The Future of Humanity in Space

An Interactive Qualifying Project Report
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the degree of Bachelor of Science

By:

Kena Dudac

Nicholas Fiorenza

Thomas Rau

Wasef Raza

Date:

March 4, 2022

Advisor:

Professor Mayer Humi

ABSTRACT

Space exploration will continue to advance our civilization in the future to come. With the aspirations of achieving a long-term sustainable environment in space, certain milestones must come first. This report proposes a mission design for the construction of a Lunar Base that will serve as an outpost for the objective of mining helium-3. To ensure a successful mission, we incorporate a relay shuttle system to serve as a mid-point between the Earth and the Moon.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

Thank you, Mr. Musk.

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AGN: Active Galactic Nuclei

APH: Advanced Plant Habitat

ARED: Advanced Resistive Exercise Device

ATM: Atmosphere

CMB: Cosmic Microwave Background

DSCOVR: Deep Space Climate Observatory

DSN: Deep Space Network

ECLSS: Environment Control and Life Support System

ENA: Energetic Neutral Atoms

GEO: Geostationary Orbit

GOES: Geostationary Operational Environmental Satellite

ICBM: Intercontinental Ballistic Missiles

ICF: Industrial Crystallization Facility

ISRU: In-Situ Resource Utilization

ISS: International Space Station

ISSR&D: International Space Station Research and Development

JAXA: Japanese Aerospace Exploration Agency

KDP: Potassium Dihydrogen Phosphate

LEO: Low Earth Orbit

LRO: Lunar Reconnaissance Orbiter

LVAD: Left Ventricular Assist Device

MEO: Medium Earth Orbit

MLI: Multilayer Insulation

MMRTG: Multi-Mission Radioisotope Thermoelectric Generator

MRI: Magnetic Resonance Imaging

NASA: National Aeronautics and Space Administration

NOAA: National Oceanic and Atmospheric Administration

NREL: National Renewal Energy Laboratory

QDSC: Quantum Dot Solar Cell

RPS: Radioisotope Power System

SOHO: Solar and Heliospheric Observatory Satellite

SRM: Solar Radiation Management

TSS: Tiangong Space Station

WRS: Water Recovery System

xEMU: Exploration Extravehicular Mobility Unit

EXECUTIVE SUMMARY

Over the past few decades, Space Exploration has impacted the lives of engineers, scientists, and citizens around the globe. With advancements in technology and newer methods of approaching problems, it is likely that within the next decade humankind will see its next attempts at creating self-sustaining life outside of Earth. This report expands on past research and interests in the possibility of a future space-faring civilization. Past IQP reports have touched on long-term sustainability, such as the colonization of Mars. This has the potential of being a long-term objective; however, this report focuses on the near future and what must be accomplished in the next decade for these aspirations to become reality.

It is important to note where we currently stand in midst of these undertakings. Private companies like SpaceX, Blue Origin, and Virgin Galactic are currently leading this space frontier into the future. It is likely SpaceX will be the next entity to set foot on the Moon. This report essentially serves as a timeline of the next set of challenges to expect and overcome. A self-sustaining civilization is a colony that can flourish without shipments from Earth. With this in mind, this report expands on the idea of harnessing helium-3 as a renewable energy source that can be used on site or sent back to Earth. With planets like Mars and Venus being the end goal, it is necessary through the scientific method that we trial with these methods somewhere close to home. The Moon will likely serve as an outpost where these methods are trialed and improved.

Before discussing the details and logistics of our proposed lunar mission, it is essential to provide a broad overview of space technology. Thus, we discuss past accomplishments and progress from the United States, Russia, and China, as well as developments in spacecrafts and space stations. We also discuss current space developments in food, trash management and water recycling, living quarters, energy, fuel, human interactions, and communications. Many of these developments are observed with the National Aeronautics and Space Administration (NASA) and the International Space Station (ISS). Our team also explores the impact of space exploration from a commercial aspect. We discuss how space technology impacts various fields such as communications, medicine, and tourism. We also explore some of the more speculative impacts in space mirrors and space elevators. Notably, we also examine space weather and Lagrange points.

The primary objective of our proposed lunar mission is the construction of a base on the Moon. The purpose of the base is to serve as an outpost for mining helium-3 from the lunar surface. With the desire to obtain helium-3 in mind, we recommend the following first five-person crew:

1. Life Support – Medical Personnel
2. Power Specialist – Electrical Engineer
3. Telecommunications – Computer Scientist
4. Expert 1 – Mechanical/Robotics Technician
5. Expert 2 – Nuclear Physicist

Desired abilities include food generation, systems upkeeping, and habitat construction and maintenance. Optimally, the lunar base is located near both ice water and helium-3, and the proposed location(s) (around 30˚S, 160˚E) take that into account. The lunar base design is credited to Foster + Partners. It is structured around an inflatable dome shell covered by hardened lunar soil that is placed by 3D printing robots, and thus providing protection against temperature swings, radiation, and meteorites. The base is solar powered and has dedicated sections for various tasks (similar to the ISS).

In order to collect helium-3, we proposed a rover design inspired by the NASA Cratos prototype lunar rover. The rover will also assist in the construction, and maintenance of the lunar outpost before human habitation. The design specifications require the vehicle to be able to scrape regolith from the lunar surface and amass the soil in a pile to be processed. The rover has the following design specifications:

- Power to weight ratio 1:1 ±10%
- Wireless transmission of data from sensors to lunar base
- Continuous operation through the use of a radioisotope power system and battery
- Maneuverability to allow for navigation into and out of a lunar crater

To ensure a successful mission, a relay shuttle system will be incorporated. Ultimately, these shuttles will serve as a ‘gas station and rest stop’ at the midway point between the Earth and the Moon. The system consists of two shuttles – one in low Earth orbit (LEO) and one in a lunar orbit. When needed, the shuttles will meet in a medium Earth orbit (MEO). Each shuttle is equipped with low electric thrusters capable of carrying out spiral transfers. They are also equipped with a solar array that can suit up to 100 [kW] and fuel tanks with various monopropellant and bipropellant fuels. The relay shuttle system enables spacecrafts and astronauts to fuel, recharge, and rotate personnel and equipment. Our team developed a render of the relay shuttle stations using SolidWorks. It is important to note that this mission was compiled assuming SpaceX’s cargo-style Starship configuration and launch capabilities.

The relay shuttle requires a solar array size of 1,040 [m^2]. The mass breakdown of these spacecraft components totals roughly 30,000 [kg]. This attributes to roughly one-third of one Starship cargo-style payload to LEO. In our calculations, the orbit is almost circularized. However, realistically anything with an eccentricity less than 0.1 should not make much of a difference. The period of this LEO will be roughly two hours with perigee and apogee around 1,500 [km], with an average velocity of 7 [km/s].

Future missions to the Moon will serve as the first test runs for manned missions since the Apollo program. Although, this time we plan on staying indefinitely. Achieving these milestones will help prepare humanity in reaching future destinations of interest. The future of humanity in space will depend on these next set of obstacles and how we tackle them. This project expands on the capabilities of SpaceX’s Starship launch vehicle and where our path through innovation may lead into the near future.

TEAM MOTIVATIONS

- Harvesting the potential power of helium-3 mined from the Moon to establish newer techniques to help suffice Earth's energy consumption.
    - This technology can go one step further with future iterations among other planets.
- Seeing humanity expand on an interplanetary scale, enlightening planets like Mars and Venus with life. Establishing a self-sustaining base on the Moon is required to progress desired milestones.
- Future investments in space technology will revolutionize international relations. Lowered costs in efficient low Earth orbit will soon be used for future transportation. Reaching further destinations like the Moon will attract exploration, testing, and tourism.
    - Low Earth orbit will attract the private industry into newer development in:
        - Space Suit Technology
        - Module Refurbishment for Living Quarters
        - 3D Printing and Welding Assemblies
        - Service Stations (Scientific)
        - Cargo & Passenger Transportation
- Study the environmental behavior of our universe; this includes the effect of radiation, solar flares, and potential asteroid collisions.
    - Protecting electronics during an electromagnetic pulse (EMP).
    - Detecting solar flares by monitoring the Sun.
- Satellite mission design experience. Allows an exploration of applied knowledge and techniques in an academic environment that is accommodating of mistakes and learning.
- A sustainable mission or program to the lunar surface that has the ability to positively impact our day-to-day life through the science and engineering done.
    - Includes establishing infrastructure for a lunar base, scientific experiments to allow for further human space travel, and passive monitoring for various threats, mainly solar flares from the Sun, or rogue asteroids.

CHAPTER 1: Technologies Overview

[1.1] Space Implications in 2022

[1.1.1] Conquering LEO (Low Earth Orbit)

The Future to Come

Space Technology has evolved exponentially in the past decades yielding a plausible promise in achieving the next set of future endeavors towards sustainability and preservation of the human race. The obstacles ahead seem favorable for particular space ventures. However, with indeterminism in development towards conquering such challenges, makes these trials foreseeable. The likelihood of achieving these milestones seem inevitable but are logically unpredictable.

The first establishment on the Moon will be our greatest challenge of survival, technology, and discovery. SpaceX is currently the number one entity that will likely tackle these next set of challenges. The 2021 development and testing of Starship demonstrates where we currently stand with these set of challenges [1]. NASA has been planning its set of Artemis missions after the discontinuation of the space shuttle program in 2011. Companies like Virgin Galactic, Rocket Lab, and Blue Origin have also been allotting time and research into achieving orbit. The space race has shifted from the public to private sectors in the past few decades. Time will only tell what entity will achieve these next set of feats.

Once getting accustomed to the reality of a Low Earth Orbit, only time will tell what companies will jump on board. The possibilities of these ventures are endless. However, most have a set expectation that these feats will happen across the Solar System far from home. This is a misunderstanding of what is truly to come. Indeed, we set goals on achieving milestones on other planets such as Mars. However, in the next decade most of these ventures will playout around the Earth and on the Moon. Examples of this include manufacturing space stations while in orbit, telecommunications advancements (similar to Starlink objectives), and achieving a settlement on the Moon. This report will reflect on the **possibility of a lunar outpost**, serving as a demonstration for what is next to come.

1

[1.1.2] LEO into Potential C3 Injections

Price per [kg]

In the next decade the realization of Potential C3 Injections will become clear to many private corporations. Currently space organizations such as SpaceX offer payload rideshares to a variety of injections, that can span across the Solar System. With bigger and more powerful launch vehicles that are scheduled to take flight in the next decade, the mass and volume of these payloads will exponentially grow. The cost of these missions is also dropping, to the point that in 2021 the average cost per [kg] into a LEO was only about $2,720 by a SpaceX Falcon 9 [2]. After achieving this orbit, the potential for certain mission objectives and injections are endless. Some of the more common destinations are denoted below.

The Moon

The Moon will primarily serve as a 'trial' or 'test run' when planning longer ventures to other planets. Due to the distance of the Moon, humankind will be able to test their spacecraft and equipment somewhere very close to Earth. If problems arise, they can be adequately resolved in a timely fashion. For the objective of mining in space, the Moon will serve as the initial testing ground, as heavy machinery has never been outfitted for the vacuum of space. The results from the lunar mission can be applied to other such ventures of the near future.

Mars, Venus, Uranus

Aside from a handful of moons on various planets, the three most common destinations scientists are interested in visiting are Mars, Venus, and Uranus, each for their own specific reasons. They all, however, share one common goal – to preserve humankind. Mars is the most sought out and desired destination, as it carries similar characteristics to Earth, with respect to its size and the presence of water. Next on the list would be Venus and Uranus. Although Venus has an atmosphere of carbon dioxide, the planet has a temperature and force of gravity that are much more comparable to that of Earth's (in contrast to Mars and Earth). Both environments (Mars and Venus) do however, have a promising possibility to suit life. Exploring other celestial bodies does not only have to be to preserve life. The aspect of financial gains is also commonly brought up. In this report, we will not be

---

2

focusing on the possibility of mining asteroids, rather we will focus on mining the Moon. The search for helium-3 may bring us one step closer to finding a more efficient fuel source for fusion reactors. The purpose of this report is to determine and discuss the logistics of mining helium-3 on the Moon's surface. However, scientists have also discovered this isotope of helium in the gas mines of Uranus. They found that the outer planet structure of Uranus is like a cold shell, venting this gas through its outer crust from the gas channels within its core.

The Sun

The Sun is a body that scientists have been researching for years. However, we have not yet had the proper instrumentations for collecting data. With advancements in thermodynamics over recent years, it is likely we will send a superior satellite to the Sun in the next decade. The purpose of this satellite is to monitor solar flares and study the inner core of the Sun. Currently, NASA's Parker Solar Probe is the best-known solar observer. Many observatories on Earth are also dedicated to capturing solar phenomena, as well. Overall, the likelihood of a catastrophic, extinction-level solar flare is very small. However, there is a lot more to be discovered about the Sun, solar radiation, and its role throughout the universe.

[1.1.3] Injection Impacts on the Commercial Agenda

Space exploration has a significant impact on humanity. Due to various aspects of space exploration, humanity stands to greatly benefit from it. The commercial agenda of space exploration is broad and encompasses a plethora of fields.

Communications

One of the more notable areas benefitting from space exploration is communications. Only about 50 percent of Earth's population has access to the internet. SpaceX and OneWeb are in the process of developing a global network of communication satellites that will enable a majority of people around the world to connect to the internet. This is particularly helpful to those in remote regions that lack infrastructure and development. Internet access will drastically increase knowledge sharing and communication. Other advanced Earth imaging satellites (which were able to be developed because of space technology) assist in various tasks. For example, they enhance agriculture through the use of special spectral bands that can determine crop yield on a pixel-by-pixel basis. Farmers use this information to better decide when to harvest. These satellites also assist in monitoring reservoir water levels. They are also used in monitoring climate change, fishing vessels, and wildlife habitats [3].

Space exploration is also responsible for improvements in communications due to the advancements made on the Deep Space Network (DSN). The DSN consists of three transmission and reception facilities located in the United States, Spain, and Australia. They are spaced 120˚ apart around the globe to provide continuous coverage for deep space communications. Communicating between deep space and Earth is a difficult process, as the Earth's atmosphere impedes radio and optical communications. Currently, the DSN uses microwaves for communication. Technology is being developed to transition to optical communications. Optical signals allow for far more efficient video and data communications over vast distances. For example, the beamwidth of a microwave communications signal transmitted from Mars is 100 to 200 time the diameter of the Earth, while an optical communications system's beamwidth is only one-tenth to one-twentieth of Earth's diameter. Furthermore, with optical communications, there is essentially no limit to the amount of bandwidth available and thus almost any amount of data can be accommodated [4]. The commercial benefit of optical communications can already be observed with fiber-optic internet. Fiber-optic internet is significantly faster than its cable counterpart. It also

3
4

provides upload speeds that are equally as fast as download speeds. Inevitably, advancements made in optical communications due to space exploration will benefit the general public, as well.

Crystals

Another commercial benefit of space exploration is the development of high-quality optical crystals. Potassium dihydrogen phosphate (KDP) is a type of nonlinear optical crystal that has well-defined laser applications. Often times these crystals receive laser induced damages that impede their use. Damages are typically caused due to impurities that occur during the crystal growth process from thermal convection. There is essentially no simple method to avoid this problem on Earth. Due to advancements made in space technology, development of the Industrial Crystallization Facility (ICF) was possible. The ICF is a commercial in-space manufacturing device for the production of high-quality optical crystals in microgravity. It successfully launched to the ISS in February 2021. The ICF uses diffusion-based crystallization methods that are not possible on Earth because of thermal convection. This is done through the use of a solution growth technique that is not dependent on gravity. The resulting crystal yields “a much higher laser damage threshold with fewer inclusions and defects”. If the process is successful for KDP, this growth technique can be applied to various other commercial use crystals and materials. This new type of “space-enabled manufacturing” exploits microgravity to create new or enhanced materials. These materials can significantly improve performance of industrial machines and systems used on Earth [5].

Medicine

The field of medicine is another area that greatly benefits from space exploration. Improvements to medicine occur from space exploration in two main ways. Firstly, technologies and discoveries made for space are applied to the medical field. And secondly, the microgravity of space allows for unique scientific work that serves to improve medicine.

There are many examples of technologies and discoveries made for space that are applied to medicine. The United States government intended for this outcome when it established NASA in 1958. NASA is required to share information about its discoveries. NASA is also allowed to patent inventions and aid businesses in the

---

5

development of commercial uses for them. A prominent example of space technology applied to the medical field is that of Magnetic Resonance Imaging (MRI). NASA's Jet Propulsion Laboratory developed digital image processing in order to enhance pictures of the Moon. This technology greatly contributed to the development of MRI and CT scans, which are prominently used in the medical field for diagnostics. Another example is that of the development of the Left Ventricular Assist Device (LVAD). NASA engineers at the Johnson Space Center worked alongside with doctors to develop the LVAD – an artificial heart pump. The LVAD was modeled based on the fuel pumps of the space shuttle. An additional example of space technology applied to the medical field is the use of light technology that was developed for plant experiments in space. That same light technology is being used to "reduce the painful side effects of chemotherapy and radiation treatment in cancer patients who have bone marrow or stem cell transplants". Some other notable medical advancements that came from space technology are cool suits to lower body temperatures, voice-controlled wheelchairs, programmable pacemakers, and tools for cataract surgery [6]. These are just a few of the numerous medical applications of space technology.

The microgravity of space allows for scientific work not possible on Earth. For example, in microgravity, cell growth differs. Scientists are able to culture cells for a longer period of time. The cells also grow in a better three-dimensional fashion compared to those grown on Earth. This allows scientists to study different aspects of the cells. Furthermore, being in microgravity in orbit causes an effect similar to rapid aging. Processes that take years on Earth (like osteoporosis) occur much quicker in space. This allows scientists to perform certain experiments in a relatively short amount of time. Moreover, protein crystal experiments are particularly effective in the microgravity of space. Certain protein crystal structures grow better on board the ISS. The protein crystals formed in microgravity are more three-dimensional and better ordered. These improved structures give scientists much better insight, which can lead to the development of new or improved drugs [7].

6

7

Tourism

Space exploration opens up opportunities for space tourism. According to the co-lead of the Aerospace Corporation's Space Safety Institute, Danielle Bernstein, human spaceflight has been predominantly government focused – only highly trained astronauts were allowed into space. This is no longer the case, as people who are not astronauts can now freely travel to space for personal enjoyment. As it currently stands, commercial space travel is only accessible to the wealthiest people on Earth. Tickets to the edge of space start from around $200,000, while an orbital expedition can reach costs of tens of millions of dollars. Comparing to the airline industry, these trips begin as extreme luxuries for the ultra-rich. However, as technologies and infrastructure improve, access to space will become much more readily available, similar to commercial flights. Eventually, low Earth orbit will become its own marketplace, complete with elements of tourism, research, advertising, and entertainment.

Blue Origin and Virgin Galactic have different methods of sending passengers to space. Blue Origin's New Shepard system launches passengers to space in a capsule that ejects from a small rocket. The capsule returns back to Earth under parachutes. Virgin Galactic uses a space plane that is dropped from a carrier aircraft. The space plane has a rocket motor that brings passengers high into the atmosphere. Both companies' rockets fly passengers over 50 miles above Earth's atmosphere.

In contrast to rockets, the company Space Perspective is developing "teardrop-shaped space balloons the size of football fields" (scheduled for 2023). The balloons carry a pressurized capsule that accommodates up to eight passengers. They travel at 12 miles per hour to a distance of 20 miles above the Earth's surface. It is an alternative method to commercially fly to the edge of space [8].

SpaceX plans to use its Starship rocket for long-distance air travel. The rocket is capable of flying 100 people around the world in minutes. SpaceX claims that a 15-hour flight from New York to Shanghai can be completed in just 39 minutes [9]. Such a feat would revolutionize long-distance travel.

NASA supports and invests in the private space industry. Notably, NASA is investing in Blue Origin, Nanoracks LLC, and Northrop Grumman Systems Corporation to develop designs for a commercial space station. The commercial space station's purpose is to conduct advanced research and foster commercial industrial activity [10].

8

9

10

In the future, commercial space stations will also serve as luxury space hotels. One such example is Orbital Assembly Corporation's Voyager Station, which is set to launch by 2027. The Voyager Station will accommodate up to 280 guests and 112 crew members. Some parts of the space hotel will simulate gravity, while other parts will include the weightlessness of space. There will be restaurants and bars available for guests. There will also be options for recreational activities, such as basketball, where guests can "soar higher due to the weightlessness of the environment". Overall, the company envisions the experience to eventually be similar to that of buying a cruise ticket [11].

Speculative Impacts of Space Exploration, Space Mirrors

A potential future outcome of space exploration is the deployment of space mirrors. There are two main uses of space mirrors. The first is for Solar Radiation Management (SRM). With thousands of foldable mirrors in space, enough sunlight could be reflected to lower Earth's temperature and reduce the warming effect of greenhouse gases. However, much more research is required. Even with computer simulations the effects of such a system are not certain. Global consensus would also be required to carry out such an experiment [12].

The second use of space mirrors is to provide solar power during the darkness of night. Current technologies only utilize a fraction of the solar energy available. During the night, solar farms are not very useful, even though the Sun is still shining (on the other side of the planet). Space mirrors can be used to redirect sunlight to dark parts of the Earth, specifically onto large-scale solar power farms. That way solar power plants can continue to run through the night. The project is named Solspace and is being research at the University of Glasgow. The space mirrors need to maintain a low orbit to effectively redirect sunlight onto a solar power farm. That makes it difficult to keep simultaneous visibility of both the Sun and the farm – a problem that is yet to be solved. Advancements in 3D printing will allow the fabrication of ultra-lightweight reflectors directly in orbit. Therefore, the reflectors do not need to be packed, folded, and launched into space, reducing time and costs [13].

Japan also has a plan to harvest the solar energy of space for use on Earth. The plan differs slightly from the Solspace project. Instead of reflecting sunlight onto solar farms on Earth, the Japanese Aerospace Exploration

11
12
13

Agency (JAXA) intends to launch solar arrays into space. The solar arrays will come equipped with technology that transforms the DC power generated in orbit into microwaves. The microwaves would then be beamed to Earth, where a farm of antennas would collect and transform them back into DC electricity. Microwaves are used instead of lasers because water molecules in clouds scatter laser light, reducing efficiency. Currently with microwaves, the process is 80 percent efficient at each end. JAXA claims that the system could supply energy equivalent to that of a nuclear power plant. In order for the solar arrays to receive constant sunlight, the design includes two extremely large mirrors that reflect sunlight onto the panels. Moreover, JAXA is attempting to design the modules in such a way that they “counterbalance Earth’s gravity and stay in position without adjustment”. A further optimization is that the microwave receiving antennas are designed to constantly adjust their orientation to maximize the energy they receive. JAXA aims to have their space solar power stations operational by the 2030s [14]. A diagram of JAXA’s proposed space solar power station is shown below.

