, the mechanical properties can be significantly increased; by adding a fiber content of 1% to the matrix powder, the flexural strength showed increased values of up to 180% (Joshi & Sheikh, 2015).

In addition to the setbacks of 3D printing on Earth, there are specific problems related to 3D printing in space, mainly the lack of gravity. Due to the microgravity environment, the media for 3D printing would not be able to be in a powder form, so a different technique or material needs to be developed. Another problem with the lack of gravity in space is the fact that each layer of extruded material is not being pressed down by anything which results in unevenly thick layers. In addition to the temperature swings experienced on other planets, the microgravity environment affects heat flow through the printing media. This could mean that the plastic parts would get either too hot or too cold, thus impacting the quality of the material or part (Joshi & Sheikh, 2015). The fluctuation in temperature could also affect things like curing time. These issues would be particularly problematic during missions where artificial or low-gravity is not available such as on the ISS or in planetary orbits. 3D printing is a fairly new technology, the full extent of its applications have yet to be determined. Exploring additional additive manufacturing (AM) technologies may provide insight into the issues experienced with 3D printing space-related applications.

Sintering technology advancements.

While 3D printing is a cutting-edge technology used for a multitude of applications, there are some significant setbacks to using the technology in space. Another AM technology known as sintering, can be used to form building materials as well. According to Finetech, 2018 "Sintering can be described as the thermal treatment of a powder or compact at a temperature below the melting point of the main constituent (metal), for the purpose of increasing its strength by bonding together of the particles". The improved mechanical and physical properties are a result of the surface area being reduced which is caused by the coalescence of the material and powder particles (Britanica, 1998).In other words, as the material becomes denser, its strength properties increase. Densification is desired to eliminate pores and obtain the highest properties, such as strength, ductility, toughness, magnetic permeability, and fatigue resistance (German, 1985). Uniform density is important in building materials to ensure the aforementioned properties remain consistent throughout the material to reduce the potential for malfunction or failure in the building system.

Among the many different AM processes, the ones that meet the aerospace industry requirements are Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Wire and Arc Additive Manufacturing (WAAM). These types of AM are able to create incredibly dense components that do not require any post-work attention and are comparable with other traditional manufactured parts in terms of mechanical and electrochemical properties (Joshi & Sheikh, 2015). Of these four, EBM technology appears to be the method favored by NASA as it was chosen for further in-house development due to its ability to produce a fully-dense metal material that yields high strength properties (Howell et. al., 2007). The Electron Beam Melting process uses a power source to heat a bed of powder layer-by-layer to additively grow a part out of that metallic powder (Howell et. al., 2007). An electron beam is the heating source for EBM whereas a laser is used for other AM processes such as SLS.

There are several advantages that the electron beam has over the laser, for instance, the electron beam is approximately five to ten times more energy efficient than laser technology (Howell et. al., 2007). Due to the energy efficiency of the system, the energy consumption is much less than that of a laser which translates to a reduction in maintenance and manufacturing costs. Another efficient part of the EBM technology is the powder bed preheating process prior to operation. This preheating step is important for two main reasons, the first being that the pre-heat lightly sinters the powder which holds it in place during the EBM process so subsequent layers may be fabricated (Howell et. al., 2007). Second, the pre-heat lessens the thermal gradient between the last melted layer and the previously melted layers; creating a more consistent temperature will reduce the chance of residual stresses (Howell et. al., 2007). Once preheating has been completed, the actual EBM process can begin which involves an electron beam gun and the use of magnetic coils for deflecting and adjusting the beam.

Figure 9: Arcam EBM Machine and Schematic (Howell et. al., 2007)

The electron beam gun fires the beam into a set of magnetic coils, the first coil is used to focus the beam to the desired diameter and the second coil deflects the beam to its desired location on the powder bed below (Howell et. al., 2007). The EBM machine and a schematic of the process can be shown above in Figure 9; it is worth noting that this deflection process requires no moving parts. Once the beam has been calibrated and adjusted, the melting of the powder can begin. As each layer is melted the build platform lowers the thickness of one of these layers and a rake comes across the top to distribute the powder for melting (Howell et. al., 2007); this process continues until the final part is completed. Upon completion, the part experiences a helium purge which can significantly reduce the cool down time needed for a freshly melted part, while this is only optional it is highly recommended. The part may require in excess of 20 hours to cool, but with the addition of the helium purge, wait times are reduced to three to eight hours depending on the part's size (Howell et. al., 2007). Once the part has cooled all of the loose powder is removed. The part is then bead-blasted to remove any additional powder particles before the post-processing of any critical locations such as machining surfaces that are to be part of a mated interface (Howell et. al., 2007) i.e. connected to another part.

The most important detail to note about EBM is that the final product comes out of the machine fully dense which results in high strength values (Howell et. al., 2007); this is the major difference between EBM and many other powder-based methods. Another incredibly significant characteristic of this technology is the availability and capability of producing unique and complex angles and shapes within the part such as internal cavities or cooling channels. Traditional methods such as CNC machining cannot easily produce these same details, EBM processing can fabricate a part that has a solid shell with a lattice core (Howell et. al., 2007) i.e. a hollow part with an internal support structure. Developing such parts is crucial for the future of our space program, with respect to Mars missions, as they can be used to create more efficient components and systems freeing up power and occupied space onboard a space craft.

NASA's Ideas

The National Aeronautics and Space Administration, or NASA, has been the largest presence in the space industry since they landed Neil Armstrong, Edwin "Buzz" Aldrin, and Michael Collins on the moon almost 50 years ago. For decades, NASA has invested in many different projects trying to develop a myriad of technologies to help reduce cost and time while increasing safety and reliability. While NASA is always developing new and sophisticated technologies not all of them are related to the colonization of the moon or Mars. The following sections highlight some of the more exciting and pertinent ideas to the research scope.

Modular units for the ISS.

NASA has been sponsoring the development of modular units, by Las Vegas company Bigelow Aerospace, that can be attached to the International Space Station (ISS) and expanded upon attachment. This expandable or inflatable unit is called the Bigelow Expandable Activity Module or BEAM (Escobedo Jr., 2017). These units could potentially serve future colonists on the surfaces of the moon and Mars as temporary or even perhaps as permanent housing units. One major benefit of the BEAM is that it is sent to space prior to inflation thus reducing the amount of volume it takes up during transport. According to NASA, 2016 "in its packed configuration the module will measure 7.09 feet long and just under 7.75 feet in diameter; in its deployed expanded configuration the BEAM will measure 13.16 feet long and 10.5 feet in diameter, providing 565 cubic feet of habitable volume". The total weight of the BEAM is approximately 3,000 pounds (Rainey, 2016). A rendering of the fully expanded BEAM attached to the ISS is illustrated below in Figure 10.

Figure 10: Fully Expanded BEAM Rendering (Rainey, 2016 [Bigelow Aerospace, LLC])

BEAM launched on the eighth SpaceX Commercial Resupply Service mission. After being attached to the Tranquility Node using the station's robotic Canadarm2, it was filled with air to expand it for a two-year test period in which astronauts aboard the space station will conduct a series of tests to validate overall performance and capability of expandable habitats (Mahoney, 2017). After the two-year mission, the BEAM will be jettisoned from the ISS fated to burn up and break apart in the Earth's atmosphere upon re-entry.

The composition of these BEAMs includes two metal bulkheads, an aluminum structure, and multiple layers of soft fabric with spacing between layers, protecting an internal restraint layer and bladder system (NASA, 2016). According to Rainey, 2016 the "BEAM module's skin is made up of multiple layers of soft goods; the different layers consist of an air barrier or bladder, structural restraint, micro-meteoroid and orbital debris (MMOD) layers, and external multi-layer thermal insulation layers". The MMOD layers are specifically designed for low-Earth orbit and designed to prevent any particles from entering the air bladder or main chamber. In the event of a puncture, BEAM would slowly leak instead of bursting (Rainey, 2016). This design feature protects the rest of the space station from potential damage in the event of a BEAM explosion. In addition to the BEAM protecting from space debris, it will be equipped with state-of-the-art radiation detection equipment to determine if the radiation shielding design is effective.

One of the primary objectives of the BEAM demonstration is to measure radiation protection capability of expandable soft-goods structures (Mahoney, 2015). NASA is poised to accomplish this goal by estimating radiation levels using computer models and then monitoring the radiation experienced by the BEAM units to determine the accuracy of the model's predictions. With respect to the MMOD protection, this unit is expected to perform as well as other ISS modules and because it is relatively small compared to the other space station modules the risk from MMOD for BEAM is typically less than other ISS modules (Mahoney, 2015). It is worth mentioning that for 15 occupied years of the ISS, it has never needed to isolate a module due to MMOD impact or dangers (Mahoney, 2015).

In addition to the space applications this technology has, such as protection from radiation and space debris as well as the reduction in volume needed for transport, it also has potential for use on Earth. Expandable modules that are safe and reliable could benefit a number of industries including infrastructure and human health. According to Escobedo Jr., 2017 "Expandables can be used as pop-up habitats in disaster areas or remote locations; storm surge protection devices; pipeline or subway system plugs to prevent flooding, fluid storage containers, hyperbaric chambers for pressurized oxygen delivery, and many other applications".

The main purpose of this mission is for NASA and Bigelow to determine how well the module can actually protect astronauts from the harsh environment of space. Astronauts aboard the station work with researchers on the ground to monitor the module's structural integrity, thermal stability, and resistance to space debris, radiation, and microbial growth (Mahoney, 2017). Thus far the experiments have shown that these soft materials can perform as well as rigid materials for these purposes. The radiation measured on the BEAM is close to the radiation experienced by other ISS modules and due to the multiple protective layers exceeding space station shielding requirements (Mahoney, 2017) BEAM has been successful in preventing punctures from space debris impacts. NASA and Bigelow have another full year for additional experimentation and monitoring before BEAM is jettisoned from the ISS.

Apollo examples.

NASA has had the most experience with traveling to the moon and back due to the success of the six manned Apollo missions that have made it safely to the surface of the moon and back home. NASA also has quite a bit of information from these manned missions to the moon; this data is useful for them in the sense that they can use it to develop better methods going forward to Mars or even for missions going back to the moon. The technology used and data recorded during the Apollo missions may be a bit outdated for current space travel; however, the information available from these missions could prove to be invaluable for future manned missions through the cosmos.

One of the most important sources of data from these Apollo missions is the radiation exposure information, this data provides NASA with the information they need for developing appropriate forms of radiation protection for future missions. The Apollo missions were relatively short when compared to a mission to Mars, though the exposure to radiation is roughly the same as there is no natural protection provided. While the astronauts employ the use of space crafts and space suits to help redirect some of the incoming radiation, current suits do not provide full protection to the harmful effects of these galactic cosmic rays. Below, Table 1 illustrates the average radiation dose received by each Apollo mission for the time spent on the lunar surface.

Table 1: Amount of time astronauts spent on the surface of the Moon during each lunar landing, and the average radiation dose they received. (Rask et. al., 2008)

Mission	Total Duration	Lunar Surface Duration	Average Radiation Dose*
Apollo 11	08 days, 03 hrs, 13 mins	21 hrs, 38 mins	0.18 rad
Apollo 12	10 days, 4 hrs, 31 mins	31 hrs, 31 mins	0.58 rad
Apollo 14	09 days, 01 min	33 hrs 31 mins	1.14 rad
Apollo 15	10 days, 01 hr, 11 mins	66 hrs, 54 mins	0.30 rad
Apollo 16	11 days, 01 hr 51 mins	71 hrs, 2 mins	0.51 rad
Apollo 17	12 days, 13 hrs, 51 mins	74 hrs, 59 mins	0.55 rad

Because the radiation information is in rads, it must be converted to sieverts in order to make an apples-to-apples comparison of the data. Using some conversation factor data (Furry Elephant, n.d. & Physics Health Society, 2016) the following conversions were calculated in order from Apollo 11 to Apollo 17; 0.036 Sv, 0.116 Sv, 0.228 Sv, 0.06 Sv, 0.102 Sv, and 0.11 Sv respectively. Recall from the Problems portion of this paper; exposure to one (1) sievert increases the risk of contracting a fatal cancer by 5.5% and the average daily radiation exposure experienced by humans is 10 microsieverts or 0.00001 sieverts. While these values are not near one sievert, prolonged exposure to these lower levels could likely result in the same effects of short-term high-levels of exposure. Because the effects of radiation can be so deleterious to the human body and mind, career exposure limits for NASA astronauts have been decided. A career exposure limit is the total amount of radiation allowed over the course of this person's career; this value changes based on the occupation, gender and age of the person at risk.

With respect to NASA astronauts, the limit is lower for younger astronauts versus older ones because according to Rask et. al., 2008 "it is presumed that although they may live longer than older astronauts, exposure to larger amounts of radiation early in their careers could present greater health risks during old age". In other words, the young person has a much longer time for the potential of health risks related to radiation to take effect than the older one, so their exposure is limited to protect their later years. Aside from career exposure limits, in order to minimize exposure NASA recommends that astronauts limit the time they spend outside in their spacesuits as well as how far they travel from their protective habitats (Rask et. al., 2008). However, the amount of radiation received does depend on a number of factors such as solar activity, location with respect to planetary magnetic fields, and the amount and type of radiation shielding used in habitats and spacecrafts (Rask et. al., 2008).

Other applicable ideas & technologies.

NASA has recently created a world-wide competition that envelopes the task of designing and creating suitable 3D printed habitats for colonists on Mars and the moon. This competition is called the 3D-Printed Habitat Challenge and it is comprised of three phases, each phase is graded on a points system and has a winner who is awarded a cash prize. The first phase of the challenge was the Design Competition which concluded in 2015 (O'Neill, 2017). The second phase, Structural Member Competition, is currently underway; this phase will focus on material technologies that will be needed to build structural components (O'Neill, 2017). The third and final phase, On-Site Habitat Competition, will focus on fabrication technologies once phase two has been completed; the total cash prize for phases two and three total $2.5 million (O'Neill, 2017). This competition will furnish new ideas and technologies to assist the progress being done by NASA and other professional scale space agencies.

In addition to 3D printing habitats, NASA is studying radiation countermeasures to better protect astronauts from the harmful effects of space radiation. In order to combat this issue, NASA has developed the Radiation Health Program and the goal of the program is to carry out the human exploration and development of space without exceeding acceptable risk from exposure to ionizing radiation (Rask et. al., 2008). Monitoring radiation is a crucial part of every mission as it supplies NASA with more data to use for developing solutions. There are three types of countermeasures currently being developed by NASA to reduce the total amount of exposure; operational, engineering, and dietary countermeasures.

Operational countermeasures are related to the mission parameters; the reduction in exposure according to Rask et. al., 2008 "is accomplished by shortening overall duration on the

Space Station to 3-6 months, reducing the time astronauts spend outside of the spacecraft during spacewalks, and planning space missions during times of reduced solar storm activity". These restrictions may be much more difficult to abide by for deep space missions and long-term missions to Mars and beyond.

Engineering countermeasures are structures of tools that are designed to shield astronauts from radiation (Rask et. al., 2008); an ideal shield is able to block different types of incoming radiations. Aboard the ISS, hydrogen-rich shielding such as polyethylene in the most frequently occupied locations, has reduced the crew's exposure to space radiation (Rask et. al., 2008). Because the ISS is in low-Earth orbit, the layer of shielding on the ISS is relatively thin as the station is partially protected by the Earth's magnetic field. A shield on the moon or Mars would have to be much thicker to protect from all types of radiation; thick layers of regolith or water would be good for radiation shielding.

