Lessons Learned from Antarctica Applied to the Phased Development of a Long-term Martian Station

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ABSTRACT

As preparations are made to send the first humans to Mars, it is important we look beyond short-term goals to develop a long-term plan for human presence on Mars. Currently, NASA plans to resume crewed missions to the Moon within the next few years and send the first crewed mission to Mars in the 2030s. The Moon will be used as a technology testbed in preparation for Mars, while Mars will eventually become a center for scientific research and part of a support infrastructure to allow further deep space exploration. To accomplish this goal, a long-term station will be necessary to provide the functions and infrastructure required. While NASA and other organizations have proposed designs for the initial habitat for a Martian surface mission, there has been little research on how the station will transition past this point. Although we have yet to develop and operate extraterrestrial surface stations, we can draw from our experience designing and operating long-term stations in extreme conditions on Earth. Using Antarctica as a design precedent, lessons can be learned from the design evolution of Antarctic stations and the operational logistics, functions, and human design factors. These lessons can be applied to the phased development of a Martian station and its growth. The goal of this thesis is to use lessons learned from Antarctica to inform the transitional phase of a long-term Martian station to enable growth towards a sustainable mature station.

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NOMENCLATURE

ECLSS = Environmental control and life support system

EVA = Extravehicular activity

GCR = Galactic cosmic radiation

ICTS = Information Communication Technology Services

IGY = International Geophysical Year

ISRU = In-Situ Resource Utilization

ISS = International Space Station

LEO = Low Earth Orbit

NASA = National Aeronautics Space Agency

SLS = Space Launch System

SPE = Solar particle event

VHF = Very high frequency

I. INTRODUCTION

Space travel and exploration has long captured the minds and imaginations of forward thinkers. Science fiction and pop culture have helped popularize the idea of human exploration and colonization of extraterrestrial bodies. Humanity had their first taste of this future when the National Aeronautics and Space Administration (NASA) orchestrated Apollo 11, the first successful human landing on the Moon, and subsequent Apollo missions. Since the end of the Apollo program, human missions have been restricted to the International Space Station (ISS) and more distant extraterrestrial exploration has been performed telerobotically. Today, public interest has shifted beyond the Moon to Mars with NASA planning to return astronauts to the Moon by 2024 and send the first crewed mission to Mars in the 2030s. NASA's Gateway program will use the Moon as a technology and human exploration testbed for Mars and develop infrastructure to support exploration to Mars and beyond. Infrastructure on Mars will support scientific research and become part of a larger support network for future deep space exploration.

A long-term station on Mars capable of supporting a human crew will be essential to fulfilling this vision. While an initial habitat and infrastructure will be sufficient to meet basic scientific goals and human requirements, considerable growth will be needed to provide additional functions and capabilities. Although NASA and others have developed proposals for an initial station and SpaceX and others have speculated what a larger settlement could look like, little research has been done on how the station will transition between the two.

As we have yet to send humans beyond Low Earth Orbit (LEO) and conduct surface operations for extended periods of time, we must turn towards our design experience on Earth to inform our design process. While differing from Mars in many ways, Antarctica was chosen because of its long history of station development in a remote, extreme environment and similarities of operational logistics, functions, and human design factors. Lessons learned from Antarctica can be applied to Martian design and used to create a strategic guide for transitioning towards a sustainable mature station.

Over the course of the thesis, the author will explore the concept and purpose of a long-term Martian station, lessons learned from Antarctic experience, a phased Martian station development, transitional guidelines, and applications to a Martian station design.

II. RESEARCH METHODOLOGY

In this thesis, the author chose to take an architectural approach to the development of a long-term Martian station through the analysis of a design precedent and the application of lessons learned to inform the strategic transition between development phases. As seen in the research flow diagram (Figure 1), the author began with defining the concept of a long-term Martian station. This section describes how the station fits into the larger timeline of deep space exploration proposed by NASA, the assumptions and limitations being used, and the long-term operations and growth of the station.

The author chose to use Antarctic stations as a design precedent because of its long history of station design in an extreme environment. In many ways, a future Martian station can be seen as an extension of Antarctic research station design evolution with Mars being the next level of design challenge. Antarctic station development was analyzed through the lens of operational logistics, functional requirements, and human well-being as design drivers and lessons learned from this process extracted (Figure 1).

The architecture program provides an overview of the Martian station development and can be divided into three main phases – initial, transitional, and mature. The initial phase will include the habitat and infrastructure established by the first crewed mission to Mars, the transitional phase will expand support capabilities to enable sustainable growth, and the mature phase will provide advanced capabilities to operate sustainably. Through analyzing the needs and requirements of the initial and mature phase, necessary infrastructure and capabilities can be defined. The initial phase will provide the functions and surface infrastructure required to meet the first mission's goals and support human life. This infrastructure will be used as the base of the station architecture and subsequent growth added to it. The mature phase will be expected to reach a level of sustainable operations and autonomy from Earth through the use of advanced technologies and provide support for future exploration endeavors. To reach the mature phase, substantial growth will be needed to support expanded functions and capabilities and additional infrastructure to support additional modules and crew. A strategic plan to transition will be essential to guiding how the station will develop incrementally to enable to desired goals for the mature phase.

Using the initial and mature phase as developmental reference points and lessons learned from Antarctic design evolution, the transitional phase can be broken down into design requirements, logistics over time, and logistical and functional sequence (Figure 1). Breaking down the transitional phase in terms of design requirements, three factors were analyzed – mass, volume, and power. These factors can be used to analyze the initial infrastructure and additional logistics modules; compare future module capabilities of a mature station; and show how mass, volume, and power may change over time. Logistical and functional sequences can then be formed reflecting how the station will grow and adapt to new growth. Finally, the thesis will cover conclusions and future work.

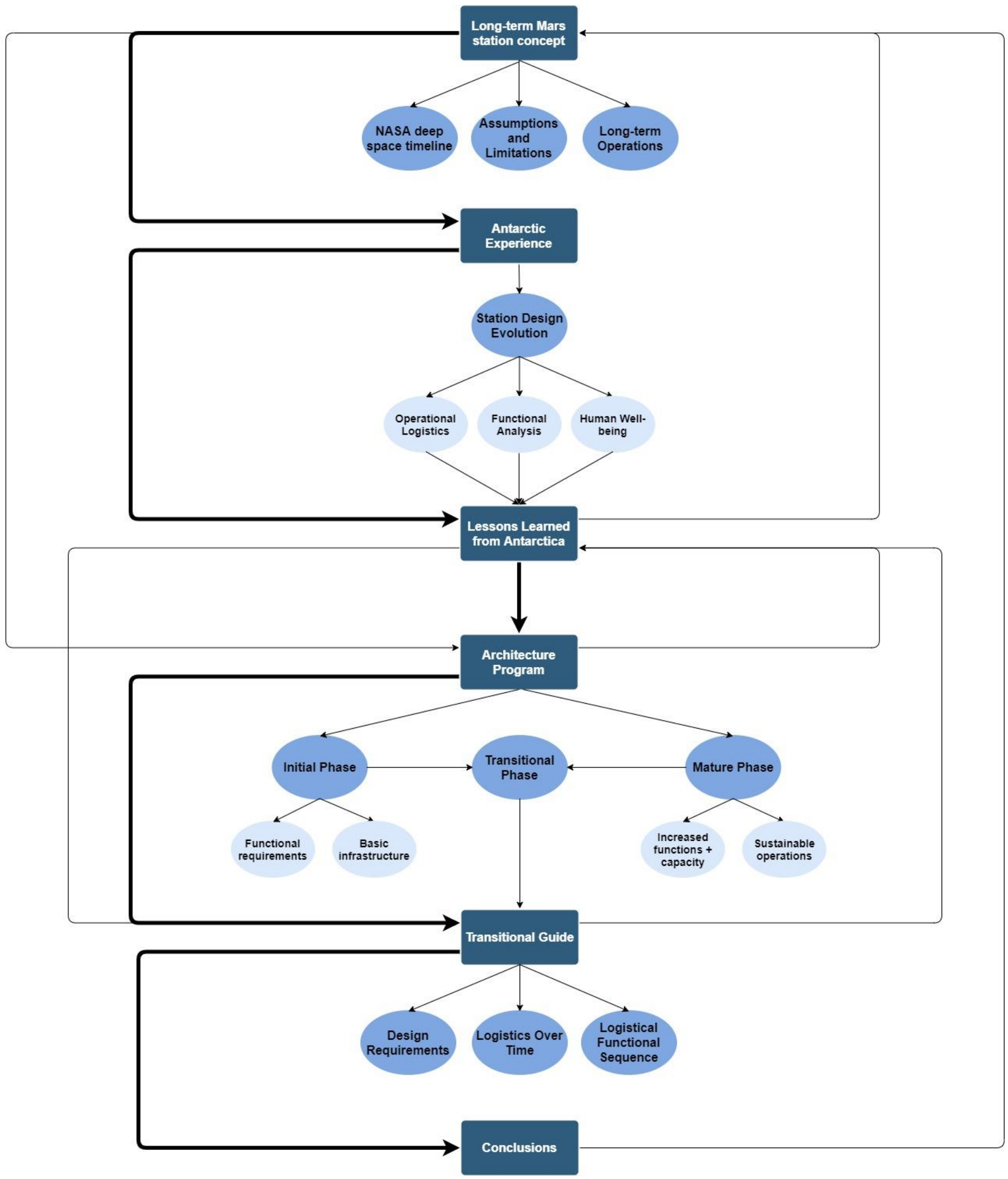

Figure 1 – Research Flow Diagram

III. LONG-TERM MARTIAN STATION CONCEPT

Although there are many differing concepts for future missions to Mars, in the context of this thesis, the Martian station concept assumes the establishment of a Martian habitat and infrastructure capable of supporting an initial crewed mission and that following missions will continue to utilize and add onto this infrastructure until reaching a mature sustainable architecture. While other approaches sending crews to multiple sites have the advantage of covering a larger area for scientific research, for example the mobile home concept in the *Human Exploration of Mars Design Reference Architecture 5.0* (MDRA) [1]; long-term, establishing and returning to a single site offers significant advantages. From a scientific perspective, establishing and operating from a single site over the course of several missions allows long-term research and monitoring of the surrounding areas of interest. The initial station will provide basic scientific analysis and support for experiments and as the station gains additional capabilities, more advanced research can be performed.

