ARES INFINITE

Creating a 3D Printed Design Vernacular for an Evolving Research Station on Mars

by

Christopher Chan

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Architecture

Waterloo, Ontario, Canada 2018

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

ABSTRACT

This thesis proposes the design of a habitat built on Mars. It speculates on the usage of 3D print technology as a construction method to address the extreme environmental conditions of the planet, as well as the changing architectural and programmatic demands of an ever evolving Martian research station.

Collectively, our design inclinations for interplanetary habitation tend to be reminiscent of metal pods which are modular, prefabricated, and adaptable. Although these designs are effective in places like on the International Space Station, Mars poses drastically different site conditions.

Given its incredible distance from Earth, a developing Mars colony will need its architecture to be constructed using in-situ materials to relinquish dependence on materials sent from Earth. Furthermore, the Martian base will require its method of procurement to also be flexible and repeatable to suit the changing research needs and occupancy.

3D printing technology offers an ideal solution to these problems since this technology allows for a hands-off, and highly flexible construction method.

This thesis will investigate the potential for an efficient evolution of a Mars habitat using 3D printing as a strategy; starting at the initial conception of the habitat as a temporary exploration outpost, then growing into a larger research station with a population comparable to those of the Antarctic research communities on Earth.

ACKNOWLEDGMENTS

I would like to sincerely thank my supervisor Terri Boake whose inexhaustible insight and encouragement always helped steer me in the right track.

Thank you also to David Correa for all of your guidance along the way. Your technical expertise made this work possible.

I am also very grateful to Philip Beesley for your help at the beginning and the end of the thesis is greatly appreciated.

To all of my friends, who have edited my work, played boardgames with me, and have made my time here so much more enjoyable.

And finally to my parents and family. Your love and support throughout this ordeal is something I will forever hold dear. It was all possible because of you.

DEDICATION

To my family and my friends.

TABLE OF CONTENTS

LIST OF FIGURES

VISIONS OF EXPLORATION

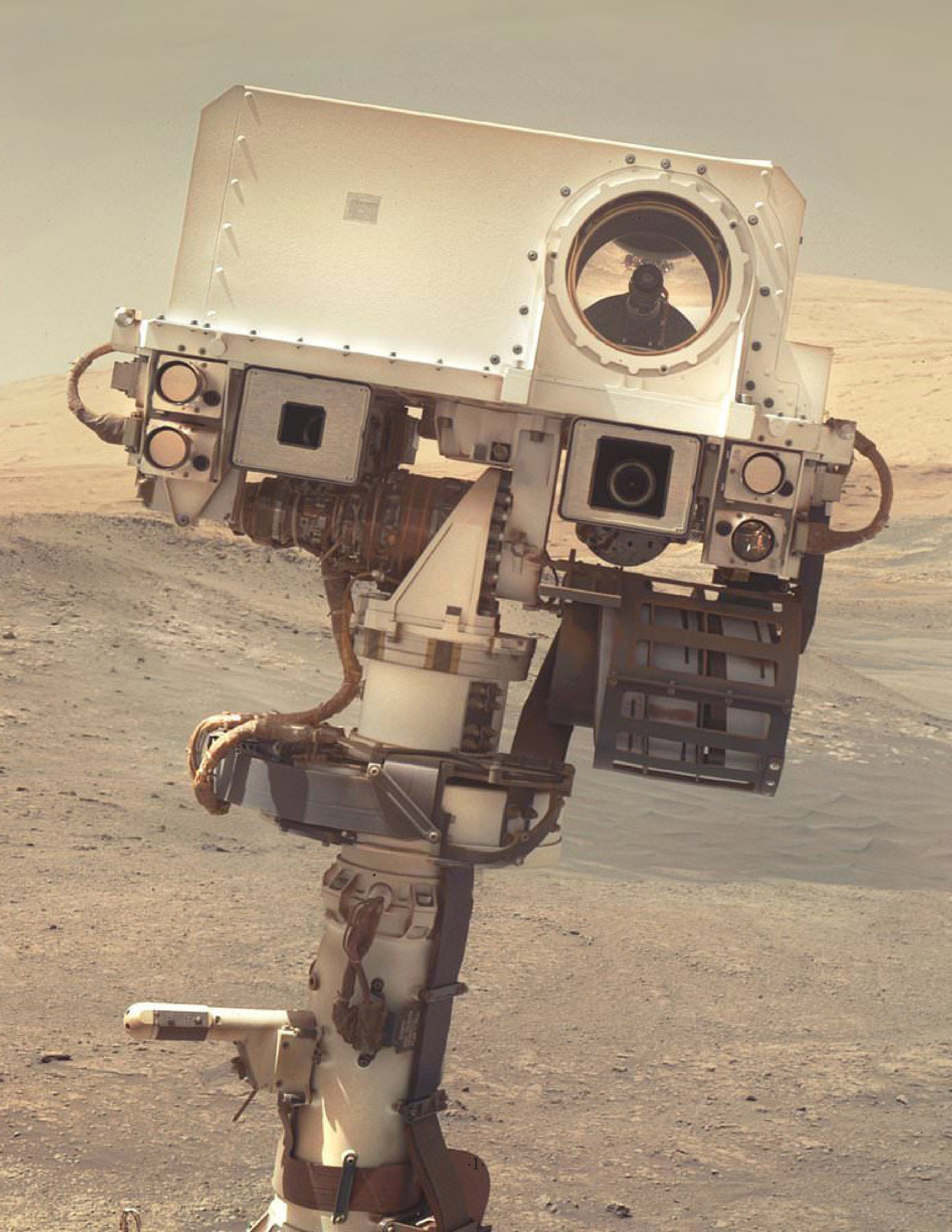
COLD COLONIES

UNDERSTANDING THE EXTREME

DEVELOPING TECHNOLOGY

DESIGN SYNTHESIS

TECHNICAL CHALLENGES



INTRODUCTION

Architects for Mars

We are born as explorers and voyageurs. The desire to travel to new places is something that is ingrained into our human nature. The societies we live in are built on the backs of those who have pushed the frontiers of human existence and knowledge into unexplored territories. This drive has helped our species thrive in its environment and our continued outward look is the reason why we can live as prosperously as we do today. While in the past, our predecessors have gone in search of riches, resources, and power, this not necessarily always the case. Currently, the discovery of new lands has slowed but the explorative nature persists in the pursuit of science. Some of the biggest example of this being the exploration of the arctic regions, the deep ocean, and low Earth orbit. These areas have some of the harshest environmental conditions, and the fewest economic advantages, yet humans have gone there for scientific research alone.

Arguably, the next frontier for human exploration and scientific gain is on Mars. The journey to Mars calls back on our pioneering culture, but also tantalizes our scientific curiosity. Similar to the moon landing in 1969, going to Mars would usher in a zeitgeist of progress and scientific discovery, pushing forward humanity's boundaries. Technological advancements that would follow a Mars landing would help to improve fields like energy, waste, healthcare, and food production, among many others.[1] The developed technologies will be useful not only to the Mars astronauts, but to our everyday lives on Earth. Furthermore, as evident from the Antarctic research stations, research can be conducted with a far greater degree of accuracy and effectiveness than with just robots and drones. This could possibly mean answering the most enticing question of whether there is or was life on Mars, definitively telling us whether or not life is as rare as we have previously thought.

While the journey to Mars will be unpaved and rugged, the end destination is also not necessarily the barren desert we once

Figure 0.1 - (previous page) Aptly named Curiosity Rover taking a 'selfie' with the Mars landscape in the background

---

[1] NASA's *Spinoff* annual publication highlights commercial uses that come out of research into NASA mission technologies. https://spinoff.nasa.gov/Spinoff2008/tech_benefits.html

Figure 0.2 - Wanderer Above the Sea of Fog

thought it was. “Unique amongst the extraterrestrial bodies of our solar system, Mars is endowed with all the resources needed to support not only life but the actual development of a technological civilization.”[2] Mars holds plentiful supplies of ice water in its soils, along with ample, readily available supplies of carbon, nitrogen, oxygen, and hydrogen.

Creating a livable habitat on Mars will be a challenging undertaking and it will require a fair amount of inventive thinking to utilizing the available resources. The planet has an environment that humans have not evolved to exist in. It is precisely here however, that architecture holds its big stake in this future. The buildings that we construct to aid us will be instrumental in the success of our stay there. They will be the boundary between humans and magnificent terror of the Mars environment; the boarder between demise and survival.

Certainly, one might imagine our space architectures to revolve around highly engineered parts and technology like HAL 9000’s[3] to ensure our survival. But although it is easy to pass off the duty to an engineer who will build a Martian habitat with a super computer personal assistant and find some way to launch it into space to land on Mars, this is not necessarily what should be done. Architects have broad skills from across fields, combining issues from the humanities to technology. It is a practice that innately has tension in that it is an autonomous field of knowledge which investigates the production, occupation, and perception of all modes of form and space.[4] The combination of these different but closely related fields cannot be lost when designing new Martian habitats, or else what would be left are the unappealing claustrophobic metal pods we tend to see portrayed throughout our present media.

The field of architecture and pragmatically, the role of the practicing and researching architect have much to gain in its involvement on Mars as well. Space architecture provides an ideal testing ground for a vast array of interdisciplinary technologies, and encourages imaginative new ideas for how we may live. Scientifically, it remains to be seen whether or

---

[2] Robert Zubrin, *The case for Mars: the plan to settle the red planet and why we must* (New York: Free Press, 2011), XXV.

[3] *2001: a space odyssey*, dir. Stanley Kubrick.

[4] Francis Field, Jon Goodbun, and Victoria Watson, "Space-Time and Architecture," Journal of the British Interplanetary Society 67 (2014): pg 322.

ex dono D. Orlandini

TRACTATUS SECUNDUS
DE NATURÆ SIMIA SEU
Technica macrocoſmi historia
in partes undecim diviſa.

AUTHORE
ROBERTO FLUDD ALIAS DE FLUCTIBUS
armigero et in Medicina
Doctore Oxonienſi.
In Nobili Oppenheimio
Ære Iohan-Theodori de Bry Typis Hierony-
mi Galleri. Anno CIↃ IↃCXVIII.

M Merian sculp.

ex dono D: Orlandini
ex Bibliotheca And: Falconet.

Figure 0.3 - Robert Fludd etching of the relationship of architecture and other disciplines

Figure 0.4 - NASA's Mars Recruitment Posters

not there *was* life on Mars. However, as our research into this progresses, a larger question that will need to be addressed is whether or not life will exist on Mars and how it will come to be.

With this in mind, this thesis is an exploration that is a loose, but informative thought experiment into the possibilities of construction methods used to settle on Mars. It will attempt to design two habitats based on a hypothesis on the evolution of human lifestyles in extreme environments. Furthermore, it will identify specific environmental obstacles that exists and which ones are the most relevant for architecture to combat.

The design of the first habitat is for an alternative small research outpost, capable of containing a small crew of six people and providing the base necessities for them.

The second design assumes the base is to be expanded to accommodate appriximately one hundered or more people. This design will be a suggestion for a possible method of expansion that will continue to use the same fundametnal technique as the previous design, but adjusting it to use at a larger scale.

Finally the thesis will examine the design methods and suggest room for which further research is needed, and how they can be improved upon.

- PART ONE -

VISIONS OF EXPLORATION

PRECONCEPTIONS

Assessing Precedents

Interplanetary architecture does not have many constructed precedents. The only built examples are a few analog experiments in extreme remote environments, whose purposes are to act as a testing place for a mission outside Earth. One example of this is the Hawaii Space Exploration Analog and Simulation (or HI-SEAS). Besides these, there are also a few precedents that come from design fictions – namely things like futurist architectures or science fiction cinema. These examples are less scientifically tested than the constructed habitats, but are useful since they are speculations for imaginative architectures and different lifestyles in space.

It must be noted however, that among this small cache of precedents, there are some which should not be considered reasonable explorations into human life on Mars. For example, the film Aelita - Queen of Mars.[1] This 1924 film is perhaps one of the earliest depictions in media of life on Mars. This film was created prior to even the first satellite being launched, and understandably holds no scientific backing in its portrayal of architecture. The architectural language of sharp pointed edges and skyscrapers juxtaposed to the repetitive swooping curves of columns and walls were meant as a way of saying, "this world is not our world". Although the purpose of this film was not to accurately depict a believable habitat on Mars, its naiveté propagates throughout popular media; films where aliens speak English, air is universally breathable, gravity is consistent everywhere, etc. While these films can sometimes offer a sense of wonder and inspiration, they often contribute to the preconception of fantasy or impossibility in designing space architectures since they omit the harsh realities of the extreme environment.

At the other end of the spectrum, there is the architecture of space-age metallic pods and toroidal colonies haunting the design world today. A first thought for architecture in space typically draws visions of people living in buildings that are of the same material and function as the vehicles used

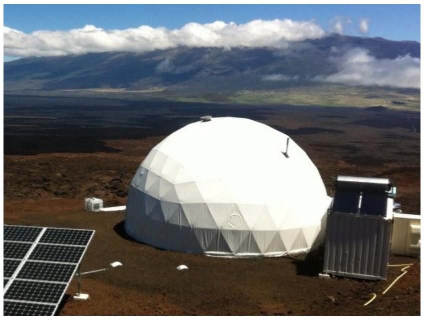


Figure 1.1 - *(previous page) Satellite image of a valley in East Jezero Crater*

Figure 1.2 - *HI-SEAS experiment dome house*

---

[1] Aelita, dir. Yakov Protazanov(U.S.S.R.: Publisher not identified, 1924), https://www.youtube.com/watch?v=je1bIhS-7G8.

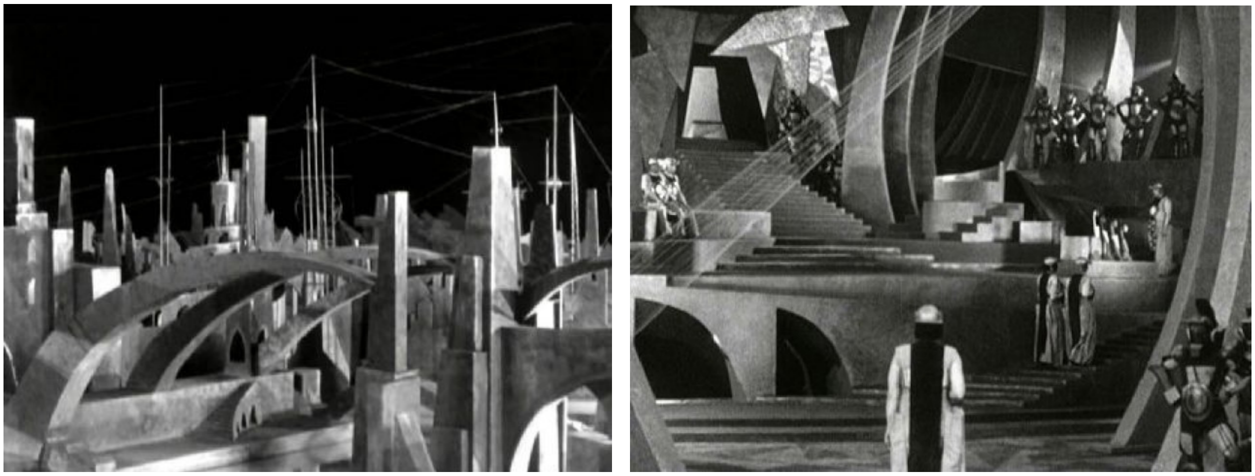


Figure 1.3 - *Stills from Aelita showing architectures from Mars*

to transport them there. A Google image search for 'Mars Colony' illustrates this exact point. Robert Zubrin[2] likens these designs as cans of tuna; everything is tightly compacted, efficient, and encapsulated in a lightweight metallic shell. Though functionally logical in their task of transporting humans across space, these designs evoke a dank sense of architecture and claustrophobia. The idea of having these places be our long-term homes in the cosmos seems unlikely. "Their prospect is marginal for supporting a large scientific population at a permanent Mars base and utterly hopeless as the basis for a program of Mars colonization."[3] Our notion about off-Earth architectures "generally fail to explore the dynamic and relational nature of space-time, and often reduce human habitation to a purely functional problem"[4]. The chasm between the functional demands of the site and our fictional imaginations tends to leave the notion space architecture as an unrealistic or frivolous feat.

A good example of this is the 1970's National Aeronautics and Space Administration (NASA) Ames drawings for the space colonies which render our lives outside of Earth in an interesting way. The rendering shows a futuristic colony of humans living in a spinning minimalistic spacecraft which

---

[2] Robert Zubrin is the founder of the Mars Society; an international organization dedicated to furthering the exploration and settlement of Mars. https://www.nasa.gov/ames/ocs/2014-summer-series/robert-zubrin

[3] Robert Zubrin, The case for Mars: the plan to settle the red planet and why we must (New York: Free Press, 2011, 189.

[4] Francis Field, Jon Goodbun, and Victoria Watson, "Space-Time and Architecture," Journal of the British Interplanetary Society 67 (2014): abstract.

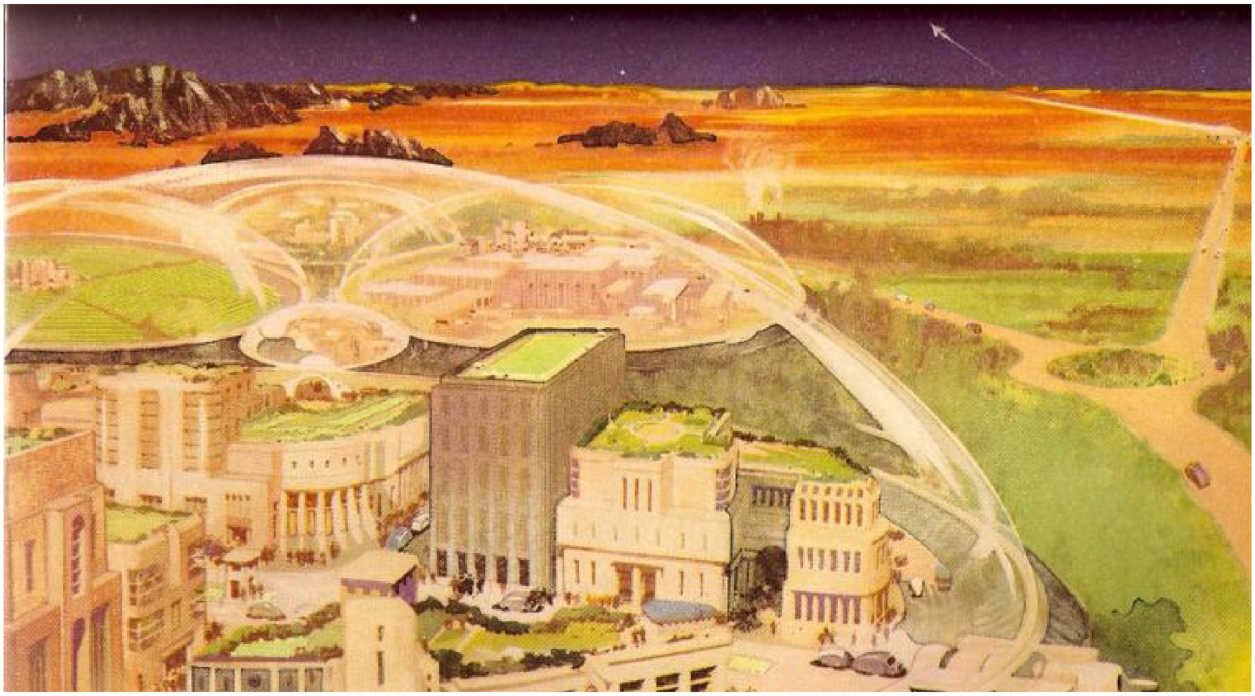
generates artificial gravity through centripetal force. Within this highly technological piece of architecture, generic homes of white stucco and terracotta tiles gives the sense of an Earth away from Earth. “What’s interesting architecturally about these images is the visual juxtaposition and, oftentimes, design friction between the ‘space age’ or modern superstructures versus the conventional landscapes and architecture contained by them.”[5] This proposal superimposes a generic all-American lifestyle onto a foreign piece of technology, grafting together two disjointed entities.