Thickness is the key to the shield, if the shield is not thick enough to contain the secondary particles then they may enter the habitat or ship and can be worse for astronauts' health than the primary space radiation (Rask et. al., 2008). Because heavier elements cause greater amounts of secondary particles, according to Rask et. al., 2008 "research has been done on a lightweight polyethylene plastic called RFX1, which is composed entirely of carbon and hydrogen atoms; research shows that polyethylene is 50% better at shielding solar flares and is 15% better at shielding galactic cosmic radiation as compared to aluminum". While the lighter materials can greatly reduce the effects, they cannot stop them altogether. In addition to physical material shields, NASA has looked into developing electrostatic radiation shields which generate positive and negative electric charges that deflect incoming electrically charged space radiation (Rask et. al., 2008).

The third type, dietary countermeasures, are drugs that have the potential to reduce effects of ionizing radiation. There are two groups of dietary countermeasures, the first group includes specific nutrients that prevent the radiation damage and the second includes drugs that are designed to increase the rate at which radioactive substances are eliminated from the body (Rask et. al., 2008). Ingestion of these nutrients will be required anyway as space travelers will not be exposed to the same vitamins and minerals as they are on Earth. For example, the nutrients we gain from exposure to solar radiation on Earth are lost to astronauts and colonists if the shielding is working properly.

Polyethylene is very high in hydrogen and fairly cheap to produce though is not strong enough to support any type of structure. It would also be very expensive to add a layer to the hull of a spacecraft that would be thick enough to not burn up upon departure. One material in development at NASA has the potential to provide structural support as well as radiation protection: according to Garner, 2015 "Hydrogenated Boron Nitride Nanotubes or hydrogenated BNNTs are tiny nanotubes made of carbon, boron, and nitrogen with hydrogen interspersed throughout the empty spaces left in between the tubes". This new material is an ideal shielding material as it is lightweight, protective and Boron is an excellent absorber of secondary neutrons (Garner, 2015) which means that this material protects against both primary and secondary particles. Researchers have successfully made yarn out of BNNT's, so it is flexible enough to be woven into the fabric of spacesuits (Garner, 2015) which would provide astronauts with much more protection than current spacesuit material.

The idea of a force field, or artificial magnetic field, could be the potential solution needed for shielding spacecrafts and habitats by protecting astronauts the same way that the Earth's magnetic field protects the whole planet. According to Garner, 2015 "A relatively small, localized electric or magnetic field would - if strong enough and in the right configuration - create a protective bubble around a spacecraft or habitat". This technology could very well be the future of colonization once a reliable and affordable model is developed and thoroughly tested on Earth; ideally on the moon or in lunar orbit as well.

According to Dunbar, 2008 "NASA's Advanced Space Transportation Program is developing technologies that target a 100-fold reduction in the cost of getting to space by 2025, lowering the price target to $100 per pound". Dunbar, 2008 goes on to say that beyond engine propulsion is "beamed-energy propulsion, which uses a remote energy source - such as the sun, a ground- or space-based laser or a microwave transmitter - to send power to the vehicle via a 'beam' of electromagnetic radiation"; this is currently the most promising technology for lowering space-related costs. In addition to this energy propulsion system, NASA is developing several other methods for reducing expense, though this technology would greatly lower cost in two ways: (1) no storage or need for liquid, combustible fuel and (2) no cargo space occupied by energy system so the craft can be lighter and smaller thus cheaper to send into space.

Moon specific ideas.

While many are focused on the mission to Mars, NASA still has plans to head back to the moon before the end of the decade. Building on the best of Apollo and shuttle technology, NASA's creating a 21st century exploration system that will be affordable, reliable, versatile, and safe (NASA, n.d.). This new system is reminiscent of the Apollo capsule though it is three times larger allowing up to four astronauts to travel to the moon at once (NASA, n.d.). This spacecraft can also support up to six crewmembers on future Mars missions and deliver crew and supplies to the ISS (NASA, n.d.). The greater size would also allow larger construction crews to be sent at one time. The new craft utilizes solar panels as a power source and liquid methane as fuel. The reason for using methane as the fuel source is foresight; NASA is planning for when future astronauts can convert Martian atmospheric resources into methane fuel (NASA, n.d.).

Figure 11: Artist Depiction of NASA's New Crew Exploration Vehicle & Lander (NASA, n.d.)

In addition to the fuel benefits and size advantages, this new system will be reusable for up to 10 missions; NASA can easily recover it, replace the heat shield and launch it again (NASA, n.d.). This larger unit also has enough propellant stored to land anywhere on the lunar surface whereas Apollo missions were limited to equatorial landings. This new system provides the potential for moon bases and outposts for astronauts heading to Mars or beyond. Planners are already looking at the lunar south pole as a candidate for an outpost because of concentrations of hydrogen thought to be water ice, and an abundance of sunlight for solar power needs (NASA, n.d.). Above, Figure 11 illustrates an artists' concept of the new NASA vehicle.

Once the mission is over, the astronauts would return back to the capsule awaiting them in orbit by blasting off in a portion of the lunar lander; after docking the crew would then return to Earth. After a de-orbit burn, the service module is jettisoned, exposing the heat shield for the first time (NASA, n.d.). The parachutes deploy, the heat shield is dropped and the capsule lands on dry land, though it does employ a splashdown as a backup option (NASA, n.d.).

The development of this system provides NASA with a huge advantage in the race to Mars; the heavy-lift rocket provides the method for getting there and the sophisticated crew capsules and propulsion systems can make use of the Martian resources upon arrival (NASA, n.d.). Having an outpost relatively close to Earth would provide scientists with valuable data regarding how humans, technology, and manmade structures will stand up to the ravages of space. Analysis of this data would be crucial prior to sending people on long-term missions to Mars and beyond.

While manned missions are the current focus of the space industry, NASA is also developing unmanned crafts for lunar exploration and data collection missions; potentially Mars missions as well in the future. After several grueling tests, the Orion space capsule is slated to launch on its first mission, Exploration Mission 1, in December of 2019 at the earliest (Skibba, 2018). It is NASA's hope that they can one day use Orion to help astronauts build a new space station beyond Earth's atmosphere, dubbed Deep Space Gateway (Skibba, 2018). This deep-space space station would provide astronauts with limitless opportunity to study the moon as well as a space dock to construct and house ships to launch into deep space.

Mars specific ideas.

Many of the ideas surrounding the red planet sound like science fiction, though they are in fact the leading technologies for reaching Mars, at least according to NASA. A group of passionate individuals from NASA and other industries came together at Langley's Engineering Design Studio in order to encourage creativity and innovation within the NASA Centers in addressing technology needs (Gillard, 2016). One of the more unique ideas with respect to colonizing Mars is the Mars Ice Home concept; ice may prove to be an excellent building material for settlements on the Martian surface.

Figure 12: Artist's Rendering of the Mars Ice Home Concept (Gillard, 2016 [NASA/Clouds AO/SEArch])

The "Mars Ice Home", shown above in Figure 12, is a large inflatable inner tube shape that is surrounded by a shell of water ice. The lightweight design of this home allows for easy transportation and can be easily deployed with simple robotics, then filled with water prior to the crew's arrival (Gillard, 2016). This home has a number of benefits inherent to the design versus other Mars habitation ideas. For instance, the water can potentially be converted into rocket fuel so the home doubles as a fuel storage tank that can easily be replenished prior to the next crew's arrival. Due to the hydrogen-rich nature of water, it serves as an excellent form of radiation shielding and even though the home is completely enclosed in ice, it still provides natural lighting because of the translucent nature of water (Gillard, 2016). This option far outweighs the subterranean method of survival where astronauts would need to excavate and dwell in caves beneath the Martian surface in an effort to stay protected from cosmic rays. Of course, this method is reliant upon the amount of water that can be retrieved from beneath the crust and how quickly it can be done. According to Gillard, 2016 "Experts who develop systems for extracting resources on Mars indicated that it would be possible to fill the habitat at a rate of one cubic meter (35.3 cubic feet), per day"; at this rate it would take 400 days to completely fill the ice home. While this option is promising, excavation technology would need to improve before this can become a viable solution.

Another ground-breaking idea in the works from NASA is their plan to develop oxygen on the Martian surface with the help of the Massachusetts Institute of Technology (MIT) on a rover mission in 2020. The plan includes bringing microbial life to Mars and using an MIT device called MOXIE to have the microbial organisms create oxygen and then harvest it for breathing (Lazzaro, 2017). According to Lazzaro, 2017 the Mars Oxygen In situ resource utilization Experiment, or MOXIE, "works using a reverse fuel cell technique, in which electricity produced by a separate machine would be combined with carbon dioxide from the Martian air to produce oxygen and carbon monoxide in a process called solid oxide electrolysis".

The success of this technology would significantly impact future missions to space as shuttles would no longer need to be equipped with liquid oxygen. This process could provide colonists with a way of developing fuel which would significantly lower the amount of fuel needed from Earth thus lowering total mission costs. The most promising aspect of this technology is that lab results have shown that it already works. NASA will be testing this process during the Mars 2020 mission (Lazzaro, 2017) as a way to see how it will perform in the real-world environment it is designed to be used. A schematic of MOXIE is shown below in Figure 13, identifying the key components of the system.

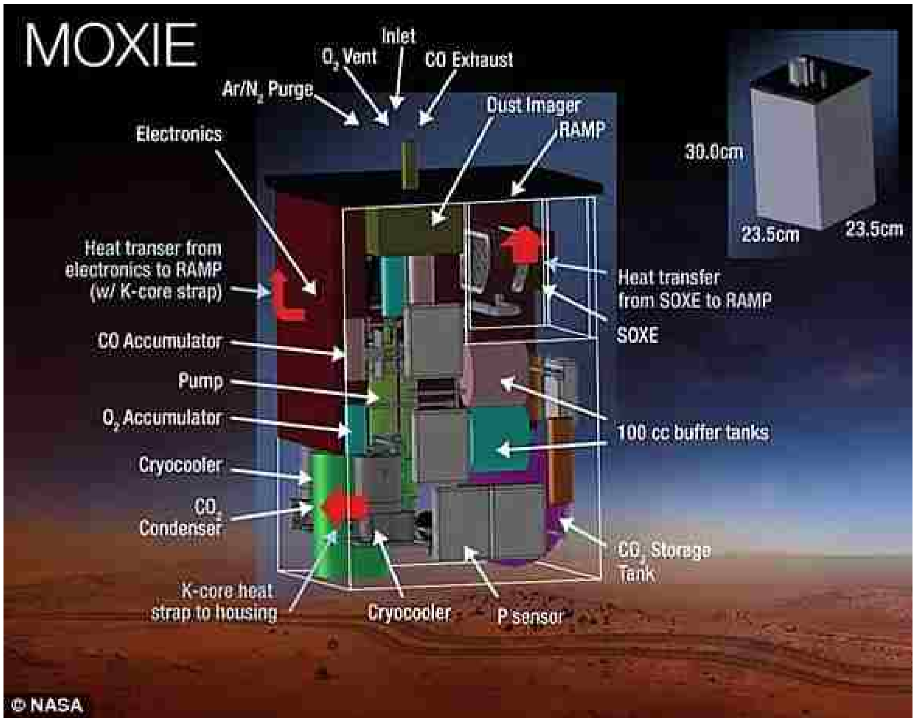


Figure 13: A Look at MOXIE, the MIT Device Used to Create Oxygen on Mars (Lazzaro, 2017)

While using natural regolith has been discussed already, a unique anomaly has been discovered about simulated Martian soil. On Earth, materials do not stay together by simply applying pressure, such a union is not structurally stable for supporting any amount of weight. The same may not necessarily be true on the Martian surface; simulated Mars soil can be packed together into a solid brick-like material without needing any added ingredients. Just adding the right amount of pressure was enough to form the soil into tiny, stiff blocks stronger than steel-reinforced concrete (Grush, 2017). The simulated soil may contain some special chemical that acts as its own binding agent when forming a solid mass; however, this simulated soil is merely developed based on what is known about the Martian soil. Actual Martian soil may behave differently under the same processes and under a different gravitational pressure. But, if this breakthrough happens to true for the actual Martian soil then this would be incredible for future missions to Mars. Colonists would be able to create habitats out of the natural regolith with minimal effort yielding maximum strength. A brick created using this method is shown below in Figure 14.

Figure 14: Processed Simulated Martian Soil Brick (Grush, 2017 [David Baillot])

Yu Qiao, a structural engineer at University of California, San Diego, and the lead researcher on a NASA-funded study about this technique, studied this compaction method on moon soil to no avail as the mixture required up to 15 percent of binder (Grush, 2017). Once the focus shifted to Mars his team performed the same tests decreasing the amount of the binding agent each time until eventually they ran the test without the binder, at this point the process still worked. According to Grush, 2017 "when iron oxide is crushed, it can crack easily, forming fractures with very clean and flat surfaces and when these surfaces are firmly pressed together, they form very strong bonds". While the testing has been a success with the smaller sized bricks, it is worth noting that larger bricks may behave differently under the same stresses. Ultimately some form of additive manufacturing will likely pave the way for planetary colonization.

While traditional concrete is obsolete for a space mission, there exists a different method of making concrete in which sulfur is used as the binding agent rather than water. Researchers at Northwestern University have studied sulfur-based concrete and found that sulfur concrete made with Martian (simulated) soil came out twice as strong as its Earthly counterpart (Spector, 2016). Gianluca Cusatis, an associate professor at Northwestern's Department of Civil and Environmental Engineering believes this to be true because the sulfur bonds chemically with the minerals found in Martian soil, whereas on Earth the sulfur only serves as glue for the gravel (Spector, 2016). In addition to the greater bonding strength, the reduction in gravity on the Martian surface translates to greater material strength as well as less gravitational force acting upon the material. An additional benefit to the nontraditional concrete mixture is that the sulfur concrete solidifies in an hour or less (Spector, 2016). This is astronomically faster than traditional concrete which takes 24 to 48 hours to fully harden.

While this technology is promising for the future of humans on Mars, there are still issues that need to be resolved prior to use by colonists. The main concern is the lack of temperature resistance which could potentially lead to a global system failure if the sulfur structure were to catch fire or be subject to an incendiary explosion. In contrast, one key advantage to this technology is that it can be melted and recast (Spector, 2016) which means that it can be recycled for future structures.

A very interesting idea from some NASA employees has been developed regarding colonizing Mars by first going through Phobos, one of the planet's moons. While the concept is not an official NASA project, there is potential use for this concept for future missions. Hoppy Price and two colleagues at the Jet Propulsion Laboratory (JPL) drew up a proposed mission architecture that gets astronauts to Phobos by 2033, then down to the surface of Mars by 2039

(Wall, 2015). Naturally, the first part is setting up a base on the surface of Phobos which according to Price, would require four separate mission launches using NASA's Space Launch System (SLS) mega rocket (Wall, 2015). The launches would consist of habitats, positioning systems, equipment and transport vehicles for going between Phobos orbit and Phobos. The main benefit to this mission would be that it essentially paves the way for the Mars mission providing real world data on mission parameters and ways to improve mission safety and success. A concept of the base for this mission is depicted below in Figure 15.