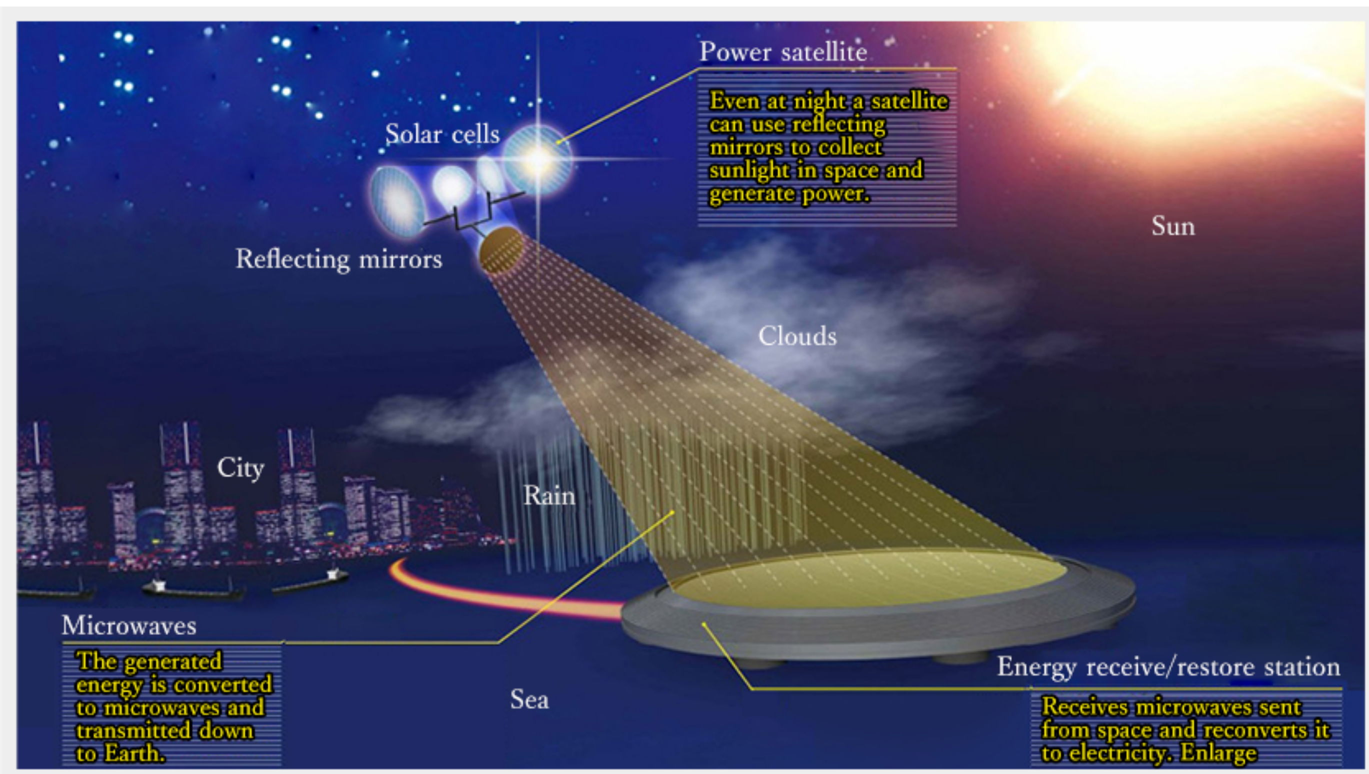


Figure 1: *Diagram of JAXA’s proposed space solar power station.*

14

Speculative Impacts of Space Exploration, Space Elevator

Another potential outcome of space exploration is the creation of a space elevator. Currently, the main method to get things to space is through the use of rockets. A space elevator is a completely different method for sending people and payloads up into space. The most basic description of a space elevator is “a cable with one end attached to the Earth and the other end roughly 60,000 miles out in space”. The space elevator will consist of motorized elevator pods that are powered up and down the tether. The end of the cable attached to the Earth will most likely be at the equator. The other end of the cable will be connected to a space station in geostationary orbit (GEO). Theoretically, the cable will be held aloft by centrifugal forces caused by the Earth’s rotation. Current estimates place the construction costs at $10 billion. However, the space elevator can drastically reduce the cost of putting things into orbit, from $3,500 per pound to as little as $25 per pound.

According to NASA and other researchers, the basic concept of a space elevator is sound. China plans to build one as soon as 2045. The global construction firm based in Tokyo, Obayashi Corporation, claims it will build one by 2050. There are still a number of issues that have yet to be solved. One such issue concerns the material of the cable. The cable will stretch for tens of thousands of miles and thus needs to be strong, yet light. Steel, for instance, is too heavy to be used. Scientists are speculating that the ultra-strong carbon-based material, graphene, might be sufficient for a space elevator. Ounce for ounce, graphene is 200 times stronger and about three and a half times lighter than steel. Long continuous sheets of graphene are required for the construction of the space elevator. However, this is not yet mass produced. Another prominent issue for a space elevator is dealing with space debris. The space elevator can be heavily damaged if struck by space debris. As of 2018, the U.S. Defense Department tracks more than 500,000 pieces of junk in space. Dealing with space debris is an important concern of the space elevator that is yet to be resolved [15,16]. Overall, the creation of a space elevator is still decades away and there are still various issues that need to be addressed. However, it does not appear to be something that is impossible to achieve.

15

16

[1.2] Current Space Development

[1.2.1] Spacecraft & Space Stations

Early Unmanned Spacecraft

In his book published in 1885, *Dreams of Earth and Sky*, Konstantin Tsiolkovsky described how an artificial satellite could be launched into a low orbit around the Earth. He is considered one of the founding fathers of modern rocketry and astronautics. It is only fitting that more than 60 years later his apprentices Valentin Glushko and Sergei Korolev oversee the Soviet space program. The first artificial satellite put into orbit was the Sputnik 1, launched in October of 1957. The satellite had a spherical shape with a diameter of 58 centimeters. Sputnik was operational in orbit for about three weeks until its batteries died. It, however, remained in a stable orbit for nearly three months before it reentered the atmosphere. From here the flood gates were opened for an already brewing space race between the U.S.S.R. and the U.S.

Early Manned Spacecraft

Only four years after Sputnik 1, the U.S.S.R. with their Vostok program and the U.S. with Project Mercury were in direct competition with each other to complete the first manned spaceflight. On April 12, 1961, aboard the Vostok rocket and spacecraft, Yuri Gagarin was launched into space on a mission that lasted less than two hours and saw him orbit the Earth exactly once. The mission was a complete success despite some lack of functionality during the reentry phase. As designed, Gagarin was ejected from the module seven kilometers above the ground and both him and the spacecraft parachuted down safely, returning the first man from space. Less than a month later the U.S. had a response from their Mercury project. Aboard the Mercury No. 7, American astronaut Alan Shepard was launched into his own trip around the globe. The successes by both the U.S.S.R. and the U.S. led to an arms race with the end goal to land a crewed mission on the Moon. The differences between the Vostok 1 and Mercury 7 missions are subtle, yet significant. The Russian Vostok mission completed a full orbit around the globe, whereas Shepard's mission was classified as suborbital. In addition, Vostok 1 was automated so that Gagarin was not responsible for any in flight inputs. This contrasts with Shepard who was required to physically fly the spacecraft throughout the mission, mostly just adjusting the attitude to align the heat shield during re-entry.

Furthermore, Shepard remained in the spacecraft throughout the entire descent and was not retrieved until after the Mercury module had landed in the ocean.

Modern Unmanned Spacecraft

Modern unmanned spacecrafts take the form of many shapes and sizes and fulfill many different purposes. Notably, on the lunar front there is the Lunar Reconnaissance Orbiter (LRO), which has been orbiting around the Moon since 2009. Its main mission is to accurately map the surface of the Moon and provide insight into the structure of the lunar surface. Data collected over the last decade from this satellite has been greatly beneficial, providing maps with calculated H_2O composition as well as helium-3 composition. Currently, there are thousands of unmanned artificial satellites in orbit. They range from GPS satellites and billion-dollar telescopes to 10 cubic centimeter school projects. These satellites provide the backbone of many communication networks on Earth and are immensely important to societal function, despite overcrowding beginning to become an issue.

Past Space Stations

Following the success of the Apollo program, the attention of the space race turned away from the Moon and towards a semi-permanent space station. In the mid-70's, space stations courtesy of the U.S and Soviet Union were popping up left, right, and center. The first of many so-called space stations was actually launched a decade earlier, however. In 1966, courtesy of the U.S. Air Force's Manned Orbiting Laboratory project, the OPS 0855 was launched. It remained in orbit for 67 days and remained unmanned. The program was eventually cancelled. The first successful space station was put into orbit by the Soviet Union in April of 1971. The Salyut 1 remained in orbit for 175 days and was occupied for 24 days by a total of six people, three at a time. The station contained 100 cubic meters of pressurized volume, or roughly one-ninth of the volume of the ISS. Following this, the Russians attempted three more space stations in the next two years, all of which were unsuccessful and unmanned. The next successful station was the Skylab, launched in May 1974 by NASA. Skylab remained in orbit for over six years until July 1979 and saw three groups of three people manning the station for a total of 171 days. In the decade from 1975 to 1985, the Soviet Union ran into a string of success with the Salyut 3, 4, 5, 6, and 7, all of which were very similar in size to the original. Across these five stations, 35 crewed visits were completed, yielding over five years of human life spent in space. The next station, the Mir, also produced by the Soviet Union was launched in 1986 and saw 15 years of service and 125 visitors. Mir was also a big improvement in terms of useable space because its pressurized volume was three and a half times larger than the Salyut stations previously in orbit. Salyut 7 and Mir were unchallenged for the better part of two decades until the European Space Agency, Roscosmos (Russian Agency), NASA, Canadian Space Agency, and Japan Aerospace Exploration Agency combined efforts to produce the International Space Station.

International Space Station (1998-present)

The ISS is currently operational and has been continually manned for the last 21 years. The pressurized volume is currently more than 900 cubic meters, or nearly three times larger than Mir. The ISS has provided ample scientific research into space and its effects on humans. In addition, it has provided a stable platform for international cooperation.

Tiangong Space Station (2021-present)

The Tiangong space station (TSS) is China's response to the space station monopoly held by NASA, the ESA, and Roscosmos. For the past 70 years, the space station scene has been dominated by the U.S. and Russia, and recently China has been looking to getting involved [17]. They currently have a functioning rocket family capable of heavy space travel, and they are now amid developing their own space station. Structurally, the TSS is similar the ISS. However, the TSS does not spark international cooperation like the ISS. This is because in 2011 NASA refused Chinese participation in the ISS, further incentivizing a national Chinese space station [18]. Nonetheless, the first launch of the core of the station occurred in April 2021. There are two more additional launches of modules yet to be officially scheduled. However, they are both expected to launch before the end of 2022. These additional modules are the laboratory cabin modules, which will be used to increase the scientific functionality of the station, as well as the habitable space.

17

18

[1.2.2] Food

Space Food

In this day and age, astronauts are able eat a varied diet similar to what people eat on Earth. Fruits, vegetables, as well as desserts are available for consumption. Moreover, condiments (ketchup, mustard, etc.) and seasonings (salt and pepper) are also available. Astronauts typically eat three main meals: breakfast, lunch, and dinner. Snacks are also available. Depending on the astronaut, calorie requirements will differ. For example, a small woman would require a lower calorie intake than a large man. Nutritionists ensure that astronauts receive sufficient sustenance [19]. The foods taken into space are all pre-planned. Astronauts are allowed to choose food they desire from a menu. Foods/ingredients that are chosen are “light-weight, nutritious and easy to eat while also remaining tasty” [20].

In the past, the main foods taken into space were either dehydrated or eaten as a paste out of a tube. As mentioned, technology has advanced to a level where astronauts are able to eat food in space very similar to food found on Earth. Food and drink packaging for space is similar to what is used in the military. Airtight zip lock bags and cans are commonly used to protect foods. Foods taken into space fall into a few categories. The first category is *fresh foods*. These are items with very short shelf lives such as fruits and vegetables. Fresh foods are refrigerated on the spacecraft and eaten quickly in order to prevent spoilage. The second category is *irradiated foods*. Irradiated foods are meat and dairy produce with applied ionizing radiation. This process increases the shelf lives of these items, as well as decreasing the chances of microbial contamination. The third category of space food is called *intermediate moisture*. Foods in this category are characterized by containing a small quantity of water and also generally having soft texture. These foods are created using salting or sun-drying. The fourth category is *natural form foods*. As the name suggests, these foods are ready to eat in their natural forms. Examples are nuts, biscuits, and chocolate bars. The fifth category is *rehydratable foods and drinks*. Food items in this category have water removed from them. When water is removed, the foods and drinks last much longer. Astronauts add water back to them before consuming. The sixth and final category is *thermostabilized*. Heat is applied to the food to kill off any bacteria, followed by immediately sealing it in air-tight packaging.

19

20

Spacecrafts now have microwaves and ovens on board. This allows the preparation of many of the aforementioned foods. The availability of microwaves and ovens in space drastically improved the variety of foods astronauts have access to. For example, in December of 2019, the first cookies were baked in space on the ISS. The cookie dough was in the oven for about two hours before it was done.

The microgravity of space affects astronauts' sense of taste. Astronauts have claimed that many foods taste bland in space. As a result, many astronauts tend to prefer foods and flavors that are spicy or tangy to stimulate their taste buds (like peppers, horseradish, or wasabi).

The main drink in space is water. Flavored drinks like coffee, tea, lemonade, orange juice, etc. are also available. These drinks are freeze-dried contained in vacuum sealed pouches. When desired, astronauts can add water to these pouches through a low-pressure hose before consuming [3].

Growing Food in Space

Growing food in space is surprisingly possible. The ISS houses the Vegetable Production System (known as "Veggie"). Veggie is a space garden, and its purpose is to aid NASA's research on plant growth in microgravity. The Veggie garden can hold up to six plants. Each plant grows in a given "pillow", which is filled with a "clay-based growth media and fertilizer". The pillows are needed for the plants to survive in space, as they serve to properly distribute water, nutrients, and air. In the weightless environment of space, plants rely on light to guide their growth. The Veggie chamber uses LEDs to support plant growth. The LEDs are set to a magenta pink color because plants mostly reflect green light and absorb red and blue wavelengths. Thus far, Veggie succeeded in growing a few different types of plants. These include three types of lettuce, Chinese cabbage, mizuna mustard, red Russian kale, and zinnia flowers. Some of these plants were eaten by astronauts, while the rest were returned to Earth for analysis. In the future, Veggie will attempt to grow things like tomatoes, peppers, berries, and beans.

The ISS also houses the Advanced Plant Habitat (APH). Similar to Veggie, it is also a space plant growth chamber. The main difference between the two is that Veggie is mostly taken care of by astronauts, while the APH is enclosed and automated. The APH has numerous cameras and more than 180 sensors. These are all used to automate and adjust water recovery and distribution, atmosphere content, moisture levels, and temperature.

Harvests from the APH are all preserved and sent back to Earth. Scientists on Earth study these plants in order to better understand how space affects their growth and development [21].

Although it is possible to grow certain plants in space, it is still a difficult process that requires care and precision. For example, one time the zinnias in Veggie got slightly overwatered, which caused a lack of air flow. Not long after, a fungus began growing on the plants causing some to die. The ability to grow plants in space demonstrates the advancements of space science. However, significant amounts of food cannot yet be produced.

21

[1.2.3] Trash Management and Water Recycling

Water

Storage space on board spacecrafts is very valuable and limited. Every astronaut in space produces a few pounds of trash per day. If not dealt with properly, trash can pose as a physical and biological health and safety hazard. The ISS can store up to two metric tons of trash on board at a time. Astronauts typically squeeze their garbage into trash bags. They then off load their trash onto supply ships, which either return back to Earth or burn up on reentry. Currently this method works fine because the ISS is only about 400 km above Earth. However, for missions traveling much farther, a more efficient trash processing system is required.

NASA is currently developing the Heat Melt Compactor. It can be used to manage trash on board a spacecraft, as well recover water and other resources for reuse. The Heat Melt Compactor compacts the astronauts' everyday trash into square tiles that take up less than one-eight of the original trash volume. The compacted trash is then heated to around 150 °C. The heating process sterilizes the material, boils off water, and vents off toxic gases. The sterilized garbage tile can be repurposed as radiation shielding, the boiled off water can be recovered and reused, and the toxic gases can be processed into safe gases and released into the air ventilation system. In this manner, the trash produced on board the spacecraft is most efficiently managed [22].

Water is essential for life. However, it is dense, making it difficult and expensive to take into space. The ISS has a complex system on board for water recycling. The Environment Control and Life Support System (ECLSS) on the ISS controls the super-efficient Water Recovery System (WRS), which is responsible for recycling up to 90% of the used water. The ECLSS captures water from sinks, showers, toilets, and even the air. Although, recovered water comes from sources like urine and sweat, it is surprisingly cleaner than most of the water people drink on Earth [23]. The diagram below simply illustrates the lifecycle of water on the ISS.

22

23

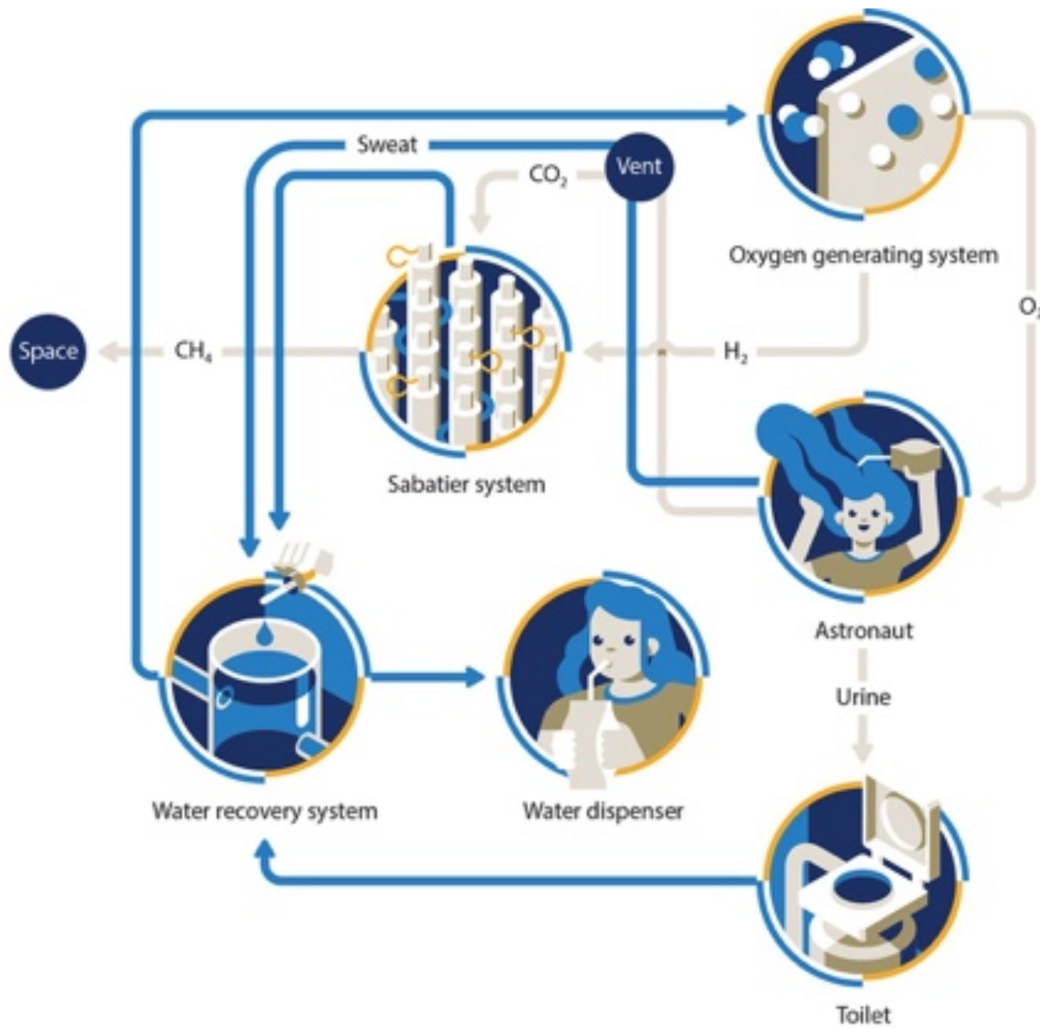


***Figure 2**: Lifecyle of water on the ISS* [24].

Even with the amazing WRS available, astronauts are still trained to consume only about a gallon of water per day. Astronauts use this one gallon of water for drinking, preparing food, brushing their teeth, and washing their bodies. In comparison, the average person on Earth uses about 80-100 gallons of water per day. Taking all costs into account, a bottle of water on the ISS costs approximately $10,000 [25]. It makes sense as to why water is conserved as best as possible.

24

25

[1.2.4] Habitat & Living quarters

Establishing a lunar base for humans is not as straightforward as it may seem. The Moon's environment is extremely dangerous and harmful. Some of the biggest causes for concern are temperature swings, radiation, and meteorites. Thus, lunar bases need to be constructed in a manner that protect astronauts from the harsh environment. There are two main ways to achieve this – an underground base or an above ground base. The underground base design relies on the Moon's extensive lava tubes, while the above ground base design relies on 3D printing technology.

Underground Bunkers

Building the lunar base underground helps deal with many of the pertinent issue's astronauts may face on the Moon's surface. Underground the temperature does not drastically vary from day to nighttime. Also, being underground provides protection against cosmic and solar radiation, as well as micrometeorite impacts. Fortunately, the Moon already has an extensive underground tunnel system in the form of lava tubes. Lava tubes, as the name suggests, are underground tunnels that were once filled with lava. Earth also contains lava tubes, which can be 30 meters wide. The Moon's lava tubes are estimated to be up to 1,000 times wider than the ones found on Earth and can be longer than 40 kilometers. The larger size is credited to the lower gravity found on the Moon. The lava tubes are likely still stable enough to serve as a base. Lower gravity means that the tubes are less likely to collapse [26]. Utilizing an entire lava tube network on the Moon will be extremely beneficial. The habitat can be expanded as needed in a protective environment and connective roads can be built throughout. A major advantage of constructing the lunar base in lava tubes is access to ice water. Initially, ice water will be one of the most important resources for astronauts attempting to habituate the Moon. The most common location for lunar ice water is "on the floors of permanently shadowed polar craters". Scientists have found that lava tubes can also contain significant amounts of ice water [27].