It is unrealistic to believe that the current vernacular in which we build and occupy our homes should simply be replicated into the context of space. The domain of the designer has extended into other worlds for which the foundations of our current design practices have not evolved alongside. This world is incredibly hostile, materials are scarce, and the site is millions of kilometers away. The visions that the engineer might have are of a highly refined and reductive form contrasts that of the movie artists, portraying habitats created through a near magical process, and surrealism. Ideally, to push the discussion of Mars habitation further, there must be some sort

Figure 1.4 - *NASA Ames 1970's Toroidal colony cutaway exposing interior environment*

---

[5] Mark S. Morris, “Galaxy Gadgeteers: Architects in Space,” Journal of the British Interplanetary Society 67 (2014): 274.



of balancing between these two forces.

The precedents that are looked at in the following sections are selected because of their accurate and or logical representations of habitation in these extreme environments. This is done to dispel some of the preconceptions of space architecture, and to narrate a story of what our lives on Mars might look like with a reasonable comparison to circumstances we have on Earth. From here, flaws and benefits can be analyzed and speculated on.

Figure 1.5 - *Leslie Carr's The Martian Base 1951, appearing on Arthur C. Clarke's book "The Exploration of Space*

BASIS FOR DESIGN

Setting Up a Framework

NASA's Human exploration of Mars design reference guide for architecture outlines various fields that should be considered before exploration of Mars can take place[1]. Within this, there are three considerations that were outlined; (1) duration of time away for astronauts and increased risk of adverse health effects, (2) adequate time on the surface to allow for the greatest return of knowledge, and (3) lowering rocket mass to reduce cost and complexity[2].

These considerations relate specifically to types of mission structures, namely: Opposition-class (or short-term) missions, and conjunction class (or long-term) missions[3]. An example structure of a short-term mission taking a total of about 650 days with 30 days on Mars, whereas a long-term mission of about 916 days with 496 days on Mars (figure 1.5). Ultimately understanding these two mission types can help determine whether a long-term mission could be justified in the added risk.

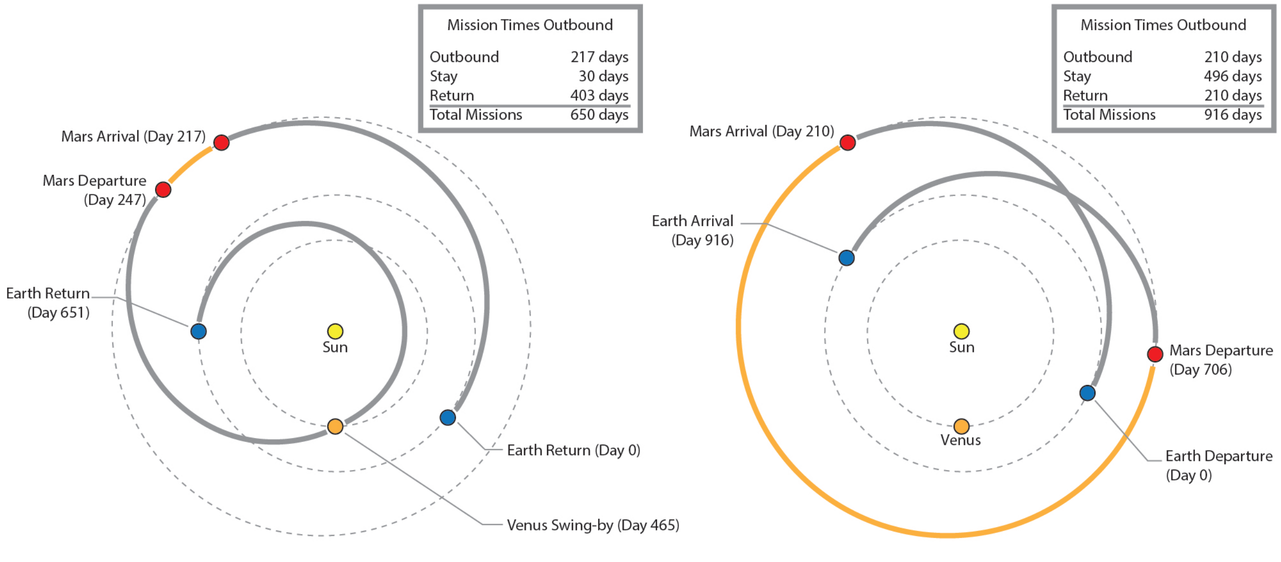
If the human experience for Mars were to be as fleeting as a couple of month-long excursions, then it would be almost passable to leave the architect out of the discussion. Humans could simply live in the metallic "tuna cans" stated prior. However, from an architectural standpoint, a long-term mission type is the best option. A longer stay would warrant the investment into a more permanent and robust architecture that could stand longer and support future missions. Furthermore, the architecture constructed would play a more significant role in countering the adverse effects of living in this environment. This does poses slightly more challenges in designing this space. Since the time spent on the planet is longer, it means the

---

[1] This guide uses the term "architecture" not specifically in reference to the construction of buildings, but as a structure for how a mission to Mars would work, from launch, transportation, surface systems, affordability, and challenges.

[2] Bret G. Drake, ed., Human Exploration of Mars Design Reference Architecture, report no. 5.0, Mars Architecture Steering Group, National Aeronautics and Space Administration (Houston, TX: NASA Johnson Space Center, 2009), 47-48.

[3] Ibid, pg 48.



Opposition Class: Short - Stay Mission

Conjunction Class: Long - Stay Mission

Figure 1.6 - *NASA Outlined Example Mission Types*

scope of the design is not simply a for a vehicle to Mars, but an actual home or society.

The selected mission type will no doubt have a very important role in how the architecture (that is the construction of built habitats) would be designed. The buildings designed should adopt the considerations of **(1) temporality and objectives, (2) safety, and (3) cost and complexity**. Therefore, the thesis will structure itself based on a long-term mission class with the above three design parameters and identify how the considerations for mission structures would directly impact the physical spaces humans would live in.

- PART TWO -

COLD COLONIES

TIME AND PURPOSE

Duration of Stay, and Objectives

A new human settlement on Mars will require some consideration into its temporality and purpose. What is the duration of the stay? How frequently is it occupied? What kinds of people are visiting and what are they doing? The evolution of the architecture, as well as our ability to speculate on what its future looks like depends largely on these factors.

Even since the primitive world, the existence of planning, as opposed to just plans, were present. The purpose and the overall direction of the collective determined how the architecture was manifested. Travelling tribes had more flexible and mobile plans, whereas more sedentary tribes had stationary, fixed plans. In their isolation, the primitive tribes evolved their architectures based off things like economic advantages, ownership of land, social hierarchies, and sometimes arbitrary forms.[01]

In a way, the isolated primitive huts of the early world slightly resemble the architectures we imagine for Martian settlements. Buildings are small, interconnected, oftentimes circular pods, huddled together to protect against outside forces and contain whatever is within. Usually they are also near some form of natural resource (be it trees, deposits of water, food, etc).

A Mars settlement may look somewhat like a high-tech primitive society, but it is unique in its objectives. Though they are still wanderers in an isolated and foreign land, the people making up this modern tribe are not hunter gatherers. Instead, they are likely going to be scientists and engineers with a mindset of research and exploration. The first settlements on Mars will be constructed for scientific knowledge, and not for obtaining wealth or social status. The resources acquired from the site will be predominately for either study, or for basic survival. Unlike the primitive tribes, these resources will be more difficult to gain access to. They would require some pre-constructed infrastructures before they could be harvested. Water for example could be extracted from the Martian air,

Figure 2.1 - *(previous page) Aerial image of present day McMurdo Station*

---

[01] Douglas Fraser, Village planning in the primitive world (S.l.: S.n., 1986), 5.

Figure 2.2 - *(top) Swazi kraals. Near Bremersdorp, South Africa*
Figure 2.3 - *(bot) - SunCity Camp - desert camp in Jordan offering a "Martian" experience*

requiring mechanical equipment (for example WAVAR)[02] before it could be consumed. This problem is coupled with the fact that Mars is a large distance away, with only short windows of opportunity where a rocket could be sent there, meaning resupplies from Earth will be infrequent and untimely.

The exact situation is strikingly similar to that of the Antarctic research stations.[03] These research centers are located across the continent, and were constructed at a variety of times. Each of them originate from different countries but most were built for the purpose of exploration and science. Additionally, although not identical, the forces at play in the Antarctic are similarly as hostile on Mars. It is not easy to sustain life there, it is difficult to get to, and without proper equipment the environment could be lethal. Average temperatures range from approximately -10°C along the coast, and towards the interior -60°C[04]. The architectures constructed in the arctic regions, as well as the subsequent human colonization of these places, are an ideal precedent for the kind of civilization that would evolve on Mars. This comparison is not unprecedented as NASA has also acknowledged this by using locations in Antarctica as testing grounds for Mars Analog experiments.[05]

Stage 1 – Exploration Outpost

The first stage of human settlement is typically exploration; somebody going out and coming back. The exploration began in was called the 'heroic age' which began in roughly 1895 when the land was still greatly unknown, and explorers

---

[02] Water vapour adsorption reactor, or WAVAR is a machine developed in the University of Washington to extract water from the Martian air.

Adam Bruckner et al., "Extraction of Atmospheric Water on Mars for the Mars Reference Mission," Lunar Planetary Institute Contribution No. 955, December 1997.

[03] Brian Grazer and Ron Howard, "What Does Colonizing Mars Look Like? | MARS," YouTube, December 05, 2016, https://www.youtube.com/watch?v=cHkiZ35trzU.

[04] "Antarctic weather," Australian Government, Department of the Environment and Energy, Australian Antarctic Division, March 01, 2012, http://www.antarctica.gov.au/about-antarctica/environment/weather.

[05] Analogs missions are simulations of real Mars missions done in remote places on Earth that share similar qualities to those on Mars. Timothy Gushanas, "About Analog Missions," NASA, February 17, 2016, accessed December 16, 2017, https://www.nasa.gov/analogs/what-are-analog-missions.

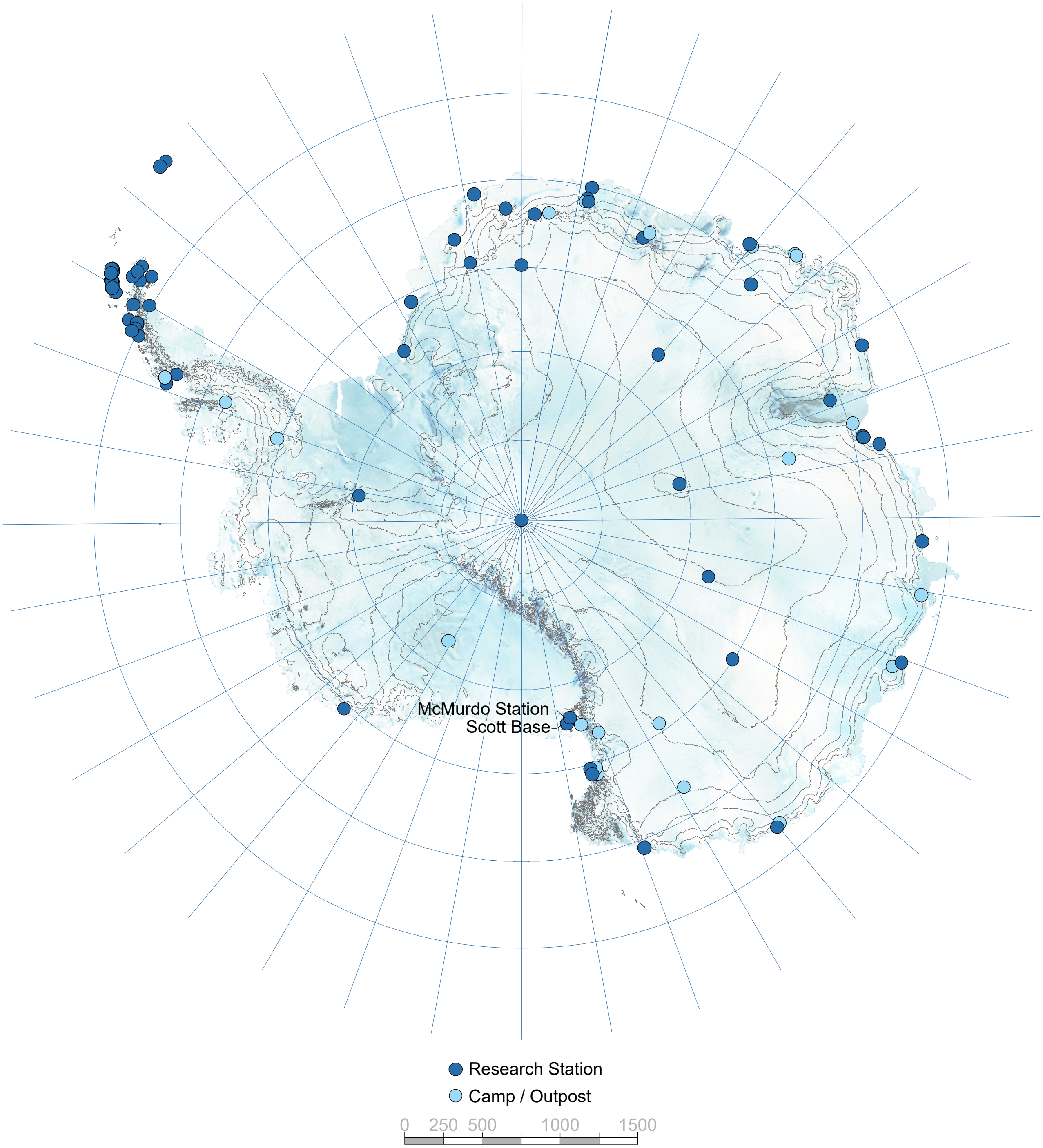


Figure 2.4 - *(top) - Map of Antarctic Settlements*

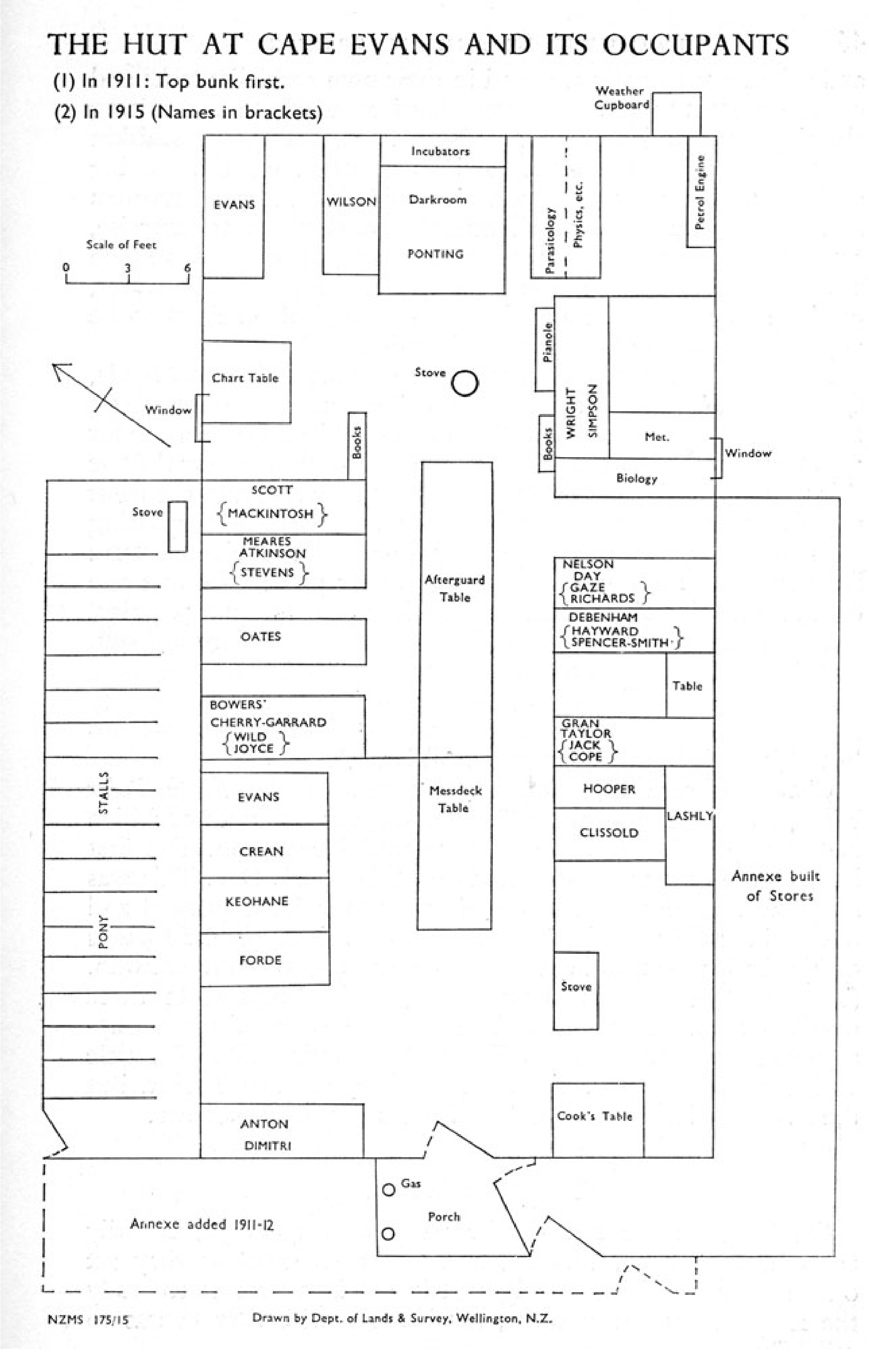


Figure 2.5 *- Conservation Plan of Scott's Hut*

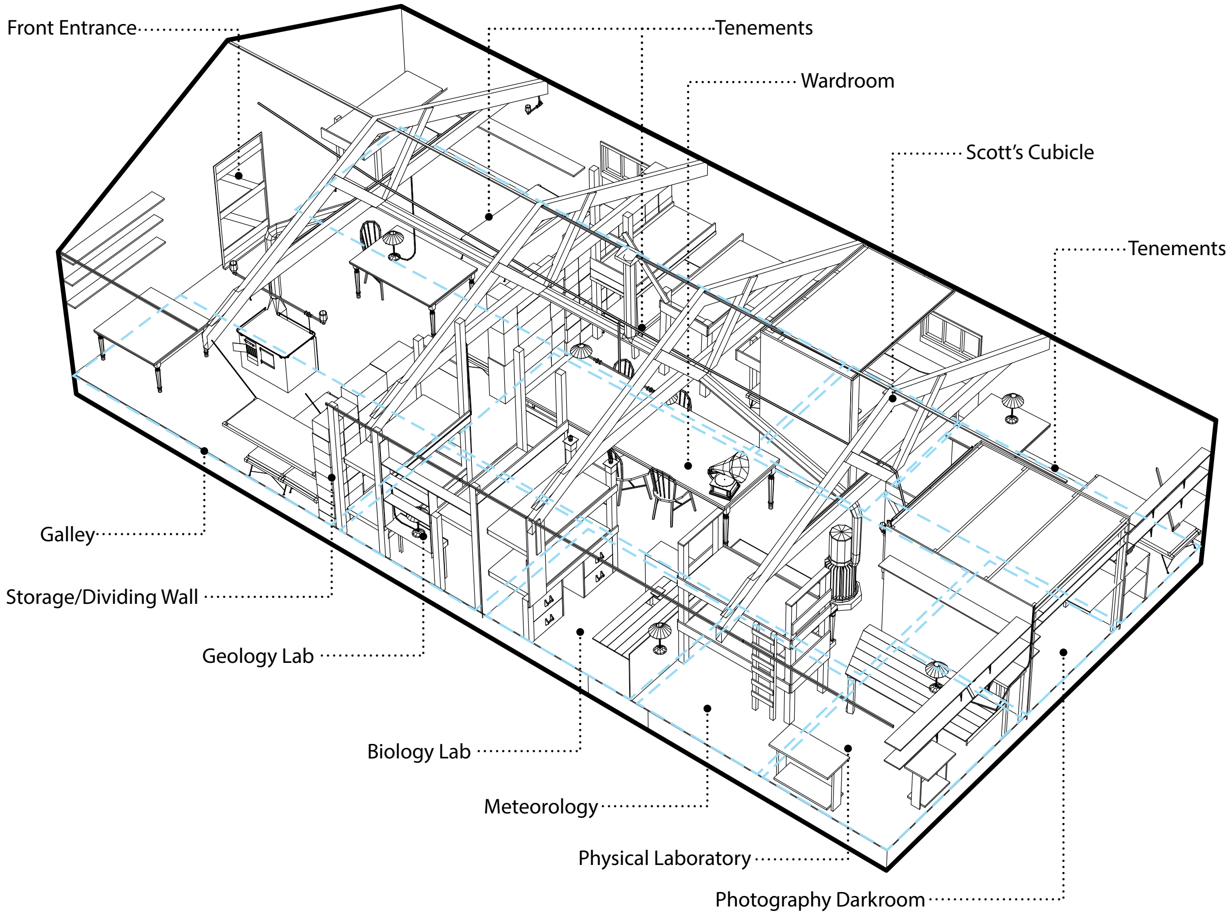


***Figure 2.6 -** Axometric of Scott Hut Interior Model information created and acquired from John Fino*

Figure 2.7 - *Present day image of Scott's Hut*

Figure 2.8 - *Robert Falcon Scott writing in his diary in his quarters in 1910/1911*

