An Exploration of Necessary Practices for Long Term Space Habitation

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Initially driven by “space race” tensions between the United States (US) and the Union of Soviet Socialist Republics (USSR), human space exploration became a goal in the 20th century (Genta & Rycroft, 2006). Fueled by competition, each nation sought to improve and expand their programs. Early victories went to the USSR such as the first satellite in space, Sputnik 1, and the first human in space, Yuri Gagarin. In an effort to establish leadership and technological capabilities, the US sought to land the first person on the moon by the end of the 1960s. At a time when the total amount of time spent in space by humans was 123 minutes (2.05 hours) this seemed like a lofty goal to accomplish.

Just 8 years later, Apollo 11 successfully landed on the moon with five subsequent missions also proving successful. Since the days of the Apollo missions and the space race, there has been a focus on human inhabited space stations of which the first, Salyut 1, was launched in 1971 by the USSR. Today, the International Space Station (ISS) and the Tiangong space station are two continuously inhabited space stations orbiting the Earth. The ISS has been continuously inhabited for the past 23 years. With this, there is a long-established history of human presence in space. In the coming decades, there are also additional space stations planned and missions to the Moon and Mars in the coming decades. However, space stations are unique in the sense they are in a low Earth orbit (LEO), allowing for instantaneous communication and a short resupply time of 6 to 48 hours. A mission to the Moon would take a few days while a mission to Mars can take upwards of 9 months. A mission to Mars also comes with the issue of delayed communication between the crew and mission control on Earth.

As human space exploration grows, and missions get increasingly farther away from the Earth, having a way to safely provide for those participating in off world missions, without the ability for quick aid from Earth, will become increasingly important. In this way, there is much that can be learned from both current and past space missions that have taken place both on Earth as analog missions and off Earth as practical missions. This research paper will examine lessons learned from past, and current, space habitation endeavors and compile practices deemed necessary for long term space habitation as a result.

Case Context: The Importance of Long-Term Space Habitation

A large part of human space exploration is reliant on available technologies. These include many technologies such as those that maintain life support systems (oxygen generators, water reclaimers, etc.) to solar panels that provide electricity to name a few. Additionally, there are numerous people, policies, and organizations related to space habitation. The main people involved are both private and public organizations such as NASA, the European Space Agency (ESA), and SpaceX. These organizations are at the forefront of designing and building space habitats whether that be for scientific research, space exploration, or commercial use. Scientific researchers are also involved in space habitation as they often implement science goals for a mission (Marconi, 2004). In the scope of space habitation, different codes need to be followed for safety. For space habitation this means certain requirements, such as those defined by the Federal Aviation Administration (FAA) including necessary training and safety measures (Human Spaceflight Requirements, 2006). These types of regulations implement standard operating procedures for launches of all types of missions, adding another dimension that influences overall design and implementation.

Currently, there has been success with long term space habitation in the form of space stations that remain in LEO which is close enough to send help or contact in the case of an emergency. There is much less available information on what long term space habitation would be like in practice outside of the confines of Earth's gravitational pull. Up to this point the longest time spent away from Earth's orbit by humans is the approximate 147.8 hours (6.16 days) spent by the Apollo 17 mission in lunar orbit. Additionally, even with the prominence of space stations in the age of human space exploration, the longest a person has been in space for, in an uninterrupted interval, is 437.7 days. With proposed missions to Mars taking upwards of 9 months each way, a minimum of around 540 days of transversal time, plus the time spent in Martian orbit, there is still a considerable amount that must be known for such a mission to be successful.

Human space exploration plays an important role in society today. In the past decade, the space industry has nearly doubled. It is continuing to grow at a rapid rate, with another doubling set to occur by 2030. The last decade has seen more reliance on commercial agencies as well as the emergence of new agencies as key players in the space exploration industry. Aside from the depths of the Earth's oceans and a few remote areas, space is the next great frontier to be discovered. The farthest technology, Voyager 1, is only about 22.5 light-hours (unit of distance it would take light to travel in an hour) away from the Earth. The radius of the Milky Way Galaxy in which Earth resides is 52.85 light-years, while the radius of the visible Universe is 45.7 billion light-years. This is an extreme amount of space that humans may not hope to uncover without major technological advancements especially with the farthest place currently visited by humans, the Moon, is only 1.28 light-seconds away.