Another advantage of developing of a long-term station is the overall cost benefit of extending the lifetime use of the habitat and infrastructure. Even short duration crewed surface missions require significant environmental control and life support systems (ECLSS) and infrastructure to provide basic life support and functions. Because of the enormous cost of developing, launching, and setting up habitats and support infrastructure for a Mars surface mission, it is more cost effective to establish a station and continuing to reuse existing infrastructure as opposed to having to repeat establishing habitable infrastructure at a new site for new missions.

This approach allows for the investment into the stations growth as it can be incrementally be added to with each mission to provide increased capabilities and functions and adding surface infrastructure with less redundancy than separate sites. Utilizing a phased development approach also allows for a more flexible design to adapt to changing needs and advancing technology as well as any unknown challenges that may arise while maintaining research and living capabilities for the crew. Regardless of the final purpose of the mature station, whether a scientific research station, an industrial production depot for deep space exploration support, a colonization settlement, or a combination, it will be essential to strategically transition to ensure long-term sustainable growth and operations.

Assumptions and Limitations

NASA Deep Space Timeline

For this thesis, several assumptions were made in order to define and limit the research. The long-term station discussed in this thesis is assumed to fit into NASA's proposed deep space exploration timeline. Currently, crewed operations are limited to LEO with NASA planning to resume crewed missions to the moon in 2024 and send the first crewed mission to Mars sometime in the 2030s [2]. As seen in Figure 2, NASA plans to use Moon as a proving ground before advancing to Mars. The Artemis Program will use the orbital Gateway station to facilitate lunar surface missions, research, and testing. These missions will provide a more easily monitored environment for testing technology and equipment that will be used on the first crewed Mars mission. While lunar testing will provide invaluable experience, many of the environmental conditions on Mars differ from the Moon limiting testing and leaving some unknowns until we reach Mars. Also based on NASA's timeline, there will be little time between the return to the Moon and first mission to Mars to collect long-term surface operational data. Logistically and operationally Mars will be much different than the Moon as it is much further from the Earth and has limited windows of access. NASA has also implied that in the future Martian infrastructure could be used to support exploration further into the solar system. In order to be able to support further exploration, a Martian station will need to reach a level of maturity and sustainability which will take a significant amount of development.

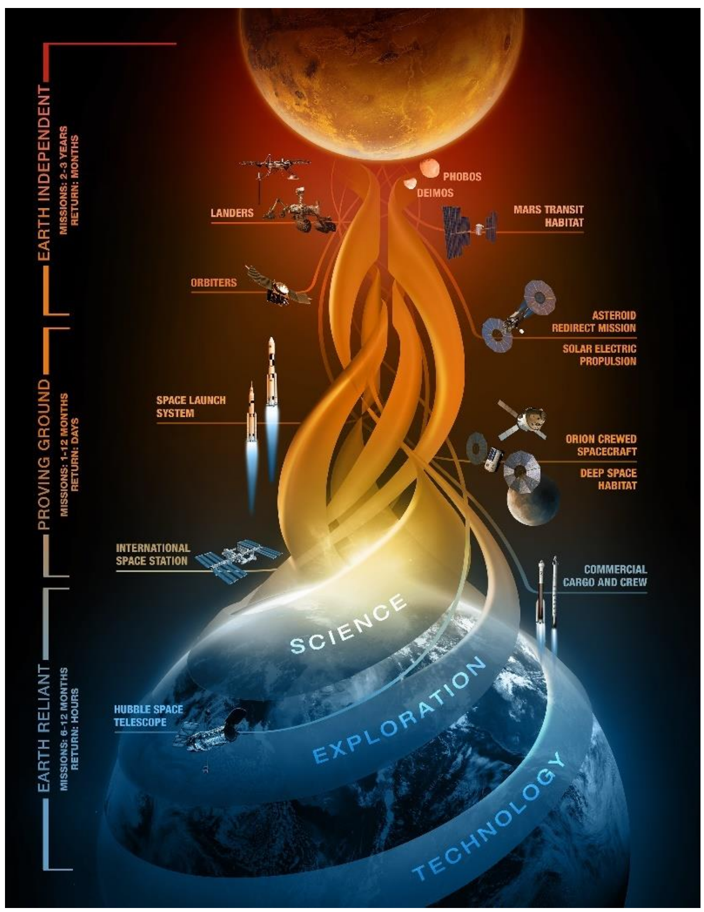

Figure 2 - NASA Journey to Mars Illustration [3]

Logistical Constraints

Several logistical assumptions were made regarding the operations of a long-term Martian station (Table1). While alternate spaceflight systems may be completed before the first Martian crewed mission, the thesis assumes that NASA's Space Launch System (SLS) system will reach maturity and that the SLS Block 2 along with the Orion crewed spacecraft will be used to transport cargo and crew to and from Mars. The SLS Block 2 will have a payload capacity of up to 45 tons with a payload diameter of 10 meters while the Mars descent vehicle (MDV) will have a landing capacity of 22 tons limiting the size and mass of any habitat and the amount of infrastructure than be sent in a mission. Missions are assumed to be consecutively scheduled in accordance with the 2.2-year launch window, allowing for the rotation of crew and resupply of cargo. Travel duration for cargo are assumed to be about 12 months using a slower transit for fuel efficiency, while 6-9 months are assumed for crew transport using a fast transit to minimize the effects of zero gravity on the crew. Basic logistical operations were also assumed to include basic consumable supply, maintenance and repair, and waste management (Table 1).

Table 1 – Logistical Assumptions [1] [4] [5] [6]

Travel Duration	≈6-9 months crew ≈ 12 months cargo
Limited Window of Access	Launch window every 2.2 years
Transit Vehicle	SLS Block 2 – Cargo + Crew Orion
Transit Capacity	45 t
Payload Diameter	10 m
MAV/MDV Capacity	22 t landed
Crew Rotation Period	16 months - 3 years
Orbital Infrastructure	Orbital satellite system
Communication	Satellite relay, 3-24-minute delay
Consumable Supply	Importation/hydroponics/ISRU
Maintenance/Repair	General repair workshop/ 3D printing
Waste Management	Recycle/ processed/ stored/ returned to Earth

Site Assumptions

Another assumption made was that the future site of a Martian research station will be in the mid-latitude range of Mars. Mid-latitude Mars is the best site candidate as it balances access to glacial deposits abundant at the pole with the need for a more fuel economical landing. This area also has numerous points of scientific interest yet to be explored [7]. Average environmental conditions for this region have been considered as factors affecting the design and operation of a long-term Martian station (Table 2). The average temperature in the region is about -50 ℃ with the lowest temperature reaching -60 ℃ and the highest temperature reaching 0℃ [8]. While the pressure on Mars is only 610 Pa and the atmosphere is less than 1% that of Earth's, weather patterns still occur across Mars with dust storms seasonally blocking light causing poor visibility and often lasting weeks [9]. Also. crews on Mars will be exposed to significantly higher levels of radiation. Galactic cosmic radiation (GCR) exposure as well as the threat of a solar particle event (SPE) will need to be carefully monitored and require crew protection.

Table 2 - Mid-Latitude Mars Environmental Conditions [10] [9]

Gravity	≈1/3 G
Atmosphere	> 1% Earth atmosphere
Atmospheric Composition	96% Carbon Dioxide, 2% Argon, 2% Nitrogen, 1% Other
Temperature Average	-50℃
Temperature Low	-60℃
Temperature High	0℃
Humidity	≈0.01%
Ice Concentration	Sub-surface ice
Radiation	GCR / SPE
Pressure	610 Pa
Day Length	≈24.6 hrs.
Daylight Cycle	≈12.25 hrs. light/dark
Solar irradiance	586.2 W/m^2
Weather Patterns	Dust storms/devils/ 30 m/s winds
Invasive/Assailants	Dust mitigation/meteoroid protection

Long-term Operations

One of the biggest reasons advocates for exploring Mars have cited has been to perform scientific research. The main scientific goals can be grouped into four main categories – the search for past or current life, understanding the Martian climate, studying the geological conditions on Mars, and to study the effects of space travel on humans to prepare for further exploration [11]. For a long-term station, the site will be chosen in an area with multiple sites of scientific interest to provide scientific diversity. Initially scientific capabilities will be limited, but over time expanded capabilities will be added allowing additional information to be gained and long-term monitoring. As the station becomes more mature, field stations may be built to allow for research at site more distant from the main station. Establishing a long-term station provides a platform for sustainable scientific research [12].

Another goal of a long-term Martian station is to sustain human life in case of a cataclysmic event on Earth and to enable humanity to live away from Earth. A large portion of sustainable long-term crewed operations relies on being able to transport crew and supplies to and from Mars on a regular basis. With a launch window occurring every 2.2 years, depending on trajectory type used crewed flights will have a shorter travel time of 6-9 months while cargo will use a longer more fuel efficient route taking closer to 12 months to arrive [5]. While short stay missions are an option, this thesis assumes that missions are long stay as it provides more surface time with crew initially staying at least 16 months [12]. Depending on accumulated radiation exposure, crew may be allowed to stay over the course of multiple rotations and eventually remain on Mars. According to research presented by Salotti, the minimum number of people needed to operate a self-sufficient station on Mars is 110 [13]. The mature phase will need to be able to support this substantial population growth.

Establishing infrastructure will be a major part of long-term operations. Before crew ever arrives on Mars, the site will need to be prepared and an initial habitat and infrastructure sent and set up telerobotically in preparation. This initial infrastructure will provide the necessary infrastructure and functions to support the crew and create a base for future growth to be added to. As the station transitions, significant support capabilities and infrastructure will need to be added to support expanded and more advanced capabilities needed for mature station operations such as greenhouse, in-situ resource utilization (ISRU) production, and industrial manufacturing [13]. These capabilities will be essential to the station becoming self- sufficient and becoming support infrastructure for exploration further from Earth.

IV. ANTARCTIC EXPERIENCE

Today, Antarctica is an established center for research; but in the past, Antarctica was as foreign as another planet. Antarctica is one of the most remote and extreme environments on Earth challenging humanity to adapt and overcome adversity throughout its exploration and occupation. The history of Antarctic exploration can generally be grouped into three main phases – early exploration, expedition, and occupation. Antarctica's early exploration began in 1772 with Captain James Cook's crossing the Antarctic circle and circumnavigation of Antarctica. During this time, visitors to Antarctica were mostly explorers and sealers. The first permanent structure in Antarctica, the "Osmond House", was built in 1902 by William S. Bruce and his crew after being forced to anchor on Laurie Island in the South Orkney Islands [14].