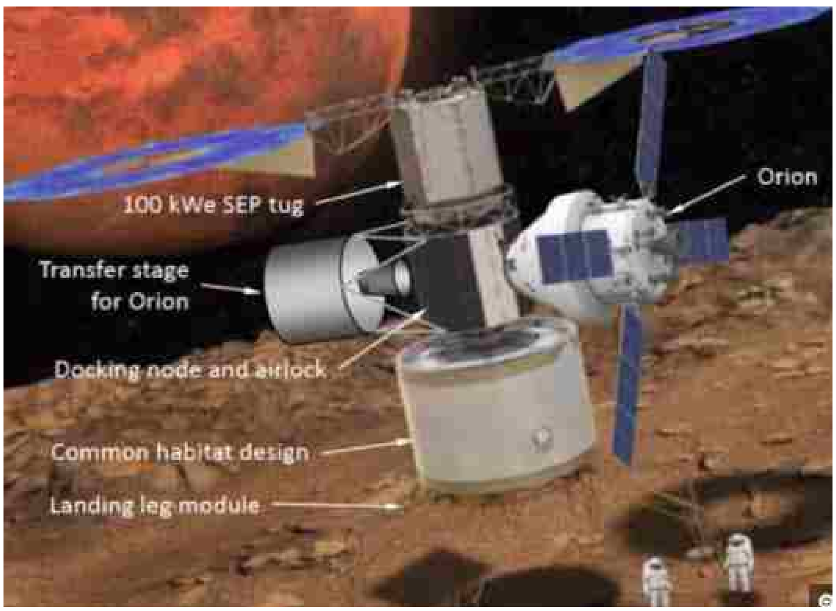


Figure 15: Artist's illustration of a base on Phobos (Wall, 2015 [NASA])

The mission would likely, according to Wall, 2015 "use a similar multistep approach - employing SEP tugs to preposition equipment - to get astronauts to the Martian surface in 2039, but this second phase of the Red Planet effort would require six SLS launches". Price declined to divulge any specific cost values though the team's proposed mission architecture was found to fit within NASA's annual budget while accounting for inflation (Wall, 2015). The potential for a base on Phobos has not really been a topic of discussion. However, now that a seemingly organized and budgeted plan has been developed by space industry professionals, the next major colony target may become Phobos or perhaps Deimos, Mars' other small moon.

Other Space Ideas

There are dozens, perhaps hundreds of companies currently focused on reaching, developing, or settling Mars; some also have ideas for the moon, but Mars appears to be the next milestone in the international space race. Aside from NASA, there are several other companies and agencies making moves with respect to achieving space-related goals, some of which are more official than others. The following ideas cover three main aspects of constructing a permanent base on the moon or Mars; how to get there safely, how to develop and sustain a habitat once there, and how to generate and maintain reliable energy. Given the recent success of the SpaceX launch, they will be discussed in some detail in the next section followed by the innovative ideas of the Mars City Design group and the breakthroughs related to the KiloPower energy technology.

SpaceX.

Figure 15: Concept of BFR Rocket with Martian Base (SpaceX, 2016)

SpaceX is one of the newer space agencies with goals for sending humans to Mars and developing the biggest and best propulsion systems for the job. Most people have heard of some of the cutting-edge rockets coming out of SpaceX such as the Falcon rocket series or the Dragon rocket. However, a new design appears to put the focus on interplanetary travel and even has the potential to revolutionize the transportation industry on Earth. On September 29th, 2017, SpaceX CEO and Lead Designer Elon Musk presented an updated vehicle design for what's currently being referred to as BFR (SpaceX, 2016). The BFR is a single system, i.e. contains one booster and one ship, that will be utilized for a variety of space missions ranging from low Earth orbit to Mars and beyond. Many of the technologies and accommodations of this rocket will be useful for all space-related activities including satellite missions, International Space Station missions, moon missions and also Earth-to-Earth transport (SpaceX, 2016). Some of the accommodations and technologies include large conditioned spaces (including 40 cabins) as well as the utilization of three types of propulsion rockets. Figure 16 on the previous page illustrates the BFR on a concept Mars base.

SpaceX has a goal to send their first cargo mission to Mars in 2022; the objectives for the first mission will be to confirm water resources and identify hazards along with putting in place initial power, mining, and life support infrastructure (SpaceX, 2016). The second mission will send both cargo and crew and is slated for just two years later. If its first launch is successful, SpaceX plans to launch a human crew to Mars in every available launch window - every 26 months (HP, 2017). The BFR rocket will play a role in these missions as it is designed to enter the Martian atmosphere in such a way that it decelerates aerodynamically, reacting similarly to the wear on a brake pad (SpaceX, 2016) versus being completely burned up upon re-entry. The BFR rocket design is loaded with a slew of state-of-the-art technologies and devices that will reduce the cost for future missions as well as increase safety and efficiency for future crews and equipment aboard these crafts.

Mars city design.

The Massachusetts Institute of Technology (MIT) has recently won the architectural design portion of a competition called Mars City Design which is an international competition with the idea in mind of creating the blueprints for future sustainable cities on the surface of Mars (Nolan, 2017). The winning design from the MIT team is called Redwood Forest which is comprised of a collection of "tree habitats" connected through a system of tunnels called "roots" (Brabaw, 2017). A depiction of these tree habitats is shown below in Figure 17. These subterranean tunnels provide connection between each tree habitat, private spaces, and protection from the many incoming hazards such as radiation, temperature fluctuation, and space debris. MIT's design incorporates a vast network of tree habitats that are all interconnected for safety and easy distribution of materials between units.

Figure 17: Concept of Redwood Forest dome habitat (Brabaw, 2017 [Valentina Sumini])

According to Brabaw, 2017 "Each dome-shaped tree habitat would house up to 50 people, and the team's vision calls for building about 200 of them, to support a settlement of 10,000 pioneers; the structures would include private and public spaces as well as plants and water harvested from the northern plains of Mars". The driving force behind the concept of these habitats was the desire and the need to utilize natural Martian resources such as regolith and ice to support life. Each dome is equipped with soft cells that would fill with water to help protect inhabitants from radiation, manage heat loads and supply water to both fish and produce farms (Brabaw, 2017). These habitats are also equipped with solar panels to provide clean energy for electric loads and fuel generation. While the design was specifically for Mars, this habitat concept has potential application for making harsh environments on Earth livable such as those at high altitudes and even the seafloor (Brabaw, 2017). Utilizing the inherent resource distribution systems (farms, tunnels, etc.), these habitats could also reduce costs related to transportation and land development.

While Mars City Design is interested in Mars specifically, some of the ideas, concepts, and designs can be applied to the moon as well or even to places on Earth. Mars City Design is an excellent organization with the goal of building the first city on Mars. Each year the specific parameters for the competition may change but the overall end goal is to develop the future infrastructure for our species on the Martian surface. In addition to their staple Mars City Design competition, they engage in other projects geared toward developing solutions for Mars.

Another city-oriented project Mars City Design is involved with is the Mars City Research Center which is an effort to develop a research center in the Mojave Desert to perform experiments, studies, and projects where all faculty and families can live comfortably. Essentially, this project aims to celebrate the winning design concept of Mars City Research

Center by realizing it (Nolan, 2017). Another project Mars City Design is running, called Made of Mars, is developing the resources civilizations will need from materials found on Mars (Nolan, 2017). This project is an echo of the industry as it shows clear focus on developing useful tools and shelters out of the natural soils and materials found on the Martian surface, a necessity for future construction-related missions to Mars.

KiloPower.

KiloPower is a space related energy endeavor, recently supported by NASA, for the future development of power plants for the future colonists of the moon and Mars. These units employ nuclear fission for energy generation, though it is much safer than traditional nuclear technology and even safer than launching the energy generation systems currently being used by astronauts (McClure, 2018). Kilowatt Power Using Stirling Technology or KRUSTy is a reliable and continuous power source that can be used for any and all space applications. Once travelers fly beyond Mars, solar power becomes obsolete due to the distance from the sun. Nuclear is an excellent option going forward as it creates energy for decades without the use of the sun.

Nuclear energy comes from the process of nuclear fission which is the splitting of an atom's nucleus either spontaneously or after a collision with another particle (McClure, 2018) which releases energy into the system. The KiloPower or KRUSTy system is comprised of seven components: a core of highly enriched uranium metal fuel (30-50 kilograms/66-110 pounds), a beryllium oxide neutron reflector, sodium heat pipes, radiation shielding, a boron-carbide start-stop rod, Stirling engine convertors, and a radiator used to remove excess heat from the system (McClure, 2018). A photograph of a 10 kW KiloPower model with schematic description is shown on the following page in Figure 18.

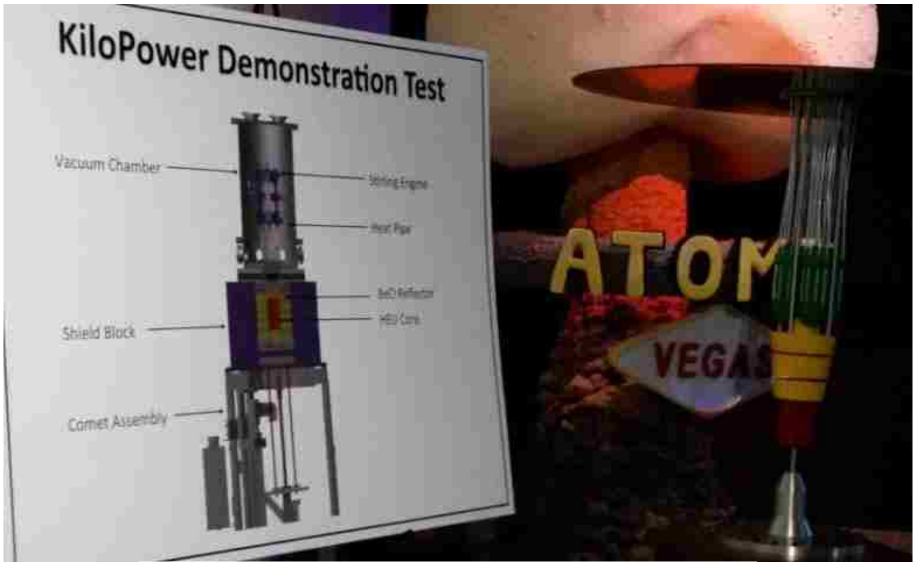


Figure 16: Model and Diagram of the KiloPower Unit

Stirling engines are heat engines used to turn heat into mechanical work or electricity; these engines are highly efficient and have a guaranteed lifespan of 10 years (McClure, 2018). Heat pipes are sealed tubes with a small amount of liquid that boils at the hot end and condenses at the cold end (McClure, 2018); a wick is used to transfer the liquid between both ends. This KiloPower system is designed to produce between 800 Watts and ten kilo Watts of energy (depending on the model) for deep space missions and planetary surface power. For reference, one kilo Watt of energy is enough to power a small appliance, five kilo Watts can provide a single home energy during peak loads, and ten kilo Watts is enough energy to power several homes continuously (McClure, 2018).

One key feature of the system is self-regulation, this means that the generator can sense when an engine malfunctions or is over-producing. When this happens the system is able to automatically adjust the power output in order to prevent a system overload (McClure, 2018) or other potential malfunctions. If an issue does occur, the reactor can be started stopped and restarted without affecting the efficiency. Nuclear effects are low so testing concerns are minimized and the solid uranium core can be easily made whereas plutonium is becoming scarce (McClure, 2018). A key safety feature is that this reactor system, prior to fission, emits 1,000s to 10,000s times less radiation than current energy systems in space (McClure, 2018) providing a much safer environment for future colonists traveling to and settling on Mars. When the KiloPower system is fully clad in radiation shielding, it weighs about 1,800 kilograms (approximately 3,970 pounds) and stands over 11 feet tall; the uranium core itself is only about the size of a box of oatmeal (McClure, 2018). Using multiple KiloPower units for one mission would be incredibly beneficial, especially in a colony setting as they can be easily installed with minimal exposure risks. Several small reactors could easily support the power needed by a lunar or Martian base.

Other ideas.

The following section will briefly describe some other notable technologies related to transportation, habitats, logistics and concepts for future colonies on the moon and Mars. One of the more exciting ideas coming out the Jet Propulsion Laboratory is a vehicle system that is designed to get itself out of tough terrain situations; this system may also have applications for moveable/mobile habitats. The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) concept, pictured on the following page in Figure 19, is based on six wheels at the ends of six multi-degree-of-freedom limbs (Wilcox, 2009). This design will ideally provide the vehicle with the capability of using wheels on typical terrain while being able to walk out of a soft or otherwise extreme terrain environment. This added feature will allow greater functionality of robot vehicles while also reducing the weight and bulkiness of the vehicle as this new model must be more agile for escaping tough situations. The ATHETE rover is a much better option than a traditional rover for several reasons including the function of using tools while on missions. ATHLETE is designed so that each wheel has a quick-disconnect tool adapter that can be used to extract any sort of tool from a holster (Wilcox, 2009), the rotating power from the wheel drive actuator powers the tools. These tools could lead to potential breakthroughs in confined space construction.

Figure 17: ATHLETE Vehicle Climbing a Natural Escarpment (Wilcox, 2009)

In addition to the benefits over traditional rovers, this ATHLETE system has the potential to create mobile habitats simply by sitting a habitat unit on top of the ATHLETE rover. The ATHLETE team has created two "micro-habitat' mockup shells that are small enough to be carried by the existing ATHLETE SDMs (Software Development Models) but are large enough that human occupancy is reasonable (Wilcox, 2009). These mobile systems are able to match hatches and connect with one another much like modules on the ISS. According to Wilcox, 2009 "one beneficial feature of ATHLETE for the hatch-matching task is that, once the vehicles are in approximately the right position for hatch mating, the wheels can be locked and planted in a single place, so that no terrain shape of properties affect the final docking process". The team has also developed a tri-ATHLETE which is basically two three-legged units that combine to form one that is capable of carry heavy loads and traversing long distances with ease.

In 2017, HP sponsored a special edition issue of *How It Works* magazine on the topic of Mars, entitled Mars Home Planet; this issue includes pages of useful solutions for the future of colonization. Many of the solutions and ideas described echo the subjects from earlier in the paper, so the primary focus from the HP resource will be new or specifically unique ideas. In 2016, Lockheed Martin unveiled its plans for a Mars Base Camp which is a space station astronauts would use for observation and experiments as well as remotely driving rovers on the Martian surface safely from the Martian orbit (HP, 2017). NASA could use this as a place to dock its Orion spacecraft (HP, 2017), but eventually the goal would be to install the base on the surface.

Another interesting concept being funded by NASA is the idea of hibernation for crews going on long-term missions, perhaps including missions to Mars. A small crew could be unconscious for two weeks at a time on a rotational basis, with one person always staying awake for a brief time (HP, 2017). Every few days the astronaut monitoring the mission would rotate out with one of the hibernating astronauts. While asleep the astronauts would be kept at temperatures as low as 32 degrees Celsius (89.6 ºF) - down from our more regular 37 degrees Celsius (98.6 ºF) - to slow their metabolisms (HP, 2017). While this technology is in its incubatory stages, as long as it is safe for use by astronauts it could be an incredibly significant solution to many of the time-related issues of space travel.

With respect to the task of terraforming Mars, this can potentially be done in one of two ways: (1) heat the vast amount of ice at the Martian poles; this would release carbon dioxide into the atmosphere thickening it, and potentially heating the planet (HP, 2017). Or (2) use factories on the surface to manufacture chlorofluorocarbons (CFCs) from the air and soil; CFCs are responsible for Earth's ozone (HP, 2017). Regardless of either solution, additional work would need to be done in order to convert the carbon rich air into something nitrogen-rich like on Earth. It is also worth mentioning that unless astronauts could develop some form of a magnetic field on the planet the atmosphere would be continuously blown away by the sun (HP, 2017).