As a result of in-space missions being costly, with a mission to the ISS upwards of $140 million, it is not always feasible to conduct certain experiments in an actual space environment. This has led to the development of analog missions which are simulated environments that are meant to be a mockup of a space mission that occurs here on Earth. Many of these analog missions are done to test both psychological and physiological effects on humans in a space habitat environment for prolonged periods of time. Still, there are more that go through the day-to-day schedules of crew or even incorporate new technologies to simulate real extravehicular activity (EVA) experiments as they would occur on a real mission such as one to Mars (Piantadosi, 2015). Additionally, the building of simulated space habitats on Earth allows for matters like habitat configuration and what is needed to sustain everyday life to be fully built out before launching a multi-million-dollar mission that puts human lives at stake. In this way, analog missions are important since they can give insight into what is needed both in terms of crew health and scheduling and space habitat architecture.

In space exploration, many entities such as people, policies, and organizations play a role. In this, there are many policies, such as the FAA's Human Spaceflight Requirements which dictate how missions must be conducted. However, these policies often only consider minimum requirements to sustain life. The reality of space travel is that conditions are harsher than can be accurately accounted for on Earth and requirements must be changed as a result. Without challenging and adding additional considerations into missions, crew members may experience negative consequences. With severe conditions such as sudden changes in force experienced during transport and prolonged periods in a zero-gravity environment, past missions and studies conducted can help improve practices in future missions to places such as the Moon and Mars to go beyond simply sustaining life and make the experience more enjoyable, and less violent or jarring, for astronauts. Additionally, new discoveries and technologies can make life in space better understood which can lead to improvements in living conditions and research practices.

As human space exploration becomes more prominent, and as humans begin to spend more time away from the Earth, making a space habitat that supports life and daily functions and makes life in space enjoyable will be key for healthy, and happy, astronauts. Knowing the best practices to implement in future space habitats will be key in prolonging the human presence in space for generations to come.

Infrastructure: An Exploration of Space Habitation as a Result of Society

To understand the connections between technology and humans regarding space habitation, Star's (1999) concept of infrastructure can be used. In this framework the built environment becomes more developed in relation to organized practices and actions. One of the nine aspects of infrastructure is *reach or scope*. This aspect highlights a technology that is beyond a one-time occurrence but is instead something that has been implemented multiple times. For example, the International Space Station (ISS) brings together multiple flight vehicles and people from around the world. Before the ISS, the United States operated Skylab which was its only exclusive space station that was occupied from May 1973 to February 1974 (Kay, 1994). Additionally, other entities have established separate space station habitats including the China Manned Space Agency (CMSA) with the Tiangong-1, Tiangong-2, and Tiangong space stations. Several others also have plans for space stations in the near future including Roscosmos' Russian Orbital Station (ROS) and several commercial stations including VAST's Haven-1 station. Around the world, many agencies are making plans for long-term space habitation including habitats for the ISS end of mission, lunar modules, and Mars habitats (Billings, 2006).

Improvements can be made in the case of mistakes or failures, leading to additional contributions to long-term survival in space and spaceflight research (Chen et. al., 2021).

Another facet of infrastructure is *links with conventions of practice,* which means that infrastructure has the potential to both impact and be impacted by norms of behavior in a community. In the case of space habitation, politics are often largely considered. The earliest example is the Space Station Freedom. This was a proposed permanent space station orbiting the Earth whose frameworks evolved into the International Space Station (ISS). Freedom was initially approved but the complexity and size of the proposed design led it to have financial and political problems. It was ultimately shut down due to differing opinions and budget constraints (Kay, 1994). Additionally, science is often a major factor in space missions. However, in the realm of space exploration science was not always at the forefront. It was not until 1965 that the first science-astronauts were selected, 6 years after the first astronaut group (Chaikin, 1998). As scientists began seeking further science focus after the technology for space missions developed, science focused missions have risen as seen with the abundance of experiments currently run on the ISS from microgravity to living organisms (Genta and Rycroft, 2003).