The expedition phase began around this time with the period known as the Heroic Age of Antarctic Exploration. The period was characterized by expeditions deeper within the continent staying longer periods of time with the goal of exploring and mapping the interior of the continent. The expeditions peaked in 1911, with the historic race between Roald Amundsen and Robert F. Scott to the South Pole with Amundsen's team becoming the first people to reach the South Pole [15]. As countries claimed territories, the first mainland bases became established to mark territorial claims and support further expeditions.

While several early bases had been established, the International Geophysical Year (IGY), 1957-1958, marks the beginning of the occupation phase as bases shifted from temporary and expedition support stations to becoming permanent research stations. Fifty-two new stations were established during this time including Halley Research Station and Amundsen-Scott Station. The IGY also helped pave the way for peaceful international scientific cooperation and led to the signing of the Antarctic Treaty in 1961 which disarmed the continent and protected the environment from industrial use and pollution [15]. Today, stations have evolved into sophisticated architectural research centers and offer lessons learned from operational logistics, functional development, and well-being design factors.

Martian exploration can similarly be grouped in phases of early exploration, expedition, and occupation. Mars's early exploration consisted of a series of flyby missions with the first successful flyby by the Mariner 4 in 1964. Mariner 6 and 7 in 1969, and Mariner 9 in 1971 also made successful Mars flybys returning thousands of photographs of Mars. Mars's expedition phase beginning can be marked by the first successful landing on Mars. The US Viking 1 and 2, orbiter and lander combos, safely landed on the surface of Mars and conducted biology experiments, and in 1996, the Mars Pathfinder became the first rover to explore the surface of Mars [16]. Since 1996, several orbiters and rovers have been successfully sent to Mars collecting data, mapping, and performing scientific analysis. While no humans have yet set foot on Mars, robotic expeditions have accumulated an extensive knowledge of Mars making it the most studied planet besides Earth [10]. While the technology between Antarctic and Martian differs greatly, looking at both from a large-scale perspective allows parallels to be drawn and lessons to be learned and applied.

Station Design Evolution

After IGY established the first permanent research stations in Antarctica, stations went through several design iterations before reaching their current designs. Early Antarctic stations were simple wooden huts offering little more than shelter and were quickly degraded over time by the harsh climate. This became a cycle as new stations would be built, discarded as they aged, and a new station built. Two of the best examples of this is the British Halley Research Station and U.S. Amundsen-Scott South Pole Station.

Founded in 1956 on the Brunt Ice Shelf, the original Halley I consisted of a wooden hut with a pitched roof built directly on the ice surface typical of early stations. Because the area receives around 1.2 meters of snow per year, Halley I was quickly buried and crushed by the weight of accumulating snow [17]. Halley II, 1967, was similarly designed with the addition of steel supports reinforcing the roof but became buried as well. Halley III, 1973, attempted to protect the huts from snow accumulation by building them within large cylindrical corrugated steel conduits designed to be buried; however, because of construction flaws the conduit warped and the station was crushed. Halley IV, 1983, strived to improve issues from the previous station changing the conduit from metal to interlocking plywood-faced panels but was also crushed and lost to the ice. Learning from the destruction of previous stations to snow accumulation, Halley V, 1992, was built on raised steel platforms that could be raised annually to compensate for accumulating snow. While this solved the threat of snow accumulation, the Brunt Ice Shelf moves about 700 meters per year and by 2007/8, Halley V had flowed too far from the mainland and was in danger of being lost or damaged during a calving event causing the station to be evacuated and disassembled [18] [19]. Halley VI, the current station, was designed by Hugh Broughton Architects and built in 2012 as the first fully relocatable polar research station [17]. Halley VI is considered to be on the cutting edge of Antarctic design inspiring many other stations to turn to architecture and implement a more holistic design approach as next generation of stations is built [20].

Similar to Halley, U. S. Amundsen-Scott South Pole Station has gone through several design iterations. Founded in 1957, the original base the first station also consisted of wooden huts built on the snow surface and became buried over time. By 1967, ten meters of snow had buried the station leading to its abandonment [21]. The next iteration was built in 1975 and consisted of a protective geodesic dome over prefabricated wooden buildings built on the surface of the ice sheet. The protective geodesic dome was 50 meters wide by 16 meters high with 14 by 24-meter steel archways built around the central area of the previous station covering fuel bladders, equipment and three modular wooden two-story buildings, accommodating living areas and laboratories within [22] [23]. The dome eventually became unusable from structural instability due to snow accumulation and was disassembled during the 2009/10 summer season [22]. The current station, 2008, was designed by architecture firm, Ferraro Choi and Associates Ltd., with the existing arches from the previous station repurposed to store fuel, cargo, and waste management as well as new arches built to house the garage shops and power plant [23]. The current station is one of the largest bases in Antarctica. The station is elevated on adjustable legs able to raise the station above the snow level and can raise the station to a maximum of two stories to compensate for future accumulation [24]. Because of its large size and movement of the ice sheet the station is built, the station is susceptible to differential sinking due to shifting ice and snow beneath the station could potentially rip the station apart. To mitigate the problem, each leg is able to adjusted individually in 25 cm increments to keep the building level and the walkways connecting the buildings are designed to be flexible [22] [24]. As one of the largest and most advanced stations, Amundsen-Scott offers a level of functions and comfort hard to find in Antarctica. Together, Halley VI and Amundsen-Scott represent the design evolution of Antarctic stations and the affects external factors can have on a station design.

Operational Logistics

Antarctica poses several logistical challenges as Antarctica's climate is extremely harsh and transportation is limited to the short summer period leaving stations inaccessible during the winter season (Table 3). As the temperature begins to drop in Antarctic autumn, ice begins forming on the surface of the sea becoming pack ice with up to 965 km of sea ice surrounding the continent [25]. While only a meter thick on average, it creates an impenetrable barrier around the continent blocking ships access until the ice melts the next summer [26]. Additionally, the continuous darkness makes aircraft travel extremely dangerous and the extreme winter temperatures are cold enough to freeze plane fuel within minutes preventing aircraft travel [25]. Because of these conditions, stations operations are heavily impacted by the seasonal cycles with stations having to endure months without access to emergency medical facilities or resupply [27]. Stations rely on aircrafts or ships to deliver cargo and for transportation with ships typically used to transport large loads of supplies and equipment too large for an aircraft and aircraft to transport smaller payloads and people. Both aircraft and ships usually stop at larger stations along the coast and then supplied and people are distributed and transported further inland by land using tractor convoys pulling cargo sleds or by aircraft specifically designed for polar conditions [28]. . Because of its immense size and capacity, US McMurdo serves as one of the primary logistics hubs in Antarctica along with Australian stations Casey, Mawson, and Davis, and supports researchers passing through to inland stations, field research camps, and supplies.

Most stations rely on a single ship visit per year to resupply stations with food, equipment, and fuel [29]. McMurdo, the largest Antarctic station, gets a delivery of dried and frozen food only once per year while fresh produce is delivered during the summer by plane about once a week [14]. While about 20 flights go to Halley VI during the summer, these are primarily to transport crew. Halley VI receives supply deliveries and waste removal only twice a year by ship. Two years' worth of supplies are kept in storage in case of delivery problems or an emergency [30]. Similarly, Concordia stores enough fuel to power the station for a whole year in case of an emergency or missed supply [31].

Because of the limited resupply and waste removal, recycling and reuse is extremely important in Antarctica. At Halley VI, water is carefully managed and recycled with a vacuum drainage system reducing water usage from about 120 liters of water per day at Halley VI to 20 liters [20]. Concordia uses a grey water recycling machine, a prototype of the one used on the ISS, with the water tested every two weeks [31]. Concordia produces about 155 kW waste heat as a byproduct of electrical production which is recycled and distributed throughout the station [29]. While most research stations rely on fossil fuels for power production, many stations are adding renewable energy to supplement and reduce the amount of fossil fuels needed. Princess Elisabeth Station, built in 2009, is the first zero emission station in Antarctica. The station uses solar, wind, and batteries to generate power recapturing byproduct heat within the station so no interior heating is needed, and recycles 100% water [32]. Integrating green technologies into station design not only reduces the amount and cost of transporting fuel to Antarctic stations, but also reduces the pollution and potential contamination of Antarctica protecting the environment and in turn the research.

While most consumables are imported, ISRU and hydroponic chambers are used to supplement resources. Many stations us to heat to melt snow to produce water for the station. At Concordia, over 250 liters of water is produced for use in the station [29]. Amundsen-Scott houses a 6,040 square meter hydroponic growth chamber that was originally meant for Halley VI but did not make it into the final design [33]. The NASA plant-growth chamber on the station provides supplemental fresh food during the summer and is the only source of fresh food during the winter period [24]. Maintenance is also a major concern in Antarctica as parts take up valuable transit and storage space. Concordia also has workshop capabilities including information communication technology services (ICTS), mechanical, metal, and woodshop capabilities to help with maintenance issues at the station (Table 3). Modular design and standardization also help decrease logistical loads. To simplify systems, construction, and reduce unique parts, Halley VI was designed as a series of connected individual modules using standardized and prefabricated parts [34]. By reducing the number of unique parts, stations can be more easily maintained and are less likely to have emergencies based on unavailability of parts.

Currently, twenty-eight countries operate stations in Antarctica with eighteen operating year-round scientific research stations [26]. Together they support up to 10,000 crew during the summer with around 1,000 staying over winter [35]. Most year-round stations are similar to Halley VI which supports up to 52 people during the summer and about 16 during the winter season with crew averaging 15 months at the station as many tend to stay throughout the winter [34]. Concordia supports up to 70 people in the summer and 13 in the winter [35]. While bedrooms are used for individuals during the winter, they are often become shared during the summer season. During the summer, a camp near the station provides additional crew capacity, but also provides storage outside the main station and provides an emergency backup year-round [31]. Larger stations have similar capacity to Amundsen-Scott Station which supports up to 150 people during the summer and about 50 during the winter [24]. McMurdo supports up to 1000 people during the summer and 250 during the winter [29].