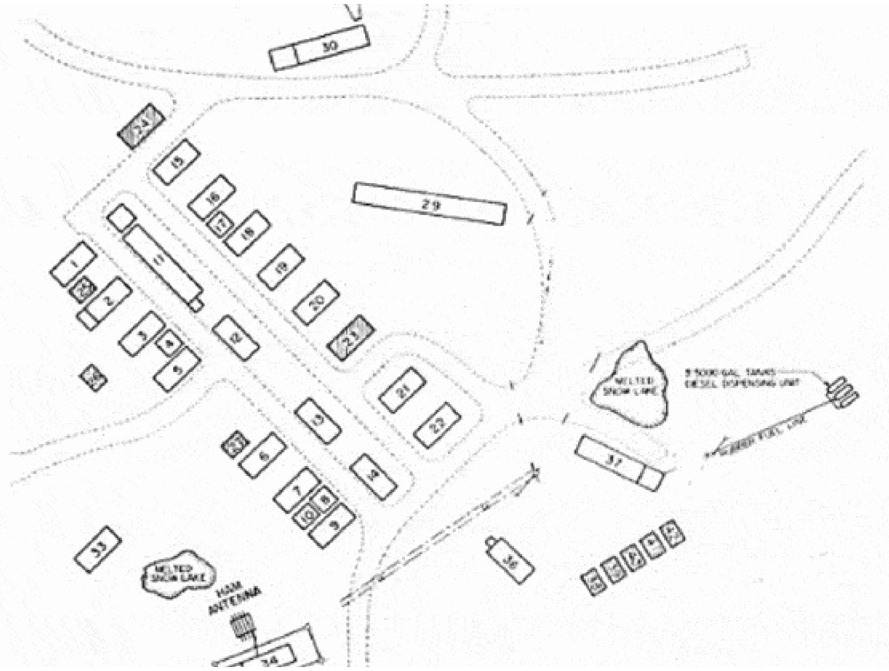


Figure 2.9 *- Layout of McMurdo Sound Naval Air Facility*
Figure 2.10 *- Aerial View of McMurdo Sound*

sought glory and scientific recognition[06]. During this time the first wave of architectures took form as small huts that acted as base camps, allowing teams to adventure deeper into the inhospitable continent.

One of such is Scott's Hut located on Cape Evans on the Ross Island. Scott's hut was erected in 1911 during Robert Falcon Scott's Terra Nova expedition. The hut had most of its materials brought in from Australia.[07] The men would predominately meet in this hut to discuss their next plans, work and sleep. There was one building which had all the essential needs of work and living spaces with peripheral equipment surrounding the perimeter. The centralized plan was laid out to push sleeping and work spaces out towards the sides and have meeting and eating spaces at the center.

Architectures that were created in the exploration stage are now scattered along the coast of Antarctica. The huts were minimal and uncomfortable and most of them are no longer in use. After Scott's crew died during the Terra Nova expedition, the hut was abandoned. Presently, it sits nearby to contemporary research stations like McMurdo Station. These modest huts however, have become a "monuments to human spirit". They offer insight into the possibility of human occupation into extreme environments while also outlining the problems that were faced: site selection, ease of construction, temperatures, transportation of materials, privacy, segregation, comfort, etc.[08]

Expeditions on Mars will likely occur in a similar manner. The first place that humans land on Mars will not necessarily be the best place to set up a large research station. Multiple expeditions will take place, and as more is learnt about the planet and its geography, a single site can be chosen to develop a more sophisticated settlement.

However, it is unfortunate and slightly wasteful that the history of Antarctic architecture shows these exploration outposts are abandoned. It is likely in part due to the fact that the technology

---

[06] Georgina A. Davis, "A history of McMurdo Station through its architecture," Polar Record 53, no. 02 (2017): pg 167-168, doi:10.1017/s0032247416000747.

[07] Gretchen Legler, On the ice: an intimate portrait of life in McMurdo Station, Antarctica (Minneapolis: Milkweed Editions, 2005), pg 16.

[08] Davis, "A history of McMurdo Station through its architecture,"pg 168.

for construction has since made these huts obsolete, but nevertheless, this kind of waste is only amplified on Mars. Since the distance is far greater, we would want to minimize as much waste material as possible, and therefore the theoretical 'huts' that we send to Mars should be resilient enough to last the test of time, or perhaps be repurposed in some way.

Stage 2 –Logistics Hub

The second stage of development is some form of a small research station or logistics hub. These facilities are meant to allow for logistical operations and occupation. This means the support infrastructures for basic function and transportation are established, as well as the essential buildings for occupancy. This could include power generating facilities, barracks, vehicular maintenance, or material production spaces. The original huts have now exploded into a plethora separate building typologies.

The early naval air facility called McMurdo Sound fits into this category. It is located close to Robert Falcon Scott's first landing site for his Discovery expedition in 1901 on Ross Island. The US government began a permanent occupation of the site in the mid 1950's, which predominately enabled air and naval support, as well as some scientific research support in the Antarctic. At the time the base was not meant to become permanent.[09]

The early architecture was laid out in a military grid format, which prioritized vehicle circulation. It had basic programs with streets, a chapel, and a parade ground. Most of the buildings constructed at this time were needed for essential function, for example barracks. However, there still were spaces for socialization and gathering, like three separate bars where scientists and workers from other fields could meet. It is important to note: "Despite the high costs of perceived 'non-essential' buildings, the [governing bodies] still understood (and researched) the need for immediate access to reasonably comfortable quarters and more than basic survival conditions for the men and officers."[10]

---

[09] Ibid, pg 170-171

[10] Davis, "A history of McMurdo Station through its architecture," pg 171

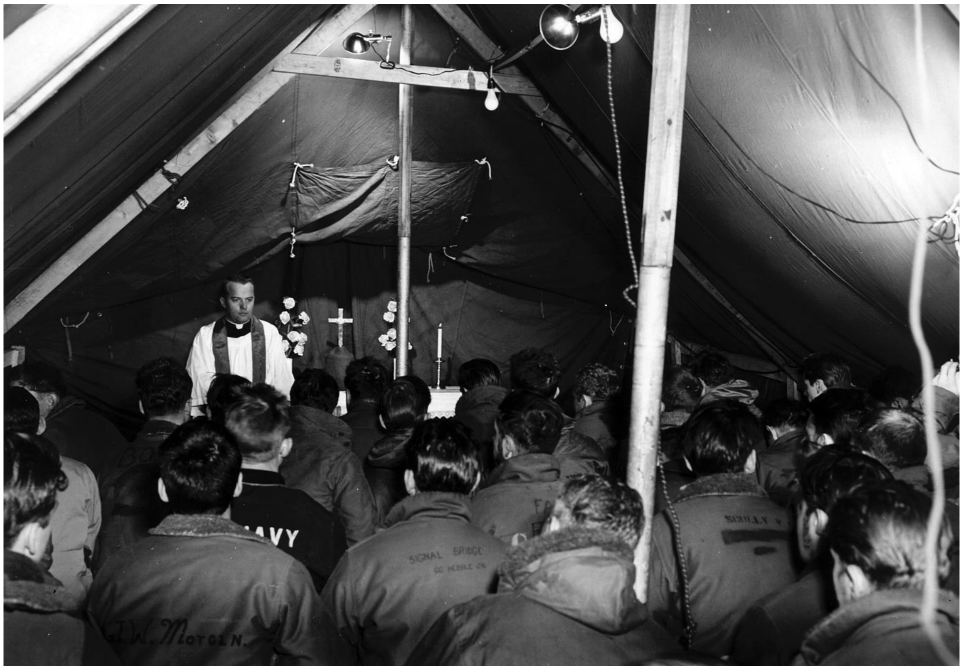


Figure 2.11 - *Men Gathering for Church Service*
Figure 2.12 - *Navy Men Relax at makeshift table at Little America IV*

Figure 2.13 - Present Day Condition of McMurdo Station

***Figure 2.14 -** Present Day Condition of McMurdo Station*

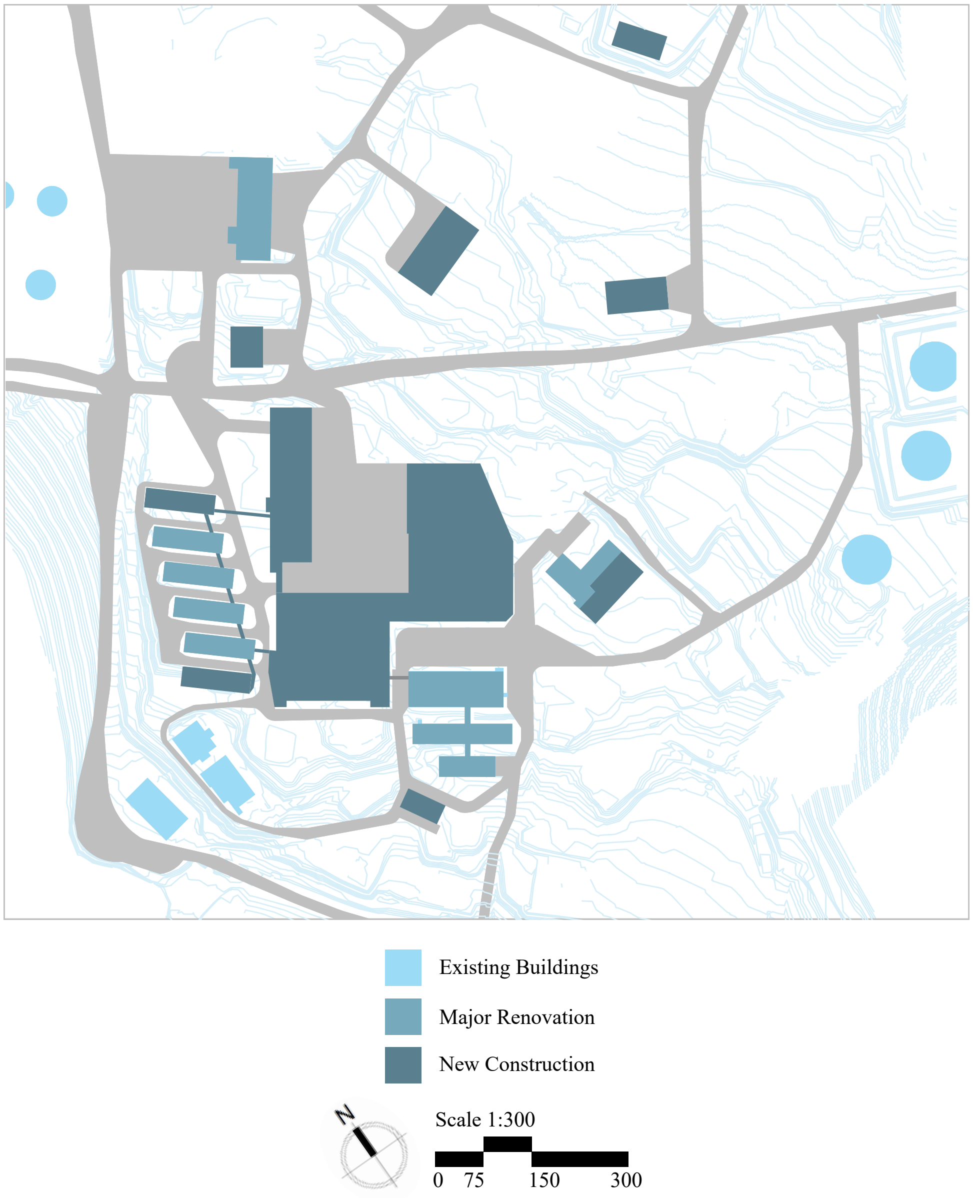


Figure 2.15 - *Redesigned Masterplan of McMurdo*

Figure 2.16 *- Exterior rendering for a new building at McMurdo by OZ Architecture*
Figure 2.17 *- Interior rendering of new lecture hall*

***Figure 2.18** - Performers at Ice Stock antarctic music Festival*

***Figure 2.19** - Aerial View of McMurdo Station*

After a variety of sites have been explored on Mars, it is likely that one of them will transition to this phase. At first, logistics will probably be prioritized. The base will require greater infrastructures to accommodate the increasing influx of supplies and humans coming from Earth. Essential spaces necessary for survival will arise first; perhaps greenhouses to increase food production or water harvesting/filtration facilities. But these will be followed shortly by non-essential living and social spaces for productivity and well-being.

Stage 3 – Scientific Research Station

Before the time of the modern Antarctic stations, there were no international governing bodies that dictated how the continent was to be occupied. It was only until the Antarctic Treaty went into effect in 1961, that the continent would be deemed a peaceful place and devoted to scientific knowledge. It was then that the McMurdo base transitioned into a more science focused establishment and clearly outlined its future objectives.[11]

McMurdo thus has become a fully realized scientific research station. McMurdo now can accommodate about 1500 people in the summer and 500 in the winter, allowing the station to be occupied the whole year with people who cycle in and out. Interestingly, some of the oldest buildings in McMurdo are still present even after 50 years. Many of them persisting through factors like technological advancements, changing research needs, and expansion. This emphasizes the flexibility needed in the architecture. As of now, McMurdo station has about 100 buildings which take up around 49 acres of land[12]. The architecture is a patchwork of different building types with varying purpose but all under the objective of science.

In a redesigned masterplan, McMurdo station plans to consolidate many of the scattered buildings into one single hub.[13] The new building will incorporate new spaces like lecture halls and warehousing spaces, further emphasizing the communities' goals for knowledge, environmental stewardship, and efficiency (figures 2.17-2.21). This is in addition to the station's own culture and sense of community,

---

[11] Ibid, pg 171,177

[12] NSF, Antarctic Support Contract, and United States Antarctic Program, McMurdo Station Master Plan 2.1, pg 9, December 16, 2015.

[13] Ibid, pg

almost resembling something of an “urban center.”[14] For example, there are annual events held around the station that give scientist and workers a break from their routine. Annually, at thanksgiving, there is a costumed turkey run[15], or on New Year’s, when a music festival named Ice Stock is held.

McMurdo's conception was not entirely simple and certain. The growth took place over many years and governing bodies which greatly impacted the buildings that resulted. Self preservation and glory transitioned to transportation and military power, which then transitioned to environmental protection and scientific research. However, its present success provides a goal for a Mars settlement to strive towards. Using Antarctica as an example, the Mars base will likely evolve in a similar manner (perhaps without military involvement). Like Scott's Hut, an initial Mars base will be compact utilizing a closed plan. However, if the site proves to be an ideal place for expansion, the base will transition into a research hub. This therefore requiring the architecture to allow for continuous plan, which minimizes a sprawling footprint while still allowing for more programs and vehicular movement.

Figures 2.21-2.23 speculate on the types of occupants and activities that will be present at the research bases during the varying stages of development. These activities help to then inform the importance of which infrastructures and program types are needed to aid in the design later.

---

[14] Christy Collis and Quentin Stevens, “Cold colonies: Antarctic spatialities at Mawson and McMurdo stations,” Cultural geographies 14, no. 2 (2007): pg , doi:10.1177/1474474007075356.

[15] The New YorkTimes, "How McMurdo Station Is Run On The Least Habitable Continent," YouTube, June 03, 2017, accessed January 11, 2018, https://www.youtube.com/watch?v=nZr5MJuNcXU&t=19s.