26

27

SpaceX's founder, Elon Musk, also founded The Boring Company in 2016. According to their website, The Boring Company "creates safe, fast-to-dig, and low-cost transportation, utility, and freight tunnels" [28]. Currently, The Boring Company is working on creating tunnels under Los Angeles, California to bypass traffic. These tunnels are created using boring machines (shown below). During a Q&A session at the International Space Station Research and Development (ISSR&D) Conference in 2017, Musk stated that he believed getting good at digging tunnels could be really helpful for Mars. This is related to building an extraterrestrial base underground for protection against the harsh environment. Musk refers to the creation of a Martian base, however, the technology is also directly applicable to a lunar base. The boring machines just need to be optimized for their specific destinations. Overall, boring machines will likely be extremely useful for the construction of an underground lunar base. They can be used to connect and expand lava tube networks. Moreover, they can be used for mining ice and raw materials [29].

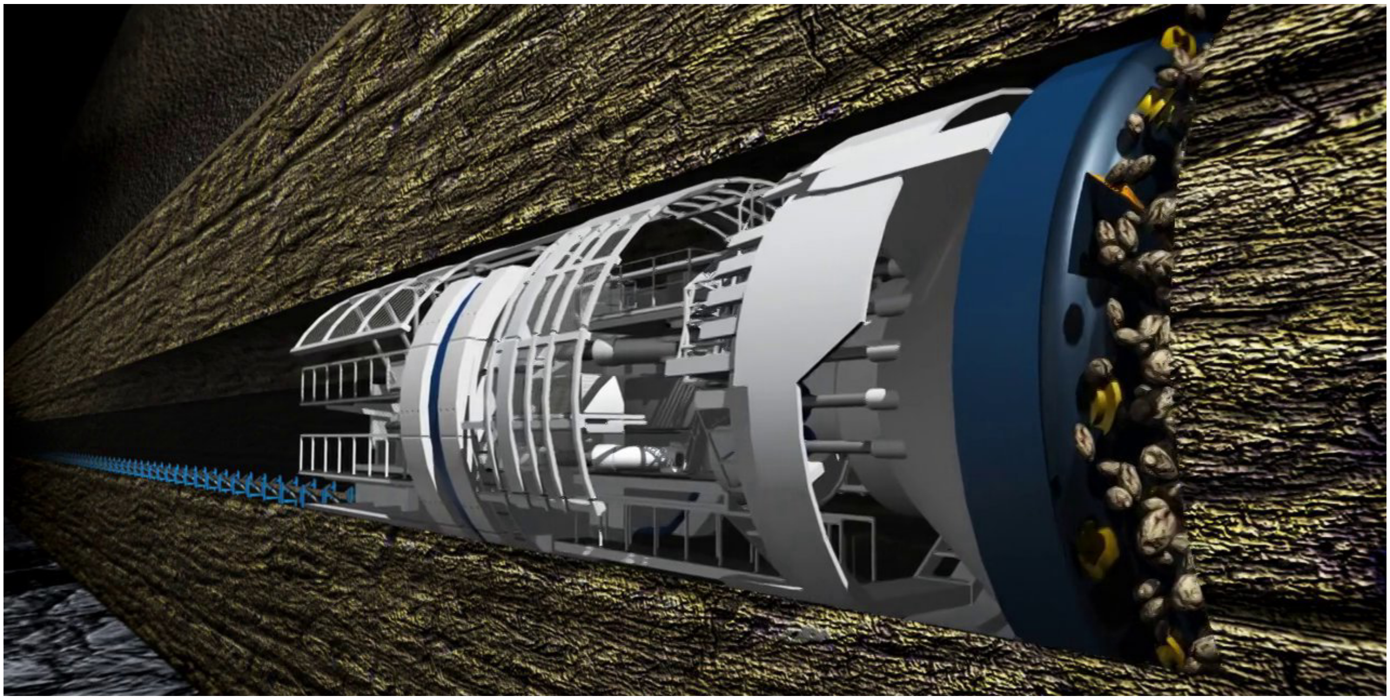


Figure 3*: Image of a boring machine digging a tunnel* [30].

28
29
30

Above Ground Outposts

NASA is investing in the research and development of a space-based construction system. They have contracted with ICON – a construction technologies company that has 3D printed entire communities of homes and structures here on Earth [31]. ICON has partnered with architecture firms BIG and SEArch+ for Project Olympus. Its goal is to “design robust lunar structures that can be built using materials available on the Moon’s surface”. Development of this technology will allow a more sustainable presence on the Moon. The printed infrastructure needs to provide superior thermal, radiation, and micrometeorite protection compared to current metal or inflatable habitats. The “Olympus Construction System” will utilize lunar soil to construct structures directly on the Moon. Both the Russian and Chinese space agencies are also developing 3D lunar printing technologies [32].

31

32

[1.2.5] Energy

Nuclear Power Plants (Fission Reactors)

Nuclear power plants use the heat produced from nuclear fission to heat up water. The heated water turns into steam, which is then used to spin giant turbines that generate electricity. Nuclear plants also contain separate structures to cool the steam back into water in order to reuse it. In nuclear fission, energy is released when larger atoms are split apart to form smaller atoms. This process occurs inside the nuclear reactor. The core, containing uranium fuel, is located at the center of the reactor. The reactor core carries numerous fuel assemblies. Fuel assemblies consist of bundles of 12-foot-long metal fuel rods. Each fuel rod is packed with ceramics pellets made from uranium. It is estimated that one of these uranium ceramic pellets produces the same amount of energy as 150 gallons of oil. Currently, nuclear power plants contribute approximately 20% of the annual electricity in the United States. In South Korea, nuclear power plants are responsible for 25% of the annual electricity generation. And, in France, an enormous 70% of electricity generation comes from nuclear power [33].

A major benefit of nuclear power is that they do not directly produce CO_2 emissions. However, mining and refining uranium ore requires a significant amount of energy. More importantly, operation of a nuclear reactor produces radioactive waste. Radioactive waste is categorized as either low-level waste or high-level waste. Most of the waste produced is low-level. The majority of the low-level waste is uranium mill tailings. These are the process waste material from a uranium mill. They contain radioactive radium (which decays to radioactive radon gas). Uranium mill tailings are typically stored near the mill they originate from, covered with clay and a layer of soil. High-level waste is generally spent reactor fuel and actual parts of nuclear reactors. These items are highly radioactive and must first be stored in pools of water. The water serves to cool the fuel and also act as a radiation shield. The high-level waste is then generally stored in specially designed dry storage containers. Nuclear waste needs to be stored indefinitely and currently the United States does not have a permanent disposal solution [34].

33

34

Fusion Reactors

Radioactive waste will always be an issue when dealing with fission reactors. This entire issue may be avoided if nuclear fusion reactors come into fruition. In theory, nuclear fusion reactors can be a source for virtually unlimited energy. This is because the fuel source for the fusion reactor is isotopes of hydrogen, which are essentially infinite on Earth. The most promising fusion reaction is given by the following equation:

$$^{3}H + ^{4}H \rightarrow ^{4}He + n + 17.6\ MeV$$

The nuclear fusion process occurs naturally in stars. There, the immensely high temperatures and densities allow positively charged nuclei to get close enough together for fusion to occur. Recreating this process on Earth has been difficult. One method involves a magnetic confinement reactor with a high temperature plasma. This reactor requires extremely high plasma temperatures. Another method involves an inertial confinement reactor, which relies on complicated laser implosion techniques. Thus far, no working reactor has been created that generates more energy than it consumes. Although, these fusion reactors do not directly produce radioactive waste, they happen to generate large amounts of fast neutrons. Fast neutrons are responsible for creating radioactive byproducts. To avoid this dilemma, an aneutronic fusion reaction needs to be used. In aneutronic fusion, very little of the released energy is carried by neutrons. The most optimal aneutronic reactions involve helium-3 as the fuel source and are given by:

$$^{2}H + ^{3}He \rightarrow ^{4}He + ^{1}p + 18.3\ MeV$$

$$^{3}He + ^{3}He \rightarrow ^{4}He + 2^{1}p + 12.86\ MeV$$

The products of these fusion reactions are helium and protons. Overall, less energy is wasted, and the entire reaction is much easier to contain as fast neutrons are not produced. Moreover, there are no concerns regarding radioactive byproducts, as none are produced. In current energy sources, up to two-thirds of the generated energy is lost to heat waste or thermal pollution. Research indicates that the helium-3 fusion reaction has essentially no waste and thus is extremely clean and efficient [35].

35

Helium-3

The greatest issue hindering the development of a helium-3 fusion reactor is the availability of helium-3. Helium-3 is extremely rare on Earth. It is only created as a byproduct of nuclear weapon maintenance (roughly 15 kg per year). Helium-3 is emitted by the Sun through solar winds. The Earth's atmosphere prevents it from landing here. In contrast, there is no atmosphere preventing helium-3 from landing and accumulating on the Moon. Sources estimate that there are about 1.1 million metric tons of helium-3 in the lunar soil. It can be mined and refined utilizing similar processes used on Earth [36,37].

Solar Power

The ISS generates all of its electricity through solar power. It contains eight solar arrays that efficiently convert solar energy into electricity. Each solar array consists of thousands of solar cells. Solar cells are created from purified chunks of silicon. The cells use a process called photovoltaics to directly convert light into electricity. In total, the eight solar arrays generate up to 160 kilowatts of power during orbital daytime. This is more power than the station ever needs at one time. Approximately half of the power generated is stored in the station's batteries for use while the station is out of sunlight. Collectively, the solar arrays contain a total of 262,400 solar cells and take up an area of about 2,500 square meters [38].

The solar panels used on the ISS are specially modified. For example, they are bifacial, meaning they are double-sided. This allows the solar arrays to absorb sunlight from a wide variety of angles. Furthermore, the "racks" that the solar arrays are attached to include gimbals. The gimbals allow the panels to rotate and thus continuously face the Sun. Specifically, the alpha gimbal tracks the position of the Sun, while the beta gimbal adjusts for the elliptical orbit [39].

Other objects in space also heavily rely on solar power. For instance, the thousands of satellites in space all require electricity to function properly. The easiest and most efficient method to provide them electricity is through solar power. Generally, satellites are equipped with solar panel arrays, similar to those found on the ISS. Moreover,

36
37
38
39

they also contain batteries, which provide power when the satellites are out of sunlight. Space rovers employed by NASA also rely on solar power to move, use “science instruments”, and communicate with Earth. The Mars Exploration Rover is fitted with solar arrays that generate approximately 140 watts of power for up to four hours per Martian day. The rover only requires about 100 watts of power to be able to drive. Expectedly, the rover also has two rechargeable batteries that provide energy when there is no sunlight available [40].

Solar power is extremely valuable for space missions. However, it also important to note its shortcomings. Overtime both solar panels and batteries are known to degrade significantly. Solar panels are unable to convert solar energy into electricity as efficiently, and batteries are unable to hold as much charge. Also, for rovers, dust accumulates on their solar panels making them far less efficient.

As the solar photovoltaic market is one of the fastest developing energy markets in the world, it is only natural that new technology is constantly developed. The efficiency of the current generation of solar cell technology is essentially at its practical limit. In order to achieve greater efficiencies and lower costs, new technologies are required. The development of the next generation of solar cells is already well underway and it relies on quantum dots. A quantum dot solar cell (QDSC) utilizes quantum dots as the photovoltaic material, as opposed to bulky materials, such as silicon or copper indium gallium selenide. Quantum dots are “tiny spheres of semiconductor material measuring only about 2-10 billionths of a meter in diameter”. They can drastically increase the efficiency of converting sunlight into energy due to their ability to generate more than one exciton per photon. Previous generations of solar cells are only able to produce one exciton per photon. Additionally, quantum dots can be modified to respond to different wavelengths of light. This is achieved by simply varying the size of the quantum dot. For example, as quantum dots get smaller, they absorb higher energy light. According to the National Renewal Energy Laboratory (NREL), QDSCs can achieve a maximum theoretical conversion efficiency of 66 percent. In contrast, current solar cells fail to achieve even half that value (theoretical maximum efficiency of 31 percent). More research is still required before QDSCs become a reality. For instance, scientists have yet to discover the most efficient method to utilize the multiple exciton generation of quantum dots. Also, certain QDSCs are extremely toxic to humans and require a highly stable polymer shell [41,42]. Overall, however, quantum dot technology promises great advances in solar cell technology.

40
41
42

[1.2.6] Fuel

Liquid Hydrogen

Liquid hydrogen is the current signature fuel of the American space program. It is also used by other countries for various things, like launching satellites. Developing liquid hydrogen technology is considered to be one of NASA's greatest accomplishments. Hydrogen is light and an extremely potent rocket propellant. It has the lowest molecular weight of any known substance and can burn to very high temperatures (5,500 °F). Liquid hydrogen combined with liquid oxygen produces the "highest specific impulse". This means that the combination of the two liquids results in the highest efficiency between the amount of propellant used and the generated thrust. Both liquid hydrogen and liquid oxygen are cryogenic, meaning that they are gases that can only be liquefied at extremely low temperatures. This property was the source of a plethora of technical challenges for NASA's engineers. Liquid hydrogen has to be kept at -423 °F so that it does not evaporate or boil off. That feat may be relatively easy to do on Earth. However, during flight and in space, it is not a simple task. The liquid hydrogen must be meticulously insulated from all sources of heat. That includes rocket engine exhaust, air friction during flight through the atmosphere, and even the radiant heat of the Sun. When liquid hydrogen is exposed to heat, it rapidly expands. Therefore, it is essential to vent the tank to prevent an explosion. The metals in contact with the extremely cold liquid hydrogen can become brittle, also causing problems. Furthermore, liquid hydrogen can leak through tiny holes in welded seams. It took NASA over a decade to fully overcome these technical issues and employ liquid hydrogen as its primary fuel source [43].

Liquid Methane

SpaceX plans to use liquid methane instead of liquid hydrogen for rocket fuel. The main reason for this switch is reusability. Methane fuel can be directly produced on the Moon and Mars, while hydrogen fuel cannot. SpaceX's goal is to establish a "propellant depot" on Mars that can create rocket fuel using just the planet's resources. The plan is intended for Mars. However, it can potentially be applied to lunar missions as well. The overall purpose of these propellant depots is to utilize local resources to create more fuel. Astronauts (or potentially robots) would obtain water and carbon dioxide and convert it into liquid oxygen and liquid methane.

43

Water would come from ice reserves and carbon dioxide would come from the atmosphere. As shown in the diagram below, electrolysis is used to split water molecules into oxygen and hydrogen, and the Sabatier process is used to convert carbon dioxide into water and methane.

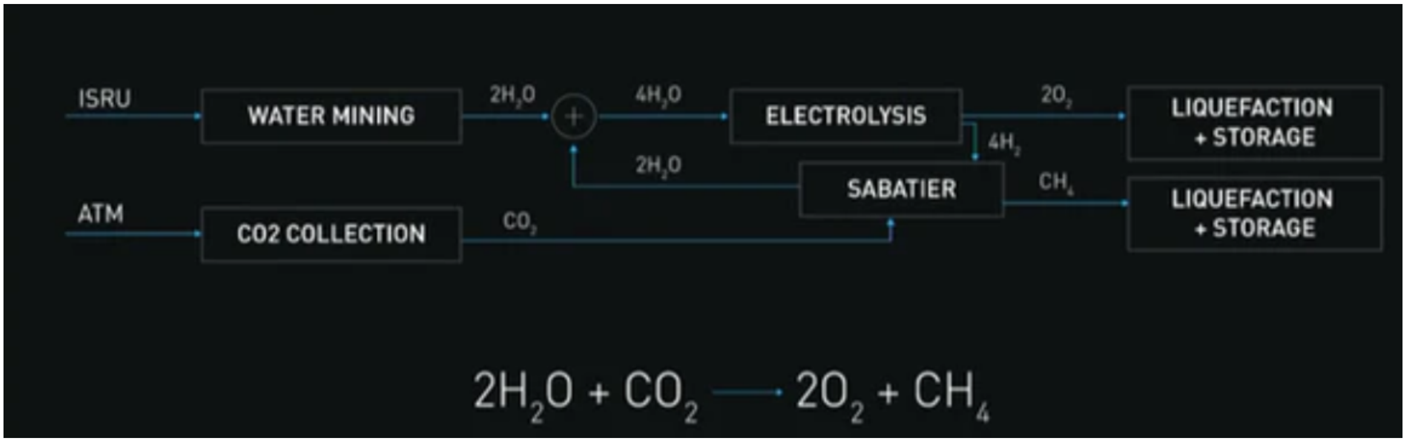


***Figure 4**: The process of creating rocket fuel on the Moon and Mars. Water is obtained through in-situ resource utilization (ISRU) and CO_2 is collected from the atmosphere (ATM).*

Both the Moon and Mars contain virtually unlimited supplies of water (ice) and carbon dioxide. The main issue that arises is powering the system. This will be done using solar power. SpaceX estimates that the system will require approximately one to ten megawatts of power. Assuming an average consumption of just one megawatt per day, a 40,000 square meter solar array would be required. Furthermore, if the array is estimated to weigh about four kilograms per square meter, then the total solar array would amount to a mass of around 160 metric tons. One megawatt of power is enough to produce two tons of liquid oxygen and liquid methane daily. The power estimate takes into account the acquisition of carbon dioxide, electrolysis, and cryogenic liquefaction [44].

44

[1.2.7] Human Interactions

Eating and Drinking Foods

The ISS has a dedicated dining room with tables and chairs attached to the floor. When eating, astronauts attach themselves onto the chairs. Food trays are magnetically connected to the tables. The astronauts eat in a relatively normal fashion using forks, knives, and spoons. The walls of the dining room contain antimicrobial materials in order to prevent bacterial growth. Drinking in space is fairly simple, as well. In the low gravity, liquids need to be sucked from a bag through a straw. Cleanliness is important on a spacecraft, as bacteria can spready quickly and easily. The astronauts dispose their food packages by squeezing them into trash bags. They also sanitize the tableware and utensils using wet wipes.

Exercise

Exercising in space is essential. Prolonged exposure to low gravity has severe negative effects on the human body. On Earth, there is resistance to every movement due gravity. This resistance is drastically reduced in space. As a result, the human body becomes accustomed to the lower gravity environment. Bone density and muscles begin to deteriorate. Figure 5 below shows the rate of bone loss for various body parts due to low gravity. These negative effects can be reduced through exercise. Astronauts need to exercise for about two hours per day. This process helps keep their muscle mass, bone density, and cardiovascular health in check.

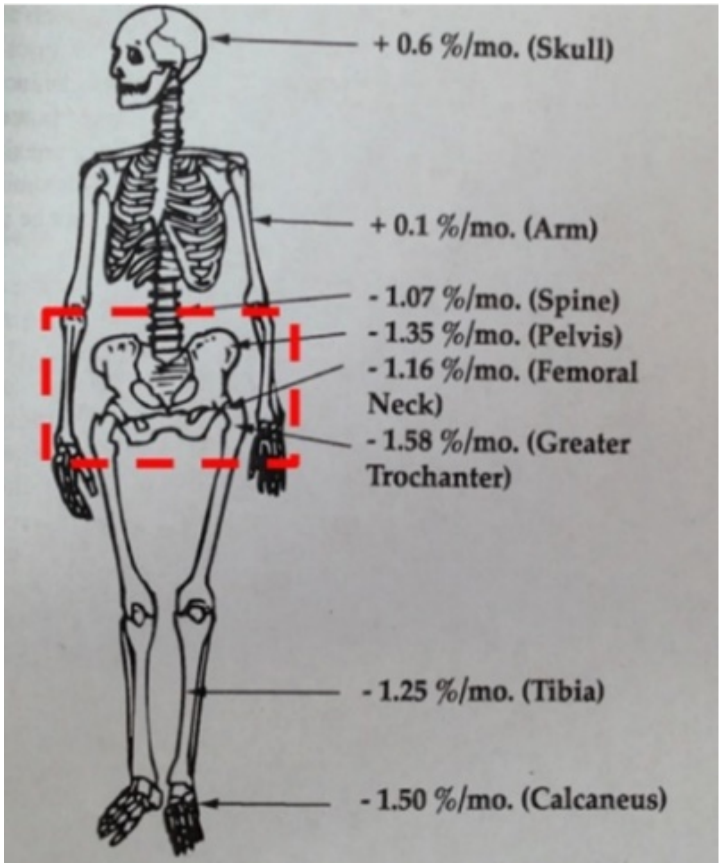


***Figure 5**: Rates of bone loss due to prolonged exposure to low gravity* [45].

Astronauts use three main exercise machines. The first type is known as the Advanced Resistive Exercise Device (ARED). This machine uses vacuum cylinders to exert resistance onto a bar or cable. It is somewhat equivalent to free weights used on Earth. The ARED can be used for exercises like calf raises, squats, and deadlifts. The second machine type is the treadmill. The treadmill used in space is a modified version of the ones found on Earth. Astronauts need to attach themselves to the treadmill using a bungee and harness system. The bungee and harness system apply an adjustable load to the astronauts' shoulders and hips. Once attached, astronauts run normally. The third and final type of exercise machine is the stationary bike. Astronauts use a harness and handles to remain stationery and pedal. Even with a rigorous exercise routine, astronauts experience loss in bone density. The effects of low gravity are similar to osteoporosis. Fortunately, once the astronauts return to Earth, the negative effects on their bodies are gradually returned to normal [46].

45

46

Sleeping

Astronauts are assigned “sleep stations” on their spacecraft. The size of a sleep station is comparable to that of a telephone booth. The sleep station contains items such as a sleeping bag, pillow, lamp, and air vent. Astronauts sleep near an air vent as a safety precaution, as exhaled CO_2 has a chance to form a bubble around their heads. Astronauts also have the option to sleep outside their sleep stations. Typically, they need to use a sleep mask and ear plugs to block out light and noise. In the microgravity of space, it does not matter which orientation astronauts choose to sleep in. They can sleep attached to the floor or the wall. Astronauts are allotted around eight hours for sleep every day. However, many astronauts report that they only need six hours of sleep to feel completely rested. This may be due to their bodies being less tired in the microgravity environment of space [47].

Bathroom

In 2018, NASA developed a new toilet system for the ISS. The new toilet is a specially designed vacuum toilet. It has two parts – a hose with a funnel for urinating and a small toilet seat for defecating. The bathroom aboard the spacecraft contains plenty of handles which astronauts can use to keep still. Urine is more than 90% water. Therefore, it is collected and recycled back into clean, drinkable water. The feces, on the other hand, is vacuumed into garbage bags and sealed in airtight containers. Astronauts load the containers onto the supply-bringing cargo ship. The cargo ship is eventually launched back to Earth and burns up in the upper atmosphere [48].