Estimates suggest that complete transformation of Mars could take 10,000 to 100,000 years though optimistically humans could live a normal everyday life within the next 1,000 years and plant life would be able to survive within the next 200 years once the atmosphere has been developed (HP, 2017). Farming is also being considered a viable option on the red planet. A team of scientists from the Netherlands using 'fake' minerals from Mars and the moon to try and grow carrots, tomatoes, weeds and wheat discovered that untreated soil found on Mars was the plant's favorite (HP, 2017).

A paper published that summarizes the 2007 Mars Design Reference Architecture 5.0 reviews many of the same technologies discussed throughout the paper, but it also provides some key information about mission logistics and risks factors for traveling to the moon and Mars. The suggested method from this paper requires a series of phases, the first of which would begin with the pre-deployment of the first two cargo elements, the descent/ascent vehicle (DAV) and the surface habitat (SHAB) (Drake et.al., 2010). Upon arrival both systems would remain in a dormant state until the arrival of crew; the SHAB would remain in Martian orbit and the DAV would autonomously land on the surface prior to engaging sleep mode. The autonomous portion is a huge key to the mission, having the infrastructure set up upon human arrival would make the transition much easier.

The second phase commences during the next available window and launches the crew's Mars transfer vehicle (MTV) which would serve as the interdisciplinary support vehicle for the crew for a round-trip mission to Mars orbit and back to Earth (Drake et. al., 2010). Upon arrival the crew would connect with SHAB and use it to reach the surface of Mars; once acclimated to the surface the focus would become the development of a fully functional habitat on the surface. According to Drake et. al., 2010 "Current human health and support data indicate that it might take the crew a few weeks to acclimate to the partial gravity of Mars after landing". Below Figure 20 provides a detailed illustration of the sequence of events during the proposed mission.

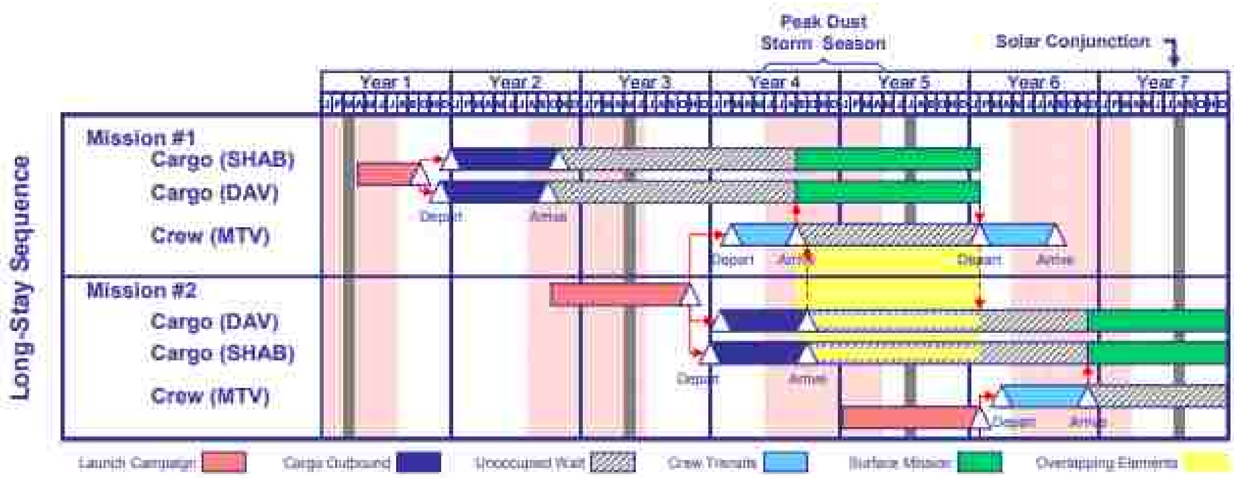


Figure 18: Example Mars Mission Sequence (Drake et. al., 2010)

When mankind does arrive on Mars, we will need means of transportation for traveling across the dusty surface; this is typically remedied by the use of rovers. On the moon the rovers resembled a dune buggy, for Mars however, NASA hopes to provide something that is more comfortable for colonists. Working in a pressured rover will be a much greater help to astronauts than current rover technology as there are many added benefits. The pressurized rover will have a greater range than current rovers and it will also allow astronauts to take off their helmets while traveling (Howell, 2016). Once the pressurized rover technology can be efficiently developed, these mobile units could serve as construction trailers on colony bases to provide a habitable space for crews to work in that is safe and much closer to the construction site.

In addition to pressurized rovers, NASA is working on other technologies for colonization such as solar power stations for Mars. Power is essential to survival in this day and age, especially millions of miles away from the Earth. The system would need to be able to withstand strong sandstorms and deep-freezing nights in order to be useful (Howell, 2016); utilizing multiple connected stations could provide backup power in the event of a failure. NASA is also working on a new and improved design for the spacesuit that will be needed for Mars missions. This new suit is an improvement on the Apollo mission suit with greater mobility in the joints and a rear-entry port that will allow astronauts to climb into the suit with minimal assistance (Howell, 2016). This new suit will not only be more amenable to the conditions on the Martian surface versus conditions on the ISS but will also be easier to wear and reduce preparation time.

The solutions discussed in this section have great potential for future missions, offering help to all four of the main problems associated with deep space travel and colonization. While each one may have provided some insight into how developments are going with current space-related technologies, not every solution will necessarily be needed or end up functioning in the way it is anticipated. Therefore, the following sections will organize the top available options for solving each significant issue. These top options will be used to develop a hypothetical mission plan for reaching Mars using the technologies specified throughout this paper. It is the hope of the author that these final sections provide useful data to future researchers and scientists studying construction and how it may be applied to planetary colonization.

Results

There are scores of real-world options in development and testing for solving the problems of traveling into space and settling on other planets and moons. After analysis of each solution and technology mentioned in this paper, the following section will be used to rank and categorize each solution based on effectiveness of solving problems as well as other considerations such as logistics and cost. While every solution in the paper has potential for space-related applications, not every solution will be described in this section in order to whittle down the total number of ideas to provide a clearer focus for research scopes for NASA and other space agency scientists.

Analysis of Existing Solutions & Technologies

The ideas discussed throughout this paper are great ground work for the future colonization of the moon, Mars, and whatever other rocky planetoids lie beyond our solar system. In the first section of this paper, four primary concerns of space travel were recognized and discussed; cosmic radiation, lack of atmosphere, time, and materials. The second portion then described multiple different solutions to combat these four main problems, pulling ideas and information from NASA and other space-related industries and organizations. This third section of the paper will be used to specifically recognize the top candidates for solving or overcoming each of these four issues. Many of the solutions and technologies mentioned throughout this paper undoubtedly have relevance to the current space mission scopes as well as a myriad of other solutions beyond the review of this paper. For the sake of redundancy only the significant solutions will be categorized in the following sections as they apply to each unique space problem; each of these solutions will be further analyzed to determine best uses and applications going forward as well as the potential for upgrades or improvements to these technologies to increase their effectiveness.

Overcoming cosmic radiation.

While cosmic radiation can be life changing (or life ending) with significant exposure, there exist potential solutions to avoiding the problem entirely. The solutions portion of this paper has highlighted many unique technologies for protecting astronauts from radiation as well as for shielding space crafts and colony bases; however, not every solution has the potential or capability to apply to long-term space travel or colonization. The following solutions in Table 2 are the current best options for overcoming issues related to cosmic radiation:

Table 2: Solution Summary for Overcoming Cosmic Radiation

Solution	***Benefits & Uses***	***Drawbacks***	***Reasoning***	***Future Improvements***
AM Processes (3D & Sintering)	Provides thick layers of protection	Difficult to use in low gravity, product quality can be fickle	This technology provides excellent shielding and uses natural materials	Developments in material types, combating gravity, creating more uniform temperatures, pressure applications
BEAM	Provides lightweight protection	TBD	Lightweight option for equal radiation shielding, currently being tested to determine feasibility	Current testing and monitoring will lead to improvements
Countermeasures	Mission specific, technology and biological protection methods	Everyone responds differently	These are currently being used, further developed would increase effectiveness	Improved dietary and engineering countermeasures
HBNN	Can be woven into fabric, provides secondary shielding	TBD	They provide two-phase protection with no harmful side-effects and can be integrated into spacesuits and other equipment	Testing and investment in spacesuit applications
Mars Ice Home	Provides full protection and allows natural light to infiltrate the living space	Excavation methods, lengthy process	This technology provides excellent shielding and uses natural materials	Improved excavation techniques and robotic capability

ATHLETE	Shielding when using mobile habitat option	Limited size and ability	Can be much more efficient when exploring alien terrain and provide enclosed protection	Additional testing with larger units will determine long-term effectiveness
Pressurized Rover	Complete protection on surface and between modules	Catastrophic damage if failure	Can be much more efficient when exploring alien terrain and provide enclosed protection	Actual development and testing needs to be done to determine if the concept if feasible or beneficial in practice

Some of the other technologies mentioned throughout this paper may also be useful for radiation shielding in future space endeavors; however, it is the author's opinion that the solutions listed in the above and subsequent tables should be the primary focus for scientists going forward as these technologies have the greatest potential for allowing us to achieve our space exploration goals.

The drawbacks for BEAM have yet to be fully determined as the two-year mission is currently about half way completed. The drawbacks for hydrogenated boron nitride nanotubes have also yet to be determined. As it stands, the benefits far outweigh the setbacks; the potential issues may be determined with further testing of the HBNN. Force fields are in pre-incubatory stages of development though some of the potential issues with this type of a technology would be that the energy required to generate an artificial magnetic field of some kind would be massive. Energy generation will be difficult for simple tasks such as lighting habitats; maintaining a continuous energy source would require a large-scale power supply which the moon and Mars are currently lacking. There are other forms of "force fields" such as electrical fields; we would likely need to develop technologies familiar to us like electrical fields before more advanced shielding technologies like magnetic fields can be developed.

Overcoming lack of atmosphere.

A planet's atmosphere is one of the most important components for supporting a thriving ecosystem; it provides many of the things needed for life to develop as well as the protection required from the ravages of space for life to sustain itself. There have been some unique ideas for developing an artificial atmosphere; the following solutions in Table 3 are the current best options for overcoming atmospheric issues:

Table 3: Solution Summary for Overcoming Lack of Atmosphere

Solution	*Benefits & Uses*	*Drawbacks*	*Reasoning*	*Future Improvements*
MOXIE	Develops and harvest oxygen	TBD	This technology already works, simple yet sophisticated	Could potentially be developed to produce other gases, elements, and materials from the Martian surface
ATHLETE	Enclosed space for astronauts to explore the planet	Limited space and ability	Provides protection via an enclosure, protecting from atmospheric issues	Additional testing with larger units will determine long-term effectiveness
Terraforming	Create a full-blown planetary habitat	Takes hundreds of years to successfully execute requiring generations of colonists	The only real way to develop a planet for human needs	Find ways to reduce the time needed to terraform or change the atmosphere
Farming	Provide food and agricultural goods	TBD	Plants grown using simulated Martian soil resulted in incredibly healthy plants	Additional testing should be continued using different compositions of Martian regolith and different foods
Pressurized Rover	Complete protection on surface and between modules	Catastrophic damage if failure	Provides protection via an enclosure, protecting from atmospheric issues	Actual development and testing needs to be done to determine if the concept is feasible or beneficial in practice

The MOXIE system has been proven to work in a laboratory environment, thus far no significant setbacks have been identified. Going forward, some potential setbacks might be exhaust or waste related such as what to do with the byproducts of the oxygen making process, though until further testing is done the actual drawbacks remain unclear. Farming has worked using simulated Martian soil; however, if it turns out that actual Martian soil does not nurture plant life in the way anticipated it may lead to significant agricultural issues for colonists.

Overcoming time.

While technology may not be able to stop the ravages of time, there exist some unique ways of slowing down and/or potentially altering the effects it has on the human body and mind as well as electronics and equipment. While time may be the most difficult of the four problems to develop solutions for, it is not quite an impossible task. The following solutions in Table 4 are the current best options for overcoming time-related issues:

Table 4: Solution Summary for Overcoming Time

Solution	*Benefits & Uses*	*Drawbacks*	*Reasoning*	*Future Improvements*
Beamed Energy Propulsion	Faster travel times, less weight, less cargo space needed	TBD	Reducing travel times reduces the effects of time on humans and equipment	Further development and testing needs to be done
Phobos Base	Preliminary plan before Mars mission, logistical kinks can be worked out	TBD	May provide insight to a Mars base thus streamlining the process	If this option is pursued by NASA it will be several years before it can be determined how useful this can be
KiloPower	Provides limitless energy, potential to develop ion drive propulsion systems	TBD	Reducing travel times reduces the effects of time on humans and equipment, if this aspect of the technology is pursued	KiloPower's energy applications will be tested on future missions though significant laboratory development would be required for new propulsion technology
Hibernation	Seemingly reduces trip duration and maximizes resources	Potential danger for long-term missions	Reduces necessary resources for missions as well as regulates sleep and sanity	Additional testing is required to assess effects on the human body and mind

Most of the solutions proposed for time are related to the shortening of time between trips to and from other planetary bodies, whereas hibernation deals with lessening the effects of time on the human body during missions. The drawbacks for time-saving technologies consist of limitations of our current technologies such as the limited developments in propulsion engine systems or sophisticated hibernation technologies. Drawbacks for hibernation are potentially health related, until further analysis can be done on this technology the long-term and short-term effects remain to be seen. If hibernation can be carried out in a safe manner, then this may be the front runner for overcoming the issues related to time.

Overcoming materials.

The biggest problem with colonization is not having materials and technology established on the desired planet. Fortunately, many solutions do exist today for reducing the burden of material needs on a faraway world allowing us to utilize the natural materials available to use on these planetoids bringing only the absolute essentials along. The following solutions in Table 5 are the current best options for overcoming material-related issues:

Table 5: Solution Summary for Overcoming Materials

Solution	***Benefits & Uses***	***Drawbacks***	***Reasoning***	***Future Improvements***
AM Processes	Can develop an array of structurally sound parts and components	Difficult to use in low gravity, product quality can be fickle	Able to develop almost any required tool or part while using natural resources	Developments in material types, combating gravity, creating more uniform temperatures, pressure applications
Sulfur-Crete	Stronger than Earth concrete, naturally available on Mars	Poor temperature properties, potential for burning or failure	Sulfur has a stronger bond with simulated Martian soil than water-based concrete does on Earth	Sulfur properties need to be investigated and assessed for future compounds
BEAM	Provides pre-made habitats for colonists	TBD	This technology can potentially be used for	Current testing and monitoring will lead to improvements

			preliminary habitats at a much cheaper rate than current methods	
Ice Home	Ice is readily available on the surfaces, allows light	Excavation methods, lengthy process	Utilizes natural resources and can be implemented through robotic assistance	Improved excavation techniques and robotic capability
KiloPower	Allows colonists to work and study using a reliable and safe source of energy	TBD	This system provides reliable energy for powering the systems required to overcome the other issues	Energy applications need to be further developed to increase the overall system efficiency

Again, until BEAM's test mission is complete the complete range of drawbacks has yet to be determined and with respect to KiloPower, the issues with this technology have yet to surface so this system will also require additional testing to determine what, if any, setbacks exist. While all of these summary tables summarize the main technology options for overcoming the four main problems, each table contains one or two solutions that the author believes to be most feasible and should be the focus of future research and scientific studies. The following section will discuss each specific technology as it applied to feasibility and usefulness in construction aspect.