Table 3 – Operational Logistics [27] [35]

	Antarctica
Limited Window of Access	December–March summer period
Crew Rotation	3 months – 1 year
Consumable Supply	Importation + ISRU
Maintenance / Repair	ICTS/ electrical/ mechanical/ metal/ plexiglass/ wood/ general repair workshops
Waste Management	Recycled/ stored/ removed annually/bi-annually

Lessons Learned

As human exploration and a Martian research station develop, it will share many of the operational and logistic challenges as Antarctica. Both Antarctica and Mars have limited windows of access requiring stations to be completely self-sufficient during their inaccessible periods. This trickles down affecting every logistical and operational aspect of the station including obtaining supplies, crew rotation, and waste management. With more extreme conditions, Mars will have to be even more self-sufficient than Antarctica. Operational logistics lesson learned are:

- A limited window of access and long crew stays equal high consumable needs and waste accumulation causing high logistical stowage requirements,
- Recycling, re-use, and waste processing is essential to waste reduction and stowage,
- ISRU and workshop production supplement consumables,
- Modular design and standardized parts reduce consumable load and stowage,
- Field stations provide supplemental storage and emergency backup,
- Adaptable station design to environmental conditions,
- Zero-emission design and green technology reduces energy consumption/waste and increases environmental protection,

and

- Automation should continue station operations during unoccupied periods.

Functional Analysis

Research station design has evolved a long way from the first wooden huts built in Antarctica. As technology and design improve, stations have shifted from spartan conditions that were dangerous and off-putting moving towards a more human centered design tailored to the environment and research as well as human needs. According to the Council of Managers of Antarctic Programs' 2017 Antarctic Station Catalogue, there are currently over 90 operational Antarctic research stations with about 63% of stations operating seasonally and 37% operating year-round [35]. Comparing average area for seasonal and long-term stations, long-term stations have almost four times as much area as seen in Figure 3. Seasonal stations tend to be smaller as they are only operational for three months at a time, support fewer people, and are not required to support the crew physically and psychologically through the difficult winter season. The design of year-round stations tends to be larger as they require more living area to support crews for a longer period of time. From this comparison we can derive the longer the period of time crew stays in the station and how remote and isolated the station is directly affects the need for living space.

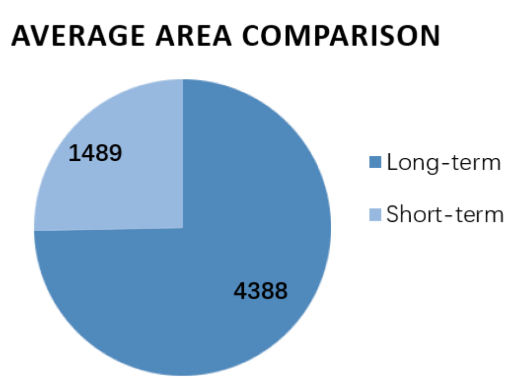

Figure 3 – Average Area Comparison

Analyzing the distribution of enclosed area within stations per function type, area distribution can be divided into four main categories – scientific lab, logistical, medical, and living area. Looking at the year-round operational stations, about 14% of the area in a station is devoted to scientific lab areas, around 1% of area to medical purposes, 49% to logistical area, and 36% to living area as seen in Figure 4. From this analysis we can see that that almost half of all area is devoted to logistical functions followed by living functions. Referencing this back to the information in Antarctic Station Catalogue, we can see that this distribution is true of seasonal stations as well showing that it applies to short-term operations as well [35].

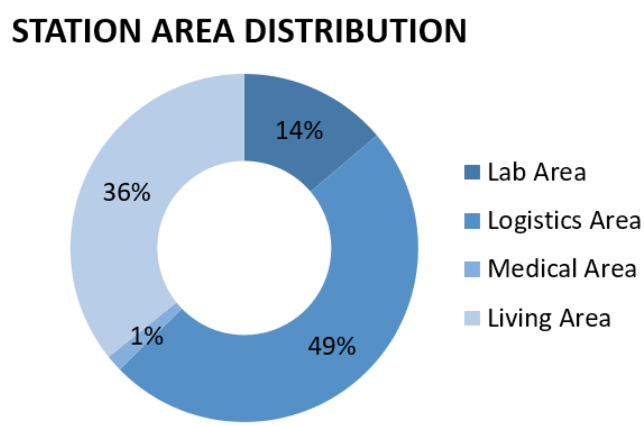

Figure 4 – Station Area Distribution

Functionally, Halley VI is divided into eight modules, seven standardized blue modules containing bedrooms, laboratories, offices, and power and logistical spaces and one larger two story red module serving as the social module containing social, dining, and recreation spaces (see Figure 5) [19]. For life safety reasons, the station is divided into two main sections with each half containing its own power center to be self-sustaining in case of an emergency. Normally the two sections are connected by a walkway allowing crew passage and linking power, drainage, and water systems [19]. Halley VI is about 2,000 square meters of enclosed space with roughly 200 square meters of scientific laboratory area, 800 square meters of logistical purposes, 100 square meters of medical capabilities, and about 800 of living areas. Halley VI is one of the few stations which have the medical surgery capacity as in a more serious emergency requiring evacuation, the closest emergency facility is over 3,150 kilometers away. [35] Halley VI was designed to be self-supporting and infra-structure free, incorporating medically operating facilities, air traffic control systems, CHP power plants as well as other logistics into self-contained modules [19]. Since 2017, Halley VI has been crewed seasonally during summer and run autonomously during winter as a safety precaution as the station is threatened by a chasm and an event during winter could result in the loss of life. Instruments to continue collecting data and running experiments using a micro-turbine power supply and a datalink to the instrumentation while unoccupied to prevent the loss of research and the system ran successfully through winter 2019 [17].

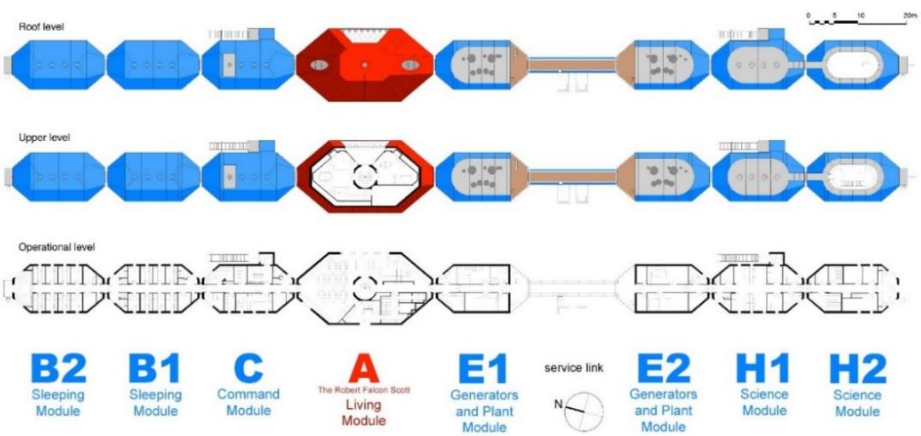

Figure 5 – Halley VI Research Station Floor Plan [36]

Concordia consists of two elevated cylindrical buildings connected with an enclosed walkway 10 meters long. Functionally the station is divided into "noisy" and "quiet" halves (Figure 6). The "noisy" half houses includes the kitchen, gym, dining, social areas, and workshop areas while the "quiet" half includes labs, bedrooms, library, and hospital with the total living space of 1500 square meters [37]. An additional detached building houses "dirty" functions including a wastewater treatment plant, power plant, and an additional workshop [37]. The station public spaces are important to the social interaction and cohesion of the crew not only during the winter, but also during the summer as it allows the people staying in the summer camp and station to interact in a social and recreational setting. The station also offers additional comfort to the summer camp as it has actual toilets as opposed to an incinerator toilet that only collects solid waste. The separation of spaces into "noisy" and "quiet" spaces also allowed for use at irregular hours for a more private use [38].

Because of the varied research conducted at Concordia, the station has an extensive infrastructure surrounding the station. At Concordia the crew must be self-reliant and be prepared to handle emergencies such as medical, fire and rescue operations independently. The station is designed with redundant systems to prevent failures and emergency simulations are run once a month for fire, rescue, medical, and emergency situations and once a year an evacuation exercise to the summer camp 500 meters form the main station which serves as an emergency shelter is performed [31]. The summer camp can be heated quickly using a small preheated generator, the summer camp usually takes about 3 days to be set up normally [31].

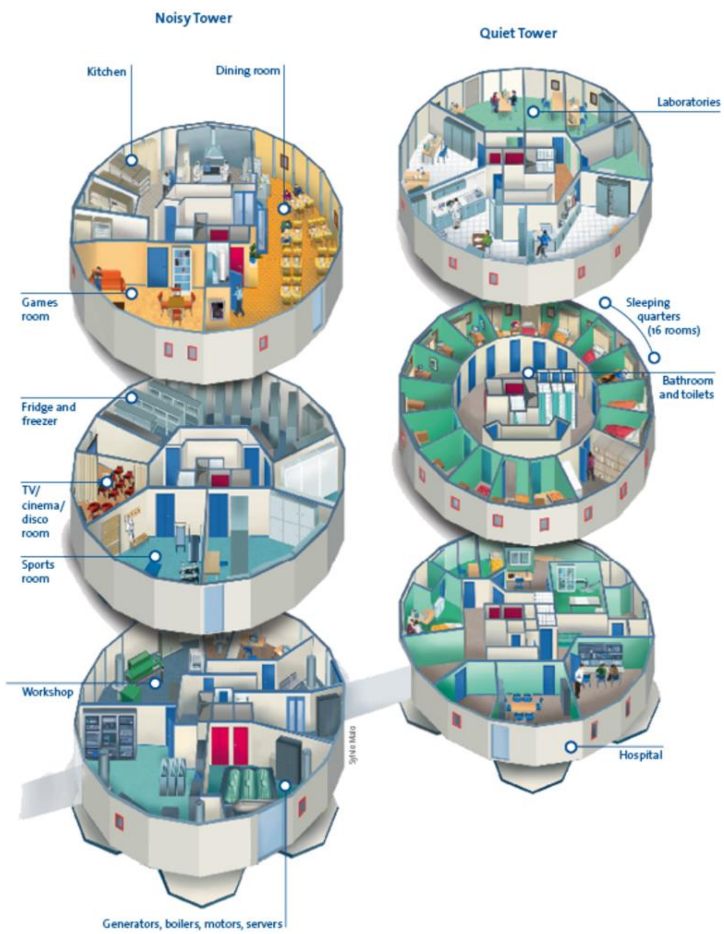

Figure 6 – Concordia Floor Plan [39]

Amundsen-Scott station consists of two large u-shaped modules linked to form the station (see Figure 7). The modules are separated for safety in case of an emergency situation like a fire and are self-sufficient [22]. This also allows parts of the station to be shut down during the winter when there is reduced need for space. Functionaly, the main station modules are roughly divided into one module for living and recreational areas and the other for work and logistical space. Inside the station, one module houses the crew quarters, dining area, bar, hospital, laundry, library, store, post office, and green house, while the second module houses the offices, a second library labs, computers, telecommunications, conference rooms, music room, gym, and an emergency power plant. The station modules contain 6,040 square meters of enclosed space [24]. The aluminum tower at the end of the station contains a cargo lift, utilities, and stairwell connecting to the exterior and underground logistical areas [37].