A third aspect is *learned as part of membership*, which details how people become familiar with tasks, routines, and behavior as they become members. Before leaving Earth, astronauts must undergo a rigorous training regime over a two-year period that complies with regulations set by the relevant human spaceflight laws such as those set by the FAA (Human Spaceflight Requirements, 2006). This is due to both challenges faced during launch and differences in forces experienced during a mission. During launch, astronauts experience extreme forces with space station missions leading to a 3-g force (a force that is three times the force of gravity). Human missions beyond LEO require even more force such as the 5-g forces experienced by Apollo era astronauts. Thus, extra precautions must take place to get astronauts used to the jarring shifts in forces that they will experience. Once an astronaut enters a space habitat, they must undergo an acclimation process. Since humans are used to the force of gravity being a constant presence, going to a place with less or no gravity takes a period of adjustment despite rigorous pre-departure training (Uri, 2020). Additionally, tests are conducted on the long-term effects of zero gravity on human physiology (Huntress, 2003). Knowing what these effects are and how to best counteract negatives is essential for long-term space habitation (Chen et. al., 2021).

Research Question and Methods

With the growing interest in long-term space exploration, there are lessons that can be learned through past experiences to influence future missions. A logical question follows: How can lessons be learned from past experiences to inform the practices that are needed for successful long-term space habitation missions in the future?

To answer this question, I conducted case studies of the ISS and on-Earth endeavors. I examined how the ISS evolved from the Space Station Freedom (Lambright, 2019) and gathered lessons learned from previous missions such as scheduling conflicts of the Skylab 4 crew (Uri, 2020). I also examined the incremental growth of the ISS (Catchpole, 2008) and the influence of international cooperation and commercial space industry efforts on life in space (Genta and Rycroft, 2003). Additionally, the Apollo era missions were investigated to provide insight into how early, shorter length missions affected current implementations (Chaikin, 1998).

The on-Earth endeavors I examined were the Crew Health and Performance Exploration Analog (CHAPEA), Mars500, and Biosphere 2. CHAPEA is a series of one-year missions that simulate life on Mars (NASA, 2023). Mars500 was a psychological and physiological experiment that simulated living on Mars (ESA, 2023). Biosphere 2 is an Earth science research facility that was originally built as a closed ecological system. Initial experiments were geared towards examining the necessity of a similar system in human space habitats (Nelson, 2021). Lessons learned from these experiments will be useful in determining necessary practices for expanding human space exploration as well as the physical and emotional well-being of astronauts.

While analyzing these instances I collected the practices needed for successful long-term space habitation by identifying practices highlighted by the aspects of infrastructure discussed previously. This data was then compared with plans for future human spaceflight and regulations as stated in the most recent Planetary Science and Astrobiology Decadal Survey, a survey outlining recommendations for the next decade (National Academies of Sciences, Engineering, and Medicine, 2023), and the FAA Human Spaceflight Requirements (Human Spaceflight Requirements, 2006). The data analysis and interpretation approach were qualitatively focused, with factors related to the infrastructure framework, and a case study approach with additional focus on the ISS. To better understand the data collected and to make more meaningful conclusions, the data was graphed based on the number of occurrences a qualitative finding has.

Results

Past experiences in space exploration and habitation give insight into the needed practices for future long term space habitation. Nine primary areas that act as necessary implementations for future long-term space habitation projects were identified including scientific experiments, psychological effects, life support systems, daily exercise requirements, international and commercial cooperation, budget and political constraints, radiation exposure and protection, in-situ resource utilization, and space debris avoidance. For the convenience of this discussion, the data of life support systems, daily exercise requirements, and radiation exposure and protection were grouped into a larger category of physiological effects, since all three deal with sustaining healthy human life and mitigating effects of space and extended exposure to microgravity. While budget and political constraints had a notable number of occurrences, this research conducted, using the methods previously discussed, indicates the most common areas identified from previous missions that influence space habitation endeavors are the physiological and psychological well-being of astronauts, international and commercial cooperation efforts, and scientific experiments that are conducted during missions. Several other areas such as space debris mitigation and in-situ resource utilization have also seen to be important considerations but often go overlooked. The full results based on the number of occurrences over six cases investigated are shown in Table 1.

Table 1: Number of occurrences of suggested implementation strategies based on six primary cases researched including Apollo, Skylab, the evolution of the ISS, CHAPEA, Mars500, and Biosphere 2 (Lambright, 2019; Uri, 2020; Catchpole, 2008; Genta and Rycroft, 2003; Chaikin, 1998; NASA, 2023; ESA, 2023; Nelson, 2021).