47

48

[1.2.8] Space Weather

The umbrella term "Space Weather" concerns the variety of Sun disturbances that occur throughout space. Such phenomena include solar flares, solar storms, solar winds, and coronal mass ejections. This group of naturally occurring space phenomena play a huge role in many of the natural occurrences that we see on Earth, including changes in our weather, increases of UV rays that contact our skin, and even disruptions to everyday electrical devices [49]. A major contributor to space weather is due to the powerful magnetic fields on the Sun becoming entangled and reorganizing themselves.

Solar Flares

The Sun produces large amounts of powerful and dangerous particles that shoot out into the vast emptiness of space. These particles move at very high velocities and carry intense amounts of electromagnetic energy, creating what are formally known as solar flares. Solar flares usually couple with the Sun's 11-year cycle, as they are weak towards the beginning and progressively strengthen. These waves of radiation can last from minutes to hours and have very high levels of thermal and electromagnetic energy. These high bursts of energy can be in the form of gamma rays and x-rays [50]. The particles that define a solar flare are known as alpha particles and beta particles. Both particles are very radioactive as they are created from the decay of radioactive elements such as uranium and polonium[51]. Energy emitted from the Sun can also be known as photons and neutrinos, which are sent out by the Sun in all directions at all times. Photons are the smallest particles of light and carry small amounts of electromagnetic radiation. Neutrinos, on the other hand, are very difficult to detect and account for approximately two percent of the Sun's entire energy.

49

50

51

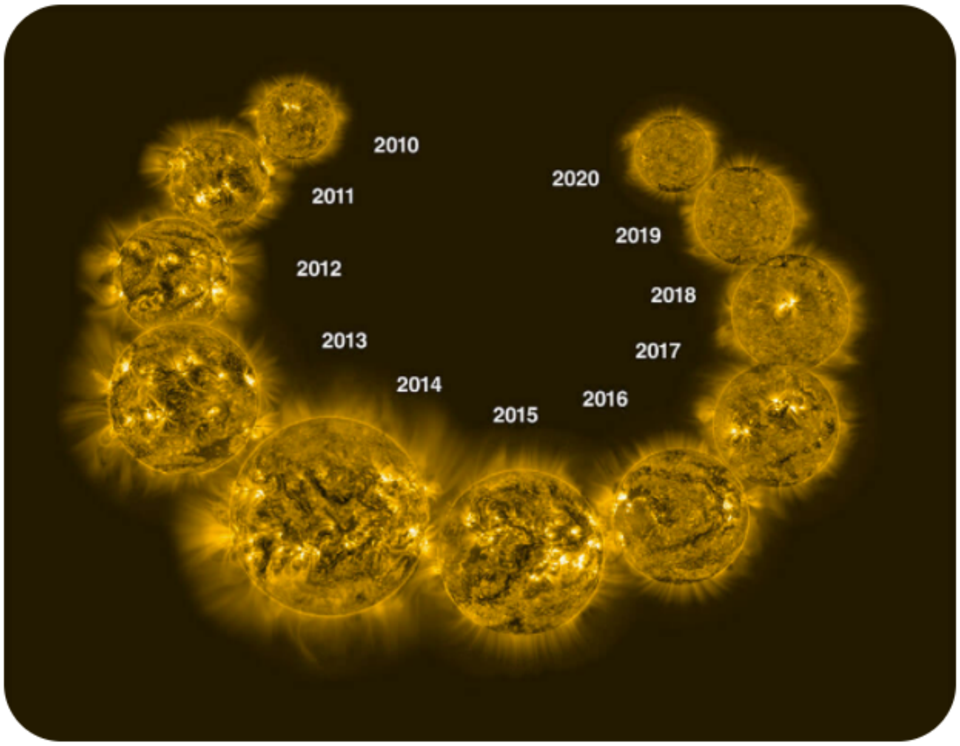


Figure 6: *The Sun's evolution in ultraviolet light from 2010 through 2020* [52].

Solar Radiation and Space Particles

One of the largest issues of going into space is dealing with solar radiation and space particles. Constant eruptions from the Sun expel significant amounts of fast-moving, ionizing particles. These particles are mostly classified as alpha particles (positive) and beta particles (negative). Furthermore, space also has the threat of galactic cosmic rays that come from outside the Solar System. These particles all have the ability to knock out electrons from atoms when they collide. This process not only damages the original entity but can also create secondary radiation particles, such as gamma rays and neutrons that may cause more damage.

The Earth's magnetic field and atmosphere protects it from these harmful particles. There is also the presence of the Van Allen Belts – highly energetic charged particles that are magnetically trapped and surround the Earth. The radiation belts shield the Earth from high-energy particles. To put in perspective, everyone on Earth receives

52

a small amount of ionizing radiation (approximately 3 mSv per year). A full body CT scan provides around 10 mSv. Moreover, as per the Department of Energy's regulations, a radiation worker can only be exposed to less than 50 mSv per year. In comparison, an astronaut aboard the ISS is exposed to about 100 mSv every six months. The ISS is only in LEO (about 400 km above Earth). It is still in the range and protection of Earth's magnetic field. Yet, astronauts aboard the ISS still receive significantly more radiation than even radiation workers on Earth. Exposure to radiation increases a person's risk of cancer and other illnesses. Traveling further from Earth (to the Moon or even Mars) only increases the amount of radiation an astronaut will receive.

Solar Winds

In addition to solar flares, the Sun also emits energy via solar winds, a phenomenon made by the Sun's outermost layer (the corona) by a large group of charged particles (plasma). The Sun produces these winds by rotating once every 27 days [53]. It twists its magnetic field over its poles into a spiral that creates the "wind" composed entirely of plasma. These winds contain high amounts of thermal energy, reaching up to one million degrees Celsius and moving at speeds as high as 900 kilometers per second. Similar to solar flares, solar winds send out alpha particles in the form of "wind" as a result of ionized hydrogen and helium being expelled from the Sun's corona. Although unlike solar flares, solar winds do not abide by the Sun's 11-year cycle and consistently shoot out of the Sun due to the expansion of the corona.

Coronal Mass Ejections

Coronal mass ejections or CMEs are large explosions of plasma and magnetic fields that originate from the Sun's Corona. CMEs can grow in size as they go farther from the Sun. Many coronal mass ejections are born when flux ropes or twisted magnetic field structures become too stressed and "realign into a less tense configuration" [54]. This process of stressing and un-stressing is called magnetic reconnection. During the formation of a solar flare, a coronal mass ejection can also be formed and often takes place in areas with strong fields and stressed magnetic flux. Just like solar flares and solar winds, CMEs travel outward through the Solar System carrying strong,

53

54

radioactive particles. Due to the strength of the strong magnetic fields in correlation to solar winds, a coronal mass ejection is capable of creating a shockwave if its speed exceeds that of the solar wind. These shock waves can then potentially accelerate the charged particles ahead of them, thus possibly causing a radiation storm to form. Radiation storms, a part of CMEs, come as a result of a large quantity of charged particles being accelerated when near the Sun [55].

Solar Radiation Storms and Geomagnetic Storms

Solar storms occur when a large-scale eruption charges particles on the Sun's atmosphere to very high speeds. This commonly causes large numbers of solar flares and coronal mass ejections. When the flux of protons is at energies greater than or equal to 10 MeV, a solar radiation storm starts. During a solar storm, multiple flares and interplanetary shocks can occur. Earth's field does provide some protection; however, since the magnetic lines at the poles extend vertically down, it allows the particles to increase ionization and break through the atmosphere [56]. Another storm that can occur is when a large amount of energy is created from solar wind and arrives in the space around Earth. This is called a geomagnetic storm. When there exists high-speed and low-speed solar winds, the two create a co-rotating interaction region that can add more energy to the Earth's magnetosphere over time. During the storms, the currents in the ionosphere add heat to the upper atmosphere [57].

Impacts of Space Weather

Based on the radioactive properties of all the space weather phenomena, as well as the dangerously high speeds their particles can go, it is certain that these solar blasts of energy can have very dangerous and harmful effects on both the Earth and the creatures that inhabit it. The protons that solar winds carry can seriously injure unprotected astronauts due to its lethal radiation. Space weather does not only affect living creatures, however. Machines and any device that uses electricity can become unresponsive due to the overload of energy passing through. In terms of Earth's satellites, if the energy level of a solar flare is above 10 MeV it can cause the electronic components of the satellites to fail. To prevent this, radiation-hardened computer chips and metal shielding are

55
56
57

added to computer chips as a good measure to protect against solar weather damage. Unfortunately, solar cells cannot be protected since they need to be exposed as much as possible to catch energy from the Sun. Thus, when a solar flare occurs and reaches the cell, it often shortens its lifespan or at worst destroys the cell entirely [58]. When a solar radiation storm occurs, the high velocity protons create an enhanced D layer (lowest densest layer) in the ionosphere, which blocks high frequency radio signals at elevated locations. This disruption creates errors on GPS systems causing them to produce incorrect position calculations. During a geomagnetic storm, the electrical power grid can be widely affected. It can cause a power outage by creating artificial current paths in power lines, making the voltages and current have a longer 60-cycle form, or forcing all transformers to show up as an inductive load.

Current Precautions

Alpha particles can be stopped by thin materials, even skin. Beta particles require thicker material to stop, like aluminum. Gamma rays are even harder to stop and require a denser material, like lead. Neutrons can be stopped by hydrogen atoms. Materials rich in hydrogen such as water, concrete, or plastic are viable options to shield against them. Radiation protection is an important factor in designing spacecrafts. Spacecrafts need to be lightweight, resistant to space debris, and serve as shields against radiation. A modern spacecraft has multiple layers of thin aluminum sheets, a Kevlar and epoxy net (hydrogen-rich material), and air gaps (to slow down space particles).

NASA measures the shielding of spacecrafts in units of areal density (grams per centimeter-squared). The hull of a 1970s Apollo command module was rated between seven to eight grams per square centimeter. A modern space shuttle is rated between 10 to 11 grams per square centimeter. The ISS, in its most heavily shielded areas is rated 15 grams per square centimeter. In stark contrast, a typical space suit is only rated at 0.25 grams per square centimeter. At times, astronauts need to leave the protection of the spacecraft to go on spacewalks. This drastically increases radiation exposure and thus the length and frequency of spacewalks need to be limited [59].

More active forms of shielding are currently being developed. One of these methods involves creating a magnetic field similar to that of Earth's. Creating a powerful enough magnetic field requires a significant amount of power. One way to achieve this is by lining the spacecraft with superconducting magnets. The problem is that

58

59

superconducting magnets are very large, heavy, and require constant cooling (liquid nitrogen is needed to cool the magnets). It would be extremely difficult to take such a system into space. Lightweight alternatives for active shielding against space particles have yet to be developed [60].

Since the ISS is heavily shielded and orbits within Earth's magnetic field, solar flares are not a significant issue for the astronauts on board. Naturally, some parts of the ISS are more heavily shielded than others. In the event of a major solar flare, in combination with an orbit near the Earth's magnetic poles, astronauts may need to temporarily take shelter in some of these more heavily shielded areas. The radiation shield from Earth's magnetic field is weakest at the magnetic poles. In those regions, radiation can be captured and held close to the surface. Simply as a precaution, astronauts may be told to take shelter to reduce the potential for any significant radiation exposure [61].

The National Oceanic and Atmospheric Administration (NOAA) utilizes the GOES satellite (Geostationary Operational Environmental Satellite) to detect solar radiation storms about three days before it arrives at Earth. For the GOES satellite to accomplish this, it needs to calculate the flux of the protons being shot at it by the large-scale magnetic eruptions. When the flux is greater than or equal to 10 MeV or if 10 proton flux units (1 pfu = 1 particle*cm^{-2}*s^{-1}*$ster^{-1}$) are exceeded, then the satellite determines this as the start of a radiation storm. The severity of a storm can range from a rating S1, all the way to S5, where the severity increases from minor to extreme, respectively. A single storm can be composed of various pulses of interplanetary shocks and flares, which can last for hours or even days at a time.

60

61

Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2} Based on this measure, but other physical measures are also considered.
** These events can last more than one day.
*** High energy particle (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

***Figure** 7: Solar radiation storm severity chart* [62].

For a proposed space station that orbits the Moon, an observatory would have to be made with similar components to the GOES satellite in order to detect solar activity more efficiently. Hypothetically, the satellite would allow anyone on the space station and on Earth to detect oncoming space weather at least four days in advance, faster than current-day satellites. The outermost layer of the observatory would be covered by solar cells, and immediately behind the cells would be a heavily protected layer to protect both the astronauts and the electrical equipment on the space station. By knowing about an oncoming storm ahead of time, it would allow the people on Earth and in space to prepare for an electrical outage and disruptions in outgoing radio waves. This technology allows us to prepare in advance for solar weather can be used to harvest energy from the Sun in an almost instantaneous manner. As it stands currently, scientists have not been able to properly store energy from solar occurrences due to the sheer amount of power that is being absorbed in an instant. With the ability to predict solar weather and a potential to harness and store the energy that comes from it, we could be one step closer to infinite energy.

62

Lagrange points, according to NASA and WMAP Science Team, are locations in space within the Solar System where objects stay put when launched there [63]. Lagrange points act in this manner due to their positions being located in the exact areas where the Sun and Earth's magnetic fields produce "enhanced regions of attraction and repulsion". Various of these points exist in the Solar System, however, there are two points of far greater importance to scientists and astronomers on Earth. These two points are known as Lagrange points one and two (L1 & L2 respectively). These two points are important due to their close proximity to Earth and the Moon, thus making it easy to house communication satellites and spacecrafts in these positions. Lagrange points one and two are currently home to many satellites including the Solar and Heliospheric Observatory Satellite (SOHO) and the James Webb Space Telescope.

The Deep Space Climate Observatory (DSCOVR) is a space station that monitors space weather activity including changes in solar winds sent from the Sun towards Earth. It was launched back on February 11th, 2015 and arrived at Lagrange point L1 four months later on June 8th, 2015. Its main and current purpose is to give real-time observations on solar weather to provide early warnings about geomagnetic storms. The DSCOVR satellite can warn meteorologists about incoming solar storms in around 15 to 60 minutes in advance [64]. SOHO was a satellite designed in order to understand the inside and outside of the Sun, as well as its surface chemical and atmospheric composition. This satellite launched in December of 1995 and is currently still in use. The SOHO satellite is equipped with 12 instruments that allow it to properly predict solar storms and assist astronomers on Earth and in space. These devices include three helio-seismometers (GOLF, VIRGO, MDI) that measure the Sun's velocity oscillations, active cavity radiometers, low resolution imaging, and its harmonic degree. It also has two spectrometers (CDS, SUMER) that visualize the Sun's electromagnetic spectrum using light with varied ranges from 15 to 160 nanometers, one disk imager (EIT) that shows the evolution of chromospheric and coronal structure, and two coronagraphs (UVCS, LASCO) that allow scientists to observe the outermost layer of the Sun by blocking out the Sun's light between 1.1 to 30 $R_\odot$. ($R_\odot$ is the radius of the Sun, with a resolution of 11.4 arcsec per pixel.) The satellite also has three solar wind instruments (CELIAS, COSTEP, ERNE) that determine the solar wind energy distribution, composition, ions, and isotopic composition, and finally one solar wind mapper (SWAN) that scans telescopes with hydrogen absorption cell for Ly-A light [65]. With all these devices, the satellite can take frequent photos of the Sun's anomalies and give Earth solar storm warnings up to ten minutes to several

63

64

65

hours in advance. It is also capable of warning about bulk plasma and magnetic occurrences 30 to 72 hours early based on the initial speed and rate of deceleration of the storm [66,67].

Lagrange point two is just as important as point one. This point is close enough to Earth for efficient back-and-forth communication between objects in the position and the Earth. This point was recently home to the WMAP spacecraft and is currently the new home for the James Webb Telescope Satellite which is the successor to the Hubble Space Telescope and the Spitzer Space Telescope. Compared to L1, this position in space is not in the Sun's line of sight. Rather than using L2 for Sun-based research, astronomers on Earth use it for space missions and more recently, for the use of the James Webb Telescope Satellite to complete certain goals. These goals are to study galaxy formations and evolution, to understand star formation and planet formation, and to properly understand and document the origins of life. The satellite does this by using infrared radiation at a wavelength range of about 0.75 to 200 micrometers to observe astronomical objects at extremely far distances. It uses infrared radiation due to its ability to freely pass-through cosmic dust and debris. It is important to note that Lagrange point two is unstable and any satellites in this position must undergo attitude corrections from time to time. From 2009 to 2013, Lagrange point two was home to the Planck Spacecraft, which was a space observatory created by the European Space Agency. This observatory was an improved version of NASA's WMAP Probe Satellite as it was able to map "the anisotropies of the cosmic microwave background (CMB) at microwave and infrared frequencies". The mission goals set for the space observatory were to detect the total intensity and polarization of primordial cosmic microwave background anisotropies, to understand the creation of galaxy clusters, to observe the gravitational lensing of CMB and active galactic nuclei (AGN), and to study nearby solar systems.

The third Lagrange point is another position in space that lies on the opposite side of the Sun. Currently, the point is not being used due to the inability to communicate with any objects in its position. This is as a result of the point being blocked by the Sun at all times. As for Lagrange points four and five, they are both stable orbits as long as any objects residing in them exceed a mass of 24.96 kilograms, and thus respecting the mass ratio of M1/M2 between two large celestial bodies. Objects chosen to be placed there are considered to be Trojans because of the three asteroids they are named after – Agamemnon, Achilles and Hector. Lagrange point four houses the OSIRIS-REx Spacecraft and has a mission to study asteroids and return with samples. It launched back in 2016 and is expected to return in September of 2023. The OSIRIS spacecraft collects samples by landing itself on moving asteroids and drilling to obtain said samples. These samples are then analyzed and transferred to scientists

---

66

67

on Earth. Lagrange point five houses the STEREO B which is a spacecraft launched back in 2006. This spacecraft is able to take stereoscopic images of the Sun which further contributes to the ongoing research on the Sun that is provided by L3. However, STEREO B is able to take stereoscopic images of the far side of the Sun, which provides crucial information about the solar flares and storms that occur away from Earth. It also allows for monitoring the magnetic fields of the Sun from another angle.

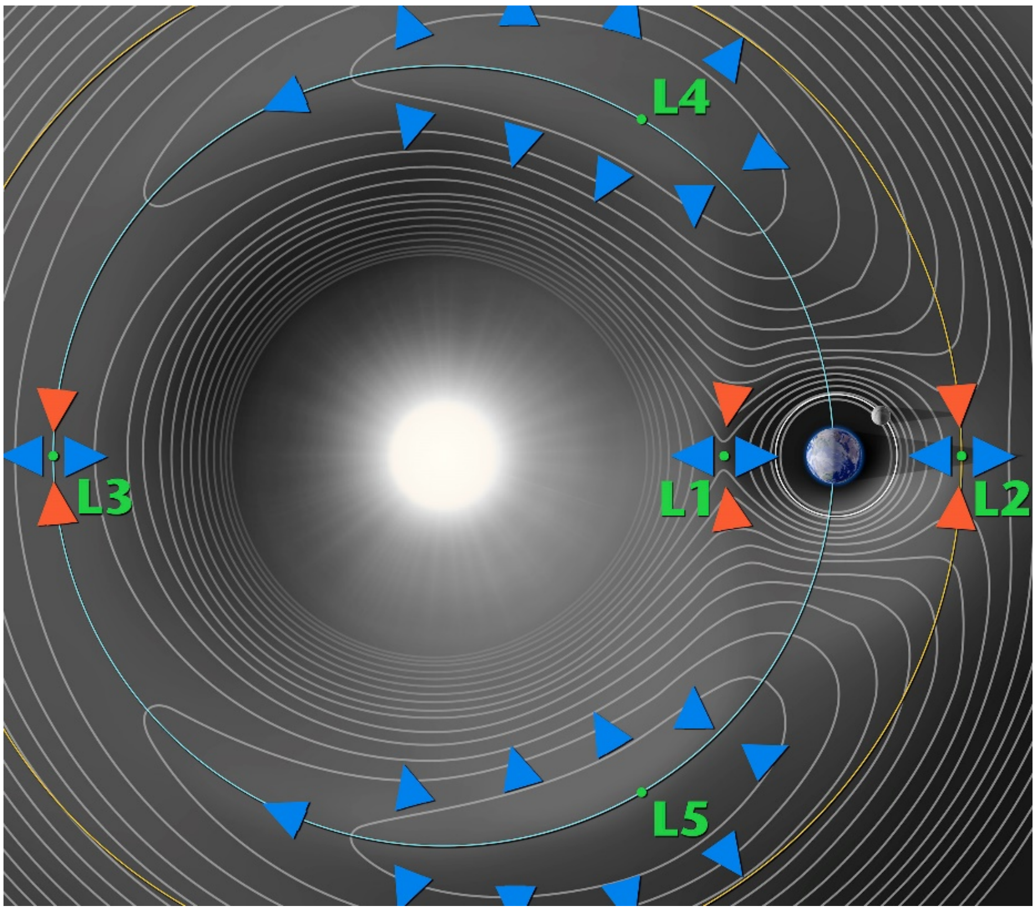


Figure 8: *Contour plot of the Lagrange points.*

[1.2.9] Communications

Emergency Protocols

Astronauts aboard the ISS have access to extensive documents relating to numerous health procedures. These procedures are for both routine/non-emergency and emergency. Routine procedures include situations such as, cough, back pain, skin rash, headache, etc. Specific emergency medical procedures include choking, chemical burn, broken bone, and seizure, among various others [68].

Relays for Moon Base

Having a reliable communication infrastructure is important for long-term space exploration, as it supports data transfers for equipment commands and emergency announcements, among other things. Earth's ground stations are only able to reach the nearside of the lunar surface due to tidal locking. As a result, the reliance on NASA's DSN is limited. Therefore, space engineers need to come up with a way to circumvent this lunar effect. The way to overcome this obstacle is through creating a series of relay communications satellites. These satellites need to be positioned in an orbit suitable for receiving data from the lunar base and be able to transmit commands to support research development.

For the development of the lunar relay communication satellite, the selection of the mission orbit is crucial. When determining the orbit, a mapping of area covered by future bases or surface exploration missions should be considered. In 2018, the Chinese Lunar Exploration program launched Queqiao, a communication relay satellite, into the halo orbit in order to send and receive data to and from a land rover back to Earth. Since Queqiao is only in orbit for five years, it cannot be used for future missions [69]. However, other satellites can be deployed into the halo orbit to maintain continuous direct communication with Earth [70].