Conclusion

We will make it to Mars; it may not necessarily be on the timelines set forth by SpaceX or NASA, but given the technologies that exist today and the potential of the technologies for the future, the human race will make it to Mars for a long-term mission. There are many published flight plans and logistics regarding the best method for colonization, but the first question is one of selecting the priority destination for the first colony; do we go back to the moon or go straight to Mars? The following section will briefly describe the step-by-step chain of events between launching from Earth and settling on Mars.

Table Discussion

Starting with the solutions to overcome the issues associated with cosmic radiation, the options shown instable 2 are all viable options going forward. One solution stands out when compared to the others and that is the hydrogenated boron nitride nanotubes or HBNN, because the technology behind these devices incorporates protection from initial incoming cosmic rays as well as secondary radiation particles due to the presence of Boron. Given the two-fold protection method, this option far exceeds available protection provided by the other solutions in this category. In addition, the nanotubes can be woven into fabric, allowing for fully-integrated spacesuits which would protect the colonists entirely except for maybe their faces. This would provide colonists with the most protection when dealing with cosmic rays, as safety is the most important part of construction. These HBNN spacesuits would be crucial for colony and habitat development on the surface of the moon or Mars, as they provide more complete protection than any of the other solutions researched.

When working to solve the problem of the lack of atmosphere on the moon or Mars, the best solution for this problem is the utilization of the MOXIE system from MIT. This device is capable of developing and harvesting oxygen to be used for breathing and potentially other applications. This solution has already worked under laboratory conditions and is ready to be tested in real world applications on a mission to the ISS or the moon. Until this device is fully tested, it remains unclear what are the drawbacks and full potential of this system. However, given the advanced state of the technology it would be best for scientists to focus their efforts on developing MOXIE into the best version of itself.

When facing the issues associated with time, the first three solutions in Table 4 shorten the time frame of missions, but do nothing to combat the effects of time on humans. While hibernation does not provide a solution for equipment, it does provide a solution with respect to lessening the effects of time on the human body. It is still unknown what problems may be experienced by astronauts after prolonged usage of this technology. The benefits include less food being consumed so less needs to be brought aboard, thus reducing the mission payload. Less oxygen needs to be used during missions, so less needs to be brought on board, and life support systems will not need to work as hard. The author concludes that time will appear to be going by quicker so mental faculties will remain sharper for longer providing better chances for mission success and safety.

Finally, with respect to the issues faced related to materials, Table 5 offers several good options, such as the Martian Ice Home which provides radiation protection and utilizes natural resources. BEAM and KiloPower also offer potential solutions as expandable habitats for regolith to cover the habitation and provide continuous reliable energy respectively. Additive manufacturing processes, specifically 3D printing, likely utilizing sulfur-based concrete, and sintering technology, specifically electron beam melting, and also incredibly useful technologies for colonization purposes. Once these technologies can be perfected for the intended application they will surpass all other options in the industry. Developing solutions to material problems should be attempted in two steps, the initial step is utilizing the ice home concepts for habitats on Mars and the moon.

The primary benefits of using the ice home concept versus subterranean habitats is the exposure to natural sunlight and the ease of installation with the help of robots. Going underground would require massive excavation equipment, which would be very expensive to send from Earth. In addition, ice homes are able to use the natural resources found on the surface to develop the habitat prior to human arrival. Once robot efficiencies have been increased, the time required for creating an ice home will likely begin to drop from the current 400-day schedule.

Once additive manufacturing processes have been fine-tuned for space applications, 3D printers and electron beam melting machines could be used for additional habitat manufacturing, however, their real purpose will be for developing parts, components and tools for colonists. Due to their ability to create any imaginable product and provide such a product with full density and strength properties, these technologies are key aspects of further colonization of the moon and Mars since they can provide colonists with nearly any device that they would need that was not brought from Earth.

Mars Mission

Many organizations have ideas and plans for how to get to Mars and create a human colony. In reality these plans do not matter if the technologies are not ready. Before any manned missions should be commissioned, the solutions specified in the Results section should be further developed and tested to ensure their reliability and functionality with respect to a long-term mission to Mars. This section will set forth a preliminary guideline for a full-scale, long-term manned mission to Mars using technologies from within this paper, as well as the author's insight with respect to these technologies and solutions. The author's proposed idea is comprised of five mission phases with an optional sixth exploratory phase provided everything to that point has gone well.

The first phase would be that the best solutions identified in the Table Discussion section are moved to the forefront of research and development efforts thus perfecting such technologies leading to full-scale space colonization missions. Phase two would be to launch these systems and technologies into orbit around the moon, and assemble the vehicles and equipment in lunar orbit, as well as send robots to the surface so they may develop the habitats and initiate the MOXIE system prior to human arrival on the surface. Humans would wait in orbit monitoring and conducting experiments as the robots completed these tasks, all the while they are protected thanks to the HBNN spacesuits. Phase three would be to land on the moon with the appropriate technologies, systems and crew to set up a moon base, likely near the southern pole due to lower light exposure and potential for finding water ice. Once a fairly sophisticated base can be established on the moon, i.e. it is self-sustaining to the point that there is continuous food and life support, the next step would be to approach Mars.

Phase four consists of sending the initial building blocks to the Martian orbit from Earth (much like phase two) and a crew from the moon base after the cargo launch. Waiting between launches provides the robots with enough time to set up a habitat prior to human arrival. Sending lunar base colonists would potentially alleviate some of the potential issues experienced on the

Mars mission as these colonists may have experience with living under similar conditions on the moon. As spaceflight duration to Mars is nearly eight months long, the crew could undergo hibernation throughout the duration of the trip until they reached the Martian orbit.

Phase five is the final step in reaching Mars, this phase begins with the crew landing on the surface to acclimate to their new environment in the habitats and structures established by the robots. Once acclimated, the crew will continue developing the surface until a base similar to the one on the moon has been established. The primary structures will be akin to the ice house example, though other structures may be developed for additional tests. The AM processes will be fully integrated into the development of the colony with respect to producing any and all spare, extra, unique or needed components for any and all colonization applications. At this point, NASA and other space agencies will likely conduct many tests and send many more manned missions to the moon and Mars both for permanent settlement missions and temporary reconnaissance missions. Once enough data has been gathered, Earth-based agencies may choose to continue the colonization of space and send manned missions to other destinations in the solar system, including Ceres and possibly one of the moons of Jupiter. Phase six is the option of further exploration and development if such an agency chooses to face the undertaking. At this point technology will be decades more advanced than it is today, so a mission to Pluto in the future may at some point in the future become as viable as a mission to Mars today.

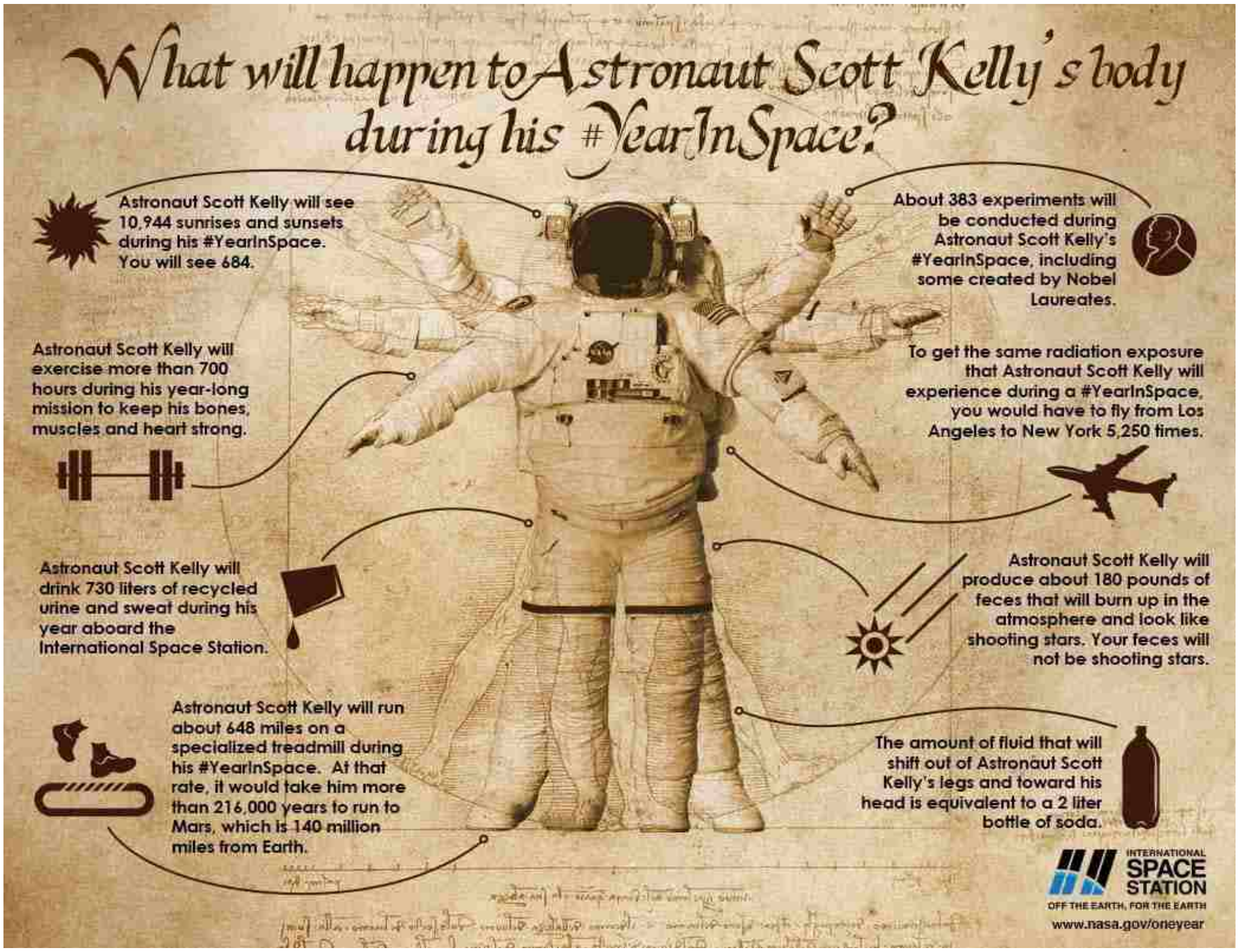
Future Research & Next Steps

Going forward, the scope of research will need to narrow to focus on the most important technologies for putting humankind on the moon and Mars in the quickest, safest, most sustainable, and most cost-efficient way possible. Proposed solutions highlighted in the Results and Table Discussion sections should be the primary focus of future research, as these technologies and solutions provide the greatest potential for humans to reach and colonize the red planet. NASA will be one of the primary research sponsors in the coming years for space-related technologies and applications for those technologies. In addition to NASA's 3D competition, they should create additional programs, activities, and competitions in which the public can participate because the public is an excellent resource for fresh perspective, potentially providing additional support and assistance for future developments.

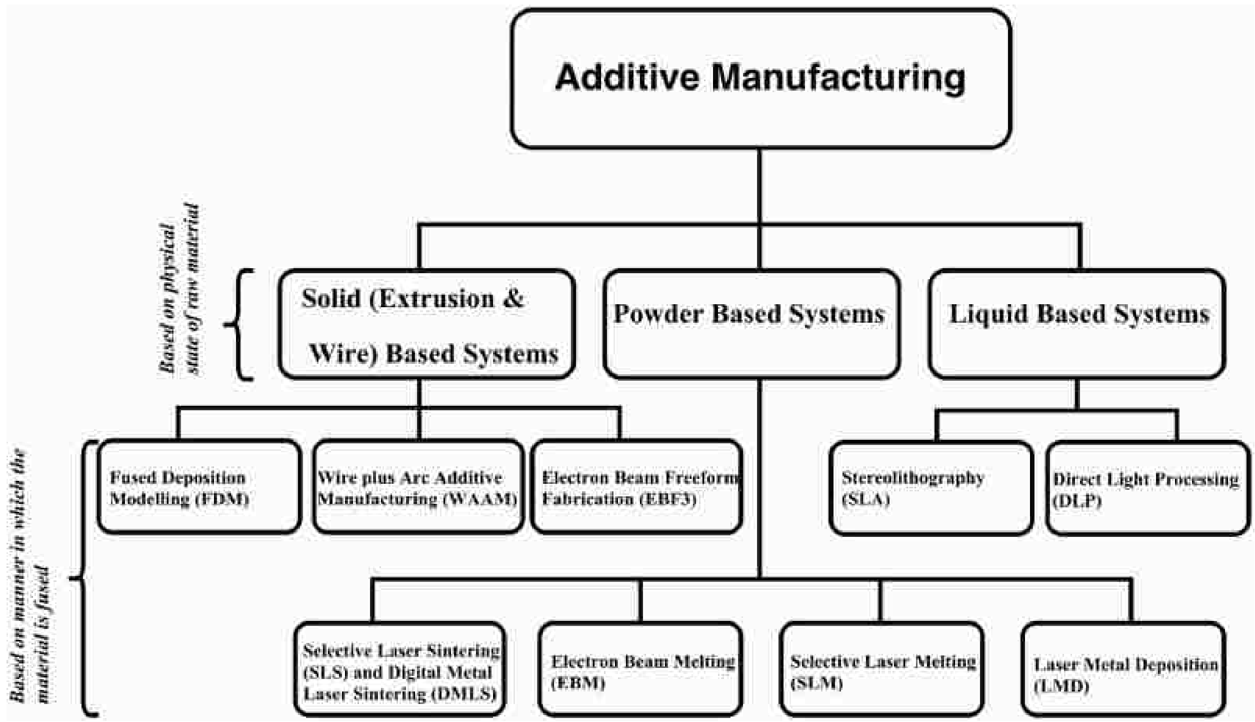
Final Thoughts & Closing Remarks

The primary objective was to survey the literature to develop an overall understanding of what it would require to carry out a large-scale construction process on the moon or Mars. Final results emphasize solutions related to material development. However, there are several technologies related to astronaut safety that translate to labor safety, as in the construction industry, safety is the most important part of any job.