Outpost

Temporary Habitat
Basic temporary essential infrastructures
Generic on site Research

Temporary occupancy of
    Astronauts - highly specialized but well rounded, trained personnel capable setting up an initial habitat

Logistics Hub

Semi-Permanent Settlement
Constructed permanent infrastructures
Established transportation logistics
Raw material harvesting and processing
Beginnings of non-essential buildings

Cyclical occupancy of
    Builders
    Support workers
    Some Researchers

Research Station

Permanent Settlement
Constructed Research Facilities
Built in infrastructure
Constructed Non-Essential Buildings
Consistent expansion for changing needs

Cyclical occupancy of
    Builders
    Support Workers
    Researchers

Figure 2.20 - *Stages of Antarctic base development*

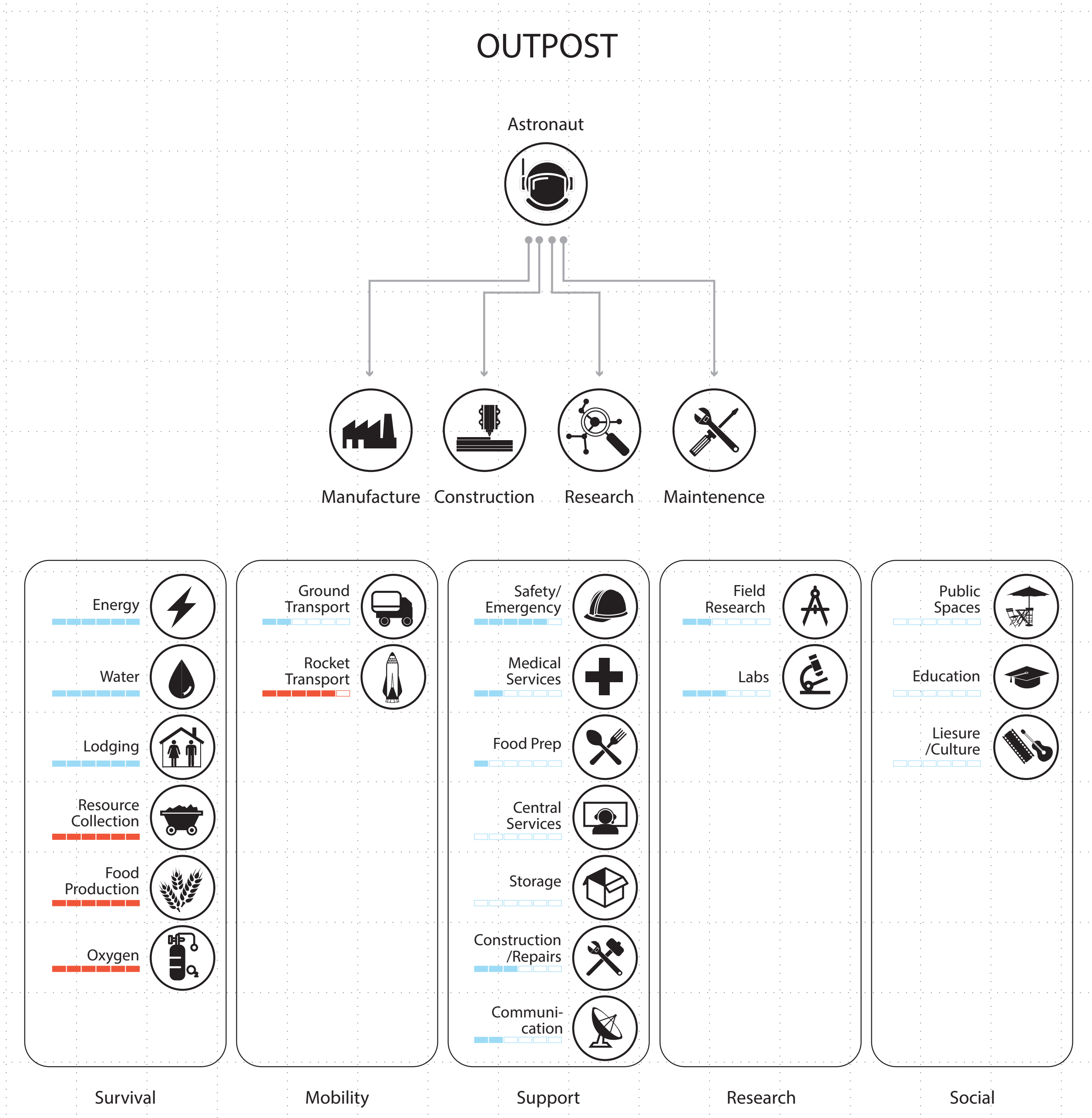


Figure 2.21 *- Outpost important infrastructure - after analyzing the building and program types from Scott's Hut to McMurdo Station, types of occupants and activities that take place inside the base are speculated on. These help to draw out notable infrastructures and programmatic spaces which were then assigned importance according on the base's current needs*

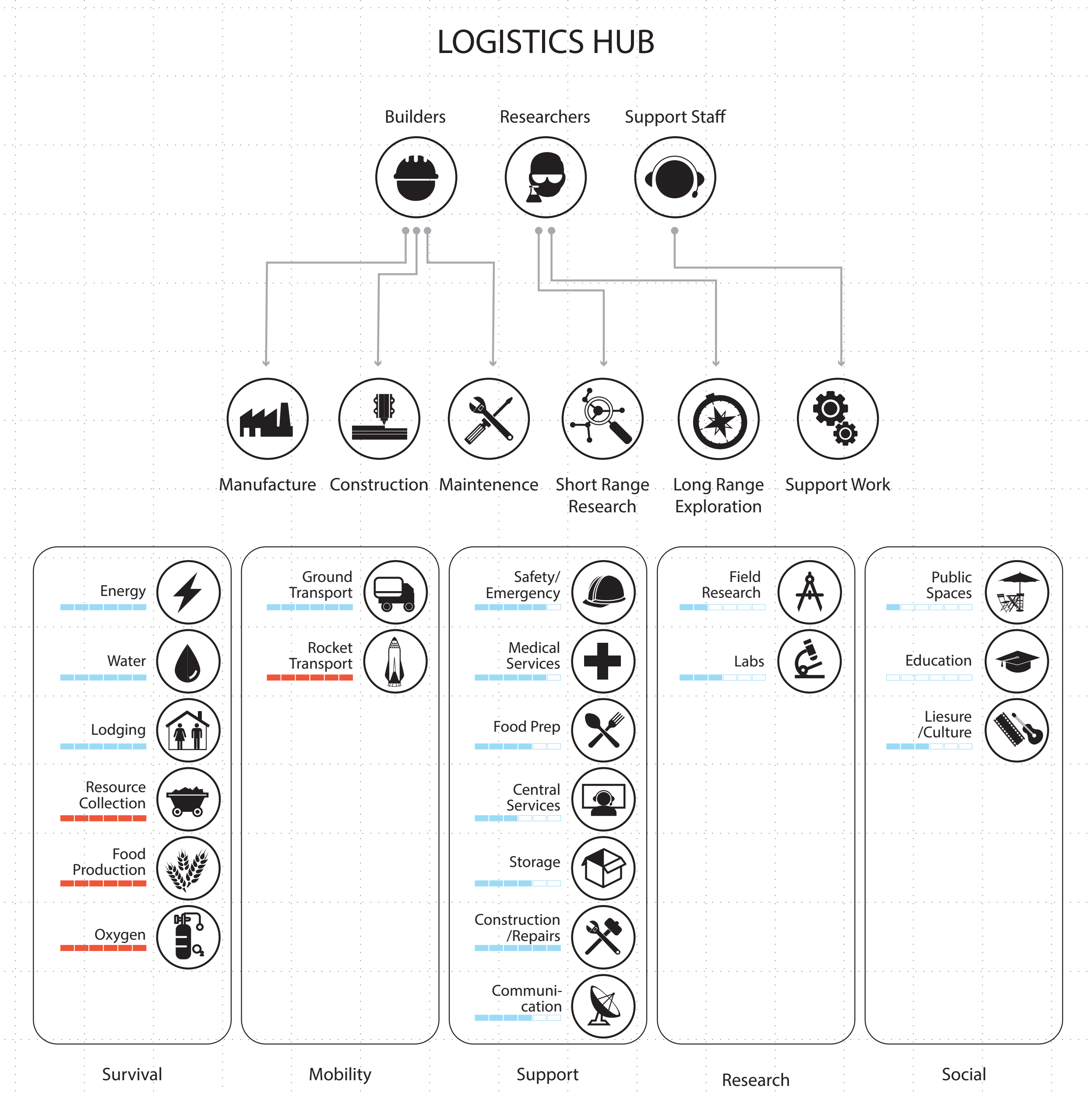


Figure 2.22 - *Logistics Hub important infrastructure*

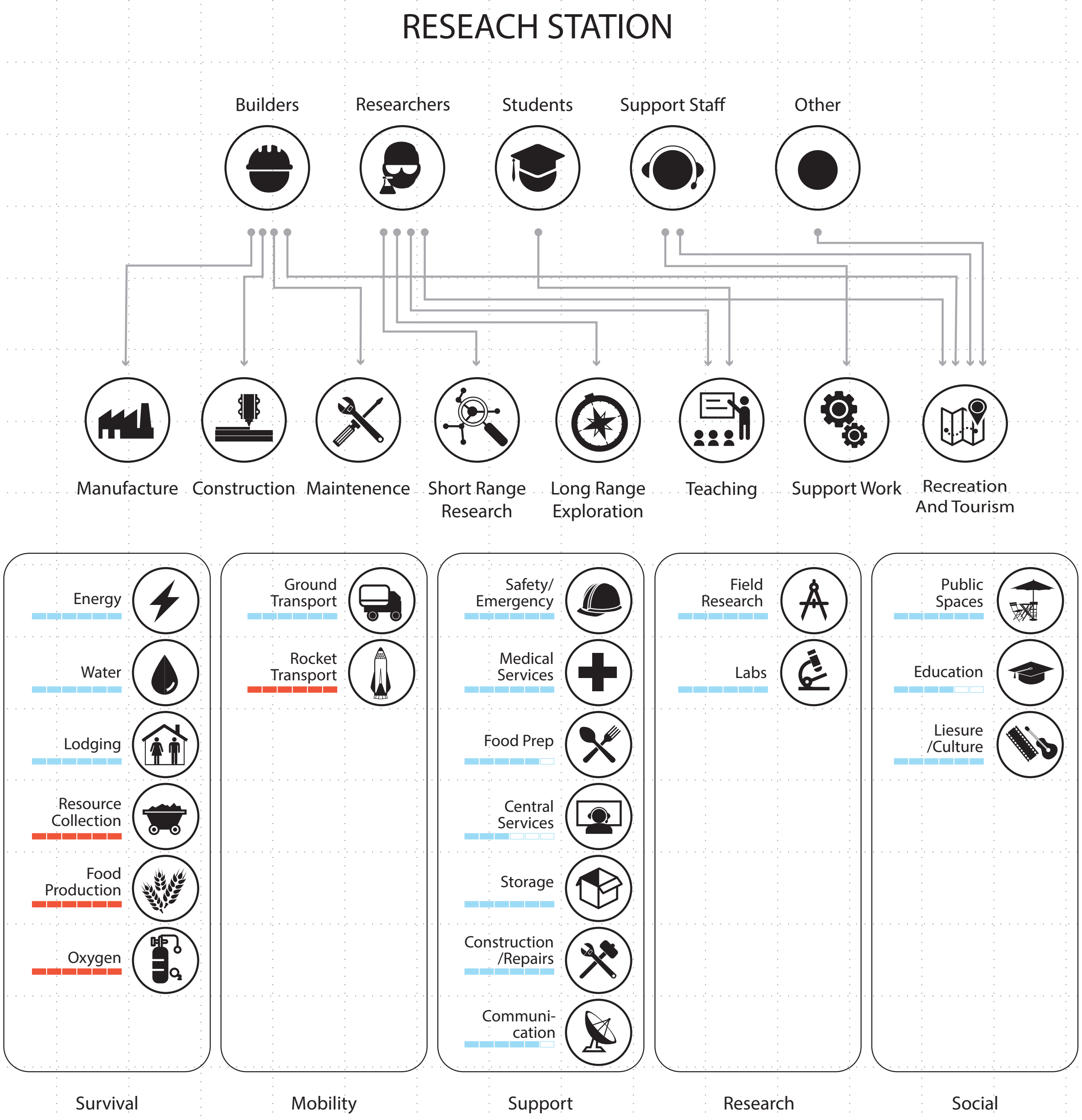
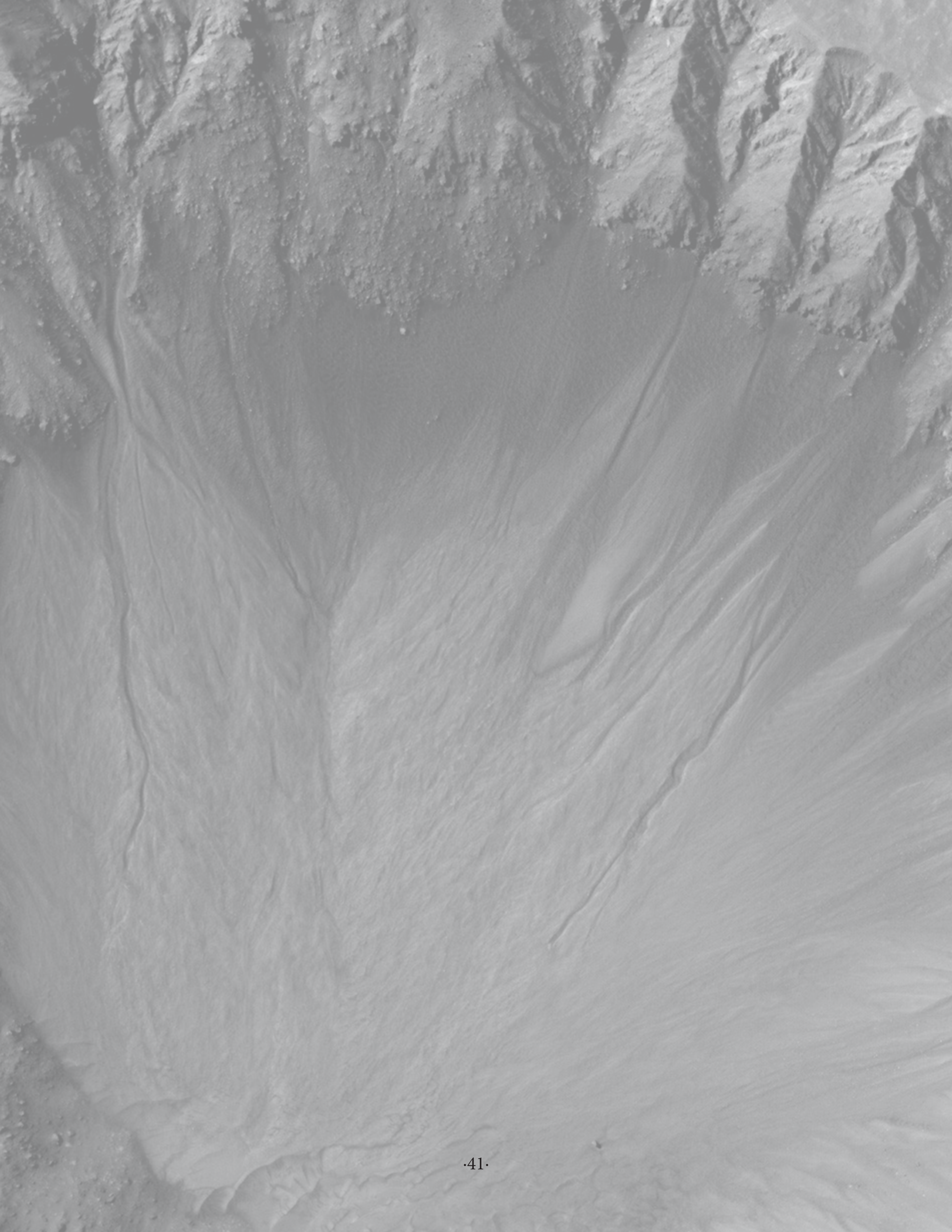


Figure 2.23 *- Research Station important infrastructure*



- PART THREE -

UNDERSTANDING THE EXTREME

SAFETY AND SITE

Understanding Site Conditions

To better design safe habitable environments, the extreme conditions of Mars must be understood. The planet poses some immediate issues that architecture must address. The conditions there are harsher than even the most extreme places on Earth which will contribute to the overall shape of the building. Outlined below are some of these forces.

Siting

The exact location of where a Martian habitat will be created will have varying site conditions, the same way that Toronto's environment is quite different than Sydney's. There are advantages and disadvantages to every site on Mars. Institutions like NASA weigh the pros and cons via satellite prior to sending anything to these locations. These sites are chosen predominately for their research advantages, safety to equipment and their potential for future manned missions[1]. It is likely that there will be a number exploratory robotic or manned missions to each location before any settlement will occur. Because of this reality, creating site specific architecture can be a challenge.

Similar to the factors looked at when sending rover missions, things like the presence of water, usable raw materials, closeness to equator for warmer temperatures, geological features, and research opportunity, are highly important for guaranteeing success. But because currently, these are unknown, creating site specific architecture can be a challenge.

For example, a geologic feature an underground lava tube[2] could change what materials are used, and what forms would be made. However, not enough information exists on which of these site are the best, and even more complication comes when a rocket must be landed in or around these tubes (for example how large are they and how would people/objects get

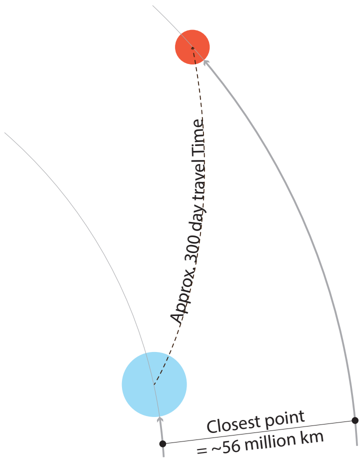


Figure 3.1 - *Crater in Sirenum Fossae region on Mars*

Figure 3.2 - *Distance between Mars and Earth*

---

[1] "Landing Site - Mars 2020 Rover," NASA, accessed January 05, 2018, https://mars.nasa.gov/mars2020/mission/timeline/prelaunch/landing-site-selection/.

2

in/out of them?) Though they could be great locations for new settlements, they cannot relied upon completely.

Instead, as a starting point, the thesis will design using what is already proven possible - landing in locations we have already explored at. Rovers like the Curiosity have proven to be able to land and function in locations of relative flatness on the surface. Therefore, the conditions of the Jezero Crater site, located just north of the equator, can be used. This site was shortlisted as a potential Mars 2020 rover mission and holds great scientific research potential, as well as a likelihood for stored water[3,4]. NASA has been using a "follow the water" approach like the explorers of ancient times[5]. The presence of water allows for the survival of human life, and the possibility of the existence of ancient Martian life.

Water

Greater than the ability for Mars water to host life, the hope to settle Mars is contingent on our ability use indigenous water sources. There may not be great lakes or oceans on Mars today, but it is believed that the planet used to have plenty of water[6]. Remnants of these missing oceans and rivers can be seen in the depressed channels across the surface planet. Though the liquid water has evaporated, some if this remains frozen near the poles or embedded up in the soils. When the curiosity rover landed close to the Gale Crater, it found that the soil alone contained up to 60% water. Some craters even hold sheets of ice directly on the surface.[7]

This news is very optimistic in terms of supporting life, but also architecturally. Although the task of collecting water can be left to machinery, water can allow for certain building

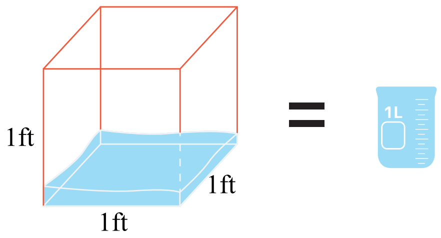


Figure 3.3 *- Water per square foot of Martian soil*

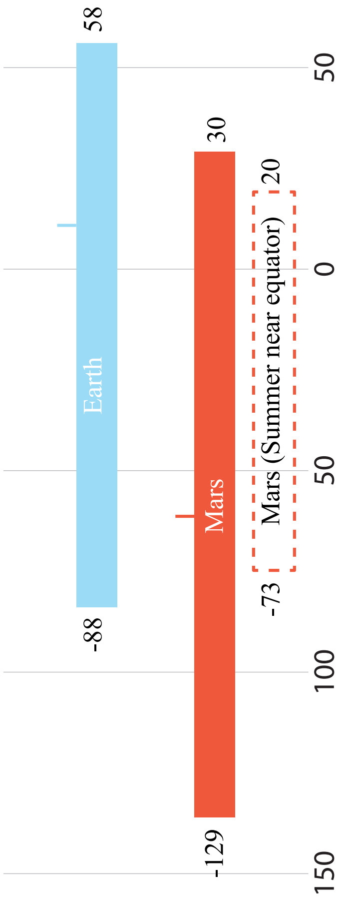


Figure 3.4 *- Average temperature ranges °C*

---

3 Ibid.

4 "Mars 2020 Landing Sites," Kenneth A. Farley and Kenneth H. Williford to Dr. Michael Meyer, February 13, 2017, accessed January 5, 2018, https://marsnext.jpl.nasa.gov/documents/Mars%202020%20landing%20site%20down-select%20Feb%202017.pdf.