Connected through a corridor off the cylindrical stair well at the end of the station, often referred to as the “beer can”, the repurposed arches from the previous station house fuel and cargo storage, waste-management facilities, maintenance garages and the power plant outside the station housed in ice caves beneath the surface of the ice sheet [40]. The first arch contains the power plant and water treatment plant, next the logistics arch with half unheated and used for food and trash storage and half which is heated for storage of things that should not be frozen, next to logistics is the fuel arch which is filled during summer and depleted during winter, last arch is the VMF vehicle maintenance facility and storage and winter carpenter shop, machine shop, and plumbing electrical shop they have 45 10,000 gallon tanks [41].

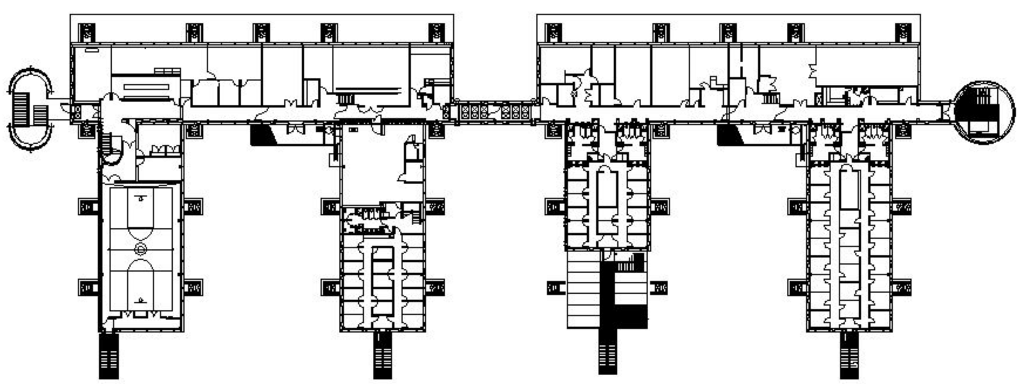

Figure 7 – Amundsen-Scott Floor Plan [42]

Lessons Learned

Like in Antarctica, provided functions are essential to the success of a long-term station on Mars. The longer the duration at the station, the more functions required, but the more functions provided, the more logistical volume needed to support the additional functions. Logistical and living area are the two largest functions required making functionality a compromise between required and desired functions to support the crew and logistical functions necessary to operate the station. Lessons learned from the functional analysis are:

- Logistical stowage accounts for almost half of all volume,
- Volume can be specialized as – cold, dry, dirty,
- Opposing functions should be separated – noisy vs. quiet, work vs. living, clean vs. dirty,
- Must be added first to support additional growth,
- Crew size and mission duration limitations,
- Long crew stays require increased functions and volume,
- Life support systems should be divided to provide redundancy,

and

- As stations grow capabilities move to newer areas with old areas becoming stowage volume and recycled.

Human Well-being

Crew working in Antarctica experience an ongoing toll on their health and must adapt to physical and psychological challenges (Table 4). Physically, the main challenges for crew are related to the high elevation reducing pressure and oxygen levels, the extreme climate, and the seasonal cycle of continuous light and darkness. The first challenge crews face on arrival is the possibility of altitude sickness. About 2% of people travelling to the South Pole experience altitude sickness with people who have previously experienced altitude sickness being likely to experience it again. While altitude sickness can have many troubling symptoms including nausea, fatigue, difficulty sleeping, difficulty breathing, tachycardia, hallucinations, and confusion, most people acclimatize and recover within a few days making most of its affects short-term. Long-term, crews suffer from chronic hypoxia caused by the low oxygen. Hypoxia causes difficulty breathing effectively doubling the ventilation needed causing hyperventilation which over time can take a toll on the heart and lungs and has been found to decrease the human immune system [43]. These affects make performing any physical activities more strenuous and tiring. This is especially felt at stations located on the Antarctic Plateau where the barometric pressure is about 30% less than at sea level [43] with crews effectively having to adapt to living with a third less oxygen they would at sea level [44]. The seasonal cycle of constant light and darkness also effects crew physical health causing chronic sleep disorders similar to that experienced by astronauts.

Psychologically, Antarctica is very challenging as crews must operate in a highly stressful and high-risk environment while being expected to perform at a high level of excellence. This mental strain is only added to by the harsh environmental conditions especially during the Antarctic winter when crews are reduced. During the winter months crews experience confinement and sensory deprivation as the extreme temperatures, bad weather, and continuous darkness keep them within the station. Crews are also isolated and unable to leave the station for nine months with the bad weather often interfering with communication to the outside world. The social limitations, isolation, confinement, and high stress conditions take a toll on the psychological state of the crew. The extreme temperature along with high winds often confine crews to the station for 2-3-week periods [20]. The crew must be completely self-sufficient during this time and be able to deal with any emergency situations that may arise without relying on outside help. This is especially important during the winter season when the number of crew is reduced and physically isolated for nine months.

Halley VI is unique in terms of design for quality of life as emphasis was placed on the preserving the psychological wellbeing of its inhabitants and the first station to develop its interior design extensively [20]. When Halley III and IV were operational, it was common for former Halley crew to develop the “Halley stare”, a mild obsession staring out windows for long periods of time, an effect from the extreme sensory deprivation cause by living under the ice in buried stations [45]. Halley VI’s interior was specifically designed to create an encouraging environment especially during the long winter darkness as well as combat Seasonal Affected

Disorder [19]. To compensate for the strain, Hugh Broughton Architects invested into developing the internal architecture to support the crew's mental health and combat sensory deprivation. The lack of sunlight can sometimes lead people to develop "night walking" a sleep disorder causing people to have irregular sleeping patterns. The design of Halley VI is designed to organize light and space to complement human activity [30]. Each crew quarter has a window for access to sunlight and a view out of the station and the corridors are lit by sunlight from above. [30] Special alarm clocks along with daylight simulation lamps, suppressing melatonin and increasing serotonin, were also implemented to wake the crew mimicking a natural daylight cycle and improving mood.

Other measures were taken to stimulate the senses. A color psychologist was consulted to develop a color palette to be used throughout the modules. The "spring palette" of bright colors - reds, greens, and blues, were used on walls and furniture to improve mood without being overwhelming [34]. Variation of ceiling heights are used to differentiate spaces and break up monotony [30]. Lebanese cedar veneers were also used in the social module to give off a natural scent to mitigate sensory deprivation and the lack of vegetation [20]. The social module utilizes the larger space and height afforded by its additional height to support large cathedral-like panoramic windows allowing the interior to be bathed in natural light and in the winter periods the aurora Australis which can be seen frequently [19]. There is also a quiet room at the north end of the station devoted to peaceful contemplation [46]. One of the changes made between Halley V and VI was how the social centers were designed. In Antarctic research stations, bars serve as the focal point for social interaction [20]. In Halley V, bar was an enclosed room with a door which sometimes would be closed causing division and exclusion. In Halley VI, emphasis was placed on creating an open plan living space and bar and removing barriers to encourage communal activities and social inclusion and minimize isolation [20]. The social module included a bar, loungers, a pool area, dining room, and gym [30] [46].

Other stations use practices to engage crew. At Concordia, crew members cope with the isolation is through socialization and the sharing of food. Concordia is also considered to have the best cuisine of all the Antarctic stations with Sundays being a special day offering wine and seven-course lunches [37]. Daily activities like making coffee becomes help provide physical comfort as well as the opportunity for socialization [38]. The station also offers recreational spaces and activities for the crew to enjoy and strengthen social bonds.

Because of the large size and capacity, the Amundsen-Scott offers a lot more amenities and recreational options than most Antarctic stations. The station has various forms of social and recreational spaces including a dining area, bar, libraries, store, conference rooms, music room, exercise room, gym, and a green house [24]. Crew living in Amundsen-Scott Station enjoy a much higher level of comfort than crews at other stations.

Table 4 – Human Well-being Factors

	Antarctica
Physical Travel Toll	Altitude sickness/ Jet lag
Ongoing Physical Toll	Hypoxia/ immune system impairment/ sleep disorders
Psychological Stress	High stress/ risk environment/ sensory deprivation/ isolation/ confinement
Communications	Satellite phone/ VHF radio/ limited internet access

Lessons Learned

Station design, regardless of location, needs to consider physical health of crew and psychological state over long-term occupation and design to alleviate stressors and promote well-being. Compared to Antarctica, the physical challenges affecting crew in Mars are more severe as they will have to endure the long journey to Mars in zero gravity resulting in deterioration of muscle, bone density and vision as well as space sickness and the effects of exposure to radiation [47]. During the Antarctic winter, crew experience many of the same conditions that will be felt by crew on Mars [25]. The station will have to be self-sufficient because of logistical challenges and crew will have to act independently as communications delays will make it difficult to effectively relay information in real time. Station design will need to address these issues to create a station that supports the physical and psychological welfare of the crew. Lessons learned from Antarctic well-being design factors are:

- Design should minimize physical and psychological stressors,
- Longer the stay equals higher level of comfort and amenities needed,
- Constant medical access will be essential to promote crew health,
- Natural light and lighting following circadian rhythm improves sleep patterns,
- Crew need a combination of social and private spaces,
- Work should be meaningful and balanced with other needs,
- Variety of color, texture, and size of spaces alleviates stress and promotes positive emotions,

and

- Crews need to be able to deal with emergency scenarios.

V. ARCHITECTURE PROGRAM

The architecture program presents an overview of the phased development of a long-term station. The development can be divided into three main phases – the initial phase, transitional phase, and the mature phase. Each phase plays an important role in the development of the station with the initial station focusing on establishing a human presence, the transitional stage on enabling sustainable growth, and the mature phase on operating sustainably. Looking at the initial and mature phase architecturally, in terms of infrastructure and capabilities, we can define a developmental starting point and goal for a long-term station.