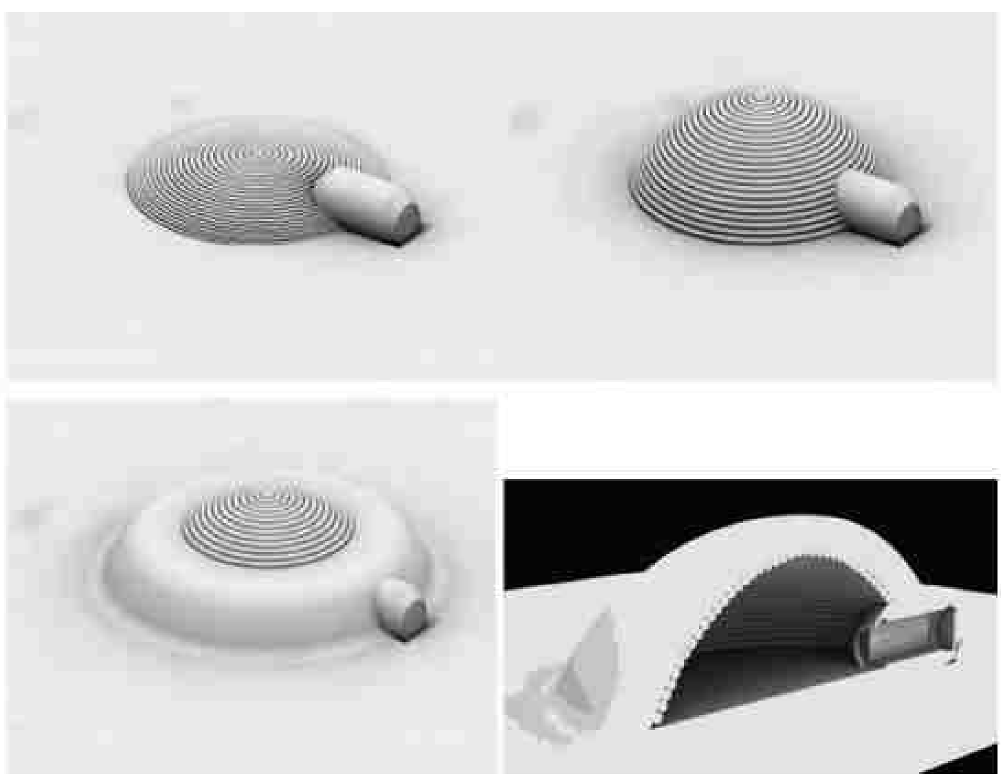
Appendix



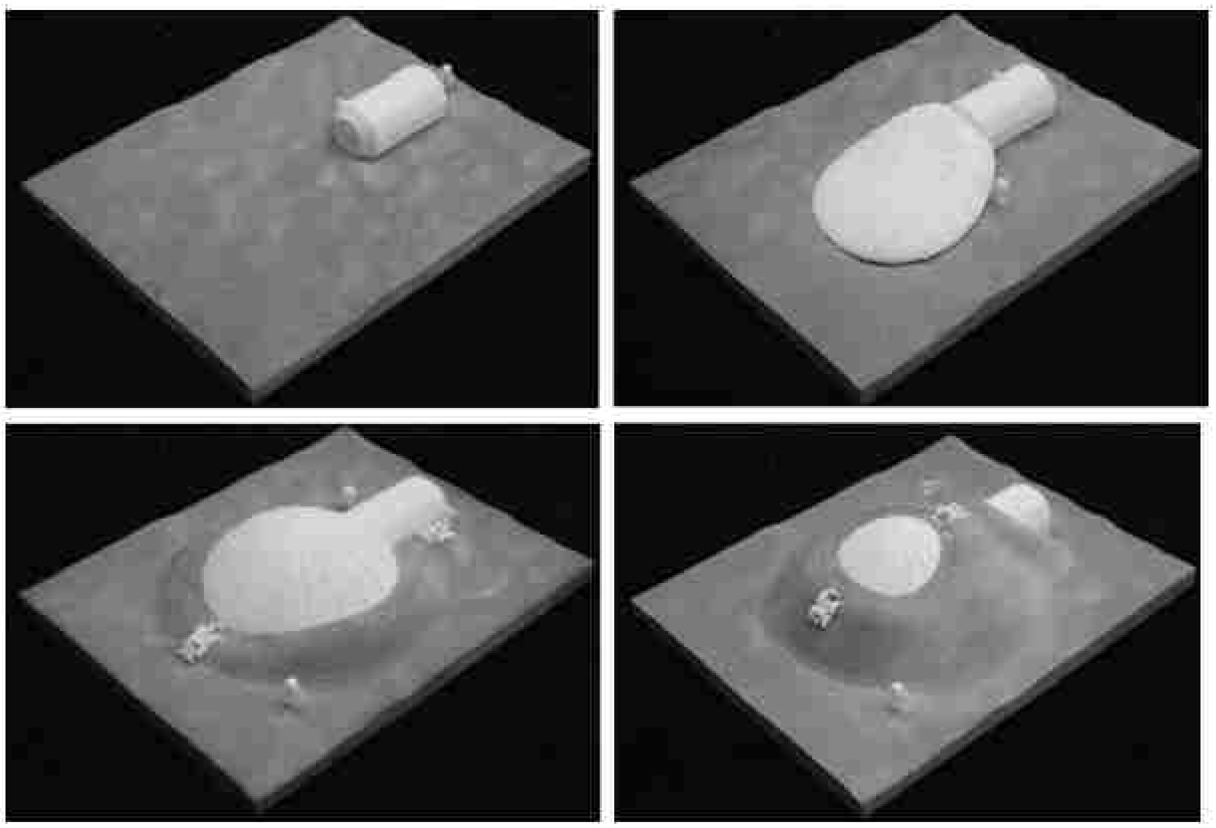
Anticipated events and activities astronaut Scott Kelly can expect to experience during his 340-dayspace mission (Wei-Haas, 2016).



Classification of different Additive Manufacturing (AM) Processes (Joshi & Sheikh, 2015).

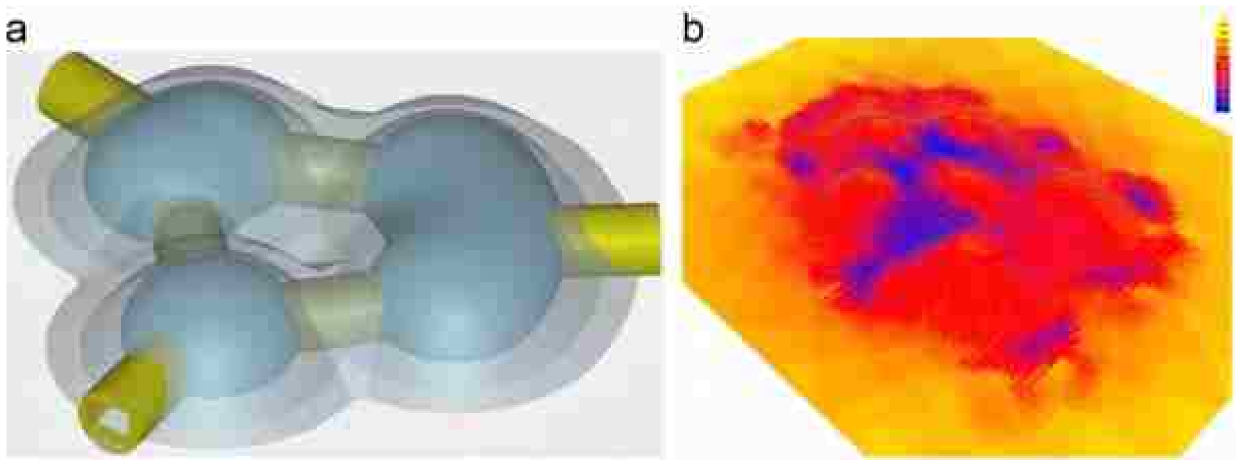


Example of wall construction sequence through an intermediate temporary inflatable support composed by tubes (Cesaretti et. al., 2014).



Sequence of construction of the lunar outpost by means of 2 cooperating autonomous vehicles (Cesaretti et. al., 2014).

Cross-section of outpost structure (Cesaretti et. al., 2014).



a. Connected outposts through a series of above ground tunnels

b. Overlay distribution of solar radiation exposure experience by the settlement

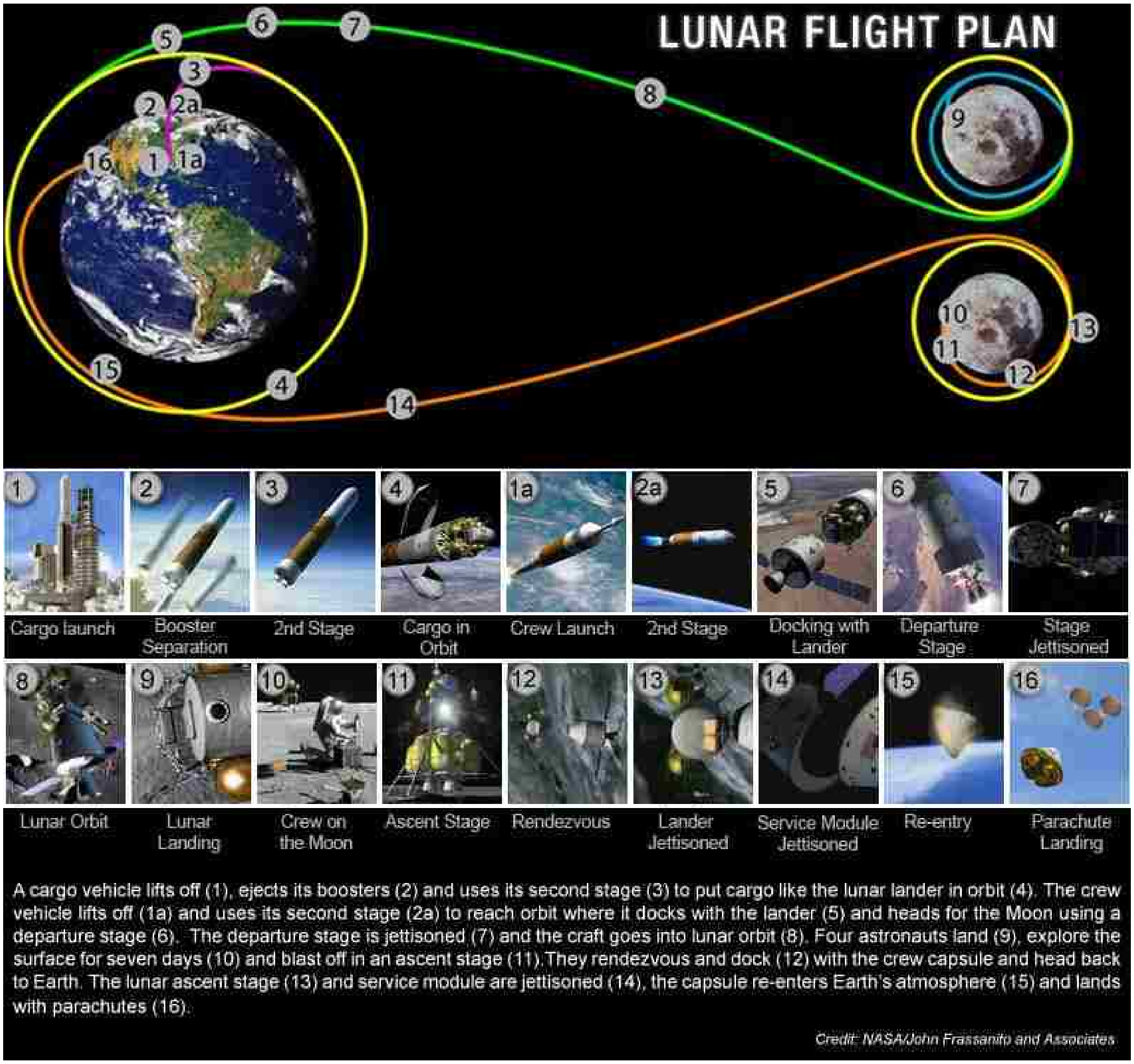
(Cesaretti et. al., 2014).

(a) (b) (c)

(a) Small Engine Block, (b) Environmental Control and Life Support Systems Component, (c) Turbo Pump Component (Howell et. al., 2007).

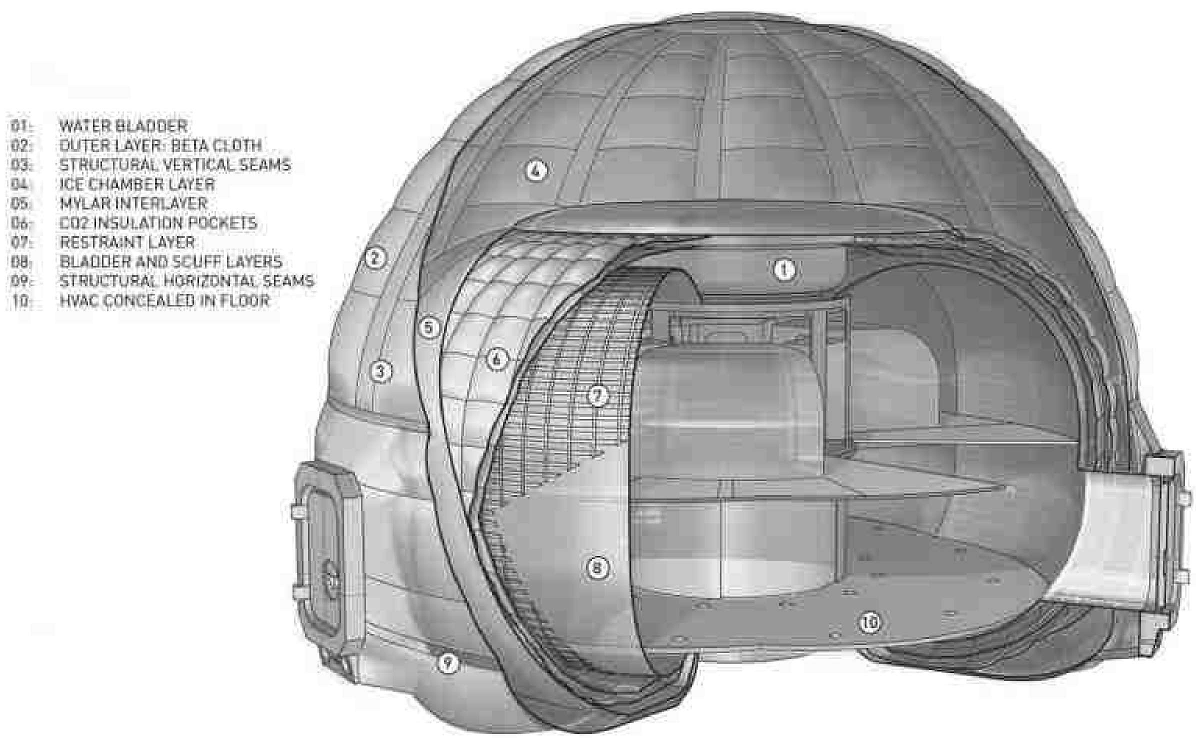
Bigelow Expandable Activity Module (BEAM) cross-sectional view (Rainey, 2016 [Bigelow Aerospace, LLC]).

Concept images of a mission to the moon using the new NASA system (NASA, n.d.).

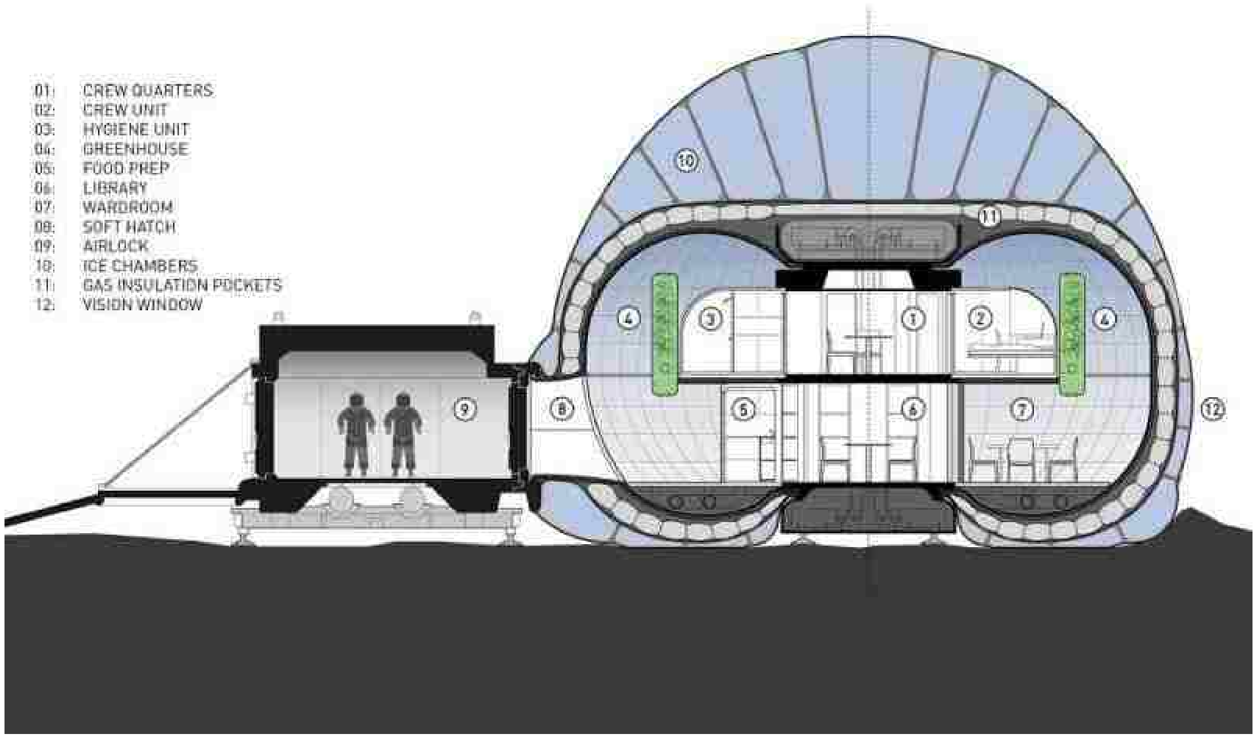


Full lunar flight plan for the new transport system (NASA, n.d.).