68

69

70

[1.3] Past Accomplishments & Progressions

[1.3.1] United States

Apollo (1961-1972)

The Apollo program launched a lunar aspect to the space race between the U.S. and U.S.S.R. during the Cold War. It was through the Apollo program that a manned lunar mission became a reality. The well-known Apollo 11 mission featuring Neil Armstrong, Michael Collins, and Buzz Aldrin is the first successful mission to place people on the lunar surface. However, the last mission, Apollo 17 in 1972, remains much more relevant. Harrison Schmitt remains the only scientist to walk on the Moon, and as such lunar geology was a focal point of the Apollo 17 mission [71]. A small sample of regolith collected on that trip proved to be extremely valuable. In 1985, it revealed that there were deposits of helium-3 on the surface of the Moon, which proves to be one of the greatest motivators for a 21st century expedition to the Moon.

Space Shuttle (1972-2011)

The space shuttle became the U.S.' beacon of space presence, completing more than 130 successful missions. The space shuttle was similar to the Apollo program in that manned spaceflight operations were the executable goal, however, in this case a lunar presence was not the design specification for the space shuttle. The space shuttle played a vital role in the construction of the ISS, and the Hubble Space Telescope. The space shuttle was largely used as a shuttle to and from the ISS, especially in the later stages of the program [72,73]. When the program was retired in 2011 the U.S. did not have a successor capable of delivering astronauts to the space station and gave up that ability to the Russian Soyuz program [74].

71

72

73

74

Atlas (1957-present)

The Atlas is NASA's current orbital launch vehicle. However, the Atlas program's origins lie in the heat of the Cold War, in which their initial design was for intercontinental ballistic missiles (ICBM). This mission specification shaped the first of the Atlas rockets, and despite the ICBM service ending in 1965, Atlas utilized the ICBM base as launch platforms for over 300 missions from 1959 to 1987 [75]. In 2000, the second-generation Atlas III was launched using an RD-180 first stage engine, which was developed and produced in Russia. The Atlas program is currently still in the RD-180 era and is responsible for over 75 successful missions. However, in 2014 legislation was passed to restrict the purchase of Russian supplied RD-180 engines. Despite this, there are still 17 planned missions utilizing the Atlas V and the RD-180 engines, even now more than seven years after the legislation was passed [76]. Because of this, the American space transport scene is set to be dominated by private corporations instead of government funded agencies, like NASA. This is evident through the recent successes of SpaceX, Blue Origin, and Virgin Galactic [77].

75

76

77

[1.3.2] Russia

Vostok (1960-1963)

A precursor to the more successful and famous Soyuz program, the Vostok program was the first Soviet human spaceflight program. Unsurprisingly, their first major success came in 1961 with Yuri Gagarin's manned trip to space. Five flights succeeded the initial Vostok 1 mission in the following two and a half years. In 1963, the Vostok program was cancelled and transitioned into the Voskhod program.

Voskhod (1964-1965)

A very short-lived program, the Voskhod completed only two crewed missions. Voskhod was essentially a bigger, improved Vostok module that allowed for multi-crewed missions. As such, the missions completed were aimed as being first accomplishments for the Russian space program in direct competition with the U.S.' Project Gemini. Ultimately, Gemini ended up completing most of the remaining goals set out by the Voskhod program. Coupled with a change in political leadership, the program was abandoned in favor of the Soyuz.

Soyuz (1966-present)

The Russian Soyuz program, much like similar American programs, began during the Cold War. Its original intent was to place a cosmonaut on the Moon. The program consists of the Soyuz rocket, and the Soyuz spacecraft. The Soyuz spacecraft became the backbone of the ISS. In fact, the first few modules were just docked Soyuz spacecrafts. Also, there is always at least one Soyuz spacecraft docked to the ISS, serving as an emergency escape module. Soyuz launch vehicles and spacecraft have been the primary method to reach the ISS, especially after the retirement of the Space Shuttle in 2011. The Soyuz program is still operation to this day, with manned launch capabilities to the ISS.

[1.3.3] China

Long March (1970-present)

The Long March is essentially China's current rocket family. It got its start in 1970. However, the first few missions were few and far between. The program faced a significant setback after a series of rather unsuccessful launches from 1992 through 1996. Nonetheless, the rocket was slightly redesigned and since then has launched nearly 340 successful missions. The program almost exclusively launches Chinese payloads, especially due to embargos placed on Chinese satellites by the U.S. [78]. Although, there are ambitions for manned lunar missions from the Chinese government, they have stated that a redesigned super heavy rocket would be needed [79].

Project 921 (1992-present)

Project 921 culminates China's 30-year interest in manned space flight research. The program launched in 1992 when the Long March 2F was officially rated as a human launch vehicle. From there astronaut training and space suit technology research was undergone. The first successful mission was launched in 1999, and just four years later in 2003 China had successfully launched their first crewed mission to space. The program is still ongoing with more missions scheduled in the coming years to continue construction of the TSS. In addition, China is still utilizing the Long March rocket family as its preferred launch vehicle.

78

79

CHAPTER 2: Lunar Mission Design

[2.1] Mission Overview

[2.1.1] Objectives

Lunar Base

The purpose of this project is to demonstrate an undergraduate knowledge of such foreseeable missions in the near future. The creation of a sustainable Lunar Habitat will be humanities first attempt at long term survival away from the protection of Mother Earth. In our opinion, these missions will be conducted in several steps, containing mission requirements and outcomes. This chapter contains a general layout for the next possible attempts in establishment for the lunar soil with varying mission-oriented objectives.

The first lunar base will serve as an **outpost** for future missions. We can conclude that there are many reasons to go back to the Moon. Realistically, we can prioritize these motives into what needs to happen first.

For the purposes of this project, this mission will be based off the idea of harnessing helium-3 from within the lunar surface. Arguably, there are other resources the Moon has to offer. Regardless, mining equipment will ultimately need to be transported.

Landing Zones:

Location A = (40˚S, 160˚E)

Location B = (30˚S, 160˚E)

[2.1.2] Requirements

These requirements are based off of the objective to mine Helium-3.

First Five-person Crew Specialties:

1. Life Support – Medical Personnel
2. Power Specialist – Electrical Engineer
3. Telecommunications – Computer Scientist
4. Expert 1 – Mechanical/Robotics Technician
5. Expert 2 – Nuclear Physicist

Desired Abilities:

- Food Generation
    - Experience with space agricultural techniques
- Systems Upkeeping Personnel
- Habitat Construction & Maintenance Personnel

[2.1.3] Assumptions

This mission was compiled using the Starship cargo-style configuration. Once in LEO, the payloads will head to the Moon.

***Figure 9**: Starship cargo-style configuration* [80].

The mission objective and timeline will determine how many Starships will need to be transported up to a LEO to dock with our designed shuttle. After all components are launched up to the station, time will be allocated for any required assembly. Afterwards, the shuttle will use low thrust electric propulsion for a spiral orbit until a lunar injection is achieved.

80

[2.2] Module Types

[2.2.1] Outpost & Living Quarters

The purpose of the lunar base is to serve **as a habitable outpost**. The success of the lunar base is a major step for future space travel. Specialized astronauts who are chosen for this mission will inhabit the lunar base and work on the helium-3 nuclear reactor. They will also have the facilities to perform other scientific experiments.

The following figure displays an above ground lunar base design by Foster + Partners, a British architectural design and engineering firm. The exterior design is structured around an inflatable dome shell. The dome shell by itself cannot provide sufficient protection for astronauts. Temperature swings, radiation, and meteorites will still pose significant threats. Thus, this lunar base design relies on the use of 3D printing robots to place layers of hardened lunar soil directly onto the shell (as shown in the figure below). The base is also designed to be modular. Dome shells can be connected together to expand the base as needed (also shown below).

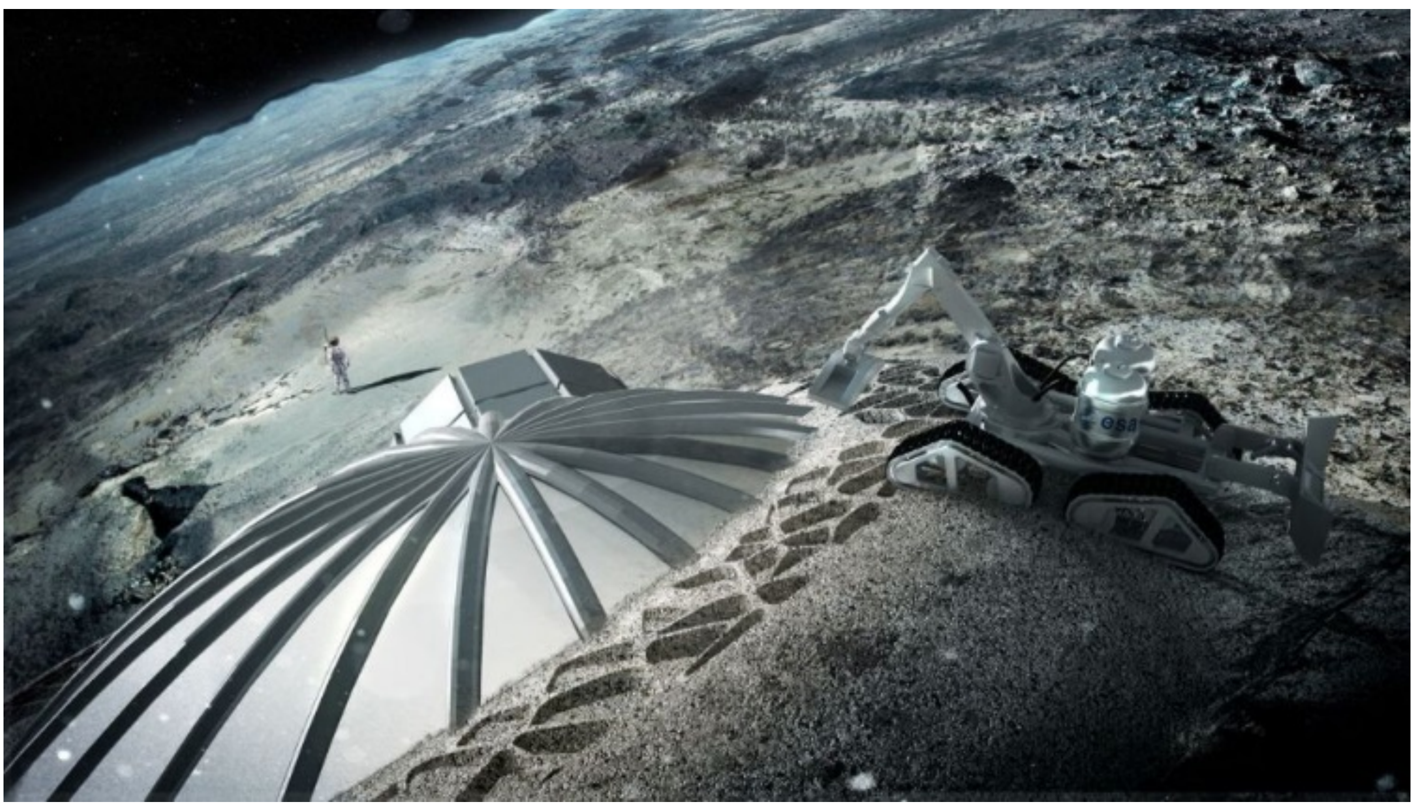


***Figure 10**: The top image showcases a render of a 3D printing robot placing layers of hardened lunar regolith on top of the inflatable dome shell. The bottom image displays a render of the completed lunar base design [81].*

The sealing capabilities of the base is decoupled from the thermal, mechanical, and radiation protection functions. The main sealed and pressurized habitable space is constructed from a mixture of hard shell ready-to-use modules and an inflatable structure. It consists of three inflatable and interconnected volumes that create airlocks to the outside environment. Again, the inflatable itself does not deliver much protection. It serves to provide an atmospheric pressure and conditioned space.

The following figure showcases a diagram for the exterior of the lunar base, as proposed by Foster + Partners. The inflatable dome is designed to be five meters tall, in order to accommodate two levels. For protection against solar radiation, a 1500 mm horizontal offset is required, and for protection against meteorite impacts, an 800 mm radial offset is required. This of course is provided by the 3D printed layers on top of the dome shell. The 3D printed layers also insulate the dome shell, providing resistance to temperature swings.

81

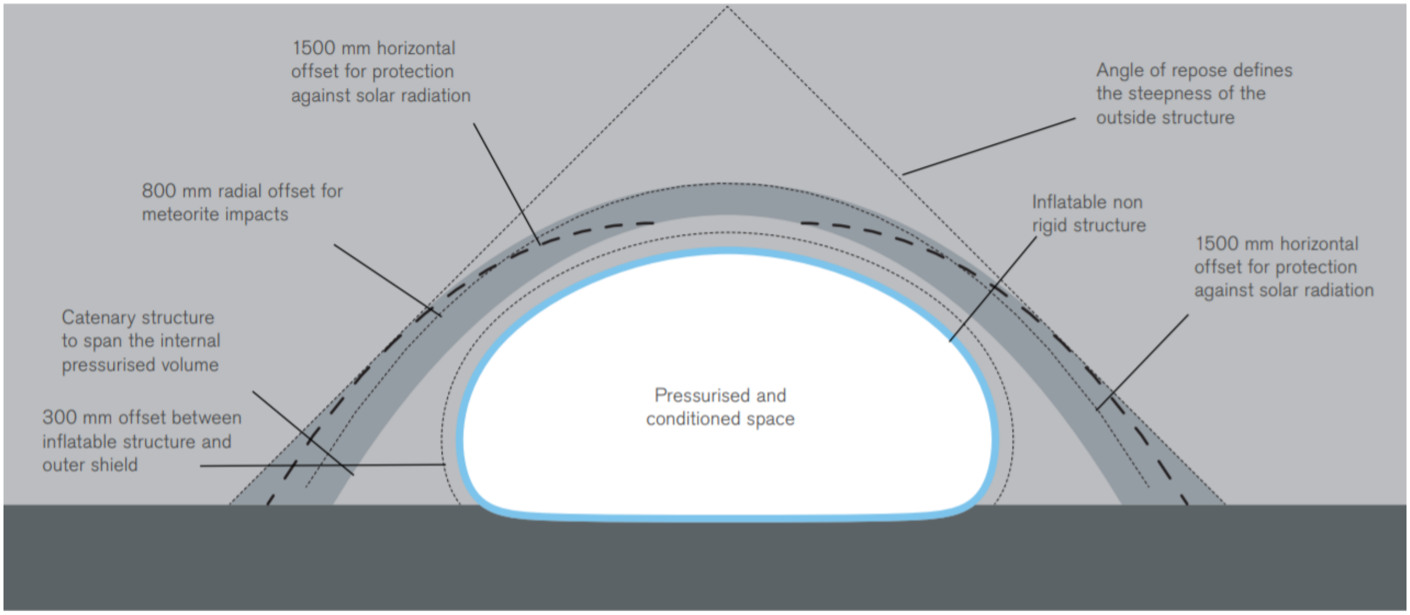


***Figure 11**: Diagram of the exterior design specifications of the lunar base.*

The interior structure of the lunar base consists of a closed wall foam system. It was chosen for a variety of reasons. Firstly, foam structures are one of the lightest, space filling topological systems, which makes it optimal for a lunar base design. Secondly, the foam system provides further protection against meteorites by absorbing and dispersing the energy of the impact. And thirdly, any section through the closed foam delivers a structural platform. This property is essential as the 3D printing robots on the exterior will need a solid platform to build off of [82].

Internally, the lunar base will have dedicated sections for various tasks (similar to the ISS). In the living area, astronauts will have space to eat and sleep. There will also be a section dedicated to a bathroom. Notably, another area will be dedicated to growing food. Veggie and the APH on the ISS have shown that it is possible to grow plants in microgravity. Similar systems will be set up in the lunar base to grow foods like kale, potato, lettuce, and cabbage. These systems are not yet able to fully sustain astronauts. However, they should be able to significantly reduce the amount of food required to be transported. Another section of the lunar base will be devoted to performing scientific experiments.

82

Power will be provided to the lunar base through solar panels. Satellites, space rovers, and the ISS all rely on solar power for electricity. The lunar base, in a similar manner, will also use solar power for electricity. The solar power system will come equipped with rechargeable batteries, which store excess energy for when there is no sunlight available. Furthermore, lasers could potentially beam energy from sunlit areas to shadowed zones [83].

The location of the lunar base is vital. In order for astronauts to remain on the Moon for any significant amount of time, they require direct access to water. Furthermore, for the purpose of this mission, the lunar base needs to be in proximity of helium-3 deposits. Optimally, the lunar base is located near both ice water and helium-3. The following map shows the reflection ratios of energetic neutral atoms (ENA) on the lunar surface. The data comes from the CENA/SARA sensor of the Chandrayaan-1 lunar probe. Essentially, areas with lower ENA reflection ratios (blue areas on the map) have a higher chance of absorbing the contents of solar wind. In other words, these locations have a greater chance of containing desired helium-3 deposits [84]. As for lunar ice water, significant amounts are typically found at the lunar poles and other dark/cold areas, such as lava tubes and craters. Notably, the Clavius Crater is located on the southern hemisphere of the Moon, near the large blue region of the ENA reflection ratio map (around 30˚S, 160˚E). NASA's SOFIA confirmed the presence of significant concentrations of ice water in the Clavius Crater [85]. Thus, the location 30˚S, 160˚E on the Moon is practical for the lunar base, as it is located near both helium-3 and ice water deposits.

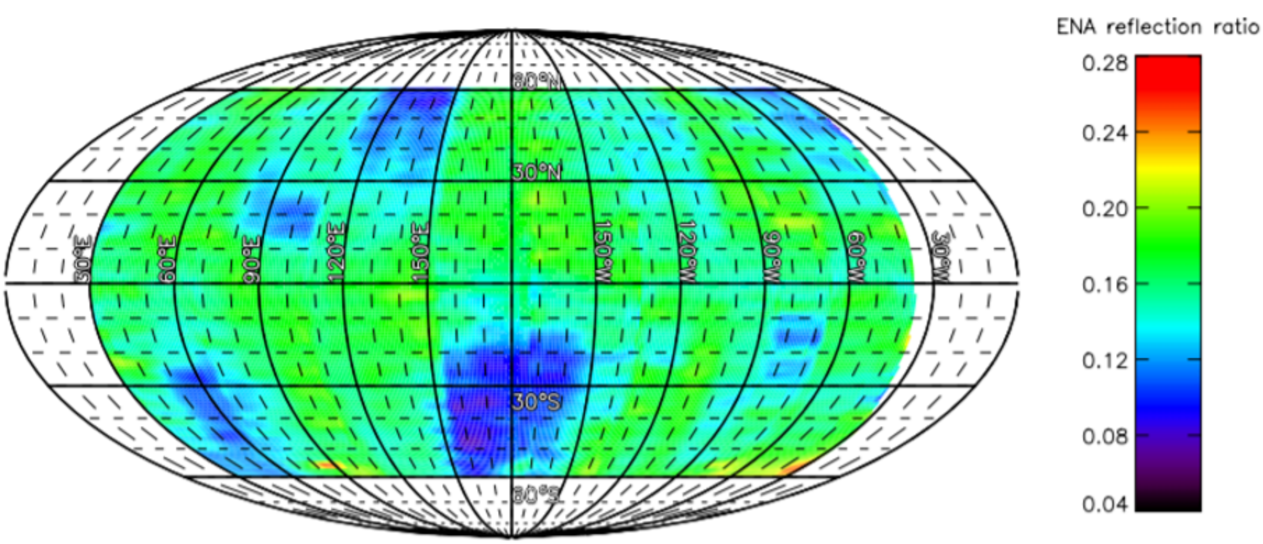


Figure 12*: Map of ENA reflection ratios of the Moon from the CENA/SARA sensor of the Chandrayaan-1 lunar probe.*

83

84

85

[2.2.2] Orbiter & Relay Shuttle

The purpose of having a relay shuttle is simply to have a midway station between the outpost and Earth. This will be beneficial when the time comes to transfer crew, supplies, and equipment. The idea is to have two independent shuttles, one orbiting Earth and one orbiting the Moon. When the time comes the two shuttles will meet in a medium Earth orbit (MEO). Having two of these shuttles instead of one help reduce the response time. For example, if there is an emergency on the lunar base and an astronaut needs to make it back to Earth, having two shuttles carry out their burns and meeting at a midway point will help with efficiency.

The shuttle itself has a wide range of options. The most basic version of this shuttle will be composed of solar panels, fuel tanks, and escape pods. In the event of an emergency this shuttle can also act as a docking station where spacecrafts can refuel and recharge.

With respect to a lunar mission, the shuttle will play a role in the construction of the lunar base. There will need to be a series of transmissions between Earth and the Moon. The shuttle will assist in the transit of raw material, equipment, and astronauts back and forth between the Moon and Earth. In the construction of an outpost, it would be necessary to rotate the astronauts on a monthly basis. Due to constraints in launching, this could possibly be closer to three to six months. It is important to note, however, that the Dragon escape pods will be available if an emergency arises during the construction of this base.

The possibilities of accessories to this shuttle are endless. The shuttle itself serves as a body, where its purpose is to assist in transits for lunar missions. Thus, modules, similar to those used on the ISS, can be constructed along the shuttle (e.g., living quarters or scientific modules). The shuttle can also serve as a docking station. Other Starships can dock to this body to refuel and recharge. The idea of this relay shuttle can be compared to problems faced on Earth. For instance, for a person traveling through the desert on a long journey, a gas station can come a long way in its ability to assist them.

[2.2.3] Industrial

Collecting helium-3 on the lunar surface has never been attempted. However, we can speculate what equipment will be necessary for this mission objective. On top of a crew of astronauts, the following industrial equipment will be needed.

Equipment Needed:

- Robots to make landing zones for spacecrafts
- Refabricated Caterpillar dozers for mining and processing raw material
- Refinery/Collection Site

All equipment listed will need to be modified in order to withstand the environment of the lunar surface. These conditions may affect the nature of what is and is not possible. Some conditions included can be as significant as being in the vacuum of space, or less obviously the texture (sharpness) at which the lunar soil will affect different textiles and materials.

[2.3] Mission Subsystems

[2.3.1] Orbiter & Relay Shuttle

The following designs (created with SolidWorks) demonstrate one half of the orbiter that will serve as a relay station for the proposed mission. Two shuttles will be cast into a LEO and a lunar orbit. Upon transferring crew and equipment from Earth to the Moon, or vice versa, the shuttles will meet in a MEO orbit. Each shuttle will carry out a spiral transfer through their low electric thrusters. The time to go from LEO to lunar orbit and vice versa is roughly six days. The shuttle will comprise of a solar array that can suit up to 100 [kW]. Each shuttle will house fuel tanks where different monopropellant and bipropellant fuels can be stored for visiting spacecrafts. They will also help assist the landings on Earth and the Moon. Some of these fuel tanks will house hydrazine (the most common monopropellant) for attitude control thrusters. Along with fuel, a docking bay will be provided where several dragon capsules can be stored for descension down to Earth. There will be extra room dedicated for the docking of our Starship cargo-style spacecraft for this mission as well.