5 Brian Dunbar, "Follow the Water: Finding a Perfect Match for Life," NASA, accessed January 04, 2018, https://www.nasa.gov/vision/earth/everydaylife/jamestown-water-fs.html.

6 Stephen Petranek, "Your kids might live on Mars. Here's how they'll survive" (speech, TED2015, Canada, Vancouver), March 2015, https://www.ted.com/talks/stephen_petranek_your_kids_might_live_on_mars_here_s_how_they_ll_survive.

7 Ibid.

processes and materials to be used, like 3D printing, or concrete. Additionally, the water itself can be considered as a building material if frozen into ice[8], very similar to primitive igloos and snow shelters.

Temperature

In general, the average temperatures on Mars are colder than they are on Earth. The average temperature of Mars sits around -63°C as opposed to Earth where temperatures are roughly 14°C. However, the temperatures on Mars are still like those on Earth in some situations. Near the equator in summer, Mars can be as warm as 30°C, whereas the record low temperatures on Earth can be at -88°C[9].

Architecturally speaking, the extreme low temperatures mean that insulation and thickness of walls is important. A strategy that has already been tested on Mars is the use of Aerogel insulation, a type of extremely lightweight, and highly insulative translucent material.

Figure 3.5 *- Residual water ice inside crater on Vastitas Borealis*

---

[8] SEArch and Clouds AO, MARS ICE HOUSE, accessed January 04, 2018, http://www.marsicehouse.com/.

[9] "Mars Facts | Mars Exploration Program," NASA, accessed December 31, 2017, https://mars.nasa.gov/allaboutmars/facts/#?c=inspace&s=distance.

Additionally, the cold may also affect the functionality of the equipment used during construction, limiting the methods or construction times to certain windows of opportunity. For example, the viscosity of oils and lubricants. As a possible solution, machinery can be used seasonally, when Mars is warmer, and during the day time, when sunlight heats up the surface. Therefore it may be best to locate a habitat closer to the equator.

Atmosphere

The planet only has a fraction of Earth's atmosphere, and it is primarily composed of carbon dioxide. This means that it is not possible for humans to be unsuited or outside shelter on the surface of the planet. Human bodies have evolved to exist with about 15 lbs of atmospheric pressure on us at all times[10], but since Mars lacks much atmosphere, then we would need to artificially create this pressure. To avoid needing to put on pressurized suits to move from building to building, the shelters that we construct will ideally be consolidated into larger and interconnected buildings. This makes it so that you could pressurize one large structure instead of many smaller ones which require individual and separate equipment. Additionally, the air on Mars is not breathable to humans directly, since it is primarily composed of carbon dioxide. Fortunately, oxygen can still be extracted from the atmosphere using mechanical processes, or it can be given to plants, which in turn will provide oxygen for humans, necessitating greenhouses.

The atmosphere on Mars is also able to create winds. However, there is a common misconception about these winds being able to whip up incredible and dangerous wind storms. For example, the 2015 Hollywood movie based off of Andy Weir's The Martian[11], depicted astronaut Matt Watney stranded on the planet after a particularly bad dust storm knocked a piece of mechanical equipment into him, incapacitating him while his team was forced to evacuate. Wind speeds on Mars peak around 60 miles per hour, less than some hurricane wind speeds on Earth. Furthermore, the less dense atmosphere makes these winds even less of a concern for damaging equipment.

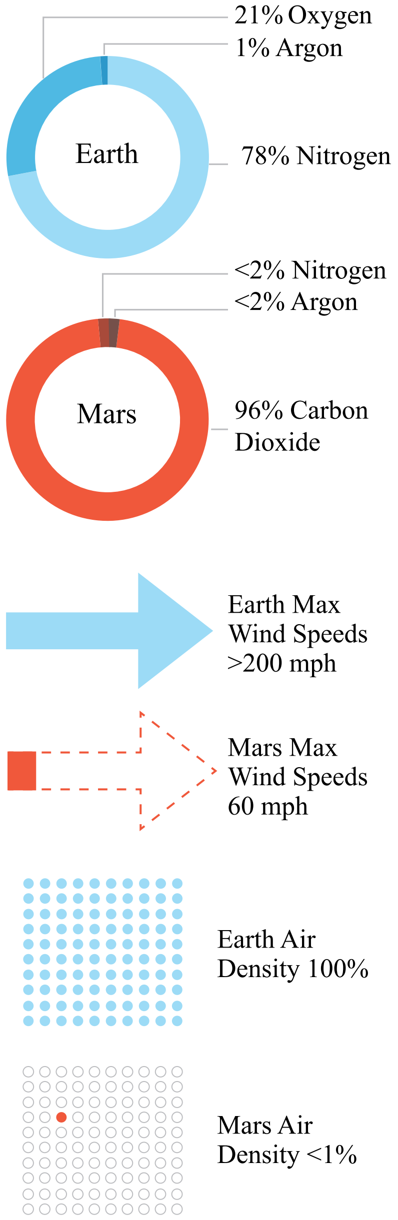
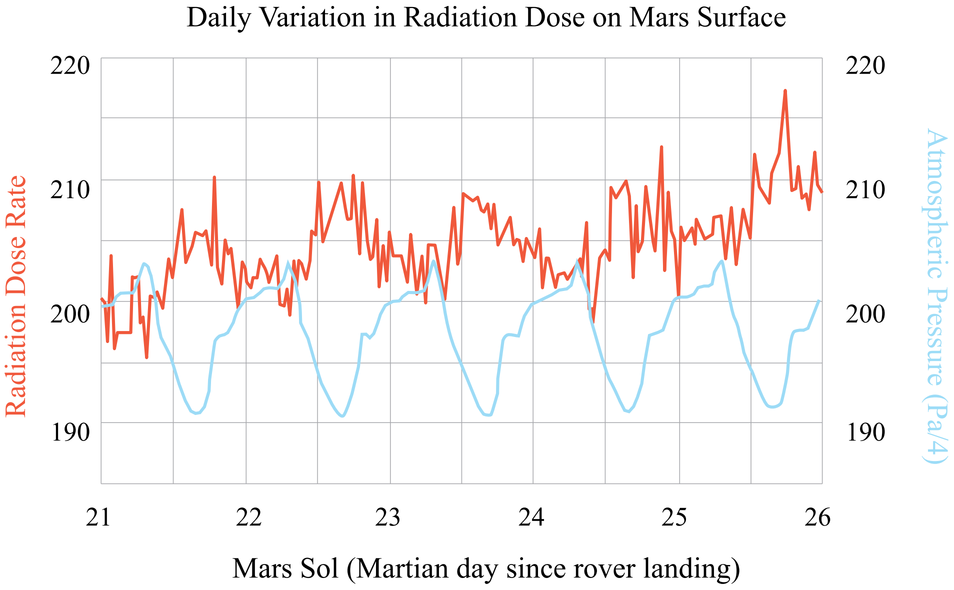


***Figure 3.6** - Air composition, wind speed, and density comparisons between Earth to Mars*

---

[10] Stephen Petranek, "Your kids might live on Mars. Here's how they'll survive" (speech, TED2015, Canada, Vancouver), March 2015, https://www.ted.com/talks/stephen_petranek_your_kids_might_live_on_mars_here_s_how_they_ll_survive.

[11] The Martian, dir. Ridley Scott, by Andy Weir (United States: 20th Century Fox, 2015), film.



However, the wind can possibly cause some architectural concern since these wind storms pick up a lot of dust, and can cover buildings with thin layers of dust, blocking windows, and gradually burying a building.

Radiation

The film depictions of Mars and space exploration typically omit the force of radiation, likely because it is a silent killer, and does not make for good cinematic effect. In reality, radiation has two forms that space-farers must face, the first being solar radiation from our sun. High doses of energetic particles coming from the sun can batter living cells causing damage to DNA, and potentially leading to adverse health effects. The second is cosmic radiation, which comes from outside the solar system. These are even more energetic particles.

Since Mars has less of an atmosphere than Earth, there is less protection and therefore, higher radiation on the surface[12],[13]. Interestingly, the greatest dosage of radiation is gained from

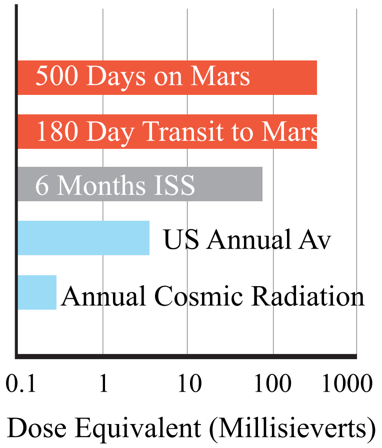


Figure 3.7 - *(top) - Increase of atmosphere pressure equates to drop in radiation on the surface. Measured by NASA Curiosity Rover*

Figure 3.8 - *(bottom) - Comparison of Radiation Dosages*

---

[12] Rob Garner, “How to Protect Astronauts from Space Radiation on Mars,” NASA, September 30, 2015, accessed January 04, 2018, https://www.nasa.gov/feature/goddard/real-martians-how-to-protect-astronauts-from-space-radiation-on-mars.

[13] Robert Zubrin, The case for Mars: the plan to settle the red planet and why we must (New York: Free Press, 2011), 126.

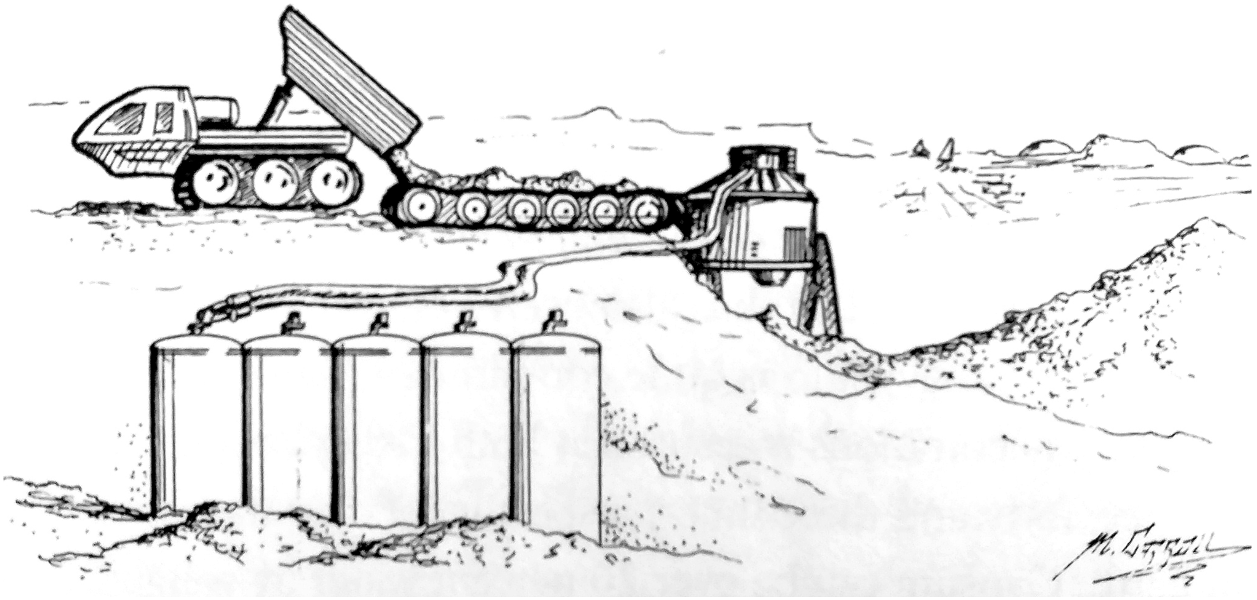


***Figure 3.9 -** Regolith collector concept that can separate soil and water*

travelling through the vacuum of space, and not on actual surface of Mars. This also bodes well for longer term missions, since there is less time spent travelling, and more time spent on the planet, possibly giving time for recovery[14]. Only about 180 days travelling in space equates the same dosage of radiation as 500 days on the surface. With proper shielding from shelter, it is possible that the stay on the surface can extend even longer.

The Martian[15], for the most part ignores radiation. The seemingly thin walls apparently have incredible radiation resistance since it shows the protagonist unfazed by it at all over the course of his long stay. Similarly, the film *Silent Running*[16] shows Earth's flora and fauna able to thrive when only separated from the the vacuum of space and radiation by a thin layer of glass.

It is critical that the shelters that astronauts will live in mitigate as much of this radiation as possible. This might be accomplished by using certain types of materials, increasing thicknesses of walls, or sheltering buildings underground. For example, water makes for a fairly good radiation blocker, so

---

[14] Ibid., 131-132, table 5.2.

[15] Weir.

[16] Silent Running, dir. Douglas Trumbull (United States: Universal Pictures, 1972).

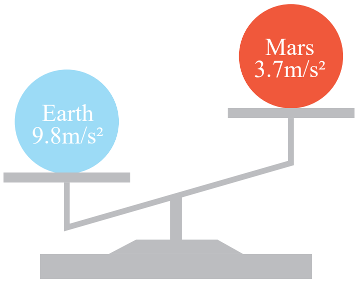
ice or snow could be a possible material.[17] The soil found on the planet can also be an excellent source of protection against radiation.[18]

Radiation becomes even more problematic since it can limit the use of windows. Since glass is not a good radiation barrier, making windows and openings can be more challenging. Other translucent or transparent materials will need to be considered as alternatives. (See Materials Section)

Gravity

On Earth, we have evolved in a gravitational pull of 9.8m/s². On Mars however, the gravity is only 3.7m/s², only about 38% of Earth's. Microgravity has adverse effects on human physiology. These effects include bone mineral loss, muscle atrophy, and cardiac de-conditioning[19]. These effects can be lessened through behavioral changes during the transit to Mars like excercise.[20] On the surface on Mars, there will be gravity, but since it is less, there needs to be spaces where astronauts can exercise and keep their bodies able.

The gravity on Mars will only really directly impact architecture by perhaps allowing for more daring structures, but it is important to look at since there will also be significant strain on humans upon landing. It would be wise then, to reduce the amount of high labour activities for astronauts immediately after landing; automating construction processes for example.



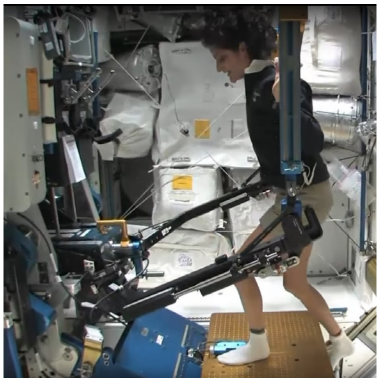


Figure 3.10 *- Gravitational Comparison*

Figure 3.11 *- Astronaut using workout equipment in the ISS*

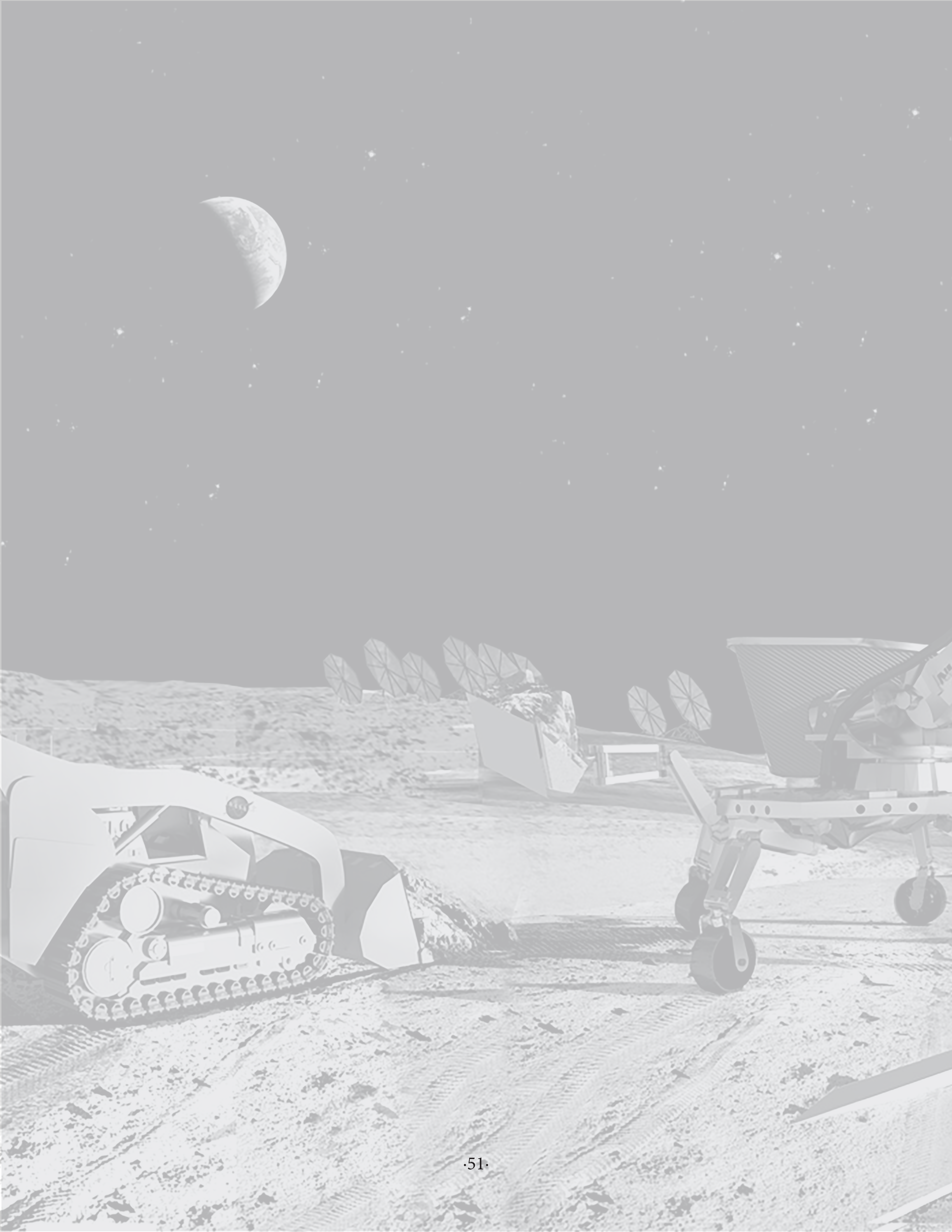
---

[17] Stephen G. Warren, Richard E. Brandt, and Thomas C. Grenfell, "Visible and Near-ultraviolet Absorption Spectrum of Ice from Transmission of Solar Radiation into Snow," Applied Optics 45, no. 21 (2006): , doi:10.1364/ao.45.005320.

[18] Zubrin, 192.

[19] D. Williams et al., "Acclimation during space flight: effects on human physiology," Canadian Medical Association Journal 180, no. 13 (2009): doi:10.1503/cmaj.090628.