Initial Phase

Before the first crew's arrival on the Martian surface, the several elements are required to be present to make first mission a success. The initial phase of station development must provide the basic infrastructure and habitat required to sustain human life and meet mission goals. Using the MDRA and the Evolvable Mars Campaign as reference along with our previous logistical assumptions, we can define an initial infrastructure (Table 5). Prior to the crew's arrival, the habitat, power, and landing sites will need to be telerobotically prepared, the habitat and power systems set up, and rovers ready to transport the crew. For safety reasons, the landing site will be at least 5 km away from the station to protect it from debris. A nuclear fission reactor will be utilized as its high power output can support the requirements of the initial habitat as well as additional modules to come as well as its reliability as it will not be affected by seasonal dust storms [1]. The reactor will also be located at a distance and require shielding to protect the crew. With a landing capacity of 22 tons, the infrastructure will be limited in terms of mass [6]. Based on the DRM, we can assume masses for the modules with a 6-ton airlock and a 16-ton habitat module. To facilitate setup, lessen the demands on the crew upon arrival, and to maximize crew time, the modules will be CLASS I pre-integrated hard-shell modules. [48] This initial infrastructure and habitat will provide the basic requirements for the station to become operational as well as a base for future growth.

Table 5 – Initial Infrastructure [1] [6] [49]

Surface Infrastructure	
Mars Ascent/Descent Vehicle	1 – 22t landing capacity
Launch/Landing Zone	1 – site 5+ km from base • Orbital + surface communication • Environmental monitoring • Operational control
Power	1 – 4x10 kW Nuclear fission reactor/ site 1+ km from habitat modules Energy storage
Transportation	2 – 4t rovers
Pressurized Structures	
Airlock Module	1 – 6t CLASS 1 Pre-integrated Module
Initial Habitat Module	1 – 16t CLASS 1 Pre-integrated Module

The initial station will also be limited functionally as it will need to provide all required functions to operate within one airlock and habitat module. While this makes it tempting to only provide the minimal functions required for survival and first mission goals, to allow long-term growth the station will have to provide beyond this to support following missions. Functions can be broken down for each module as seen in Table 6. The airlock provides interfacing with the habitat allowing the transfer of crew and cargo in and out of the station and houses four extravehicular activity (EVA) suits. The habitat module is the center of mission operations and primary living and working volume of the station at this phase. The habitat will provide station command control capabilities, off planet communications, safety, ECLSS and waste systems, crew living and working functions, stowage, and maintenance capabilities. Although initial missions have been proposed using a crew of four, the station will be designed to support up to a crew of six as that is the max capacity of the Orion spacecraft and it provides a larger capacity to support future missions [50].

Table 6 – Initial Required Functions [1] [48] [49] [51] [52] [53]

Airlock Module	
Command Control	• Internal + external monitoring • Pressurization control • AI passive environmental + pressure + combustion monitoring
Communications	Internal + surface communications
EVA	4 – EVA suits
ECLSS	• Integrated into the habitat module • Pressurization/depressurization
TCS	Passive + active control
Fire Suppression	CO2 suppression tanks
Docking	2 – docking ports • Rover interfacing • Habitat interfacing
Habitat Module	
Command Control	• Internal + external monitoring • EVA monitoring • AI passive environmental + pressure + combustion monitoring
Communications	• Orbital + satellite relay to Earth communications • Internal module + internal station communications • Surface communications
ECLSS	• Closed loop system • 42%+ O2 recovery from CO2 • 90% H2O recovery • Air revitalization
Waste Management	• Collection/processing tank • Trash collection/compression • Dry/wet storage
TCS	Passive + active control
Fire Suppression	CO2 suppression tanks
Radiation Protection	• Passive protection • 1 – SPE storm shelter area with 4 days of consumables
Docking	2 – docking ports minimum • Rover interfacing • Airlock interfacing • Future pressurized module interfacing

Table 6 – Required Functions (Continued)

Crew Quarters	4 – private quarters • 1 – bed • Personal work area + table + task lighting • Personal item stowage • Adjustable lighting • Private audio
Galley	Food prep area • Food rehydration system • Food heating system
Hygiene	• 1 – toilet • Hygienic wipes • Water for oral hygiene • Personal hygiene area • Hygiene product stowage
Exercise	Fitness equipment • Bicycle • Treadmill • A-red (resistance)
Recreation	• HD projector + screen
Laboratory	Scientific equipment • Human research • Geological science • Glovebox
Medical	Level VI care • Basic first aid care • Telemedicine capabilities
Stowage	Localized storage • Cold storage for medical supplies • Cold storage for food • Dry storage for shelf stable food • Dry storage for equipment + clothing • Dry storage for spares • Secure storage for lab specimens and experiments
Maintenance	• Spare parts • Basic repair equipment

Mature Phase

While we cannot fully predict what form a mature station design will take, a notional mature phase can be determined through the consideration of needs, requirements, and desired capabilities to break the station into notional building blocks to support this vision. Building from the initial, we can project the mature surface infrastructure (Table 7). While technological advances may allow for greater transit and landing capacity in the future, because it is an unknown the mature stations assume the same capacity as a minimum base point. Based off Salotti's calculations of 110 people as the minimum number of crew necessary to operate a self-sustaining station, we know that expanded transit logistics, surface infrastructure, and transportation system will be needed to support this population growth. Multiple MA/DVs will be needed to transfer the increased loads as well as additional landing sites. Support infrastructure will also be added to give additional capabilities and safety (Table 7).

Table 7 – Mature Notional Infrastructure [1] [6] [49] [52]

Surface Infrastructure	
Mars Ascent/Descent Vehicle	3+ – 22t landing capacity
Landing Zone	4+ – site 5+ km from base • Orbital + surface communication • Environmental monitoring • Operational control • Refueling capabilities • Payload processing • Maintenance area • Logistical stowage
Power	5+ – 4x10 kW Nuclear fission reactors 1+ - 4x10 kW backup generator Energy storage
Transportation	6+ – 4t rovers
ISRU production	• H2O production from ice deposit • Propellant production from atmosphere • 3D printing materials from soil
Pressurized Structures	
Airlock Module	1+ – 6t CLASS 1 Pre-integrated Module
Initial Module	1 – 16.5t CLASS 1 Pre-integrated Module
Logistic Module	CLASS 2 hybrid inflatable module
Lab Module	CLASS 2 inflatable lab
Living Module	CLASS 2 inflatable module
Greenhouse Module	CLASS 2 inflatable greenhouse
Workshop/Manufacturing	CLASS 3 ISRU 3D printed module

The station will also need to include advanced capabilities such as large-scale food production, ISRU industrial extraction and production, and manufacturing as these capabilities are essential to self-sufficient operations as well as at this level of population it would be unsustainable to solely rely on importation from Earth. ISRU production on the surface will established to collect water, create propellant, and obtain minerals from the earth to be used for manufacturing and 3D printing of modules. This information can be used to develop notional module types for advanced modules for lab, living, greenhouse, and workshop and manufacturing functions. We can also project that over time module types will change. During the first mission, CLASS 1 pre-integrated hard-shell modules will be used followed by CLASS 2 hybrid and inflatable modules and eventually CLASS III in-situ derived and constructed modules [48].

The station will also have to substantially advance its functions provided, not only in capacity to support the population growth but also providing a higher level of functionality. With a population of 110 people, it is likely many of them are staying longer than a single rotation or are living there permanently necessitating a higher level of comfort and functions provided. Building off functions provided during initial phase and considering design needs and requirements for a station and population of this size, we can project what expanded and additional functions will be included (Table 8). While some functions will be general across modules, functions specific to a type of module have been listed below and should be taken as a minimum guideline and not an exact plan. Functions in Table 8 are also listed per single module of that type and multiple modules will be needed to provide the total necessary functions.

Table 8 – Mature Required Functions [1] [48] [49] [51] [52] [53]

Command Control	• Internal + external monitoring • AI passive internal environmental +pressure • AI combustion monitoring + fire + safety suppression/control • Emergency automation • Greenhouse automation
Communications	• Orbital + satellite relay to Earth communications • Internal module + internal station communications • Surface communications
ECLSS	• Integrated into habitat module • Bio-regenerative system • 75%+ O2 recovery from CO2 • 98% H2O recovery • Air revitalization
Waste Management	• Collection/processing tank • Trash collection/compression • Dry/wet storage
TCS	• Passive + active control
Fire Suppression	• CO2 suppression tanks
Radiation Protection	• Passive protection • 1 – SPE storm shelter area with 4 days of consumables
Docking per Module	2 – docking ports minimum • Rover interfacing • Airlock interfacing
Living Module	
Crew Quarters	10 – private quarters • 1 – bed • Personal work area + table + task lighting • Personal item stowage • Adjustable lighting • Private audio + video • Personal entertainment
Galley	Food prep area • Heating and cooking capacity • Water for drinking and cooking • Communal dining area • Cold storage for food • Dry storage for shelf stable food
Hygiene	• 4– toilet • 2 - shower • Water for oral hygiene • Personal hygiene area • Hygiene product stowage
Exercise	Fitness equipment • Bicycle • Treadmill • A-red (resistance) • Group/team fitness/sport area

Table 8 – Required Functions (Continued)

Recreation	• HD projector + screen • Virtual reality • Communal gathering space
Medical	Level V care • First aid care • Telemedicine • Dentistry • Surgical capability • Cold storage for medical supplies
Stowage	Dry storage for equipment + clothing
Laboratory Module	
Scientific Capabilities	• Human research • Geological science • Biological science • Climatology science • Seismology science • Astronomy science
Stowage	• Dry storage for equipment • Refrigerated storage for lab specimens • Secure storage lab specimens and experiments
Greenhouse Module	
Greenhouse Capabilities	• Food production • Oxygen production + CO2 removal • Greywater recycling + filtering • Plant waste recycling
Stowage	• Cold storage for harvest • Dry storage for equipment
Workshop/Manufacturing Module	
Maintenance/Production Capabilities	• Basic repair equipment • Workshop repair and maintenance • Manufacturing clothing, parts, equipment with in-situ materials • 3D printing
Stowage	• Dry storage for equipment • Storage for ISRU materials • Storage for manufactured parts

VI. TRANSITIONAL GUIDE

To bridge such a large gap in terms of station and infrastructure development and functional capabilities provided between the initial and mature phases, major growth will have to occur. From our lessons learned, we know that logistical capabilities are required in order to support growth. The goal of the transitional phase is to enable the future growth of the long-term station by providing the logistical support necessary to add additional modules and functions. The design will also need to provide adaptable design to adjust functions to changing needs. Analyzing transitional design needs and requirements, logistics over time, and the logistical and functional sequence of growth will allow us to form a strategic transitional guide.