These shuttles are a necessity for the next set of missions to the Moon. Ultimately, these shuttles will serve **as a 'gas station and rest stop'** at the midway point between the Earth and the Moon. This is where the spacecraft and astronauts can fuel, recharge, and rotate personnel and equipment.

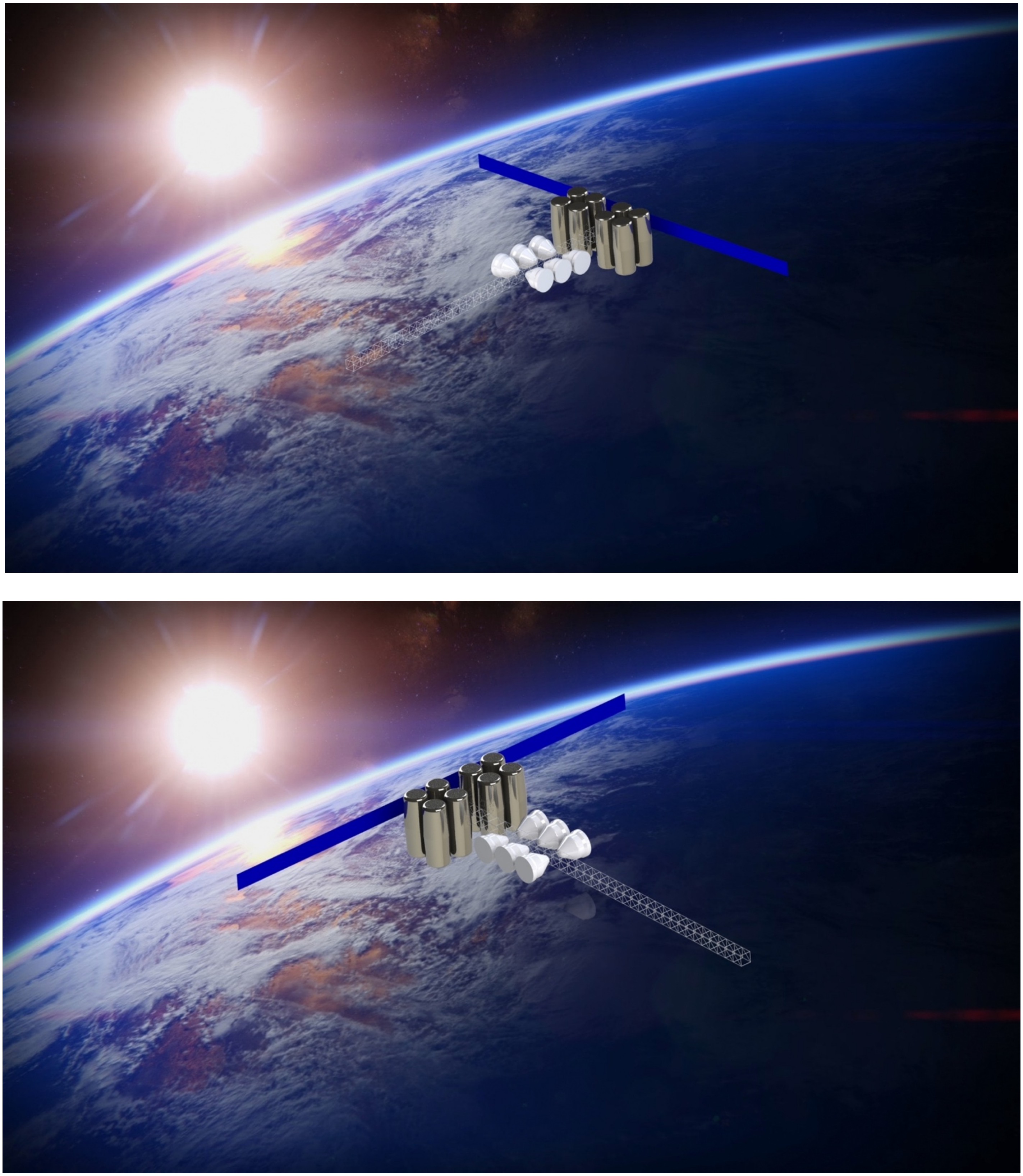


Figure 13: *Rendered image of one of the relay shuttle stations.*

Figure 14: *Close-up view of relay shuttle station.*

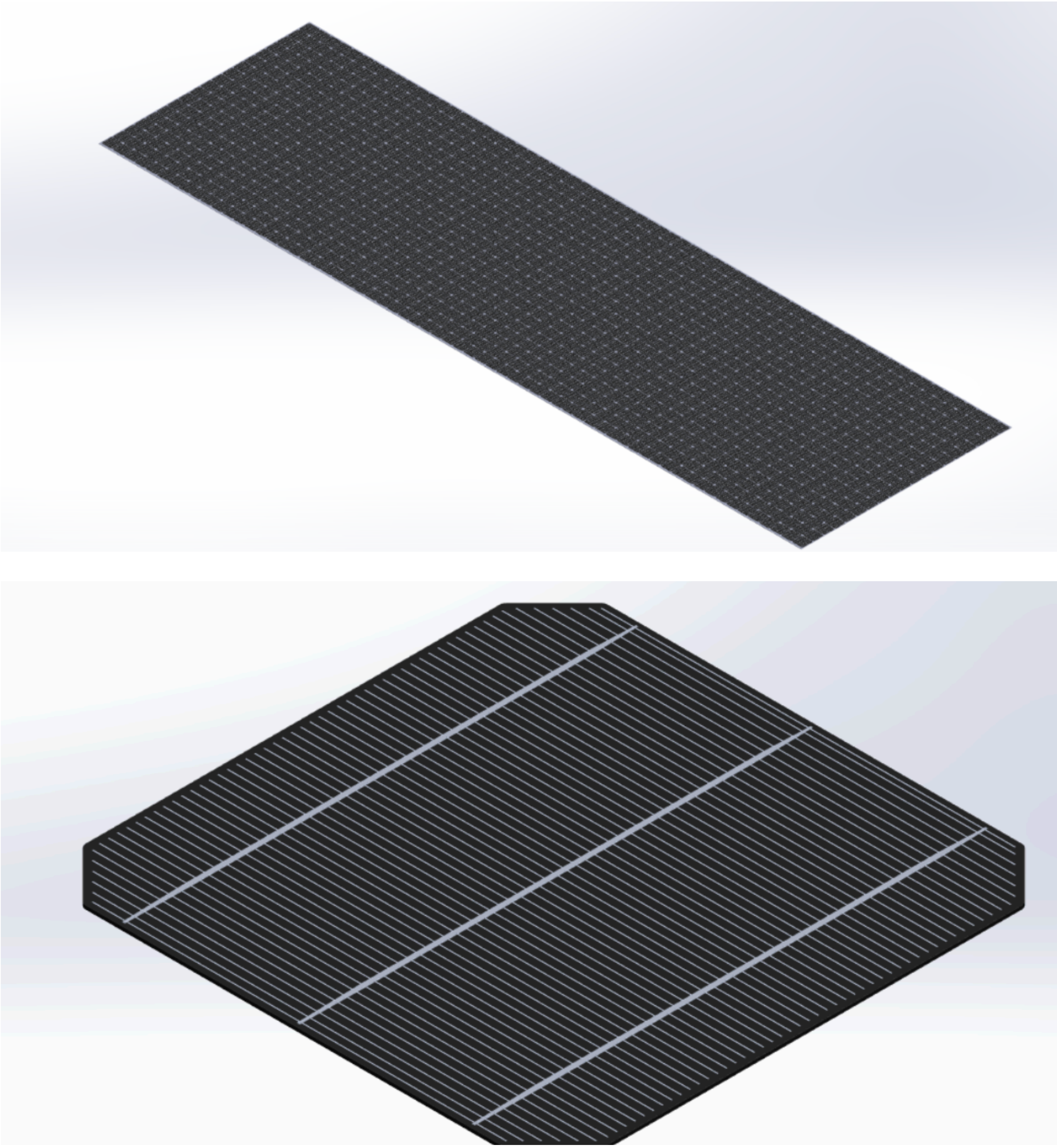


Figure 15: *Rendered image of solar panel wing.*

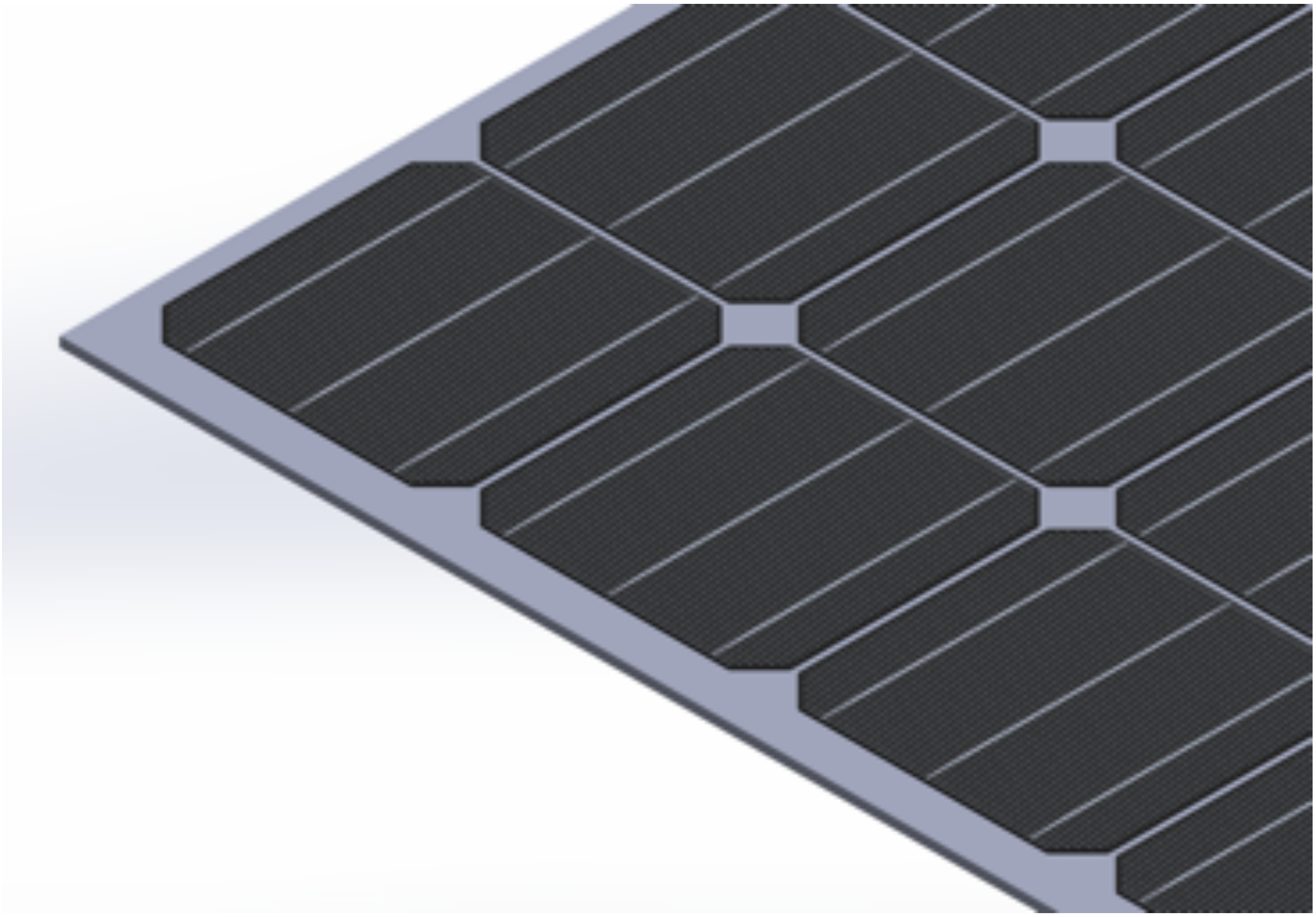


***Figure 16**: Close-up view of solar cells.*

[2.3.2] Autonomous Vehicles

Overview

The design of our rover is inspired by the NASA Cratos prototype lunar rover. The objective of the rover is to provide a solution to gathering helium-3 to be processed later. In addition, the rover would assist in the construction and maintenance of the lunar outpost before human habitation. The design specifications primarily require the vehicle to be able to scrape regolith from the lunar surface and amass the soil in a pile to be processed later [86]. In addition, due to the lengthy lunar night (roughly 15 days long), it is required that the rover remain heated and operational. This requires the use of a radioisotope power system (RPS). The power system relies on the energy produced by radioactive plutonium-238. Due to the high load required by the drilling equipment, it would be best for the RPS to store energy in a battery, which will better account for power surges.

Design Specifications

- Power to weight ratio 1:1 ±10%
- Wireless transmission of data from sensors to lunar base
- Continuous operation, i.e., no hibernation mode during lunar night
- Maneuverability to allow for navigation into and out of a lunar crater

Structures

As noted, the design takes inspiration from the NASA Cratos robot. Their robot is a tracked vehicle with a one cubic meter footprint. The robot has a dozer-like blade on the front with a bucket on top to facilitate the maneuvering of regolith. In subscale tests, the robot has proven to be effective in climbing uneven terrain on lunar stimulant. In addition, it outperformed required capabilities in load-bearing capacity and the transportation of regolith.

86

***Figure 17**: NASA Cratos undergoing testing on volcanic soil in Hawaii.*

The proposed rover is significantly larger than Cratos so that it is more practical for use on a human scale. Given its ability to move regolith effectively, it would likely be used to assist in the construction of the lunar outpost early in its operational mission. In addition, Cratos has proven to be capable of towing vehicles many times its mass. Therefore, the rover can be fit with a ball joint in the rear and be used to transport and assist in construction of the outpost. After that has been done, it will be able to go explore lunar craters and start work on stockpiling regolith for later processing.

Communications

During space missions, data is primarily transmitted through Nasa's Deep Space Network, otherwise known as the DSN. Cratos requires a wireless communication solution to be able to transmit data back to the outpost on the surface of the Moon. In addition, the ideal transmitter and receiver would be very small, lightweight, and have low power consumption. This is so that the rover expends more resources on operational goals instead of communications.

Power

Typically, solar arrays are used to generate energy for space missions. The energy is stored in batteries until it is required. However, there is a precedent for RPS utilization in lunar surface rovers. This is because the lunar day is nearly 30 days long, meaning that there is a period of nearly 15 days of zero sunlight. In addition, locations within lunar craters see no sunlight. Due to these reasons, it is best to supply the rover with an RPS because it is a reliable source of power without any need for consideration of the external environment. RPS's are a type of nuclear energy that relies on the natural radioactive decay of plutonium-238. The decay of plutonium generates heat. Within the RPS, thermocouples capture the heat and convert it into electrical energy. The RPS can be used directly to power the rover, or the energy can be stored in a battery. In this case, a battery will be implemented to store the energy. In addition, the RPS is the primary source of heat for the rover to survive the fortnight long lunar night. Because of this, the operational capacity of the rover during the lunar night is going to be somewhat affected. The specific power source to be used is the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). It produces 125 [W] of electrical power at the beginning of its life and falls slowly to roughly 100 [W] after 14 years. It also has a mass of 45 kilograms, yielding a 2.8 [W/kg] ratio at the beginning of the mission [87]. To ensure design requirements are met, two MMRTG's will be used in the lunar rover. This equates to 90 kilograms with an electrical power supply of 200-250 [W], depending on the life of the mission. The power draw requires roughly two [kWh] of battery capacity, which is still to be investigated.

87

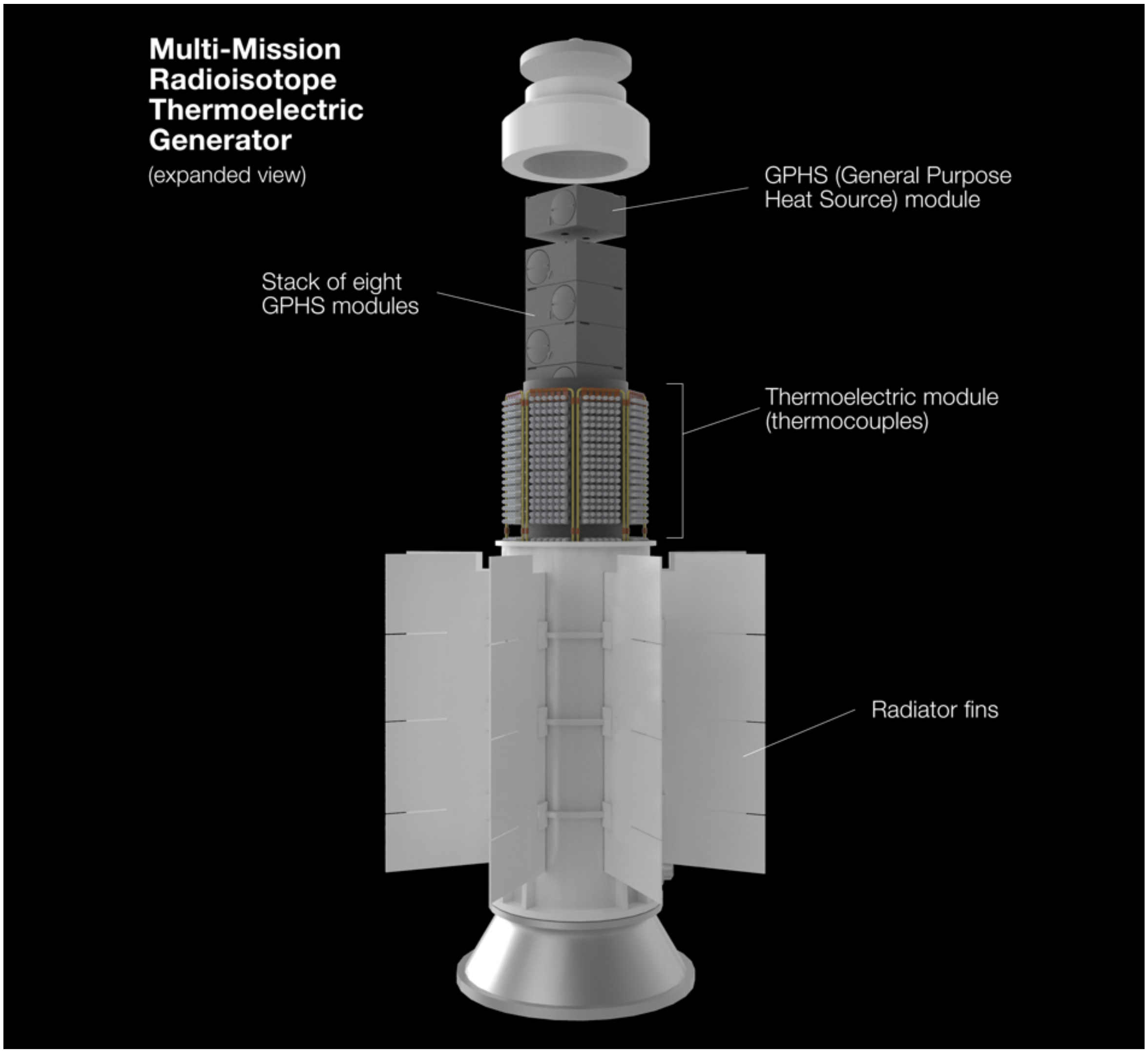


Figure 18: *Schematic of Multi Mission Radioisotope Thermoelectric Generator.*

Thermal

A rover on the lunar surface experiences drastic temperature changes from 127 ˚C to -173 ˚C in the hot and cold cases, respectively. A steady state analysis was conducted for each extreme. The hot case assumes full exposure, and the cold case assumes zero exposure to sunlight. Many electronic components on board are unable to function through these extremes. Therefore, both a heating and a cooling method are needed to ensure that the rover can remain within its operational range indefinitely. The limiting factor is the batteries, which are only operational in a very small temperature range (from ~10 to 25 ˚C depending on the model used). Nonetheless, for the cold case, the RPS will be used to passively heat the rover. Because of this, the operational capacity of the rover is going to be limited while the rover is in the dark. However, using energy from the RPS is a very cost-effective measure of heating, given that the RPS is producing constant heat. In addition, energy can be stored in the battery which can be used for scientific operation in the dark regardless of the state of the RPS. The cold case is a bit more complex because thermal convection is not possible due to the lack of an atmosphere. The best solution is a series of different cooling techniques, including internal conduction, multilayer insulation (MLI) blankets and covers, and the most robust – a wax block designed to melt at a certain temperature. Several wax blocks were used as the main method of cooling, or rather minimizing the temperature increase, in the Lunar Roving Vehicle utilized during the Apollo missions. The wax is designed to slowly melt at a set temperature. This means that the energy going into the block is being used to change its state and thus the temperature of the component is not increasing. On the other hand, the wax will resolidify in the cold and is ready to be fully used again. The main benefit of this system is that it is reusable and passive. Therefore, the power draw is negligible, and the risk of failure is extremely low.

CHAPTER 3: Mission Calculations

[3.1] Power Subsystem Mass

[3.1.1] Orbiter

Power

Based off of the ISS, we will assume that the required power for each of these stations will be 100 [kW]. At this distance from the Sun, the flux is roughly 1,367 [W/m^2]. Therefore, a required solar array size of 1,040 [m^2] would be needed. The following table represents the mass breakdown of these spacecraft components. This power system would total roughly 30,000 [kg]. With the assumptions in using silicon solar cells and nickel cadmium batteries, the mission life is projected at 15 years.