[20] The below tour through the ISS shows the kinds of exercise equipment used in zero gravity. https://www.youtube.com/watch?v=bhGydrid-bEA



- PART FOUR-

DEVELOPING TECHNOLOGY

METHOD

Minimizing Costs in Construction

The method used for construction on Mars will be pivotal in determining the design of the first architectures that arise on Mars. On Earth, designers are much freer in their decisions. For example, importing materials from across very large distances to achieve niche aesthetics is something that is rather commonplace. However, this luxury is not shared on Mars. For example, to import materials from Earth, there is an extremely large cost associated with it. It is approximated to be 2 million US dollars to send a single brick to the just the moon[1], let alone Mars. Every extra pound added onto a rocket means more fuel needed to break Earth's gravity, and even more to slow down during its descent on Mars. Even with the reusable, fuel efficient and remarkably large Space X rocket, colloquially named BFR rocket[2], the cost of sending components for an entire building is unreasonable.

Similar to the Antarctic researchers of the Scottish National Antarctic Expedition's outpost, the materials and equipment that we use will need to be small, lightweight, compact, or better yet, be found on site. Much of the Antarctic's first permanent bases were created with prefabricated wood pieces and used on site rocks or snow to insulate and fortify their walls.

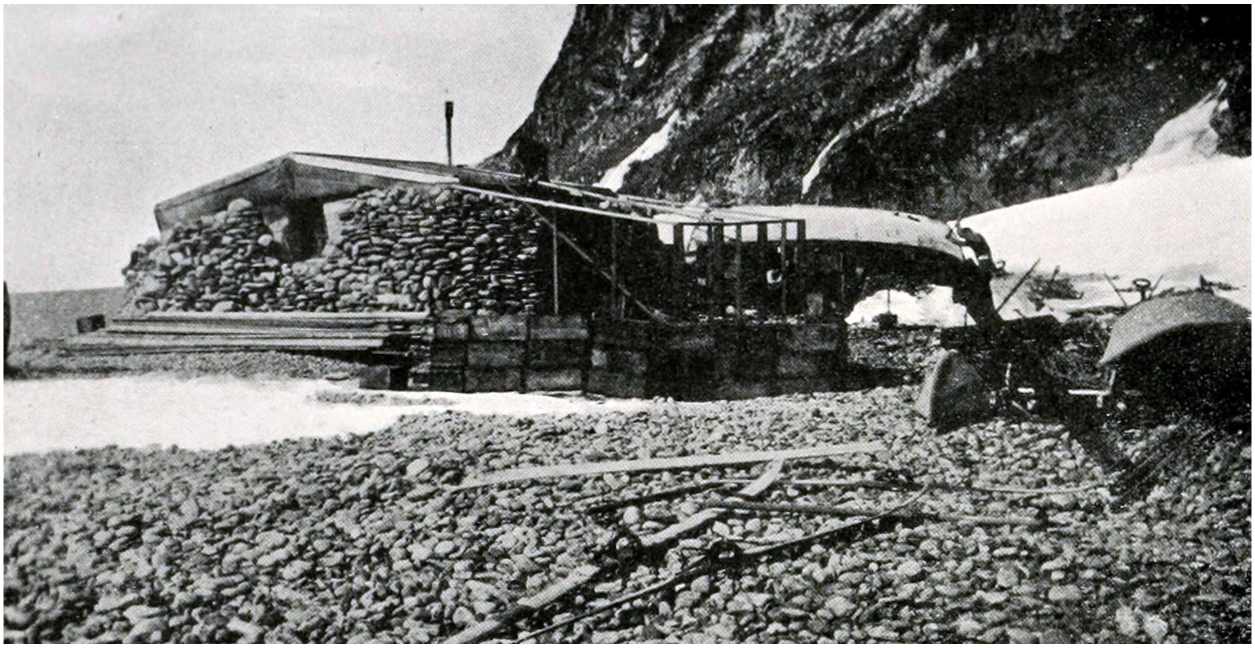
Along with the financial impact on sending materials, there is an issue with the timing of the construction. It takes approximately 6 months travel time between Earth and Mars. This means that sending any resupplies to the planet will be greatly delayed and costly. Greater problems arise when humans are involved. Like the first settlers of the Antarctic, the first astronauts will need a place to shelter themselves from the harsh elements of their environment. Without proper shelter, the astronauts spending time out on the surface of the planet risk exposure to

---

[1] Leach, Neil. "3D Printing in Space." Architectural Design Volume 84, issue 6 (2014): 109-113.

[2] Elon Musk, "Making Humans a Multiplanetary Species" (lecture), accessed March 19, 2018, https://www.youtube.com/watch?v=H7Uy-fqi_TE8.

Figure 4.1 - *(previous page) Contour crafting 3D Printing robot creating structures on the Moon*



high levels of radiation or accidents. Therefore, construction must either be very quick to assemble or constructed prior to human arrival.

In addition to the short term requirements, the architecture should also aim to satisfy long term desires. The success of beginning a sustained settlement on Mars is contingent on the interest of parties on Earth. At least in its infancy, the settlement will likely be reliant on resources coming from the Earth; food, equipment, and people. The architecture will need to be constructed with expansion or repetition in mind.

To ensure that the occupants are comfortable, and would like remaining in the Mars settlement, it is beneficial to also have the architecture reflect a sense of *firmitas* or permanence.

It is easy to think that the first explorers could just live temporarily in the vehicles used to transport them to Mars. However, this would be akin to living in an RV (relaxation vehicle) on a campground. The RV is a feasible option for short camping trips, but you would not expect this mobile home to be a suitable space in the long run for fostering enriching environments. Like the rocket, the RV is built for portability and temporary living. A Martian architecture which is rooted to the ground would give the habitat a sense of place, permanence and fortitude against the elements. Besides the fact that this

Figure 4.2 - *Omond House - First permanent antarctic base 1903, Scottish National Antarctic Expedition*

would be more suitable for the inhabitants to have this kind of home, the habitat would also present itself as a more attractive place for people on Earth to visit or possibly migrate.

In summary, the construction method used for the first habitats on mars will be required to be: lightweight and small, automated and/or quickly built, be designed to grow, and evoke a sense of permanence.

There are three space habitat construction methods that have been looked at as possibilities given these constraints: telescopics, inflatables, or 3D printing. Telescopic architectures involve building sections that fit within one another. When fully expanded, their total volume can be as much as the sum of the volume of all the sections. This technique already has applications in modern large scale architecture, as seen in the Diller Scofidio+Renfro project "The Shed". These structures can be fairly compact built using fairly robust materials, but they are limited to movement along a track, and would be difficult to transport since the entirety of the building materials would need to be pre-assembled and sent at once.

The most lightweight and compact structure would be inflatable architectures. They are essentially folded fabrics and require little machinery to inflate into a large structure. Examples of these are seen in many temporary architectures. However, this strategy fails in its design flexibility and permanence. Inflatables require complicated stitching to create, and their structures are not very robust unless reinforced through other materials. This problem is further exacerbated on Mars where sharp rock could potentially cause tears or punctures in the thin membrane.

Probably the most promising strategy is 3D printing. With the use of a robotic material collector, in situ materials could used to directly generate buildings using computer modeling. Although there is an initial investment cost of sending 3D printing machinery, and maintenance these printers have the added benefit of using in-situ materials to create free forms only limited by the capabilities of the printer. Additionally, 3D printers have a slight advantage in that they can be recycled or upgraded. Printers components can be replaced or upgraded overtime to keep the machine running, whereas inflatable membranes are generally single use.

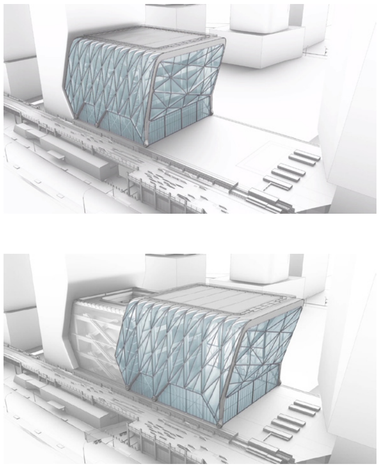


Figure 4.3 - *(top+mid) Diller Scofidio+Renfro telescopic project "The Shed" contracted and expanded*

Figure 4.4 - *(bot) Museo Inflable Guachimontones by Estudio 3.14*

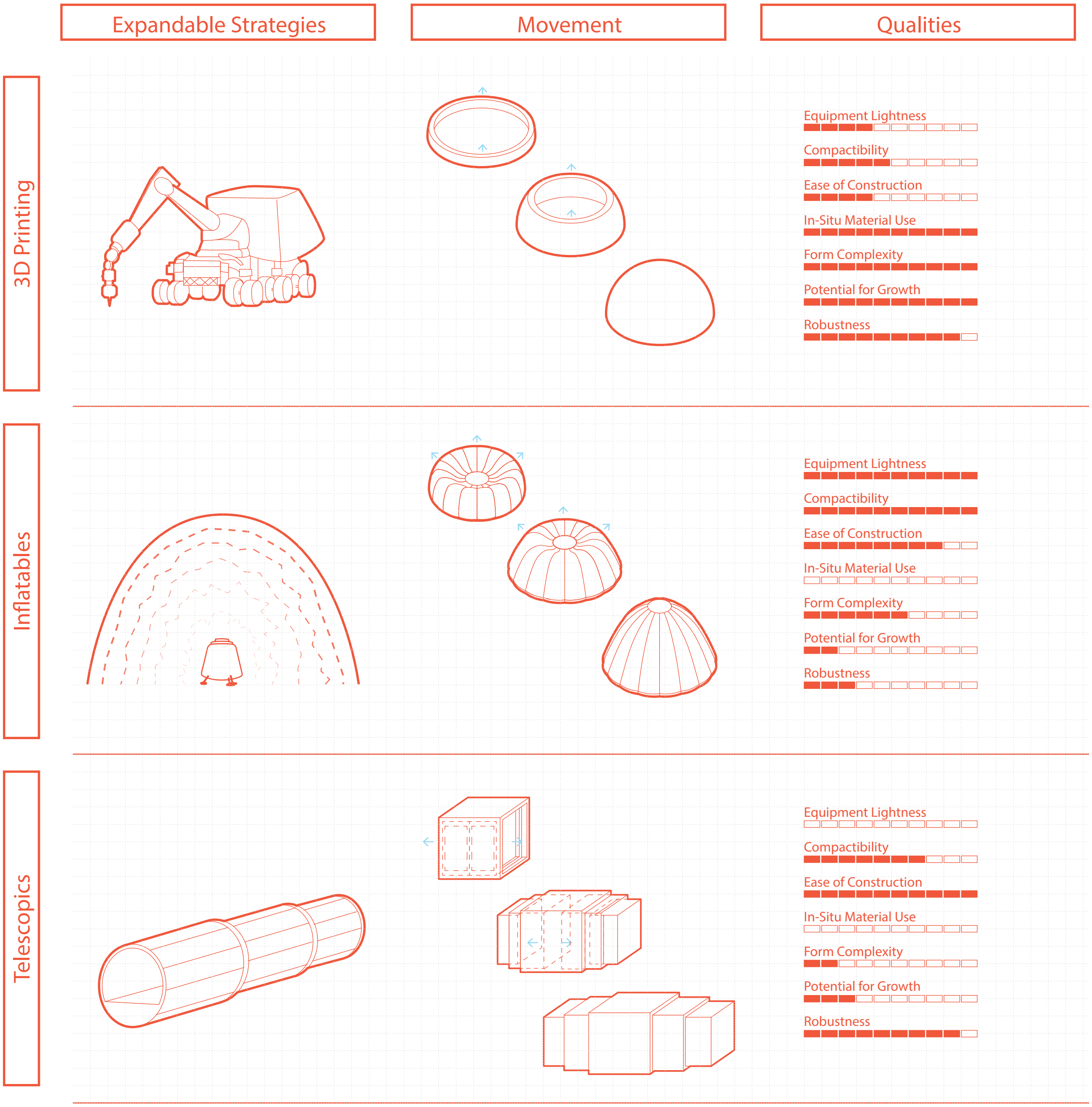


Figure 4.5 **-** *Comparison between expandable construction methods*

PRINTER VERNACULAR

3D printing begun to be studied as a viable application in space starting with the turn of the 21st century. There were two rival methods of 3D printing in space that were gaining attention: these being D-shape and contour crafting.[1]

D-Shape is a process developed by Enrico Dini that involves the use of binder jetting - a layer by layer printing process that deposits a liquid binder onto a powder bed made of a solid reactant and aggregate to create stone-like objects. The process requires a constant amount of particulates to be added on top of the bonded areas. After the printing is complete, the bound the excess particulates could be removed, to create voids, or left in place. The benefit of this process is that virtually any geometry can be printed since the non bonded particles help to support the entire structure as it is printed. However, the disadvantage of this method is that it requires layers of particulate to be spread on each layer, and requires a high amount of post processing once the print is complete.

Contour crafting is a digitally controlled process that was invented by Professor Behrokh Khoshnevis.[2] This method is more typically seen in 3D printed buildings, where a liquid building material is extruded out of a nozzle, to print objects layer by layer. This method is beneficial because the printing material can be fed through a tube and the object can be printed directly with little to no post processing. However, the forms can be slightly limited since the geometry of the object is bound by gravity during the printing process. Overhangs are difficult to print since there is nothing underneath to support the object. Careful attention to geometry should be taken to use this method. Otherwise support material can either be printed underneath overhangs or placed by an outside source.

Both methods have their advantages and disadvantages and have both been proposed as promising solutions to the

Figure 4.6 - *(top+mid) D-shape printed large object*

Figure 4.7 - *(mid) D-shape Printer*

Figure 4.8 - *(bot) Rendition of lunar contour crafting robots*

---

[1] Neil Leach, "3D Printing in Space," Architectural Design 84, no. 6 (2014): pg 112, doi:10.1002/ad.1840.

[2] Ibid, pg 112

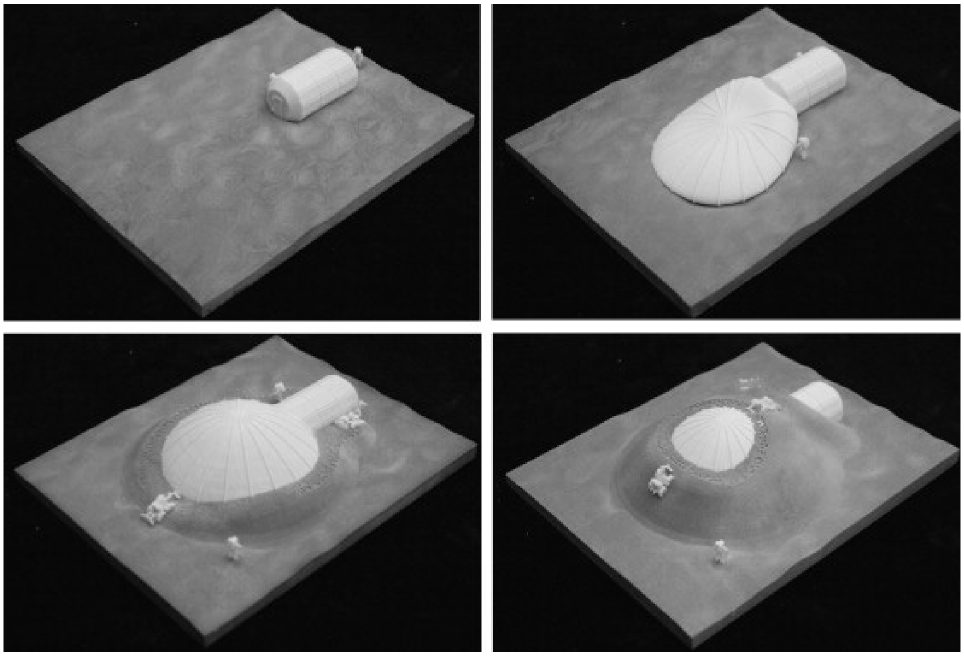


Figure 4.9 - *Foster+Partners Lunar Habitat section*

Figure 4.10 - *D-shape printing the exterior shell*

challenge of constructing habitats in space[3,4,5].

For example, a proposal for a lunar habitation proposed by Foster+Partners used the D-shape method and small mobile robotic 3D printers to create an outer shell of lunar regolith which encases a preconstructed pressurized living space sent from Earth. The design is quite sophisticated in that the habitat reduces the need to remove support material by printing around a bubble. However, this bubble is something that should be minimized to allow a greater amount of expansion. Furthermore, the bonding agent would be brought from Earth and there would only be a finite amount of it. For expansion of the habitat to occur, more shipments of this agent would need to be sent.

Contour crafting has already proven a highly successful techniques for printing buildings on Earth. For example, the

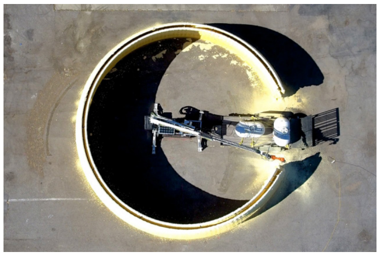


Figure 4.11 - *(top) Apis Cor 3D printer*

Figure 4.12 - *(middle) Apis Cor final 3D printed house*

Figure 4.13 - *(bottom) Keating's 3D printer constructing a dome*

---

[3] Adam E. Jakus et al., "Robust and Elastic Lunar and Martian Structures from 3D-Printed Regolith Inks," Scientific Reports 7 (March 20, 2017): , doi:10.1038/srep44931.

[4] Benjamin Kading and Jeremy Straub, "Utilizing in-situ resources and 3D printing structures for a manned Mars mission," Acta Astronautica 107 (March 2015): , doi:10.1016/j.actaastro.2014.11.036.

[5] Giovanni Cesaretti et al., "Building components for an outpost on the Lunar soil by means of a novel 3D printing technology," Acta Astronautica 93 (January 2014): , doi:10.1016/j.actaastro.2013.07.034.

Figure 4.14 - *(top) Keating - 3D printer*

Figure 4.15 - *(middle) Half completed dome*

Figure 4.16 - *(bottom) Horizontally printing with adhering spray foam material*

Apis Cor company have successfully printed a small house in under 24 hours. The house used a fast hardening geopolymer concrete and was able to print at temperatures of around -35°C with the use of a temporary tent. The Apis Cor house however, is slightly limited as an application on Mars since need to print a roof separately and crane it into place. In this case, a 3D printed dome-like structure with a curved roof would be more advantageous since walls integrate themselves seamlessly into roofs. A 3D printer designed by Andrew Keating exemplifies this ideal concept, in which the 3D printer is solar powered, and uses an adhering spray on material to build a full scale dome.[6]

For the purpose of design, this thesis will use the contour crafting method, since this process can succeed even with little to no support material, reducing waste and post processing. Additionally, if Martian soils are used, no additional bonding agents would need to be imported

---

[6] Steven J. Keating et al., “Toward site-specific and self-sufficient robotic fabrication on architectural scales,” Science Robotics 2, no. 5 (2017): , doi:10.1126/scirobotics.aam8986.

MATERIALS

The materials that can be extruded from a 3D printer are limited to those available resources found on site. The most and plausible material is the Martian regolith. Being high in sulfur content, it is possible to create a pseudo Martian concrete using sulfur as a bonding agent.[1] Sulfur concrete products are made by heating up the sulfur and mixing it with aggregates.