Design Requirements

The main transitional design needs and requirements affecting logistics are mass, volume, and power. Based on the DRM and ISS capabilities, the initial station modules and following logistic modules mass, volume, and power can be approximated and compared (Table 9 and Figure 8) [1] [52]. Compared to the 22-ton landing capacity, the airlock has a relatively low mass because of its size in spite of being a CLASS I pre-integrated module with most attributed to the structural components and connections. Functionally, the airlock requires minimum volume to efficiently pressurize/depressurize the space for crew passage. The airlock also requires minimum power compared to the rest of the station with power consumption spiking during usage for EVAs and remaining lower between uses. Overall, the airlock requires minimal mass, volume, and power (Figure 8). As a CLASS I pre-integrated module, the initial habitat module mass will be fairly high accounting for most of the lander's capacity with a significant portion of the mass being the habitat's internal components and equipment. The initial habitat module will have moderate volume as it is constrained by the max diameter of the transit vehicle but will be multi-level to provide the most volume possible from a Class 1 module. The initial habitat module will also consume a medium amount of power depending on the exact capabilities leaving sufficient power to support additional modules. Overall, the initial habitat will have fairly high mass with moderate volume and power requirements. Together the airlock and initial habitat provide a base for additional modules and sufficient power to support them.

Table 9 – Transitional Needs/Requirements [1] [54] [52] [53] [55] [56] [57]

Module	Crew	Mass	Volume	Power
Airlock Module Class 1 Pre-integrated module Minimum 2 connection ports	6	6 t	34 cu. m.	1 kW
Initial Habitat Module Class 1 Pre-integrated module Minimum 2 connection ports Closed loop ECLSS+ 90% H_20 recovery 8t food + 8t water + 2t expendables/spares = 18t consumables	6	16 t	250 cu. m.	11 kW
Logistics Module 1 Class 2 Prefabricated module Minimum 3 connection ports 8t food + 8t water + 2t expendables/spares = 18t consumables <5t stored solid waste capacity	6	<13 t	≈100 cu. m.	<11kW
Logistics Module 2 Class 2 Prefabricated module Minimum 2 connection ports 8t food + 8t water + 2t expendables/spares = 18t consumables 5t waste Cold + dry + dirty stowage	6	<13 t	≈100 cu. m.	<11 kW

Assuming the first Martian mission will have a crew size of 6, consumables will be needed to sustain the crew throughout the mission. Using data from NASA, we know that a human needs about 2.5 kg of food per day [58]. Multiplying this by the number of crew (6) and the mission duration (550 days + contingency) we can calculate about 8 tons of food will be required. Similarly, we can calculate the required water based off the 2.2 L/day needed per person with a 90% H_2O recovery system comes out to about 8 tons [55] [53]. Added with approximately 2 tons of expendables and spares [56], the total consumables is about 18 tons. The initial habitat will also need to stow these consumables until a logistics module is added.

The first logistics module will have a moderate mass as a Class 2 hybrid inflatable module with contents being loaded after landing and set up. As a smaller module, the logistics module will provide lower volume but will provide additional volume per mass as a Class 2 module. Because it will primarily be used for stowage capacity, the logistic module requires fairly low power. The logistics module will be used to store crew consumables as well as the less than 5 tons of accumulated waste [56] [57]. Similarly, the second logistics module will have moderate mass and volume requirements but moderate power requirements as it will likely provide increased cold stowage capacity. The second logistics module will provide cold, dry, and dirty stowage and share the stowage for consumables and accumulated waste.

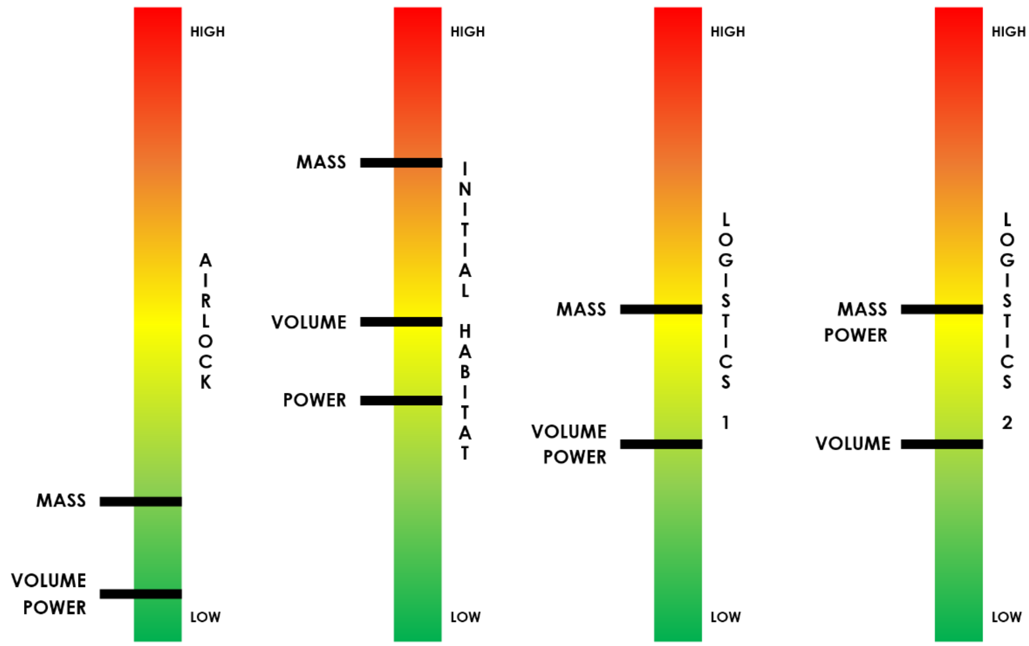

Figure 8 – Early Module Design Requirements

Mass, volume, and power design needs and requirements can be further analyzed across the notional mature station habitat types providing insights (Figure 9). Insights from the mass comparison are:

- Initial mass will be higher as modules need to arrive ready to use requiring modules to be pre-integrated hard-shells,
- Following modules will likely use inflatable and hybrid module technology as they provide reduced mass with higher volume and the initial habitat will support the crew while the newer modules are set up,

and

- As 3D printing technology improves, future modules can be made from Martian resources requiring much lower mass imported.

Insights from the volume comparison are:

- Initial volume will be moderate as hard-shell modules will be restricted by the transit vehicle payload diameter,
- Following modules using inflatable and hybrid module technology will allow modules to be compact during transit and provide a higher volume,
- Logistic volume will be necessary to support additional modules,

and

- As future modules become 3D printed, modules will no longer be restricted by transit payload limitations allowing for the maximum volume.

Finally, insights form the power comparison are:

- Initial power will be moderate as functions and capabilities will be limited,
- Following logistics modules will have a relatively low power consumption,
- Larger modules with more functions and capabilities will have a higher power consumption,
- Modules for living functions having moderate power consumption,

and

- Modules used for production having the highest power consumption.

Overall, looking at Figure 9 we can see that as module types become more specified and advanced functionally, power and volume requirements will increase while mass requirements depend on the type of module used. These insights provide us with information to project the mass, volume, and power requirements as the station grows.

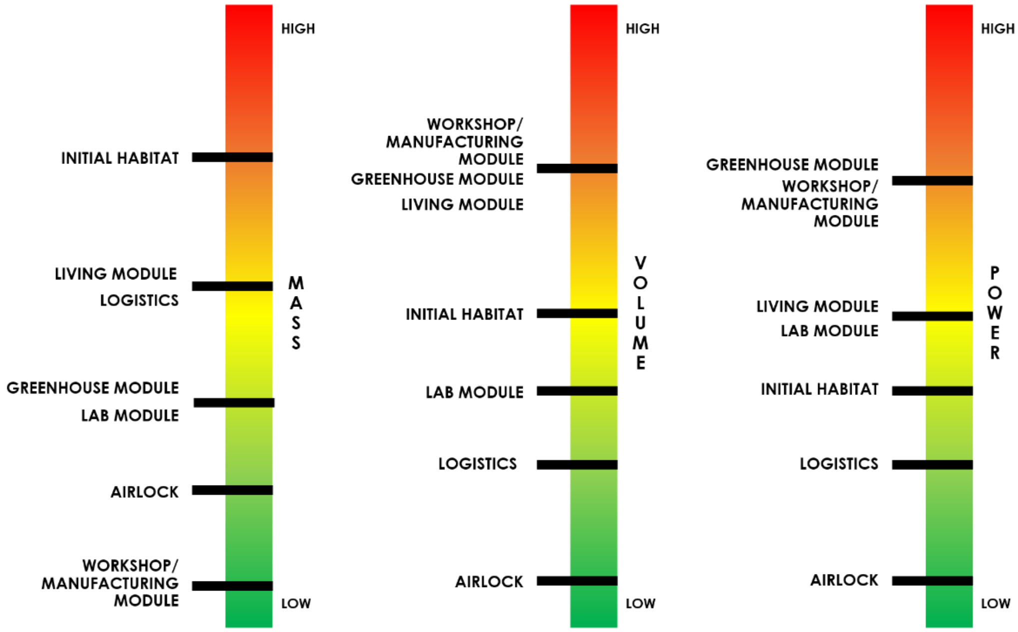

Figure 9 – Mature Module Design Requirements

Logistics Over Time

Using the comparison data from the previous section, we can further compare the logistical factors of mass, volume, and power over the initial, transitional, and mature phase. Because the mass, volume, and power will depend on the specific end design, which is unknown, exact numbers are unknown but general assumptions can be made as seen in Figure 10. Also, because the station will not be changing evenly across missions making change over time difficult to define, these factors were compared to population as we can calculate the amount of consumables and logistics needed to support a human being.