Table 1: *Relay shuttle power subsystem mass.*

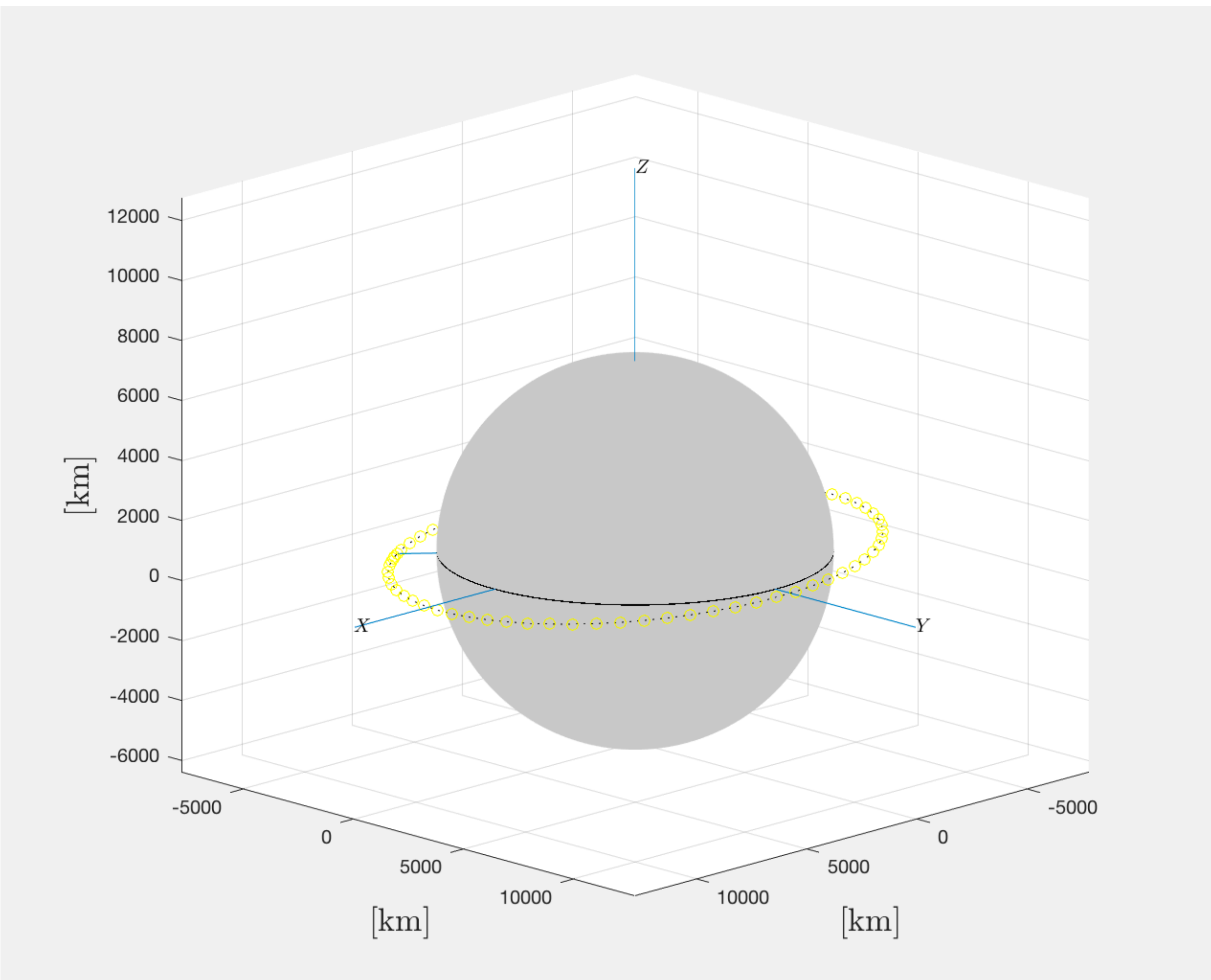
Lunar Post		
Power Subsystem:		
flux =	1367	[W/m^2]
P_required =	100	[kW]
required array size =	1040	[m^2]
solar array mass =	7074.60	[kg]
battery mass =	14355.44	[kg]
regulators/converters =	4626.94	[kg]
power control unit =	3701.56	[kg]
total =	29758.54	[kg]

This mass would attribute to roughly one-third of one Starship cargo-style payload to LEO.

[3.2] Shuttle DeltaV and Orbits

[3.2.1] LEO and Lunar Injections

LEO will be used as each shuttles' initial orbit. A LEO is beneficial for the descension of dragon capsules back to the Earth's surface. It is possible for these capsules to be launched from a lunar orbit to Earth. However, crew and equipment will be rotating back and forth and thus it is much more reasonable to have a midway point between the Earth and the Moon. The proposed orbit is at an inclination of roughly five degrees, which is precisely the inclination of the Moon. After this orbit is established from the launch vehicle, a low finite thrust will be maneuvered to achieve a lunar injection for one of the shuttles. Electric propulsion is more efficient in offering a spiral transfer (mistaken as Hohmann transfers). Unlike in Hohmann transfers, thrusting the entire time allows for better course correction. The proposed LEO is depicted below.



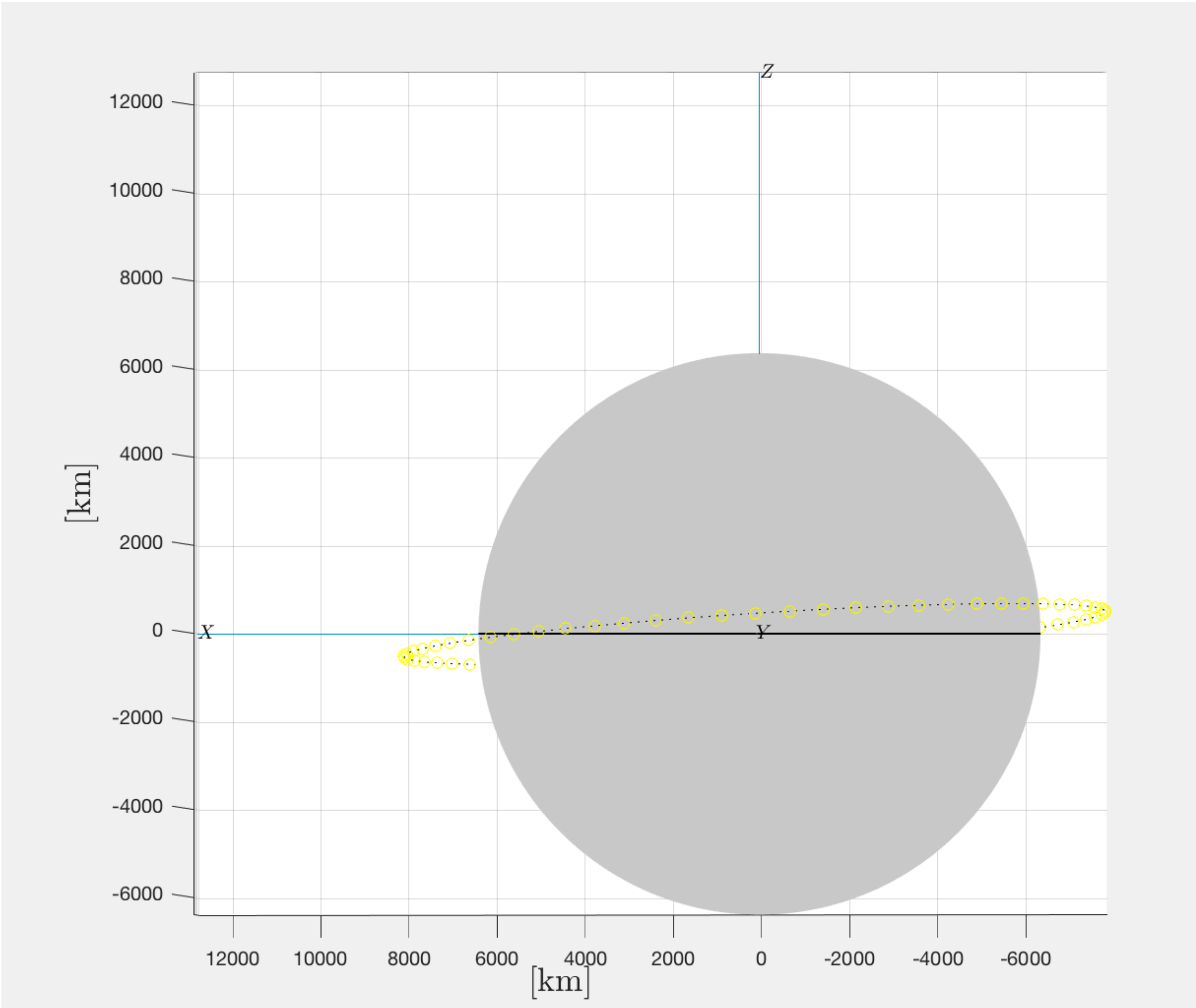


***Figure 19**: LEO of one of the shuttles.*

LEO typically encompasses orbits within an altitude of 2,000 [km]. Where the distance between Moon and Earth is roughly 384,400 [km]. The mass breakdown of the shuttles will determine the deltaV. However, they will be powered by Hall electric thrusters and thus there will be no need to bring mono- or bipropellant. These thrusters will be powered by the solar panels on each of the stations.

The proposed LEO was calculated on the following parameters.

Table 2: *Calculated variables of LEO.*

Gravitational Parameter	μ	=	398600	[km^3/s^2]
Angular Momentum	h	=	56370	[km^2/s]
Eccentricity	e	=	0.02138	NA
Right Ascension	Ω	=	48.3762	[deg]
Inclination	i	=	4.94873	[deg]
Argument of Perigee	ω	=	181.437	[deg]
True Anomaly	θ	=	70.715	[deg]
Semimajor Axis	a	=	7975.53	[km]

State vectors at ascending node for low thrust transfer:

$$\vec{r} = \langle 4000, -6800, -650 \rangle \ [km]$$

$$\vec{v} = \langle 6.2, 3.5, -0.2 \rangle \ \left[\frac{km}{s}\right]$$

Table 3: *Calculated LEO period.*

Period of LEO:		
Seconds	=	7088.44
Minutes	=	118.141
Hours	=	1.96901
Days	=	0.08204

The minimum altitude is 1425.57 [km] at time = 1.57776 [hours].

The speed at that point is 7.22364 [km/s].

The maximum altitude is 1764.78 [km] at time = 0.594614 [hours].

The speed at that point is 6.92272 [km/s].

CHAPTER 4: Future Work

[4.1] Beyond the Moon

[4.1.1] Mars

As previously mentioned, missions to the Moon serve as testing runs for future missions beyond. A destination of interest for future manned space exploration is Mars. In order for a mission to Mars to be possible, there needs to be a number of significant advancements in space technology.

One required advancement in space technology for a manned mission to Mars is the development of more powerful propulsion systems. Astronauts will need to travel tens of millions of miles through space to get to Mars. To reduce travel time, the propulsion system needs to be nuclear enabled. Two notable nuclear enabled systems that are being developed are nuclear electric and nuclear thermal propulsion. Both systems fundamentally utilize nuclear fission, but still differ from each other. The nuclear electric system is more efficient. However, it lacks in thrust power. The nuclear thermal system, on the other hand, generates far more thrust. It, however, is not nearly as efficient. It is still unclear on which propulsion system will be used for deep space travel.

In order for a large spacecraft to enter the Martian atmosphere and land safely, there needs to be advancements and development in heat shield technology. NASA is currently working on an inflatable heat shield that takes up significantly less space compared to a rigid heat shield. The proposed heat shield is designed to expand and inflate before entering the Martian atmosphere. With this technology, spacecrafts can safely land on any planet with an atmosphere.

Another required advancement in space technology is the development of better spacesuits. Older spacesuits were heavy and bulky, making them unsuitable for Mars. NASA's next generation of spacesuits, the exploration extravehicular mobility unit (xEMU), is designed to allow "more natural, Earth-like movements". In these improved spacesuits, astronauts are able to accomplish tasks that were not previously possible. For a mission to Mars, spacesuits may need to include life support functionality for the carbon dioxide-rich atmosphere. Moreover, the spacesuit needs to be able to compensate for extreme temperature swings, keeping astronauts warm or cool as needed.

A further requirement for a mission to Mars is the development of a reliable power supply. The power system needs to be lightweight and have the ability to run in any location or weather condition. Solar power may not be the optimal choice, as Mars has a day and night cycle. There are also occasional long-lasting dust storms that will inevitably cover up solar arrays, making solar power not very reliable. Nuclear fission power is much better suited for a mission to Mars. NASA has already confirmed its efficiency and reliability over solar power.

Improvements to deep space communications is another necessity. Specifically, communications need to transition from the current radio system to a laser system. With the current system, sending a map of Mars to Earth may take up to nine years. In contrast, laser communications would only take nine weeks. With a laser communications system, real-time information and data, including high-definition images and video feeds, can be transmitted directly from Mars. It would also allow for much better communication with the astronauts.

According to NASA, the initial Martial base will likely need to be mobile. Combining the first base and vehicle into a single rover drastically reduces the number of items initially transported to Mars. Also, Mars is significantly larger than the Moon. By having a mobile base, the astronauts are not bound to a specific area. They can comfortably travel away from their spacecraft. The mobile base will be pressurized and have breathable air. It will come equipped with everything astronauts need to live and work for multiple weeks [88,89].

Initially, it was thought that those astronauts traveling to Mars may not return back to Earth, as they would not have a reliable method to do so. They would have to survive on Mars for many years and live off of potential supply drops. With significant advancements in space technology, this is most likely no longer the case. Due to the smaller size of Mars, launching from the Red Planet is easier than launching from Earth. Only a small compact spacecraft is required to enter Mars orbit. From there, the small spacecraft can dock onto a much larger return spacecraft that will travel back to Earth.

88

89

[4.1.2] Our Vision

No one can say for certain what the future of space exploration beholds. However, our team has a certain vision for how future space exploration may occur. We believe that robots and artificial intelligence will be an integral part of future space exploration. This is something to be expected, as the harsh environment of space is not particularly favorable for human beings. Humans outside of Earth appear fragile compared to robots engineered for space. They require food and water, breathable air, and protection (against factors such as solar radiation, temperature swings, and meteorites). Simply put, human beings are vulnerable in space and are not well-suited for deep space travel.

Advanced robots are already being developed. Boston Dynamics' Atlas is the most advanced humanoid robot in the world. The 4'11", 176-pound, battery powered robot has 28 hydraulic joints and can move at speeds up to 3.4 miles per hour. Atlas is capable of performing complex movements resembling that of humans [90]. Tesla is also in the process of developing an advanced humanoid robot. The Tesla Bot is expected to be 5'8" and 125 pounds. Tesla claims that it will be able to move up to five miles per hour, carry up to 45 pounds, and deadlift up to 150 pounds [91]. In the distant future, advanced robots like these may be specifically modified for space. Paired with artificial intelligence, these robots may very well replace humans for deep space exploration.

90

91

[4.2] Future IQP Suggestions

[4.2.1] Potential Interest Extents

We conclude this report by providing suggestions for future IQP teams. There are multiple ways future IQP teams can expand on our project of “The Future of Humanity in Space”. For example, details of a helium-3 nuclear fusion reactor can be explored. A major question that arises is where to build such a reactor. The reactor can be built on the Moon. However, this then leads to the issue of sending energy back to Earth, which could potentially be done through the use of lasers. The reactor could also be built on Earth, in which case helium-3 would need to be transported from the Moon to Earth. The process of mining and refining helium-3 could also be further examined.

Another item future teams can explore is different mission objectives. For example, one such objective is placing an observatory on the far side of the Moon. This would allow for a view of the dark cosmos unhindered by radio interferences and Earth’s atmosphere. Another such objective is to incorporate the architecture, design, and construction of the lunar base. Raw materials will need to be sent to the moon for this undertaking. When it comes to launching into space, every [kg] will need to be accounted for. Therefore, a CAD render of this base with a materials list, timeframe, and building procedure can be explored by future IQP groups. It is important to note that robotic configurations may be of use in this construction. However, there are a few things that cannot be autonomous that a human must be present for. The ratio of work through this partnership between man and machine can be explored further.

Finally, future teams can design a mission to other bodies in the Solar System. The most obvious choice is Mars. The section above briefly highlighted some of the technological advances required in space technology for a manned mission to Mars. It may also prove worthwhile to explore the benefits and risks of missions to other planets, such as Venus and Uranus. Venus, for instance, has a similar force of gravity and temperature as Earth. Uranus is interesting because helium-3 was discovered in its gas mines. Overall, the future of humanity in space is bright and future teams have a plethora of options to explore.

APPENDIX I: MATLAB Calculations

The following MATLAB Calculations were obtained from Howard D. Curtis' *Orbital Mechanics for Engineering Students* Fourth Edition (2020). Appendix D4, D6, D18, and D22 were considered.

Appendix D6:

```
% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
function orbit
% ~~~~~~~~~~~~
%{
  This function computes the orbit of a spacecraft by using rkf45 to
  numerically integrate Equation 2.22.

  It also plots the orbit and computes the times at which the maximum
  and minimum radii occur and the speeds at those times.

  hours     - converts hours to seconds
  G         - universal gravitational constant (km^3/kg/s^2)
  m1        - planet mass (kg)
  m2        - spacecraft mass (kg)
  mu        - gravitational parameter (km^3/s^2)
  R         - planet radius (km)
  r0        - initial position vector (km)
  v0        - initial velocity vector (km/s)
  t0,tf     - initial and final times (s)
  y0        - column vector containing r0 and v0
  t         - column vector of the times at which the solution is found
  y         - a matrix whose columns are:
                 columns 1, 2 and 3:
                    The solution for the x, y and z components of the
                    position vector r at the times in t
                 columns 4, 5 and 6:
                    The solution for the x, y and z components of the
                    velocity vector v at the times in t
  r         - magnitude of the position vector at the times in t
  imax      - component of r with the largest value
  rmax      - largest value of r
  imin      - component of r with the smallest value
  rmin      - smallest value of r
  v_at_rmax - speed where r = rmax
  v_at_rmin - speed where r = rmin

  User M-function required:   rkf45
  User subfunctions required: rates, output
%}
% --------------------------------------------------------------------

clc; clf; clear all

hours = 3600;
G     = 6.6742e-20;

%...Input data:
%   Earth:
m1 = 5.974e24;
R  = 6378;
m2 = 1000;   %% satellite mass
```

```
r0 = [ 4000, -6800, -650];
v0 = [6.2, 3.5, -.2];



t0 = 0;
tf = (2)*hours;
%...End input data


%...Numerical integration:
mu    = G*(m1 + m2);
y0    = [r0 v0]';
[t,y] = rkf45(@rates, [t0 tf], y0);

%...Output the results:
output

return

% ~~~~~~~~~~~~~~~~~~~~~~~~
function dydt = rates(t,f)
% ~~~~~~~~~~~~~~~~~~~~~~~~
%{
  This function calculates the acceleration vector using Equation 2.22

  t          - time
  f          - column vector containing the position vector and the
               velocity vector at time t
  x, y, z    - components of the position vector r
  r          - the magnitude of the the position vector
  vx, vy, vz - components of the velocity vector v
  ax, ay, az - components of the acceleration vector a
  dydt       - column vector containing the velocity and acceleration
               components
%}
% ------------------------
x    = f(1);
y    = f(2);
z    = f(3);
vx   = f(4);
vy   = f(5);
vz   = f(6);

r    = norm([x y z]);

ax   = -mu*x/r^3;
ay   = -mu*y/r^3;
az   = -mu*z/r^3;

dydt = [vx vy vz ax ay az]';
end %rates


% ~~~~~~~~~~~~~
function output
% ~~~~~~~~~~~~~
```

```
%{
  This function computes the maximum and minimum radii, the times they
  occur and and the speed at those times. It prints those results to
  the command window and plots the orbit.

  r          - magnitude of the position vector at the times in t
  imax       - the component of r with the largest value
  rmax       - the largest value of r
  imin       - the component of r with the smallest value
  rmin       - the smallest value of r
  v_at_rmax - the speed where r = rmax
  v_at_rmin - the speed where r = rmin

  User subfunction required: light_gray
%}
% ------------
for i = 1:length(t)
    r(i) = norm([y(i,1) y(i,2) y(i,3)]);
end

[rmax imax] = max(r);
[rmin imin] = min(r);

v_at_rmax   = norm([y(imax,4) y(imax,5) y(imax,6)]);
v_at_rmin   = norm([y(imin,4) y(imin,5) y(imin,6)]);

%...Output to the command window:
fprintf('\n\n--------------------------------------------------------\n')
fprintf('\n Earth Orbit\n')
fprintf(' %s\n', datestr(now))
fprintf('\n The initial position is [%g, %g, %g] (km).',...
                                                     r0(1), r0(2), r0(3))
fprintf('\n   Magnitude = %g km\n', norm(r0))
fprintf('\n The initial velocity is [%g, %g, %g] (km/s).',...
                                                     v0(1), v0(2), v0(3))
fprintf('\n   Magnitude = %g km/s\n', norm(v0))
fprintf('\n Initial time = %g h.\n Final time   = %g h.\n',0,tf/hours)
fprintf('\n The minimum altitude is %g km at time = %g h.',...
            rmin-R, t(imin)/hours)
fprintf('\n The speed at that point is %g km/s.\n', v_at_rmin)
fprintf('\n The maximum altitude is %g km at time = %g h.',...
            rmax-R, t(imax)/hours)
fprintf('\n The speed at that point is %g km/s\n', v_at_rmax)
fprintf('\n--------------------------------------------------------\n\n')

%...Plot the results:
%   Draw the planet
[xx, yy, zz] = sphere(100);
surf(R*xx, R*yy, R*zz)
colormap(light_gray)
caxis([-R/100 R/100])
shading interp

%   Draw and label the X, Y and Z axes
line([0 2*R],   [0 0],   [0 0]); text(2*R,   0,   0, '$X$','Interpreter','latex');
line(  [0 0], [0 2*R],   [0 0]); text(  0, 2*R,   0, '$Y$','Interpreter','latex');
line(  [0 0],   [0 0], [0 2*R]); text(  0,   0, 2*R, '$Z$','Interpreter','latex');
```

```
%   Plot the orbit, draw a radial to the starting point
%   and label the starting point (o) and the final point (f)
hold on
plot3(y(:,1), y(:,2), y(:,3),'k:')
line([0 r0(1)], [0 r0(2)], [0 r0(3)])
text(y(1,1), y(1,2),y(1,3), '','FontSize',15,'EdgeColor','green','LineWidth',2)
text(y(end,1),y(end,2),y(end,3), '','FontSize',15,'EdgeColor','red','LineWidth',2)

%   Select a view direction (a vector directed outward from the origin)
view([1,1,.4])

%   Specify some properties of the graph
grid on
axis equal
xlabel('[km]','Interpreter','latex', 'fontsize', 17);
ylabel('[km]','Interpreter','latex', 'fontsize', 17);
zlabel('[km]','Interpreter','latex', 'fontsize', 17);
%%%%%%%%%%%%%%%%%
%% do the Cool animation
for k = 1:length(t)
    hold on, plot3(y(k,1), y(k,2), y(k,3),'oy')
    pause (0.1)
    hold off
end
%%%%%%%%%%%%%%%%%


% ~~~~~~~~~~~~~~~~~~~~~~~
function map = light_gray
% ~~~~~~~~~~~~~~~~~~~~~~~
%{
  This function creates a color map for displaying the planet as light
  gray with a black equator.

  r - fraction of red
  g - fraction of green
  b - fraction of blue

%}
% -----------------------
r = .8; g = r; b = r;
map = [r g b
       0 0 0
       r g b];
end %light_gray

end %output

end %orbit
% ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

Appendix D18:

```
deg = pi/180;
mu = 398600;

r = [ 4000, -6800, -650];
v = [6.2, 3.5, -.2];


coe = coe_from_sv(r,v,mu);

fprintf('-----------------------------')
fprintf('\n Example 4.3\n')
fprintf('\n Gravitational parameter (km^3/s^2) = %g\n', mu)
fprintf('\n State vector:\n')
fprintf('\n r (km)                         = [%g %g %g]',r(1), r(2), r(3))
fprintf('\n v (km/s)                       = [%g %g %g]',v(1), v(2), v(3))
disp(' ')
fprintf('\n Angular momentum (km^2/s)     = %g', coe(1))
fprintf('\n Eccentricity                  = %g', coe(2))
fprintf('\n Right ascension (deg)         = %g', coe(3)/deg)
fprintf('\n Inclination (deg)             = %g', coe(4)/deg)
fprintf('\n Argument of perigee (deg)     = %g', coe(5)/deg)
fprintf('\n True anomaly (deg)            = %g', coe(6)/deg)
fprintf('\n Semimajor axis (km):          = %g', coe(7))

if coe(2)<1
    T = 2*pi/sqrt(mu)*coe(7)^1.5;
    fprintf('\n Period:')
    fprintf('\n   Seconds         = %g', T)
    fprintf('\n   Minutes         = %g', T/60)
    fprintf('\n   Hours           = %g', T/3600)
    fprintf('\n   Days            = %g', T/24/3600)
end

fprintf('\n-----------------------------\n')

time_stamp = datestr(now)

function coe = coe_from_sv(R,V,mu)

eps = 1.e-10;

r = norm(R);
v = norm(V);

vr = dot(R,V)/r;
H = cross(R,V);
h = norm(H);

incl = acos(H(3)/h);

N = cross([0 0 1],H);
n = norm(N);
```

```
if n ~= 0
    RA = acos(N(1)/n);
    if N(2) < 0
        RA = 2*pi - RA;
    end
else
    RA = 0;
end

E = 1/mu*((v^2 - mu/r)*R - r*vr*V);
e = norm(E);

if n ~= 0
    if e > eps
        w = acos(dot(N,E)/n/e);
        if E(3) < 0
            w = 2*pi - w;
        end
    else
        w = 0;
    end
else
    w = 0;
end

if e > eps
    TA = acos(dot(E,R)/e/r);
    if vr < 0
        TA = 2*pi - TA;
    end
else
    cp = cross(N,R);
    if cp(3) >= 0
            TA = acos(dot(N,R)/n/r);
    else
        TA = 2*pi - acos(dot(N,R)/n/r);
    end
end

a = h^2/mu/(1 - e^2);

coe = [h, e, RA, incl, w, TA, a];

end
```

REFERENCES

[1] SpaceX. (n.d.). SpaceX. Retrieved 2021, from https://www.spacex.com/

[2] Jones, H. W. (2018, July 8). *The recent large reduction in space launch cost*. TTU DSpace Home. Retrieved 2022, from https://ttu-ir.tdl.org/handle/2346/74082

[3] Marshall, W. (2017, July 17). *Space Technology is improving our lives and making the world a better place. here's how*. World Economic Forum. Retrieved 2022, from https://www.weforum.org/agenda/2017/07/using-space-to-help-global-development/

[4] Manz, B. (n.d.). *Communications in space: A deep subject*. Mouser Electronics. Retrieved 2022, from https://www.mouser.com/applications/communications-deep-space/

[5] Redwire. (2021, February 19). *Space crystals: Developing Laser Optics Products in space*. Redwire Space. Retrieved 2022, from https://redwirespace.com/newsroom/space-crystals-developing-laser-optics-products-in-space/

[6] Brinson, L. C. (2011, March 3). *What breakthroughs in medicine came from NASA?* HowStuffWorks. Retrieved 2022, from https://science.howstuffworks.com/innovation/nasa-inventions/nasa-breakthroughs-in-medicine.htm#:~:text=Here%20are%20a%20few%20of,angioplasty%2C%20using%20fiber%2Doptic%20catheters

[7] Thompson, A. (2019, August 7). *Medicine in space: What microgravity can tell us about human health*. Scientific American. Retrieved 2022, from https://www.scientificamerican.com/article/medicine-in-space-what-microgravity-can-tell-us-about-human-health/

[8] Skibba, R. (2021, December 29). *2021 was the year space tourism opened up. But for whom?* Wired. Retrieved 2022, from https://www.wired.com/story/2021-was-the-year-space-tourism-opened-up-but-for-whom/#:~:text=In%20the%20early%20years%20of,to%20be%20far%20too%20ambitious

[9] Taylor, D. (2021, March 31). *The Future of Space Tourism: Op-ed*. Space.com. Retrieved 2022, from https://www.space.com/future-of-space-tourism-op-ed

[10] Margetta, R. (2021, December 14). *NASA selects companies to develop commercial destinations in Space*. NASA. Retrieved 2022, from https://www.nasa.gov/press-release/nasa-selects-companies-to-develop-commercial-destinations-in-space

[11] Mafi, N. (2021, March 5). *The world's first space hotel to open in 2027*. Architectural Digest. Retrieved 2022, from https://www.architecturaldigest.com/story/worlds-first-space-hotel-open-2027

[12] Abela, P. (2020, October 12). *Can space mirrors save humanity from climate catastrophe?* Medium. Retrieved 2022, from https://medium.com/climate-conscious/can-space-mirrors-save-humanity-from-climate-catastrophe-6a3cb548b950

[13] Leprince-Ringuet, D. (2020, April 1). *Solar Power, even at night: These giant space mirrors could send sunlight back to Earth after dark*. ZDNet. Retrieved 2022, from https://www.zdnet.com/article/solar-power-even-at-night-these-giant-space-mirrors-could-send-sunlight-back-to-earth-after-dark/

[14] Fang, J. (2014, April 28). *Japan's 25-year plan to have Space Solar Power*. ZDNet. Retrieved 2022, from https://www.zdnet.com/article/japans-25-year-plan-to-have-space-solar-power/

[15] Snowden, S. (2018, October 2). *A colossal elevator to space could be going up sooner than you ever imagined.* NBCNews. Retrieved 2022, from https://www.nbcnews.com/mach/science/colossal-elevator-space-could-be-going-sooner-you-ever-imagined-ncna915421

[16] Edwards, B. C., & Westling, E. A. (2003). *The space elevator*. Spageo Inc.

[17] Jones, A. (2021, August 20). *Astronauts conduct second Chinese space station spacewalk*. SpaceNews. Retrieved 2022, from https://spacenews.com/astronauts-conduct-second-chinese-space-station-spacewalk/

[18] Alamalhodaei, A. (2021, June 17). *China launches 3 astronauts to its New Space Station Core Module*. TechCrunch. Retrieved 2022, from https://techcrunch.com/2021/06/17/china-launches-3-astronauts-to-its-new-space-station-core-module/?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmNvbS8&guce_referrer_sig=AQAAALFaQenjKr6Yk1nOd0T9WFTCqkpinp161JJmZrQV_bHyeurdf38UVtMhntqjatvnwCrsWYbua1uNar_JJ9xQIQaIMdCd_M2Kaovl9bHuqzIYhSXcKEnufSPvuFrXLBBuFRqoRFSQLVgdsoH4hMkBRX3eH-5wcn_SMbTayRbOv8La

[19] May, S. (2018, June 27). *Eating in space*. NASA. Retrieved 2021, from https://www.nasa.gov/audience/foreducators/stem-on-station/ditl_eating

[20] *What do astronauts eat in space?* Royal Museums Greenwich. (n.d.). Retrieved 2021, from https://www.rmg.co.uk/stories/topics/what-do-astronauts-eat-space

[21] Heiney, A. (2021, July 12). *Growing plants in space*. NASA. Retrieved 2021, from https://www.nasa.gov/content/growing-plants-in-space

[22] NASA. (2018, August 20). *NASA's trash talk: Managing garbage in space*. Design World. Retrieved 2021, from https://www.designworldonline.com/nasas-trash-talk-managing-garbage-in-space/

[23] McAuliffe-Shepard Discovery Center. (2020, May 26). *Distance learning module: Recycling water in Space*. McAuliffe-Shepard Discovery Center. Retrieved 2021, from https://www.starhop.com/blog/2020/5/26/distance-learning-module-recycling-water-9b42j

[24] Sullivan, K. (2019, June 21). *How the ISS recycles its air and water*. Popular Science. Retrieved 2021, from https://www.popsci.com/how-iss-recycles-air-and-water/

[25] Allison, P. R. (2016, May 18). *How much does a bottle of water cost on the International Space Station?* Alphr. Retrieved 2021, from https://www.alphr.com/space/1003486/how-much-does-a-bottle-of-water-cost-on-the-international-space-station/

[26] Griffin, A. (2020, August 6). *Mars and the Moon have underground tubes so big they could host bases, scientists say*. The Independent. Retrieved 2021, from https://www.independent.co.uk/life-style/gadgets-and-tech/news/mars-moon-base-astronaut-lava-tubes-a9657471.html

[27] David, L. (2019, July 31). *Will future lunar bases be underground?* Scientific American. Retrieved 2021, from https://www.scientificamerican.com/article/will-future-lunar-bases-be-underground/

[28] The Boring Company. (n.d.). The Boring Company. Retrieved 2021, from https://www.boringcompany.com/

[29] Strange, A. (2017, July 19). *Elon Musk reveals what his tunnel under La has to do with Mars*. Mashable. Retrieved 2021, from https://mashable.com/article/elon-musk-boring-company-mars-colony

[30] Lambert, F. (2016, December 19). *Elon Musk is apparently serious about launching a tunnel digging company to reduce traffic in cities*. Electrek. Retrieved 2022, from https://electrek.co/2016/12/17/elon-musk-tunnel-digging-boring-company/

[31] Mohon, L. (2020, October 1). *NASA looks to advance large-scale 3D printing for the Moon and Mars*. NASA. Retrieved 2021, from https://www.nasa.gov/centers/marshall/news/releases/2020/nasa-looks-to-advance-3d-printing-construction-systems-for-the-moon.html

[32] Hanaphy, P. (2020, October 2). *Icon partners with NASA to develop 3D printed Moon Infrastructure in 'Project Olympus'*. 3D Printing Industry. Retrieved 2021, from https://3dprintingindustry.com/news/icon-partners-with-nasa-to-develop-3d-printed-moon-infrastructure-in-project-olympus-176744/

[33] U.S. Energy Information Administration (EIA). (2021, April 6). *Nuclear explained - Nuclear power plants*. U.S. Energy Information Administration (EIA). Retrieved 2021, from https://www.eia.gov/energyexplained/nuclear/nuclear-power-plants.php

[34] U.S. Energy Information Administration (EIA). (2021, December 17). *Nuclear explained - Nuclear power and the environment*. U.S. Energy Information Administration (EIA). Retrieved 2021, from https://www.eia.gov/energyexplained/nuclear/nuclear-power-and-the-environment.php

[35] *Nuclear fusion power*. Guide to the Nuclear Wall Chart. (2000, August 9). Retrieved 2021, from https://www2.lbl.gov/abc/wallchart/chapters/14/2.html

[36] NASA. (1988, April 25). *Lunar helium-3 and fusion power.* NASA. Retrieved 2021, from https://ntrs.nasa.gov/citations/19890005471

[37] Barnatt, C. (2016, January 30). *Helium-3 power generation*. ExplainingTheFuture. Retrieved 2021, from https://www.explainingthefuture.com/helium3.html

[38] Garcia, M. (2017, August 3). *About the space station solar arrays*. NASA. Retrieved 2021, from https://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays-about.html

[39] Dana, R. (2017, August 7). *Solar in space: Powering the international space station*. Solar Tribune. Retrieved 2021, from https://solartribune.com/solar-space-powering-international-space-station/

[40] NASA. (n.d.). *Rover energy*. MARS Exploration Rovers. Retrieved 2021, from https://mars.nasa.gov/mer/mission/rover/energy/

[41] Calderone, L. (2018, May 22). *Quantum dot solar cells are coming*. AltEnergyMag. Retrieved 2022, from https://www.altenergymag.com/article/2018/05/quantum-dot-solar-cells-are-coming/28547

[42] National Renewable Energy Laboratory (U.S.). (2013, August). *Quantum dots promise to significantly boost solar cell efficiencies (fact sheet)*. UNT Digital Library. Retrieved 2022, from https://digital.library.unt.edu/ark:/67531/metadc841846/

[43] Zona, K. (2010, July 29). *Liquid hydrogen--the fuel of choice for space exploration*. NASA. Retrieved 2021, from https://www.nasa.gov/topics/technology/hydrogen/hydrogen_fuel_of_choice.html

[44] Brown, M. (2019, October 15). *SpaceX: How elon musk plans to power Mars' space-age fuel depots*. Inverse. Retrieved 2021, from https://www.inverse.com/article/60133-spacex-how-elon-musk-plans-to-power-mars-space-age-fuel-depots

[45] Frost, R. (2015, May 13). *How long can you stay in space, and what happens if you stay too long?* Gizmodo. Retrieved 2021, from https://gizmodo.com/how-long-can-you-stay-in-space-and-what-happens-if-you-1704271789

[46] Canadian Space Agency. (2019, May 16). *Physical activity in space*. Canadian Space Agency. Retrieved 2021, from https://www.asc-csa.gc.ca/eng/astronauts/living-in-space/physical-activity-in-space.asp

[47] Canadian Space Agency. (2019, August 22). *Sleeping in space*. Canadian Space Agency. Retrieved 2021, from https://www.asc-csa.gc.ca/eng/astronauts/living-in-space/sleeping-in-space.asp

[48] Gregg, T. (2021, March 23). *How do astronauts go to the bathroom in space?* University at Buffalo. Retrieved 2021, from http://www.buffalo.edu/ubnow/stories/2021/03/gregg-conversation-bathroom-space.html

[49] US Department of Commerce, N.O.A.A. (2020, August 7). *The Sun and Sunspots.* National Weather Service. Retrieved 2022, from https://www.weather.gov/fsd/sunspots

[50] Center for Science Education. (2013). *Solar Flare.* National Weather Service. Retrieved 2022, from https://scied.ucar.edu/learning-zone/sun-space-weather/solar-flare

[51] United States Environmental Protection Agency. (n.d.). *Radiation Basics*. Retrieved 2022, from https://www.epa.gov/radiation/radiation-basics

[52] NASA. (2021, July 22). *What is the solar cycle?.* NASA Science. Retrieved 2022, from https://spaceplace.nasa.gov/solar-cycles/en/

[53] National Aeronautics and Space Administration (n.d.). *Solar Wind*. Retrieved 2021, from https://www.jpl.nasa.gov/nmp/st5/SCIENCE/solarwind.html

[54] US Department of Commerce, N.O.A.A. (n. d.). *Coronal Mass Ejections.* National Weather Service. Retrieved 2022, from https://www.swpc.noaa.gov/phenomena/coronal-mass-ejections

[55] Center for Science Education (2012). *Coronal Mass Ejection (CME).* Sun and Space Weather. Retrieved 2022, from https://scied.ucar.edu/learning-zone/sun-space-weather/coronal-mass-ejection

[56] US Department of Commerce, N.O.A.A. (n. d.). *Types of Space Weather Storms.* National Weather Service. Retrieved 2022, from https://www.weather.gov/safety/space-storm-types

[57] US Department of Commerce, N.O.A.A. (n. d.). *Geomagnetic Storms.* National Weather Service. Retrieved 2022, from https://www.swpc.noaa.gov/phenomena/geomagnetic-storms

[58] Lang, K. R. (2010). *Danger Blowing in the Wind.* Tufts University. Retrieved 2022, from https://ase.tufts.edu/cosmos/view_chapter.asp?id=29&page=3#:~:text=Intense%20radiation%20from%20solar%20flares,farther%20into%20space%20than%20usual

[59] Wilson, J. (2007, November 30). *Sickening solar flares*. NASA. Retrieved 2021, from https://www.nasa.gov/vision/space/livinginspace/27jan_solarflares.html

[60] The Royal Society of Victoria. (2021, May 28). *Surviving the journey: Protecting astronauts from Space Radiation*. The Royal Society of Victoria. Retrieved 2021, from https://rsv.org.au/space-radiation/

[61] Roylance, F. D. (2000, November 11). *Space station astronauts take shelter from solar radiation*. The Baltimore Sun. Retrieved 2021, from https://www.baltimoresun.com/news/bs-xpm-2000-11-11-0011110386-story.html

[62] US Department of Commerce, N.O.A.A. (n. d.). *Solar Radiation Storms.* National Weather Service. Retrieved 2022, from https://www.swpc.noaa.gov/phenomena/solar-radiation-storm

[63] NASA. (2020, June 23). *What is a Lagrange Point.* Solar System Exploration. Retrieved 2022, from https://solarsystem.nasa.gov/resources/754/what-is-a-lagrange-point/

[64] NASA. (2019, July 24). *DSCOVR.* NASA Solar System Exploration. Retrieved 2022, from https://solarsystem.nasa.gov/missions/DSCOVR/in-depth/

[65] Rougeot, R., Flamary, R., Galano, D., & Aime, C. (2017, February 20). *Performance of the hybrid externally occulted lyot solar coronagraph - application to ASPIICS.* Astronomy & Astrophysics. Retrieved 2022, from https://www.aanda.org/articles/aa/full_html/2017/03/aa29259-16/aa29259-16.html

[66] NASA. (n.d.). *SOHO: The Sun, Inside Out.* Retrieved 2022, from https://www.nasa.gov/mission_pages/soho/overview/index.html

[67] Solar System Research. (n.d.). *Das Sonnen- und Heliophären-Observatorium.* Max Planck Insitute. Retrieved 2022, from https://www.mps.mpg.de/solar-physics/soho-mission

[68] SpaceRef. (2000). *Space station user's guide*. SpaceRef. Retrieved 2021, from http://spaceref.com/iss/medical.ops.html#routine

[69] Zhang, L. (2021). Development and prospect of Chinese Lunar Relay Communication Satellite. *Space: Science & Technology*, *2021*, 1–14. https://doi.org/10.34133/2021/3471608

[70] Bhasin, K., Hackenberg, A., Slywczak, R., Bose, P., Bergamo, M., & Hayden, J. (2012). Lunar Relay Satellite Network for Space Exploration: Architecture, Technologies and Challenges. *24th AIAA International Communications Satellite Systems Conference*, 1–15. https://doi.org/10.2514/6.2006-5363

[71] Popular Mechanics. (2004, December 7). *Mining the Moon*. Popular Mechanics. Retrieved 2021, from https://www.popularmechanics.com/space/moon-mars/a235/1283056/

[72] ISS National Laboratory. (n.d.). *History and timeline of the ISS*. ISS National Laboratory. Retrieved 2021, from http://www.iss-casis.org/about/iss-timeline/

[73] Staats, E. B. (1972). (rep.). *Cost-Benefit Analysis Used In Support Of The Space Shuttle Program* (pp. 1–53). Washington, D.C.: NASA. Retrieved from http://archive.gao.gov/f0302/096542.pdf.

[74] McCartney, F. S. (2006). *National Security Space Launch Report: The congressionally mandated national security space launch requirements panel*. RAND.

[75] Krebs, G. D. (n.d.). *Atlas-5*. Gunter's Space Page. Retrieved 2021, from https://space.skyrocket.de/doc_lau/atlas-5.htm

[76] *LRE RD-180*. Liquid Propellant Rocket Engines. (n.d.). Retrieved 2021, from http://www.lpre.de/energomash/RD-180/index.htm

[77] Clark, S. (2020, August 5). *Ula, spacex win contracts to launch satellites for SES in 2022*. Spaceflight Now. Retrieved 2021, from https://spaceflightnow.com/2020/08/05/ula-spacex-win-contracts-to-launch-satellites-for-ses-in-2022/

[78] Zelnio, R. (2006, January 9). *A short history of export control policy*. The Space Review. Retrieved 2021, from https://www.thespacereview.com/article/528/1

[79] Lin, J., & Singer, P. W. (2016, May 5). *China aims for humanity's return to the Moon in the 2030s*. Popular Science. Retrieved 2021, from https://web.archive.org/web/20160508225643/https:/www.popsci.com/china-aims-for-humanitys-return-to-moon-in-2030s

[80] SpaceX. (n.d.). SpaceX. Retrieved 2021, from https://www.spacex.com/vehicles/starship/

[81] Kramer, M. (2013, June 25). *Moon Base Visions: How to build a Lunar Colony (photos)*. Space. Retrieved 2021, from https://www.space.com/21583-moon-base-lunar-colony-photos.html

[82] De Kestelier, X., Dini, E., Cesaretti, G., Colla, V., & Pambaguian, L. (n.d.). *Lunar outpost design for ESA*. SpaceArchitect. Retrieved 2021, from https://spacearchitect.org/portfolio-item/lunar-outpost-design-for-esa/

[83] Gibney, E. (2018, October 24). *How to build a Moon base*. Nature. Retrieved 2021, from https://www.nature.com/articles/d41586-018-07107-4#content

[84] Bhardwaj, A., Dhanya, M. B., Alok, A., Barabash, S., Wieser, M., Futaana, Y., Wurz, P., Vorburger, A., Holmström, M., Lue, C., Harada, Y., & Asamura, K. (2015). A new view on the solar wind interaction with the Moon. *Geoscience Letters*, *2*(1), 1–15. https://doi.org/10.1186/s40562-015-0027-y

[85] Potter, S. (2021, January 4). *NASA's Sofia discovers water on sunlit surface of Moon*. NASA. Retrieved 2021, from https://www.nasa.gov/press-release/nasa-s-sofia-discovers-water-on-sunlit-surface-of-moon

[86] Greer, L. C., Krasowski, M. J., Prokop, N. F., & Spina, D. C. (2013, February 1). *Cratos: The evolution of a robotic vehicle*. NASA. Retrieved 2021, from https://ntrs.nasa.gov/citations/20130010983

[87] Piazza, E. (n.d.). *Power systems*. NASA. Retrieved 2021, from https://rps.nasa.gov/power-and-thermal-systems/power-systems/

[88] Hall, L. (2020, July 20). *6 technologies NASA is advancing to send humans to Mars*. NASA. Retrieved 2022, from https://www.nasa.gov/directorates/spacetech/6_Technologies_NASA_is_Advancing_to_Send_Humans_to_Mars

[89] ABC Science. (2015, September 28). *What we would need to do to send people to Mars*. ABC News. Retrieved 2022, from https://www.abc.net.au/news/science/2015-09-28/five-key-technologies-needed-to-get-people-to-mars/6802314

[90] Boston Dynamics. (n.d.). Boston Dynamics. Retrieved 2022, from https://www.bostondynamics.com/atlas

[91] ResearchFDI. (2021, September 22). *Here's everything you need to know about Elon Musk's 'Tesla bot'*. ResearchFDI. Retrieved 2022, from https://researchfdi.com/tesla-bot-elon-musk-robot/#:~:text=Musk%20says%20his%20robot%20will,know%20about%20cryptocurrency%20and%20blockchain