If large amounts of Martian regolith are collected, it can be processed and made into an effective concrete for creating built structures. This novel material has been simulated on Earth using Martian soil simulant and it is found to be optimal for construction on Mars given its "easy handling, fast curing, high strength, recyclability and adaptability in dry and cold environments." The ideal mixture calls for about 50% sulfur to 50% Martian soil with a maximum aggregate size of 1mm.[2] Therefore, in addition to the actual 3D printer, there will need to be some system of material collection and processing to feed into the 3D printer.

Another important architectural feature to consider is the use of transparent or translucent materials. Access to natural lighting or windows can sometimes be a luxury in extreme environments such as Mars. Windows and punctures oftentimes require increased difficulty to a building process. They also are typically made with less insulating material as the rest of the building. However, this luxury is extremely rewarding when it comes to the experience of a space. Even aboard the ISS, there is a built-in cupola which offers the astronauts a panoramic view of the earth below. It is a favoured place for all the astronauts living in the ISS.

On Mars there are a few plausible options for creating windows. In the May of 2015, NASA launched a competition for a 3D

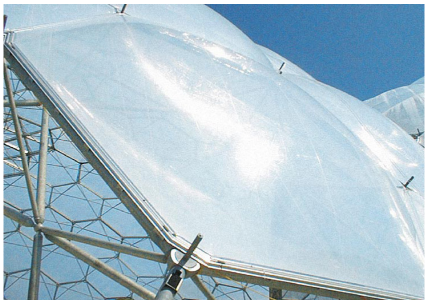


Figure 4.17 - *(top) - 'Marscrete' beams with 1mm and 5mm aggregate size respectively*

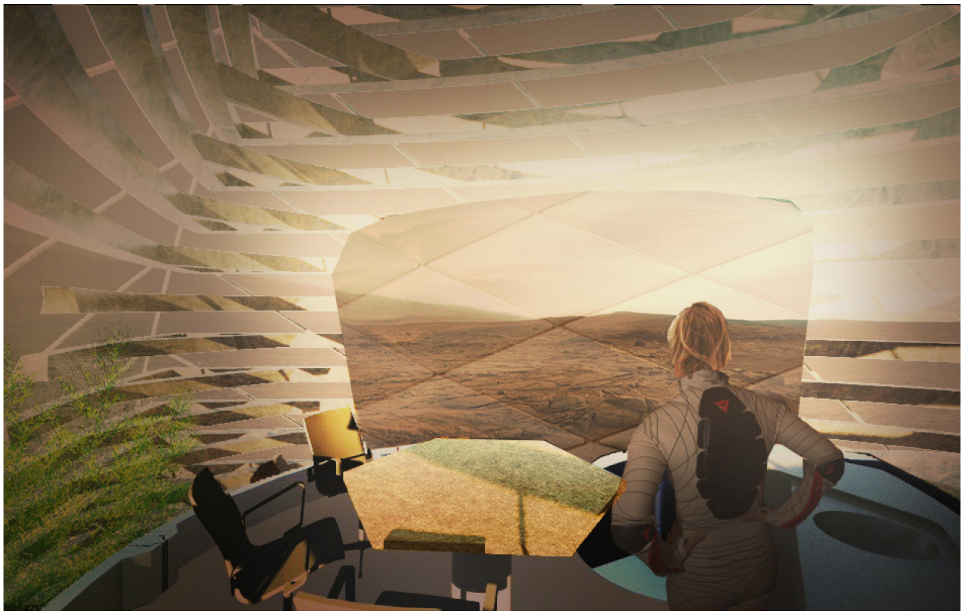
Figure 4.18 - *(top) - ETFE Membrane on the Eden Project*

Figure 4.19 - *(bot) - Hydrogel hydrated, and dehydrated*

---

[1] Lin Wan, Roman Wendner, and Gianluca Cusatis, "A novel material for in situ construction on Mars: experiments and numerical simulations," Construction and Building Materials 120 (2016): pg 2-3, doi:10.1016/j.conbuildmat.2016.05.046.

[2] Ibid. pg 22



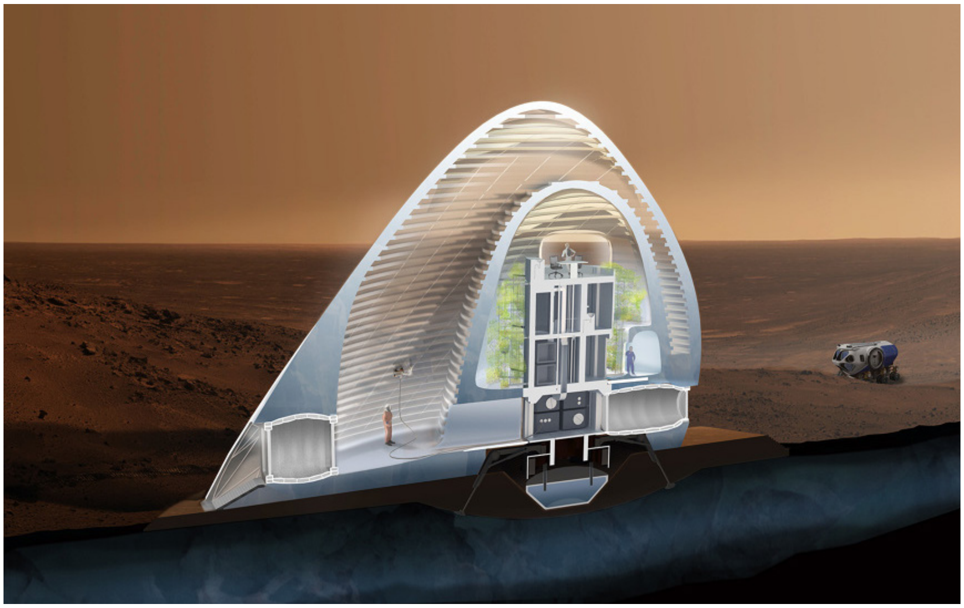


Figure 4.20 - *(top) - Winning design of the NASA Mars 3D printed Habitat Challenge, section of the Mars Ice house*

Figure 4.21 - *(bot) - Mars Ice house ETFE Windows*

printed habitat on Mars. The winning project was designed by Clouds AO and SEArch for their design of the Mars Ice House. Like the name implies, the building is made almost completely out of ice. This strategy is quite innovative, since water is a very good barrier for radiation, while still allowing for visible light to pass through.

If sited in the cooler regions of Mars, the temperature would not drop below zero, keeping the house in tact. Furthermore, if the printing occurred inside of a 70kPa pressurized Ethylene Tetrafluoroethylene (ETFE) balloon, the water would stay solid, and would not sublimate into the atmosphere.[3] Other transparent materials include ETFE membranes which are lightweight and highly flexible materials with good radiation protection, or experimental hydrogel windows which can absorb and retain water. It seems however, that with any strategy, a pressurized ETFE container for any water-based window is a prerequisite, meaning that windows would not be printed in place, but rather made off site and installed after the building is completed. Furthermore, any time there are punctures or changes in materials in the building shell, there are seams which need to be sealed. For the construction of an outpost, prior to any human settlement, if a 3D printing strategy is adopted, it may be more practical to forego windows.

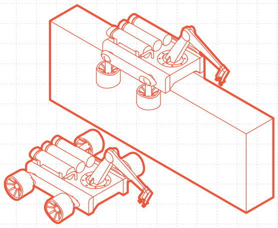
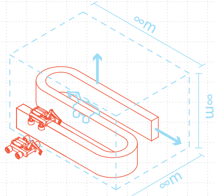
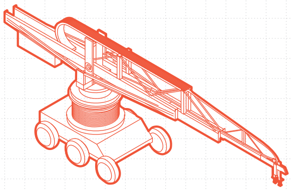
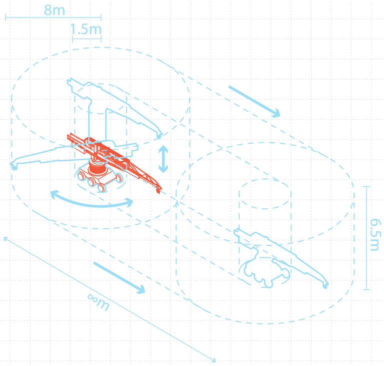
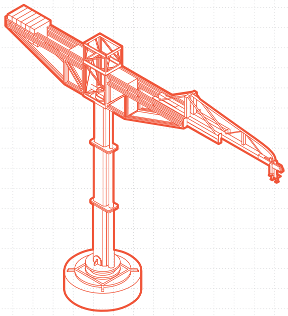
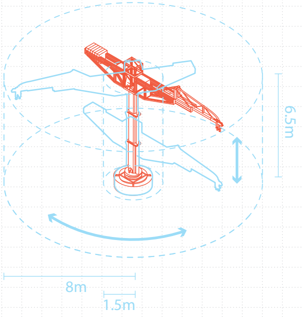
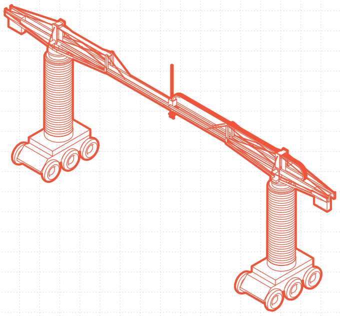
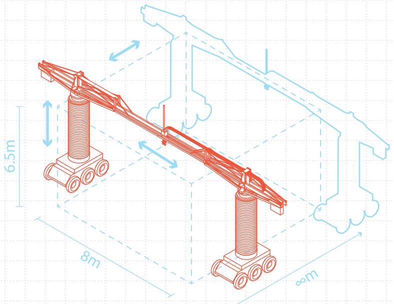
The forms that can be printed are also dependent on the kind of 3D printer that is brought to Mars. There are a couple things to consider when choosing these printers. First, is their size; smaller being more preferable. Second is its portability; on the planet, how easy would it be to move the printer from one location to the other. Third is the printer's ability for design flexibility. Namely, if the printer can create full sized forms with minimal restrictions and additional support material.

Four types of printers were studied. A wall riding printer, a roaming printer, a crane printer, and a gantry printer. The riding printer is very advantageous since it is very small and can print with large distances in all directions. This printer uses the walls that it prints as a track to continue printing higher. However, where it falls short is in its ability to print a roof. It can only ride up the walls that it constructs making it difficult to close the structure above. A separate roof would need to be

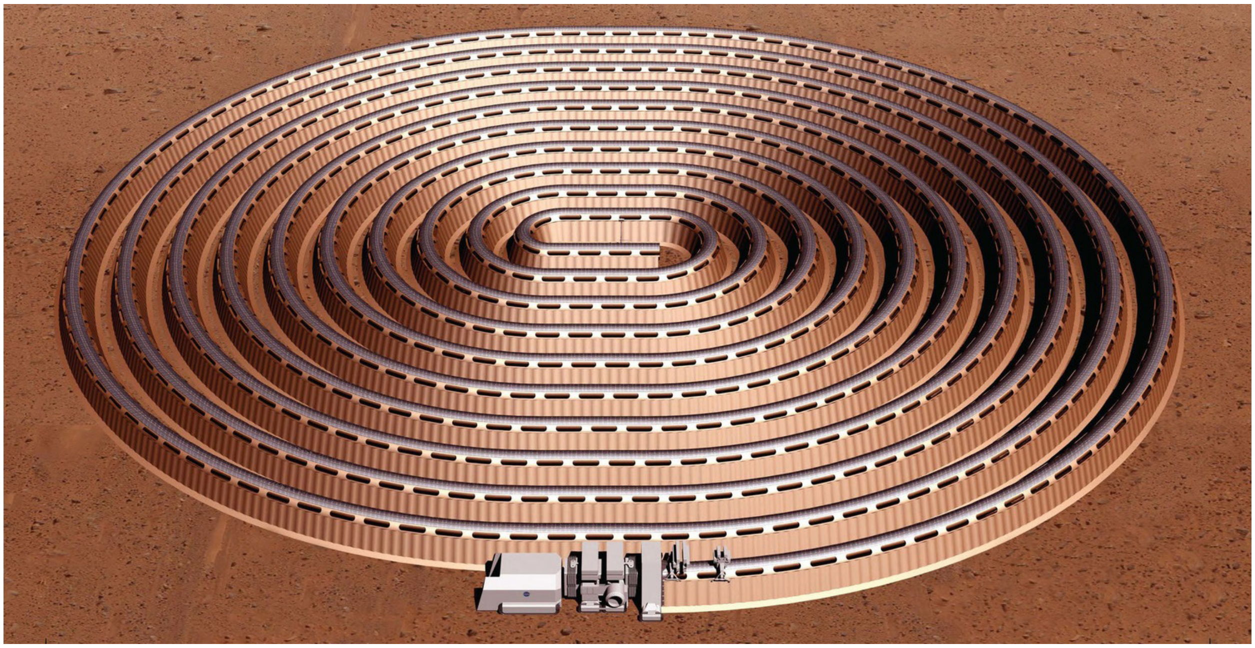
Figure 4.22 - *(right) - Potential types of 3D printers*

---

[3] SEArch and Clouds AO, MARS ICE HOUSE, accessed January 04, 2018, http://www.marsicehouse.com/.

	Printer	Movement	Qualities
Riding			Machine Size ■□□□□□□□□□ ⊗ Portability ■■■■■■■■■■ ⊕ Design Flexibility ■■■■■□□□□□ ⊗ Structural Support Req ■■■■■■■■■■ ⊗ *Requires additional support material to close roof/create openings
Roaming			Machine Size ■■■■■□□□□□ ⊗ Portability ■■■■■■■■□□ ⊕ Design Flexibility ■■■■■■■■■□ ⊗ Structural Support Req □□□□□□□□□□ ⊗
Crane			Machine Size ■■■■■■■■■■ ⊗ Portability ■■□□□□□□□□ ⊕ Design Flexibility ■■■■■■□□□□ ⊗ Structural Support Req □□□□□□□□□□ ⊗
Gantry			Machine Size ■■■■■■■■■■ ⊗ Portability ■■■□□□□□□□ ⊕ Design Flexibility ■■■■■■■■□□ ⊗ Structural Support Req □□□□□□□□□□ ⊗

Legend: ⬚ Printable Area □ Printer Positions ↔ Movement of Printer



created, and lifted on top of the walls for this strategy to work.

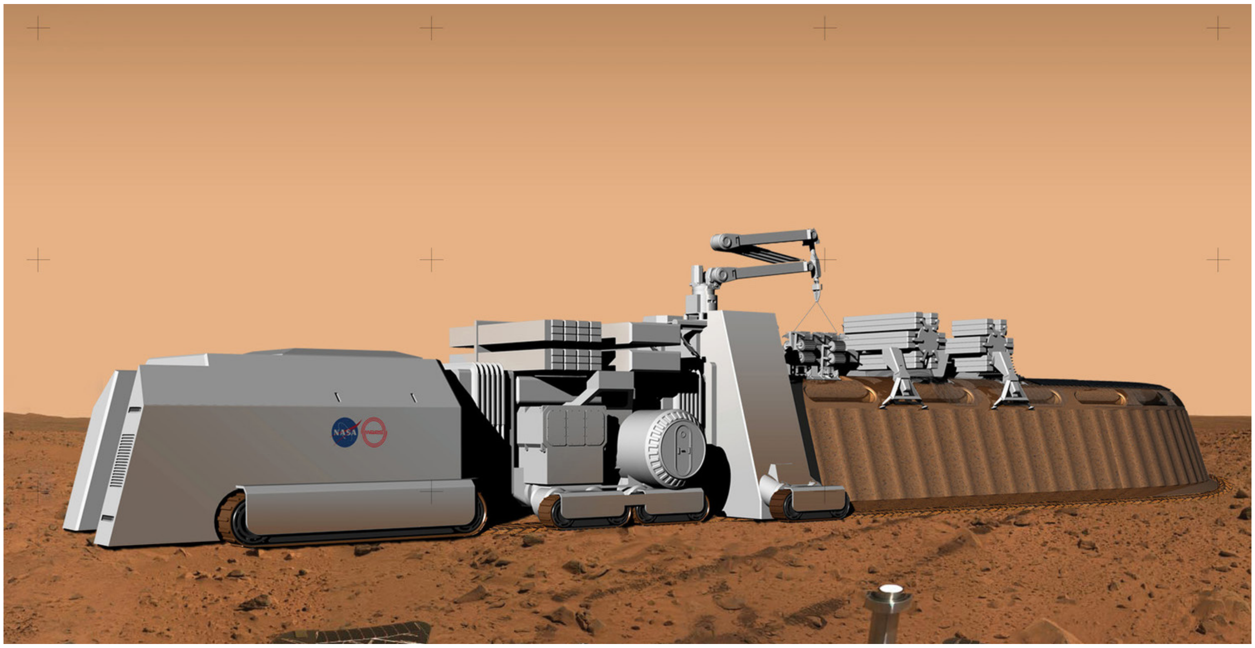
The crane and roaming printer are similar in design. They have a 360 degree rotating arm that can print anything in a circular radius. The crane printer is immobile and is planted on the ground. It would need to be moved and repositioned either by disassembly, or by lifting it away by crane. The roaming printer is essentially a crane printer on wheels, however, its size is likely to be smaller to allow it to move easier.

The gantry printer is the largest of the three printers. It works similar to two roaming printers attached at the tips. The gantry also prints from overhead and can move in all directions. It has an added benefit that its maximum printable area is not obstructed by the machine itself, unlike the crane and roaming printer.

Since the wall riding printer cannot enclose the structure, it will be omitted from consideration. The remaining three techniques however, if made large enough can print a roof directly on top of the walls or enclose it via a dome or an arched roof.

The kind of printer that is selected also has a big effect on the ability for the architecture to expand to accommodate more people or changing needs. The mobile printers can allow for buildings to be printed in as one continuous entity. The

Figure 4.23 - *RB systems design for a spiral Mars base that can continue to grow*



benefit of this is that astronauts would not need to go outside to traverse between buildings. Any connecting paths needed to link individual modules couple be printed in place creating a completely contained and continuous interior environment.

The same NASA 3D printed Habitat competition that the Ice House won, also beat out a project submitted by RB systems. Understandably, the top three designs utilized 3D printing to construct shells around a prefabricated transportation vessel. However, the RB systems project used a brilliant alternative which employed variation of a roaming printer to create a growing spiral with a continuous interior environment.[4] The printer in this design essentially uses a mobile gantry printer. It is fitted with a regolith collector which immediately feeds into the printer nozzle. It was one of the few which effectively tackled the important problem of a base beyond a single solitary outpost.

Figure 4.24 *- Mobile 3D printer used to generate the building*

---

[4] RBSystems, "NASA 3D-PRINTED HABITAT CHALLENGE," accessed March 20, 2018, http://www.rb-systems.us/projects/#/new-gallery-58/.

- PART FIVE -

DESIGN SYNTHESIS

GEOMETRIES

Contour crafting is similar to the 3D print style of fused deposition modelling (FDM). Typically in these methods, 3D printers will use printed support material to allow for the printed product to have features like cantilevers or overhanging elements. After the print is completed, the support material is removed and disposed of. On Mars, the use of support material is not ideal. Any supports that are made are wasted material and requires a lot of effort to remove afterwards.

To greatly reduce or eliminate the need for 3D printing support material, the geometry of the structure can be optimized to support its own weight while it is being printed. For this design, the catenary arch was chosen for its structural abilities. The catenary "is the name for a curve that occurs naturally when a chain of uniform density is allowed to hang"[1]. It is the ideal arch in supporting its own weight.