The Mars Ice Home concept, Cloud Architecture Office, NASA Langley Research Center, Space Exploration Association (Atkinson, 2016)

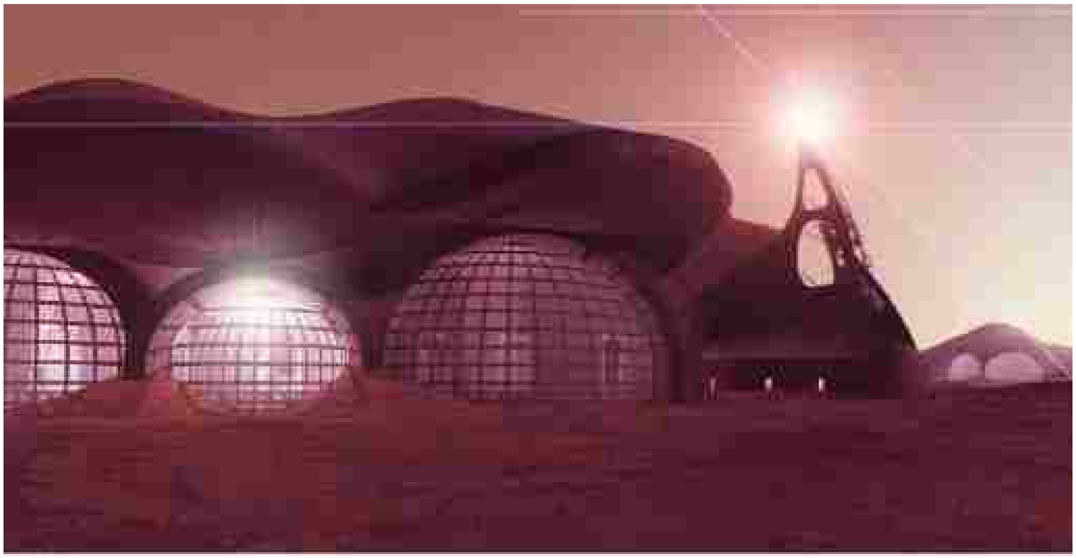


Interior cutaway of the Mars Ice Home concept, Cloud/NASA/Space (Atkinson, 2016)

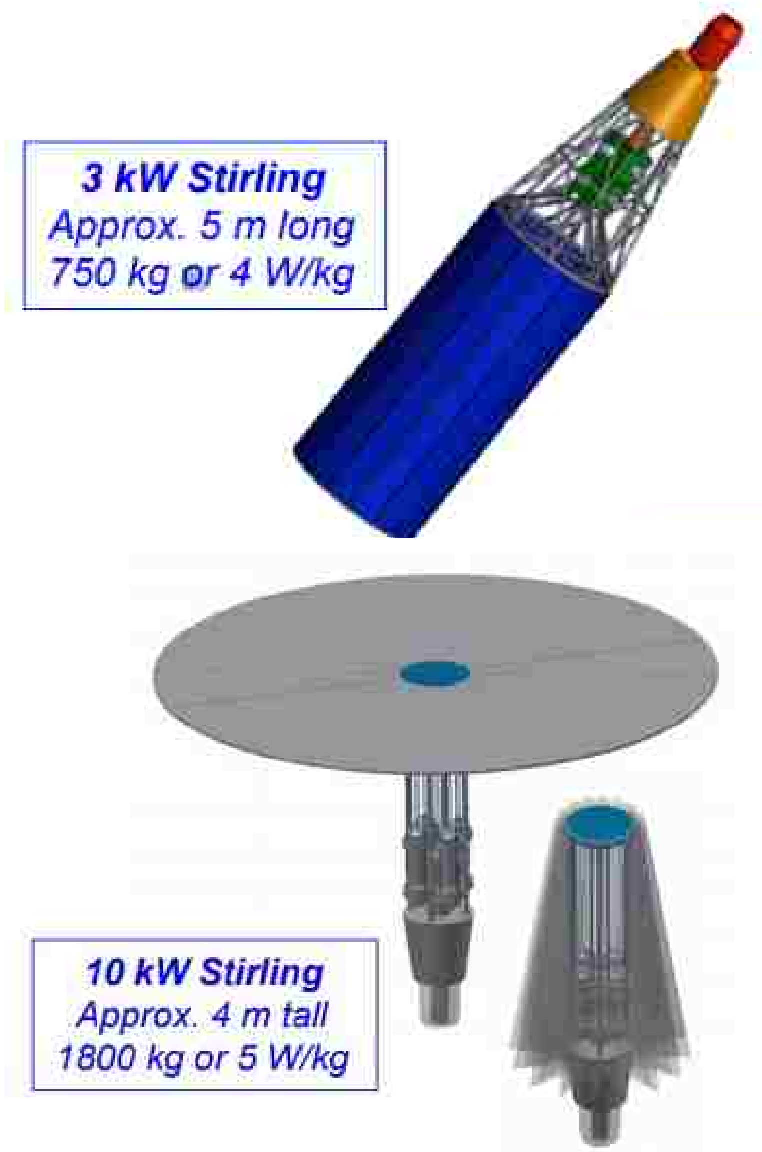


Additional interior cutaway (Atkinson, 2016).

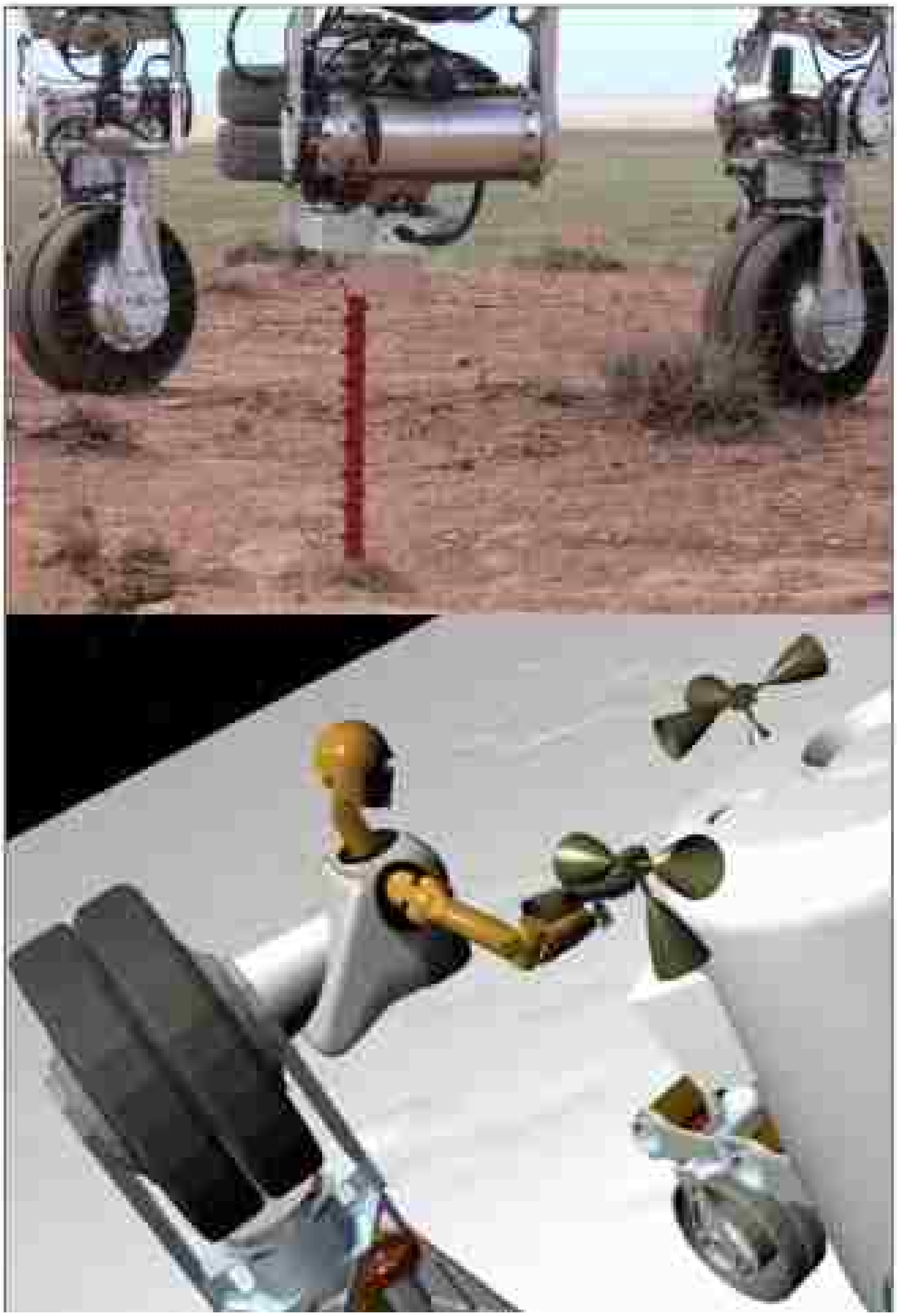
Cross-section of regolith mount (Nolan, 2017).



Concept for "The Upper Ground" Martian habitat (Nolan, 2017).



KiloPower concept renderings (Gibson et.al., 2016)

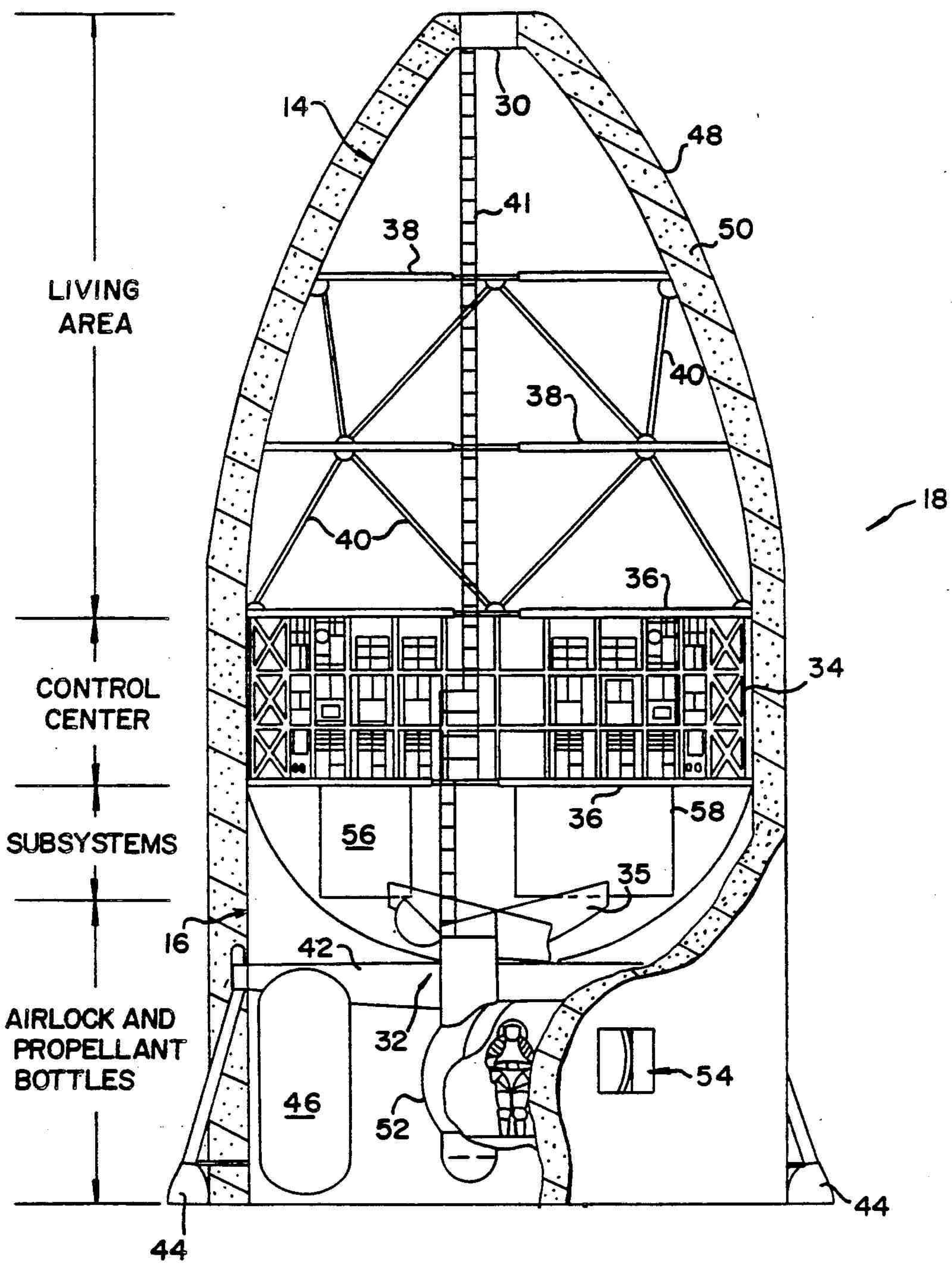


Top - ATHLETE drilling tool in natural terrain

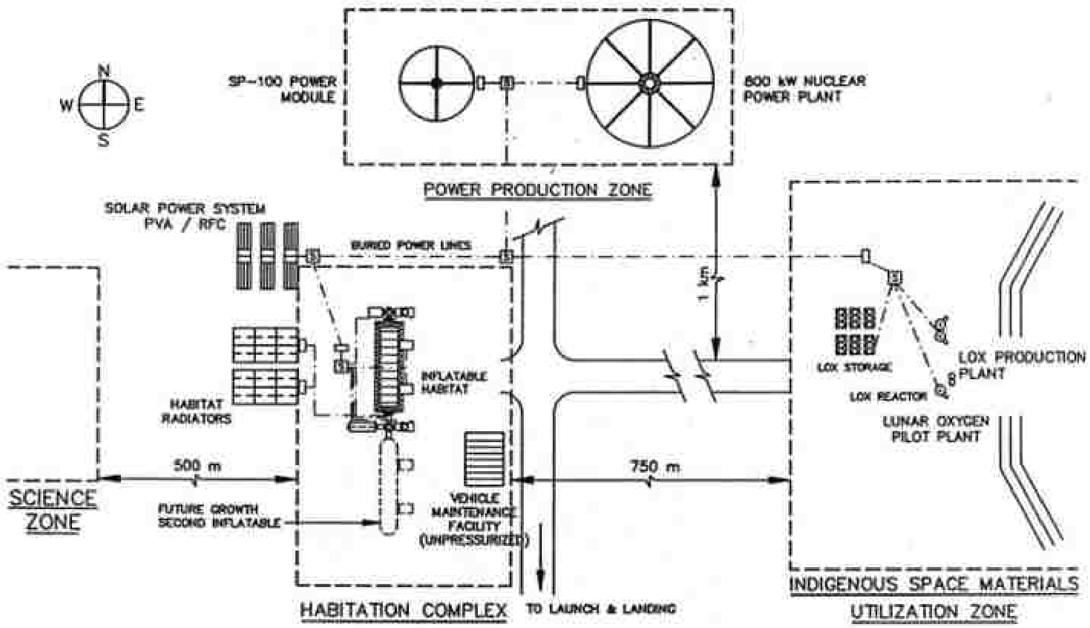
Bottom - ATHLETE using Robonaut anthropomorphic robot developed by the Johnson Space Center for tasks requiring human-like dexterity