Using our starting information (Table 5), we know that the initial station mass is 22 tons, the power production is 4x10 kW, and the station volume is about 284 cubic meters for a crew of 6. Compared to the initial power consumption of 12 kW, initial power capacity is high. We also know that because the initial phase will use CLASS I pre-integrated hard-shell modules mass is on the higher end and volume will be moderate. As the station transitions, newer modules will be CLASS II hybrid and inflatable modules reducing the mass and increasing volume. Power will increase in increments of 4x10 kW at a time as consumption approaches capacity. Based on the minimum crew for a sustainable station, a crew of 110 was used for the mature phase [13]. Power will continue to remain higher than the station consumption although consumption at this phase will be much higher. At the mature phase it is assumed that 3D printing technologies will have matured and be used to print new modules from in-situ resources. This will drastically reduce the mass required as only premanufactured parts, such as airlocks, will need to be imported. This will also allow volume to rise drastically as it will only be limited by 3D printing capabilities and printing materials.

Looking at Figure 10, the following insights can be seen:

- Power capabilities will increase in jumps to support new growth,
- Volume will incrementally increase to along with population increase,

and

- Logistical mass of modules + consumables will decrease as station approaches self-sufficiency.

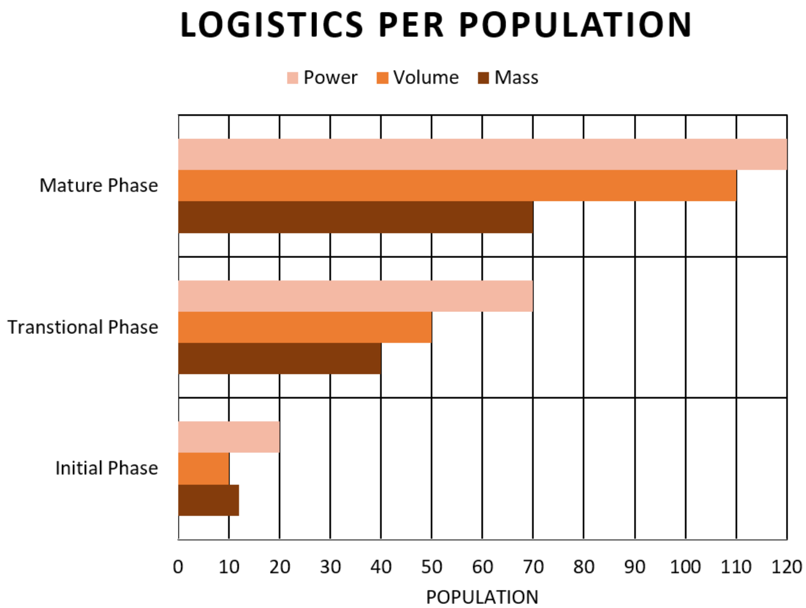

Figure 10 – Logistics per Population

Logistical and Functional Sequence

Building on our analysis, a logistical sequence can be developed starting with the initial infrastructure and adding logistics. In Figure 11, the station development can be sequentially seen throughout early missions. The first mission will establish the station with an airlock nodule and initial habitat providing multifunctional capabilities. The second mission will add a logistics module providing stowage for consumables, waste, and equipment stowage freeing space within the initial habitat. The third mission will provide a second logistics module expanding stowage capacity and types to help stow consumables, accumulating waste, and increasing equipment. The fourth mission will bring a third logistics module. At this stage the initial habitat will have aged somewhat and some functions such as will be moved out to the first logistics module making it multifunctional and part of the initial habitat converted to logistical stowage. By this point, sufficient logistics will have been provided to support new growth. The fifth mission will provide a large secondary habitat with expanded and advanced functions. At this stage, the initial habitat will be completely converted to logistical stowage as the module has aged. The sixth mission will add another logistics module restarting the cycle of preparation for the next step in station growth. This pattern will provide the basis for development throughout the transitional phase as logistical capabilities build up to support advanced modules until reaching the mature phase.

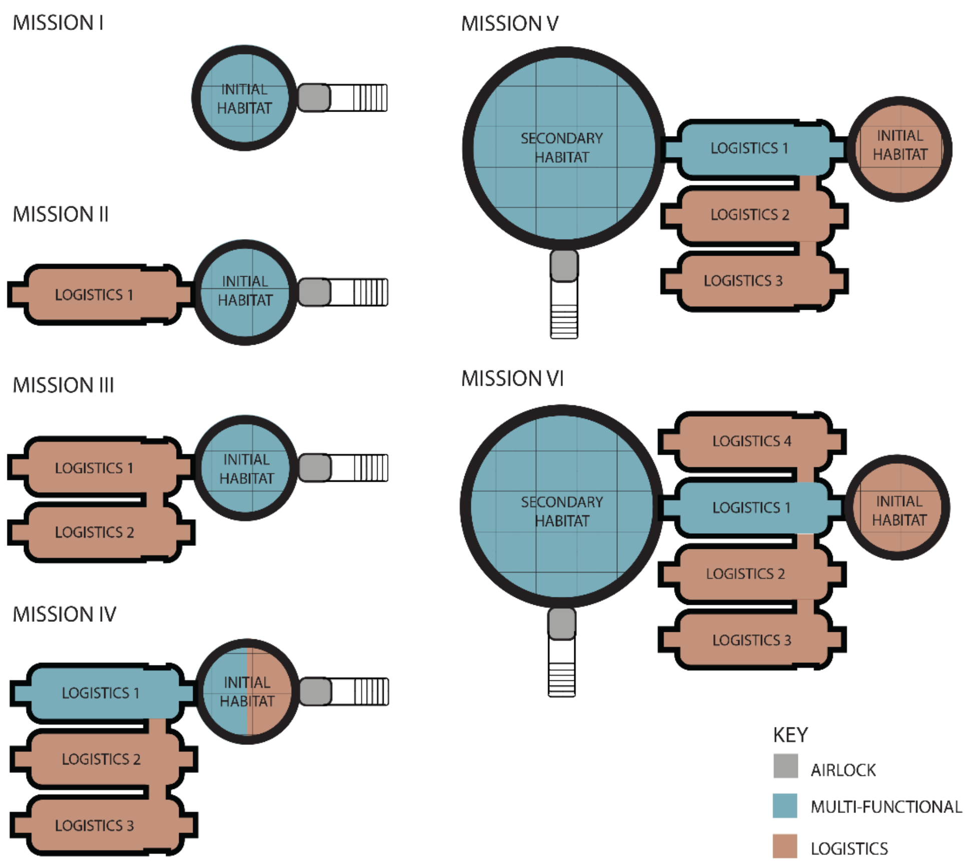

Figure 11 – Logistical Sequence

This sequence can also be shown looking at the development functionally. In Figure 12, we see the development as functions provided increase. The first mission will provide the initial habitat which will provide all necessary functions to operate the station. These functions include living, logistical, medical, laboratory, and control functions as seen in Figure 12. Living and logistical functions will account for most of the provided functions. The second and third missions provide additional logistical functions as modules are added. During the fourth phase, the new module provides logistical functions and the initial habitat becoming partially converted to logistics compensating for the first logistics module becoming multifunctional. Additional living and lab capabilities are acquired. The fifth mission provides the secondary habitat increasing all functions throughout the station and allowing the aging initial station to be fully converted to logistics. At this stage, it is likely the population able to be supported will increase and functions advance. Finally, the sixth mission provides another logistical module to support the increasing demand and prepare for further growth.

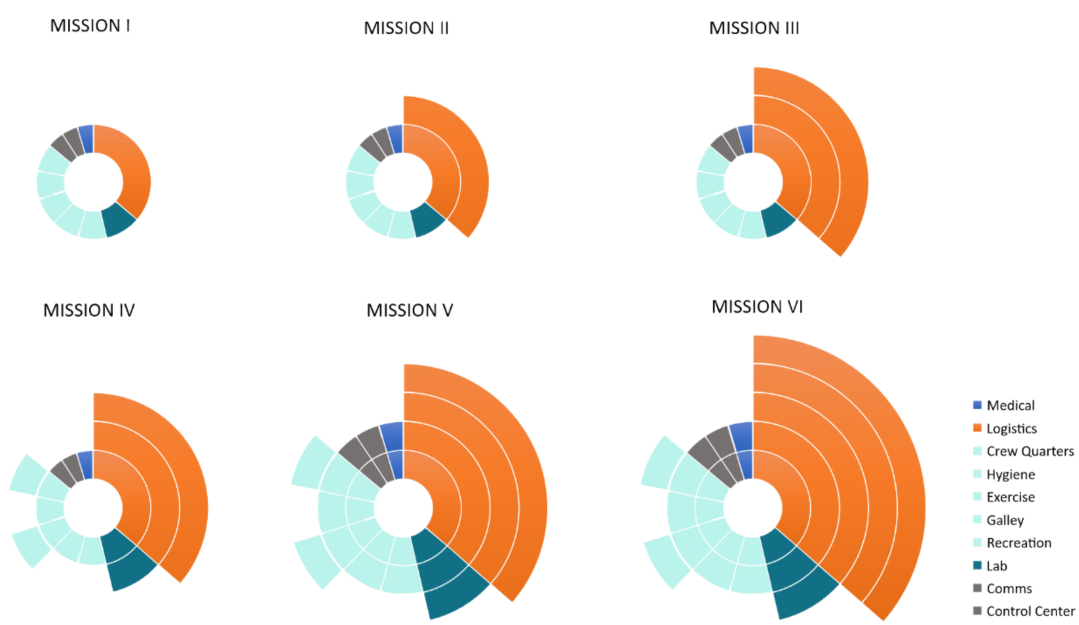

Figure 12 – Functional Sequence

VII. CONCLUSIONS AND FUTURE WORK

Through the analysis of Antarctic station design and impact on the transitional phase of a long-term station, several applications to sustainable Martian station development became apparent. Unlike Antarctica where each station iteration is built new, Martian station design must build on earlier modules and incorporate their life cycle into the design. As the station develops, logistic capabilities are the backbone of station operations and essential to enabling sustainable growth. Furthermore, logistical mass, volume, and power needs and requirements affect when station and population growth occur and change as the station transitions from an initial to mature design. Because of these changing needs, station design must be able to adapt logistically and functionally to reuse spaces over time. Finally, no matter how thoroughly we may prepare, unexpected scenarios and unknown factors will always exist and the station design must be able to adapt to them.

Future work on this topic would require further analysis of mass, volume, power needs and requirements for more advanced stages of the transitional phase. The impact of ISRU production and manufacturing on long-term logistical requirements is also of interest as it may affect the rate of development. Another area that was not covered would be a logistical comparison of needs and requirements of different mature station types. Finally, if the research were continued, it would be essential to design parameters to allow functional repurposing the modules over time.

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