Suggested Implementation for Future Space Habitats	Mission						Total Number of Occurrences
	On Earth			Off Earth			
	Biosphere 2 (1991-1994)	Mars500 (2007-2011)	CHAPEA (2023-present)	Apollo (1963-1972)	Skylab (1973-1974)	ISS (1998-present)	
Life Support Systems	X	X	X	X	X	X	15 (noted as Physiological Effects)
Daily Exercise Requirement		X	X	X	X	X	
Radiation Exposure/Protection			X	X	X	X	
Psychological Effects	X	X	X	X	X	X	6
Scientific Experiments	X	X	X	X	X	X	6
International/Commercial Cooperation		X	X	X	X	X	5
Budget/Political Constraints			X	X	X	X	4
In-Situ Resource Utilization	X					X	2
Space Debris					X	X	2

Reach or Scope: Microgravity and Cooperation

In this analysis, Star's (1999) concept of infrastructure was used. *Reach or scope*, one of the nine aspects, highlights a technology that is beyond a one-time occurrence but is instead something that has been implemented multiple times. This is prevalent in each of the four main practices identified that are necessary for the implementation of long-term space habitation. For the physiological effects, which made up the largest portion of identified occurrences over the six cases investigated, every case identified one or more ways where this was a featured concern. Microgravity could have detrimental effects on the human body and other living organisms. It is true that they can survive but with negative effects such as space sickness (nausea, sweating, vomiting, loss of appetite for the first few days), general redistribution of all bodily fluids, cardiovascular changes, loss of bone material, and a height increase (Genta and Rycroft, 2003). This can be problematic during reentry but can be limited with regular physical exercise. Several suggestions related to space stations after the ISS is decommissioned also suggest the possibility to create artificial gravity through rotation (Chen, et. al, 2021). In accordance with this, a prominent feature of many space modules and simulations including the Apollo modules, Skylab, the ISS, CHAPEA, and Mars500 is exercise equipment.

Additionally, international and commercial cooperation efforts have played a major role in space habitation endeavors. For example, Space Station Freedom was initially an endeavor between the U.S., Europe, and Japan before it grew beyond what was realistically sustainable (Kay, 1994). Following this, came the ISS which is an effort of seven international and commercial partners. There are two segments the Russian Orbital Segment assembled by Roscosmos, and the US Orbital Segment assembled by National Aeronautics and Space Administration (NASA), Japan Aerospace Exploration Agency (JAXA), European Space

Association (ESA), and Canadian Space Agency (CSA). In total it consists of forty-three modules and elements installed, each launched and added to the ISS separately which began with the launch of the ISS module, Zarya, on November 20th, 1998, and was followed by second module Unity two weeks later. After Zvezda was launched in July 2000, the crew was able to stay on the ISS permanently (Catchpole, 2008).

Links with Conventions of Practice: The Evolution of Scientific Experiments

Another facet of infrastructure is *links with conventions of practice*, which means that infrastructure has the potential to both impact and be impacted by norms of behavior in a community. This means that technology may change as a result of implementations common in an industry. In the case of an incident that has negative consequences, it may also change these common implementations for the better. In this research, it was found that scientific experiments have the opportunity to advance as technology and occurrences advance. For example, earlier space habitation missions, including the early Apollo missions and early days of the ISS, included fewer scientific experiments as the focuses of the missions were to prove the feasibility of the new technologies being used and to maintain crew safety. Additionally, as more missions in space took place, more different reactions to technologies in space were known. This allowed for later missions such as the later Apollo missions (Chaikin, 1998) and current state of the ISS (Lambright, 2019), to focus on more advanced scientific experiments such as lunar geology focuses and plant growth in zero gravity environments.

In the case of the three analogs, those resembling expected experience for life in a habitat in space, investigated Earth missions, these were used to inform primarily the psychological effects of long-term isolation that a long-term habitation mission would require. While not able to inform different effects of being in a space environment, these missions were able to simulate all other aspects of daily life in space including simulated scientific experiments and in some cases surface missions (ESA, 2023). In the case of CHAPEA (NASA, 2023) and Biosphere 2 (Nelson, 2021), in-situ resource utilization in the form of crop production and usage was also prioritized. As on Earth endeavors become more common, more scheduling and scientific experiments under given conditions can be figured out for future long-term habitation missions beforehand to mitigate negative outcomes during a mission.