(Wilcox, 2009)

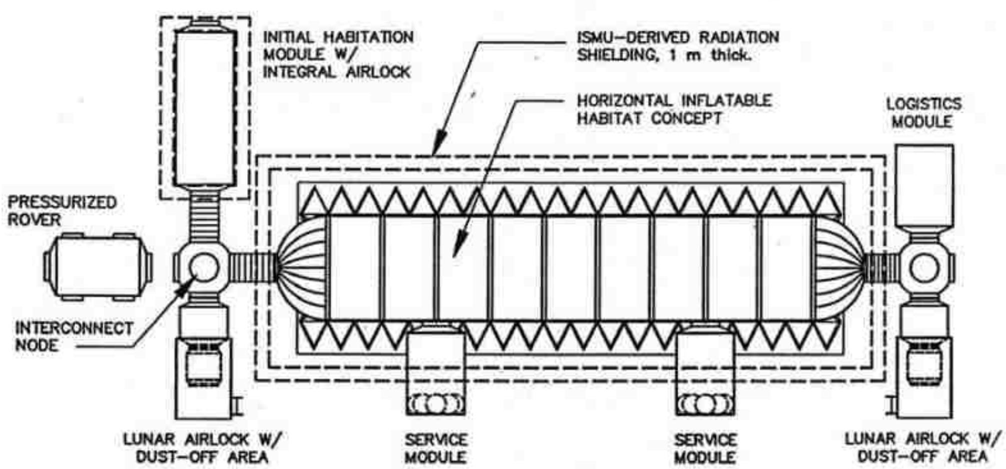
ATHLETE prototypes with habitat mockups during field testing at Moses Lake WA, June 2008 (Wilcox, 2009)



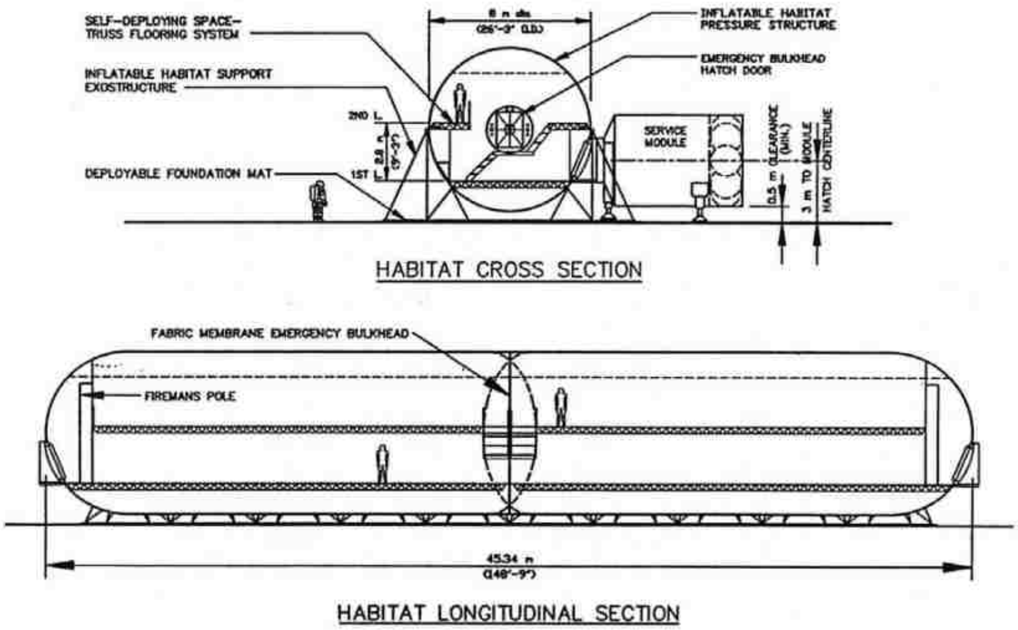
Cross section of tank habitat system after installation of accommodations (King et. al., 1992).



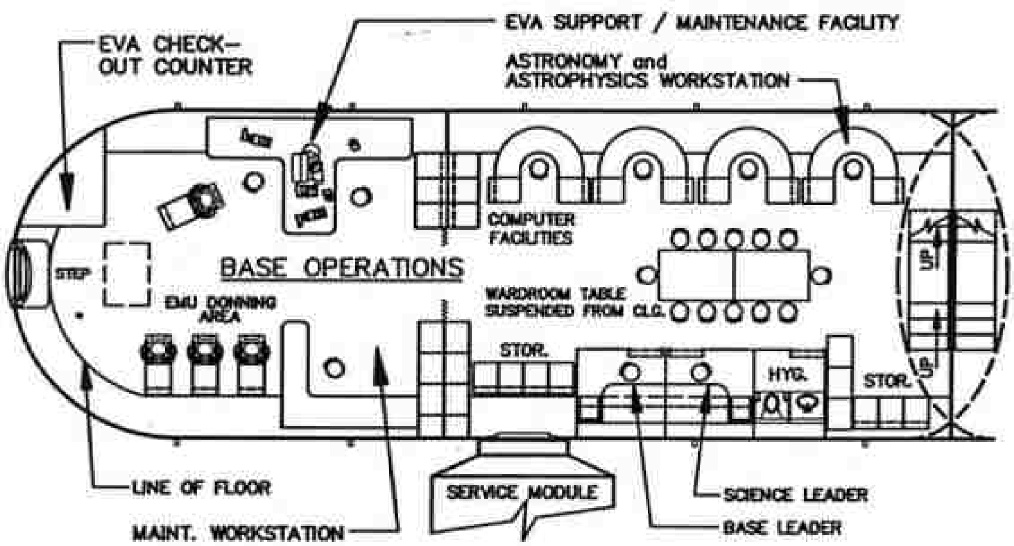
Lunar Base Master Plan (Kennedy, 1992)



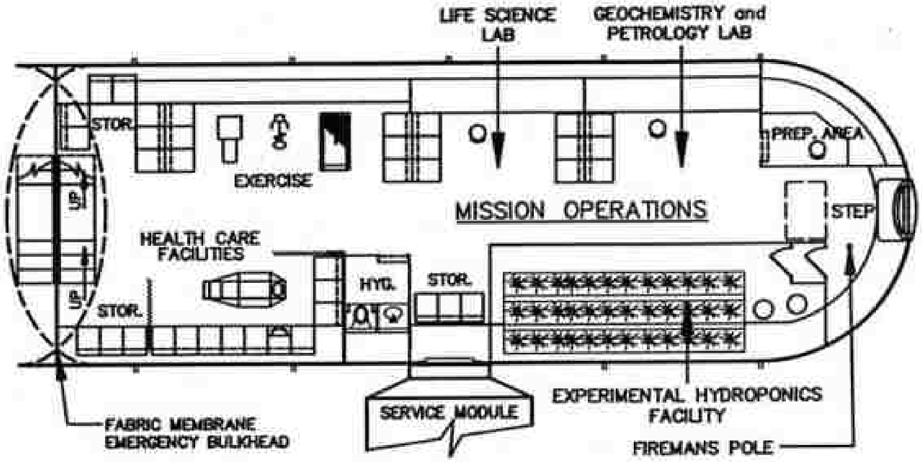
Lunar Base Habitat Complex (Kennedy, 1992)



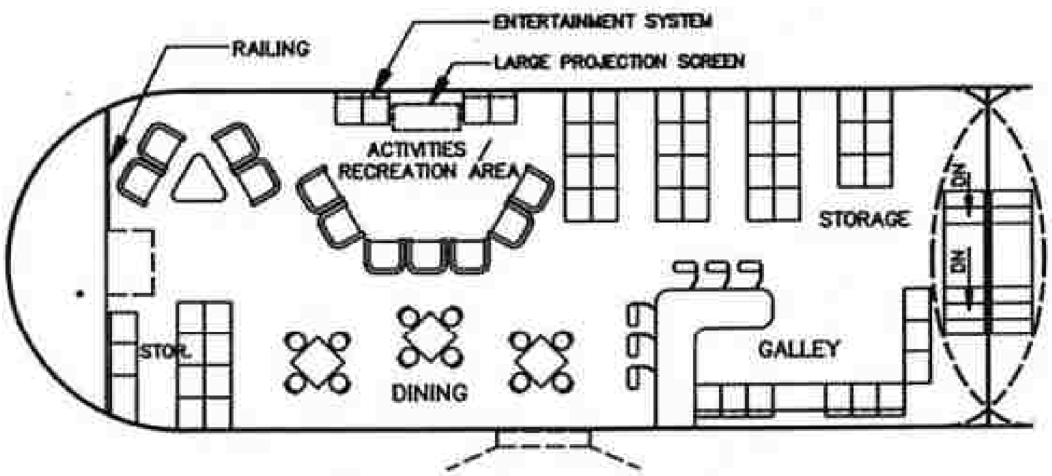
Horizontal Inflatable Habitat Sections (Kennedy, 1992)



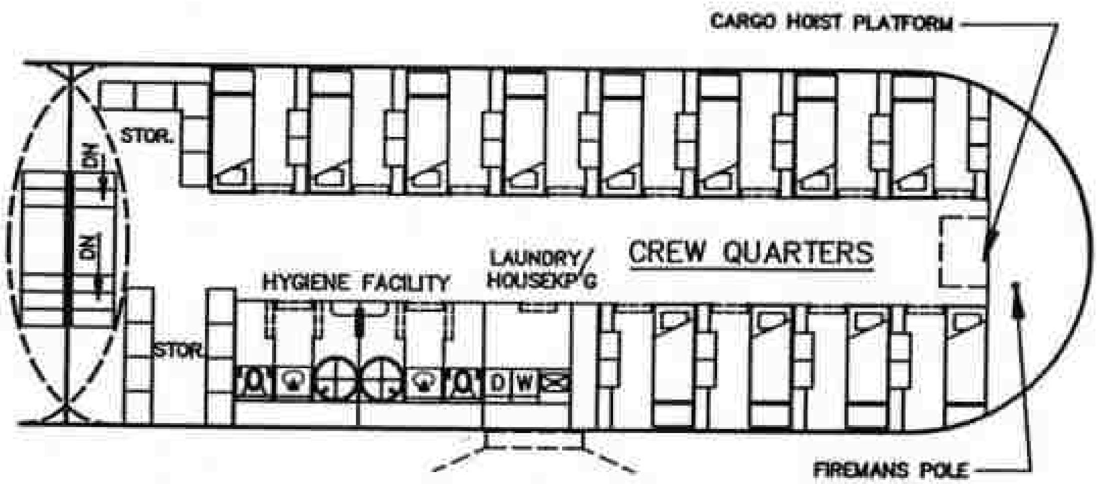
Level One: Base Operations (Kennedy, 1992)



Level One: Mission Operations (Kennedy, 1992)



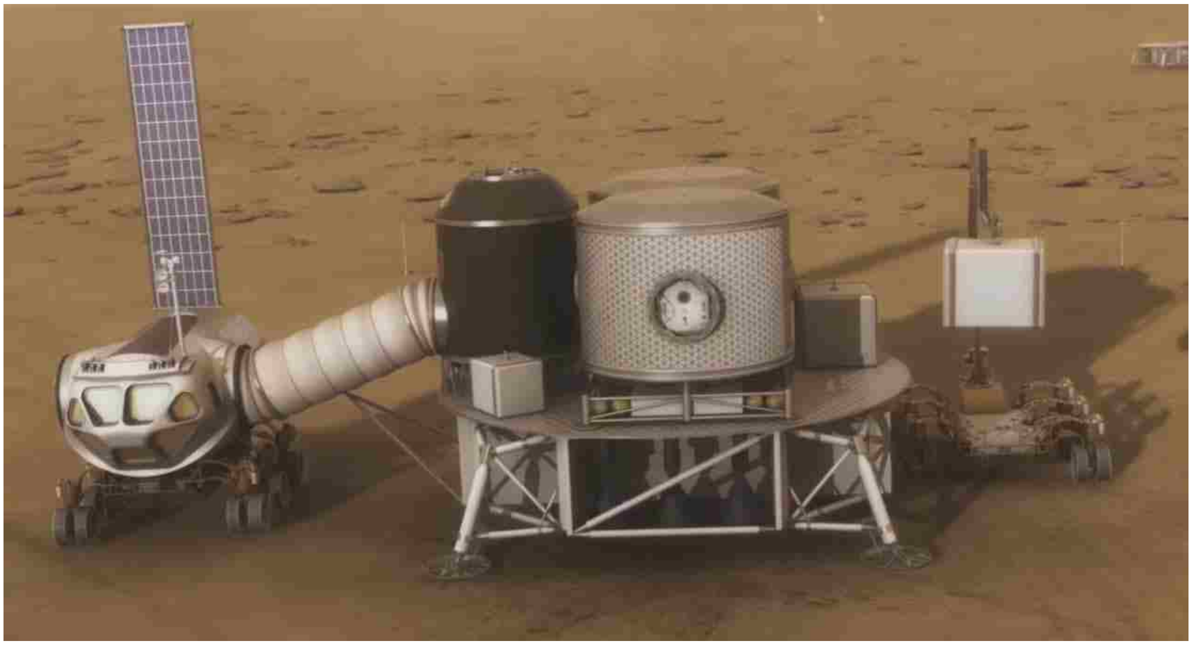
Level Two: Crew Support (Kennedy, 1992)



Level Two: Crew Quarters (Kennedy, 1992)

	Moon	Mars
Distance from Earth	384,000 km	58,000,000 – 400,000,000 km
Two-Way Communication Time	2.6 seconds	6 – 44 minutes
One-way Trip Time	4 days	180-210 days
Stay Time	7 days (sortie mission)	495 – 540 days
Total Mission Duration	18 days (sortie mission)	895 – 950 days
Aborts	Anytime return	Limited to early in the mission or multi-year
Logistics Delivery	Daily	Every 26 months
Total Mission Mass (Note: ISS ~ 400 t)	~200 t	~800 – 1,200 t
Total Delta-V (LEO to surface and back)	9.5 km/s	12 – 14 km/s

Comparison of Lunar and Mars Mission Challenges (Drake et. al., 2010)



Concept of a pressurized rover unit (Howell, 2016)

Concept of an interconnected solar power system on Mars (Howell, 2016)

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