Learned as Part of Membership: Training and Scheduling

A third aspect is *learned as part of membership*, which details how people become familiar with tasks, routines, and behavior as they become members. In terms of physiological and psychological effects, the launch process can be extremely taxing on a human both physically and mentally. Before leaving Earth, astronauts must undergo a rigorous training regime over a two-year period that complies with regulations set by the relevant human spaceflight laws such as those set by the FAA (Human Spaceflight Requirements, 2006). Astronauts can undergo extreme forces during launch depending on the distance from Earth they are traveling, with instances from the lunar missions of Apollo clocking in at upwards of 5-g forces (a force that is five times the force of gravity). While the training is in an effort to acclimate astronauts to what they might experience in reaching their destinations, simulations are not always an accurate depiction of launches, with one Apollo astronaut describing one particularly violent stage of the launch as “, [feeling] as though [they] were helpless prey in the mouth of a giant, angry dog,” (Chaikin, 1998, p. 86).

Still, astronauts must go through an acclimation process to zero or reduced gravity once reaching their destination such as a space habitat. This requires time taken off mission objectives. In some cases, such as the scheduling errors of the Skylab 4 mission, this is not accounted for, and the crew is scheduled like they were already acclimated. With the Skylab 4 crew, this added frustrations and allowed no time for familiarization or recovering from errors or hardware malfunctions. It was not until several weeks into the mission where scheduling was discussed which resulted in several new implementations for all future long-term habitation missions including protecting crew off-duty days every 10 days, minimizing scheduling activities during the crew's pre-sleep and post-sleep periods, allowing time between different activities for the astronauts to clean up, and not splitting up the crew's exercise periods (Uri, 2020).

Discussion

The largest influence on space habitation endeavors identified from the cases researched are the physiological and psychological well-being of astronauts, international and commercial cooperation efforts, and scientific experiments that are conducted during missions. Through the utilization of Star's infrastructure framework, these influences on space habitation were able to be examined in a way that allowed for deeper contextualization in a wider viewpoint.

Ever since the beginning of human spaceflight, a key feature has been to return the astronauts safely back to Earth. With an emphasis on maintaining the health and wellbeing of astronauts, it is unsurprising how both physiological and psychological wellbeing is a priority. Space exploration is extremely physically strenuous with increased, and decreased, gravitational forces, radiation exposure, and atmospheric differences. Rapid crew turnovers in space would also be difficult and costly so long stays would be encouraged in a distant long-term space habitation mission. This would leave crews isolated in smaller spaces with limited resources for extended periods of time. As shown in several of the on-Earth missions, this can have negative impacts on the psychological wellbeing of people. Therefore, increasing priorities to mitigate harmful physiological and psychological effects on humans during long-term habitation missions will be essential.

Space is one place where international and commercial cooperation can thrive even during times of political disunity. Additionally, having different organizations form partnerships on a space habitat can help mitigate the cost for any one organization. With less financial burden, these habitats can also be built bigger than any one organization can make on their own, take the small size of Skylab when compared to the forty-three modules of the ISS for instance.

Space exploration, and efforts to further it, are increasing at a rapid pace. Therefore, the research conducted in this paper was limited to only a few examples of different space endeavors that have been pursued. In an ideal case, a wider array of missions, both on and off Earth, would have been examined, compared, and analyzed to view necessary practices for long-term space habitation from a more complete lens. Additionally, as this was only looking for lessons learned from previous missions, and changes made as a result of policy, or organizational changes were not taken into account. In terms of the infrastructure framework, each aspect was not applicable to each influence identified which may have left some of the implications from the mission examples not analyzed in the manner that they could have if an alternate framework was used.

In the future, it would be beneficial to conduct research including more missions. It may also be beneficial to do more in-depth research on an individual basis. In particular, more missions occurring in space should be investigated. There is only so much that training and simulations can prepare astronauts for missions in space. Conditions and physiological reactions are often much different when actually in space (Chaikin, 1998). Additionally, it would be beneficial to further investigate several of the occurrences that are overlooked such as in-situ and space debris mitigation since they will become more prevalent in future missions especially as they progress towards the possibility of permanent settlements in orbit around and on the moon and Mars.

Conducting research on past missions for the necessary practices for future long-term space habitation endeavors is extremely important for the success of future missions. Space missions on the scale of a space habitat can cost upwards of billions of dollars and can last over a decade (Genta and Rycroft, 2003). On this scale and with political pushbacks often causing a decrease in budgets, there is little room for error. One error can often mean bad publicity for the mission which can decrease public opinion and in turn affect future budgets (Billings, 2006). The more that can be determined ahead of time will lead to missions that run smoother and are therefore more successful. Additionally, in a complex field, knowing the best practices and potential effects of a space environment can lead to more complex technologies being implemented and more advanced scientific experiments being conducted.

Conclusion

In conclusion, space exploration is a rapidly growing field with additional long-term space habitats being considered for the not-so-distant future. From effects on humans in space to political and cooperation interests of those on Earth, space exploration and habitation are topics affected by many competing interests and groups. In the interest of future space habitats and with the goals of a lunar space station and additional Earth orbiting space stations following the ISS end of life planned by the 2030s, investigating additional lessons learned from past missions will ultimately lead to more advanced and successful missions (NASA, 2022; NASA OIG, 2021). Before such missions will be able to occur, there is still much research on lessons learned from past missions that must be done. There is also more that needs to be done regarding technologies that must be developed before such a habitat can be created. However, successful analysis and implementations in a long-term space habitation mission can aid future missions and may contribute to humans one day establishing colonies in space. Space is often considered to be the final frontier and long-term space habitats are the key to exploration missions beyond the Earth.

References

Billings, L. (2006). To the Moon, Mars, and Beyond: Culture, Law, and Ethics in Space-Faring Societies. *Bulletin of Science, technology, & Society*, *26*(5), 430–437. https://doi.org/10.1177/0270467606292504

Catchpole, J. E. (2008). *The International Space Station: Building for the Future*. Springer Science & Business Media.

Chaikin, A. (1998). *A Man on the Moon: The Voyages of the Apollo Astronauts*. Penguin Books.

Chen, M., Goyal, R., Majji, M., Skelton, R.E. (2021). Review of space habitat designs for long term space explorations. *Progress in Aerospace Sciences*. 122, 100692. https://doi.org/10.1016/j.paerosci.2020.100692

ESA. (2023). *Mars500: Study Overview*. The European Space Agency. https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Mars500/Mars500_study_overview

Genta, G., & Rycroft, M. (2003). *Space, the final frontier?*. Cambridge University Press.

Genta, G. & Rycroft, M. (2006). Will space actually be the final frontier of humankind?, *Acta Astronautica*, 58(5), 287-295. https://doi.org/10.1016/j.actaastro.2005.12.005.

Human Spaceflight Requirements, 14 C.F.R. § 460 (2006). https://www.ecfr.gov/current/title-14/chapter-III/subchapter-C/part-460#sp14.4.460.a

Kay, W. (1994). Democracy and Super Technologies: The Politics of the Space Shuttle and Space Station Freedom. *Science, Technology, & Human Values*, *19*(2), 131–151. https://doi.org/10.1177/016224399401900201

Lambright, W. (2019). Administrative Leadership and Long-Term Technology. *Space Policy*. *47*, 85-93. https://doi.org/10.1016/j.spacepol.2018.07.003

NASA. (2022). *International Space Station Transition Report*. NASA. https://www.nasa.gov/wp-content/uploads/2015/01/2022_iss_transition_report-final_tagged.pdf

NASA. (2023). *Crew Health and Performance Exploration Analog*. NASA. https://www.nasa.gov/humans-in-space/chapea/

NASA OIG. (2021). *NASA's Management of the Artemis Missions*. NASA. Retrieved April 8, 2024, from https://oig.nasa.gov/wp-content/uploads/2024/02/IG-22-003.pdf

National Academies of Sciences, Engineering, and Medicine. (2023). *Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26522.

Nelson, M. (2021). Biosphere 2's Lessons about Living on Earth and in Space. *Space: Science and Technology*. 2021, 8067539. https://doi.org/10.34133/2021/8067539

Piantadosi, C. (2015) *Mankind Beyond Earth: The History, Science, and Future of Human Space Exploration*. https://doi.org/10.7312/columbia/9780231162432.001.0001

Star, S. L. (1999). The Ethnography of Infrastructure. *American Behavioral Scientist*, *43*(3), 377–391. https://doi.org/10.1177/00027649921955326

Uri, J. (2020, November 16). *The Real Story of the Skylab 4 "Strike" in Space*. NASA. https://www.nasa.gov/history/the-real-story-of-the-skylab-4-strike-in-space/