The catenary has already application in architecture, for example Antonio Gaudi's Casa Mila, in which the catenary is used as a series of structural ribs organized in a tunnel, or in Christopher Wren's St. Paul's Cathedral where it was used in a dome. Because of its ability to support itself, the catenary will be used as the cross section for the initial Mars base. The catenary arches will be arrayed into a ring, creating the shape of a ring or a torus. To maximize the efficiency of the 3D print machine, the building's floor plan will use the entirety the printable area.

As opposed to traditional dome designs, the torus is more beneficial in several ways. Firstly, in terms of 3D printing, the torus is ideal since it leaves a space at the center where a rotational 3D printer could print around it. Secondly, the torus also has a circular plan, helping to distribute its weight uniformly into the ground. It also has the potential to be constructed with a much shorter height as opposed to a dome, allowing for a shape that is both more easily buried for greater

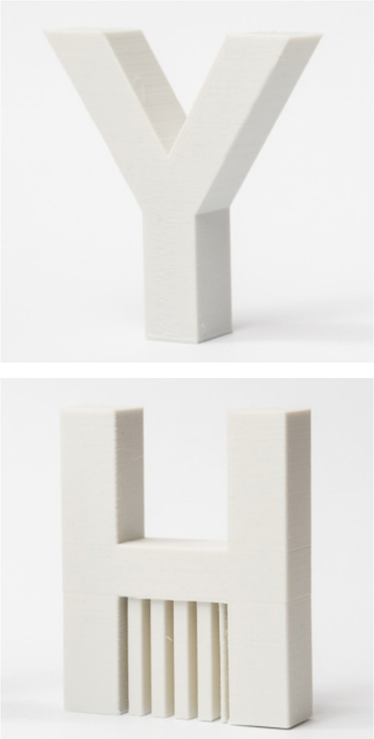


Figure 5.1 - *Author rending of a Mars research station*

Figure 5.2 - *(top, mid) FDM printed letters showing support requirements*

Figure 5.3 - *Concrete printed dome test*

---

[1] Gail Kaplan, "The Catenary: Art, Architecture, History, and Mathematics," in Bridges Leeuwarden: Mathematics, Music, Art, Architecture, Culture (Tarquin Publications, 2008), 47-54.

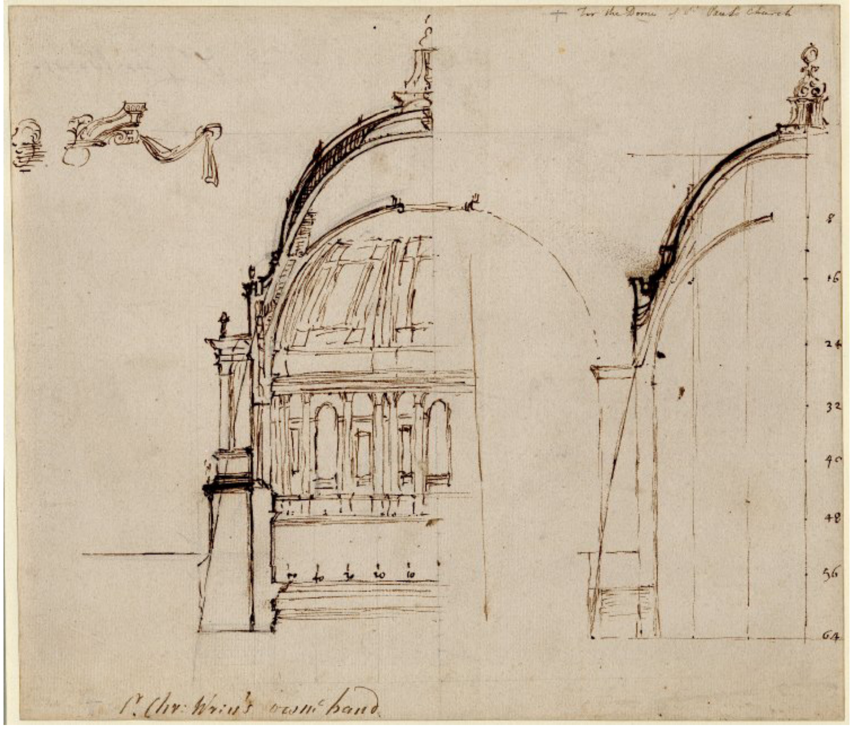


Figure 5.4 - *(top) - Christopher Wren's sketch for a dome with a catenary profile*

Figure 5.5 - *(bottom) - Antonio Gaudi's Casa Mila. Catenary curves are used as structural ribs*

radiation shielding, and produces similar floor areas. Finally, the natural ring shape allows for better air circulation since it is one continuous path, and the ability to segment the building into multiple zones.[2]

When testing this form through a Makerbot 3D printer in polyactic acid (PLA), the outer shell could print fully without the use of structural material, regardless of the extreme angles. It is likely that the success of this print is owed to the properties of the material used. This may not necessarily be the same when using a fast curing concrete, however, to push forward the design speculation, this geometry will be selected since the area for which support is needed has be dramatically reduced.

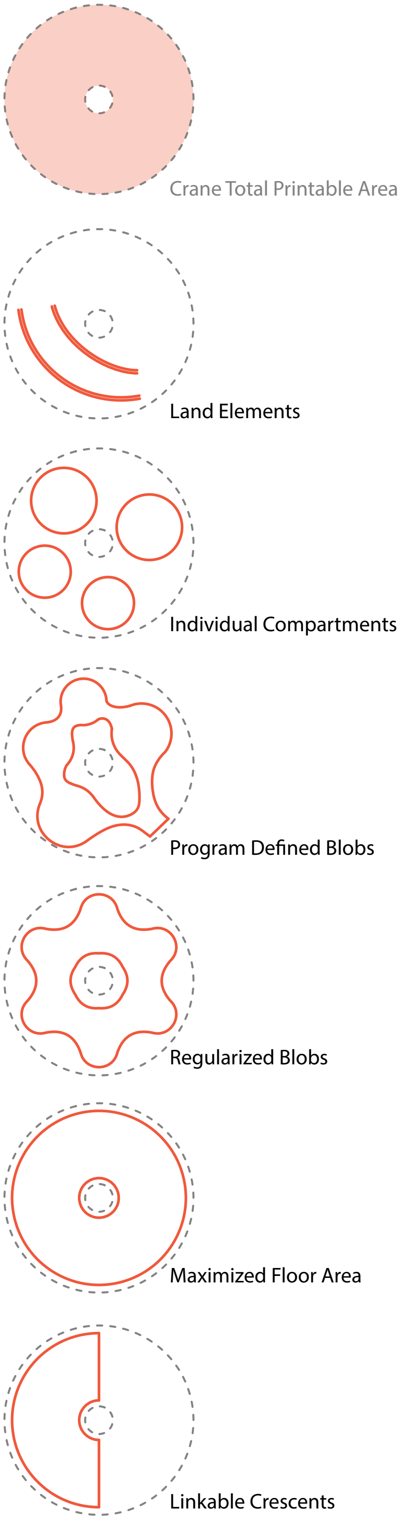
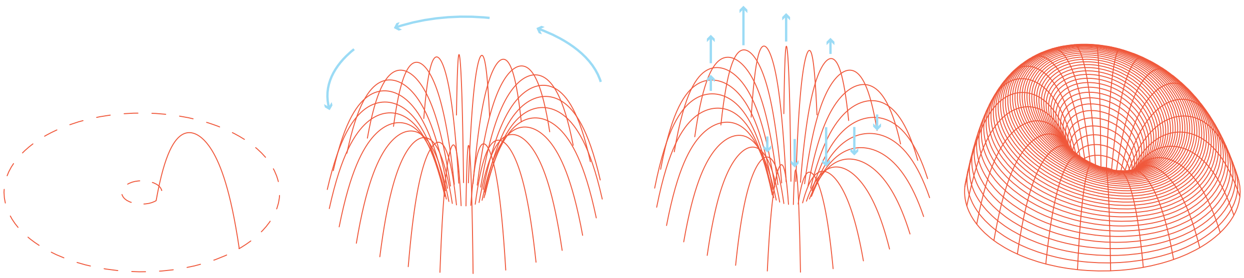


***Figure 5.6 -** Outpost floor plan options*

---

[2] Gary C. Fisher, "Torus Or Dome: Which Makes The Better Martian Home," 1999, pg 8-12, table 1, accessed March 18, 2018, http://www.marshome.org/files2/Fisher.pdf.



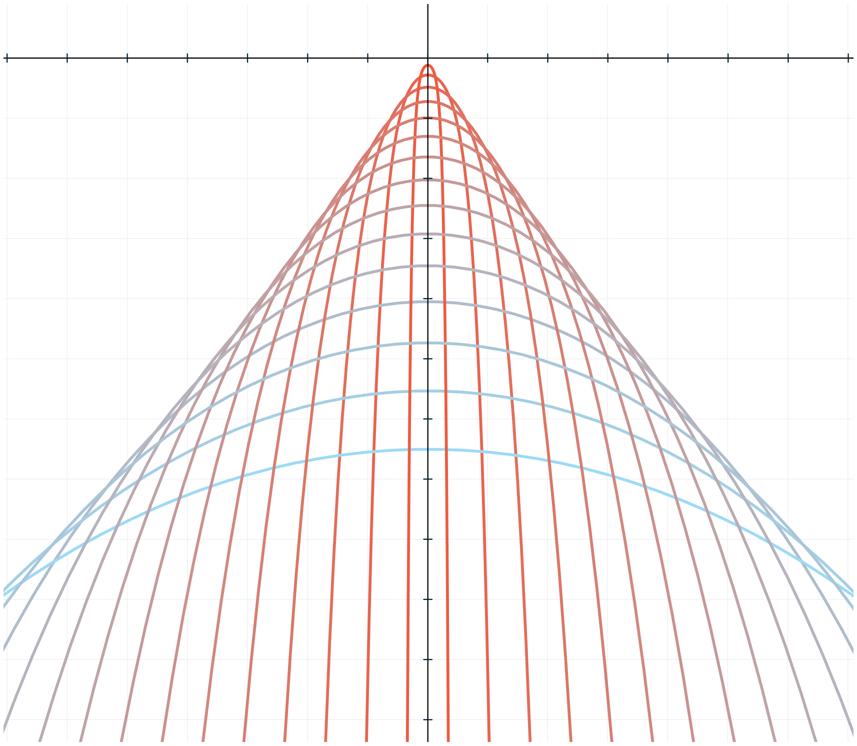


Figure 5.7 - *Outpost form creation*

Figure 5.8 - *Graph showing multiple variations of catenary curves*

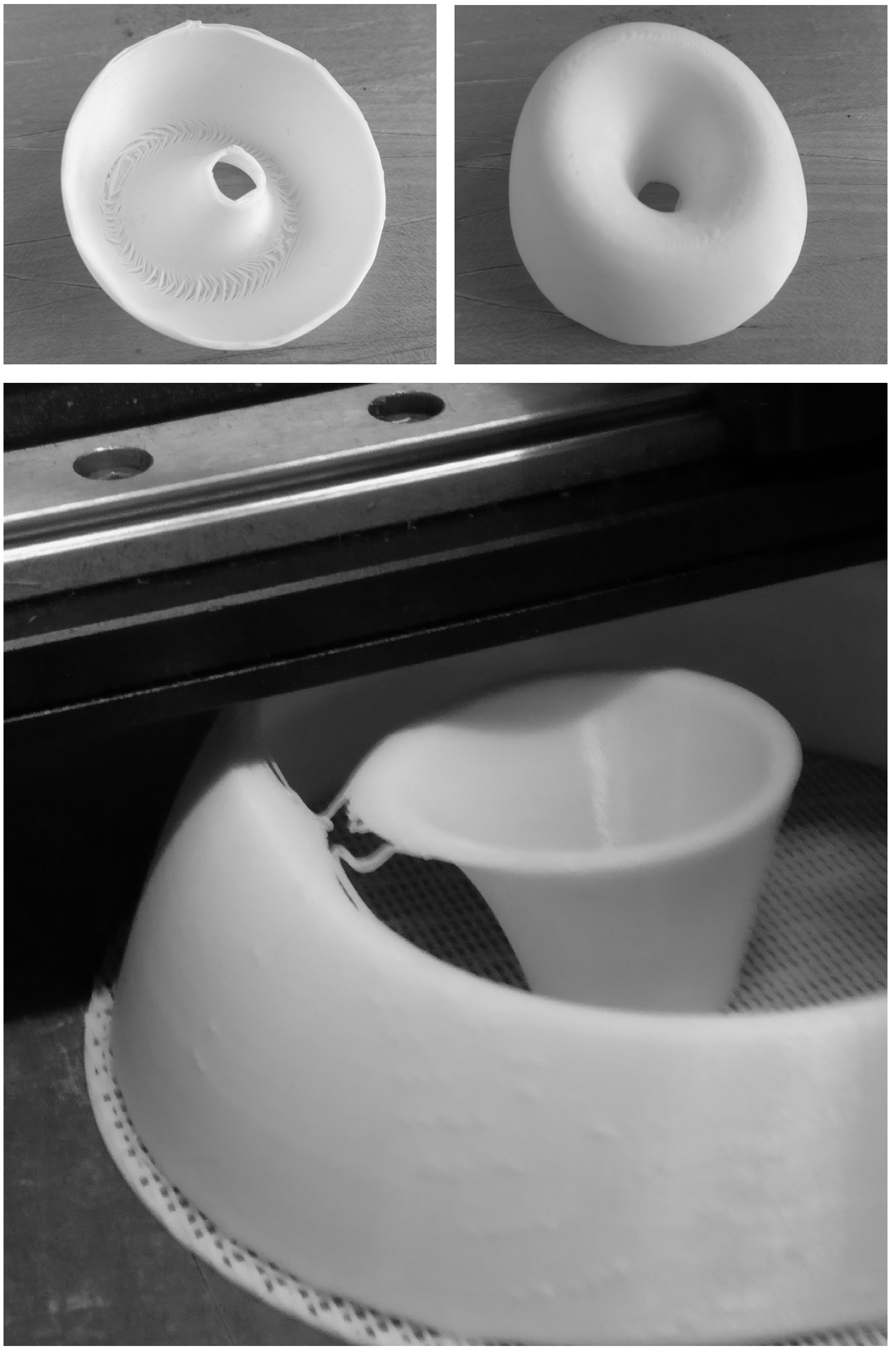
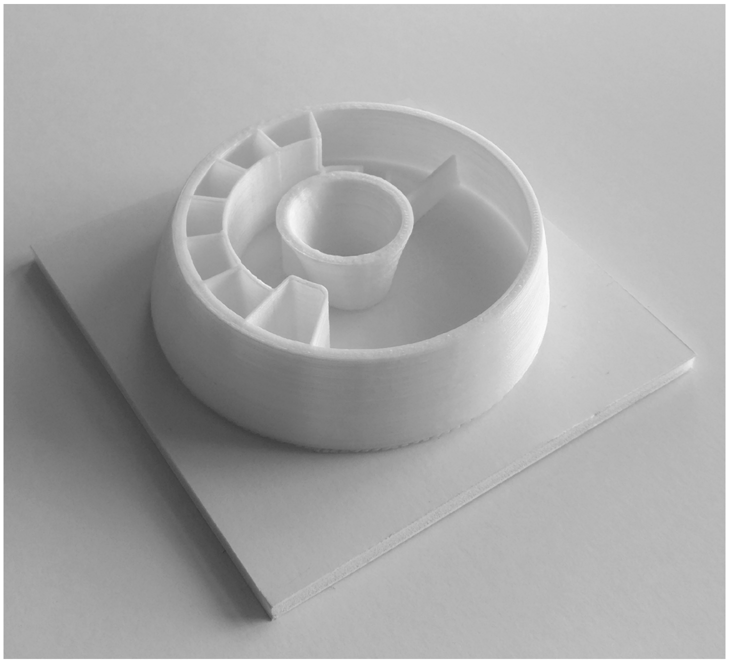


Figure 5.9 - *PLA 3D Printed test models. Initial small scale test prints were printed without use of support material and proved successful. Some bridging of the material is used towards the top of the arch however.*



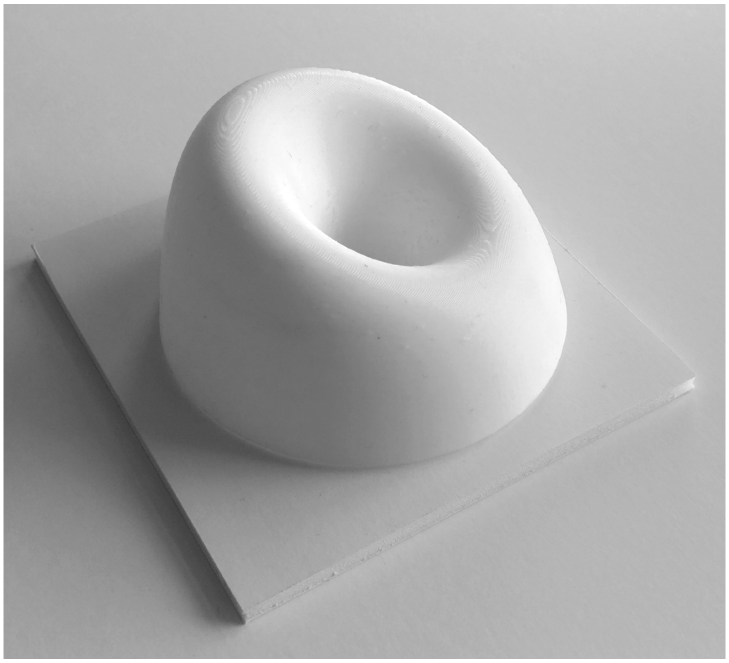


Figure 5.10 - *Half 3D printed test model showing potential buildup of interior walls*
Figure 5.11 - *Completed 3D print test model at 1:100*

OUTPOST

Designing an Autonomously Constructed Base Camp

In the summer of 2028, the first manned mission to Mars is taking place. Six crew members are on board for the 6 month journey to Mars and set up camp in the small Martian outpost located near the Jezero Crater. This mission is part of a series of explorations, known as the Ares missions, scattered at multiple interesting areas on the planet. The astronauts aim to conduct on site research, as well as judge the feasibility for a long term settlement in this area.

The team consists of highly trained, specialized crew members, each with unique talents ranging from engineering, piloting, medicine, to research. The crew will be closely observed, and the research that they conduct will be crucial to our understanding of Mars. The mission type is a conjunction class long term stay. This means that the crew will spend approximately 496 days on the surface of Mars, establishing home and sending findings back to Earth.

Two years prior to human arrival in 2026, another Mars launch window, robotic construction had been sent and deployed to the site to generate the shell of the habitat. The remote operated robotic 3D printers have already excavated an area of regolith, as well as collected it to extrude through the printer as sulfur based Martian concrete. This was done because the effects of transitioning from weightlessness to gravity can be taxing. The process minimized the amount of work that the astronauts will need to do on arrival. Once the shell had been printed, the habitat is buried under a mound of regolith, to help with thermal insulation and radiation protection.

On arrival to the red planet, the crew can live in the landers as a temporary measure, while the rest of the habitat is fully completed. They will immediately begin work on completing the habitat, implementing life support systems, such as insulation, oxygen, sanitary and water reclamation. Eventually the crew will be able to move in, establishing the first constructed habitat on Mars.

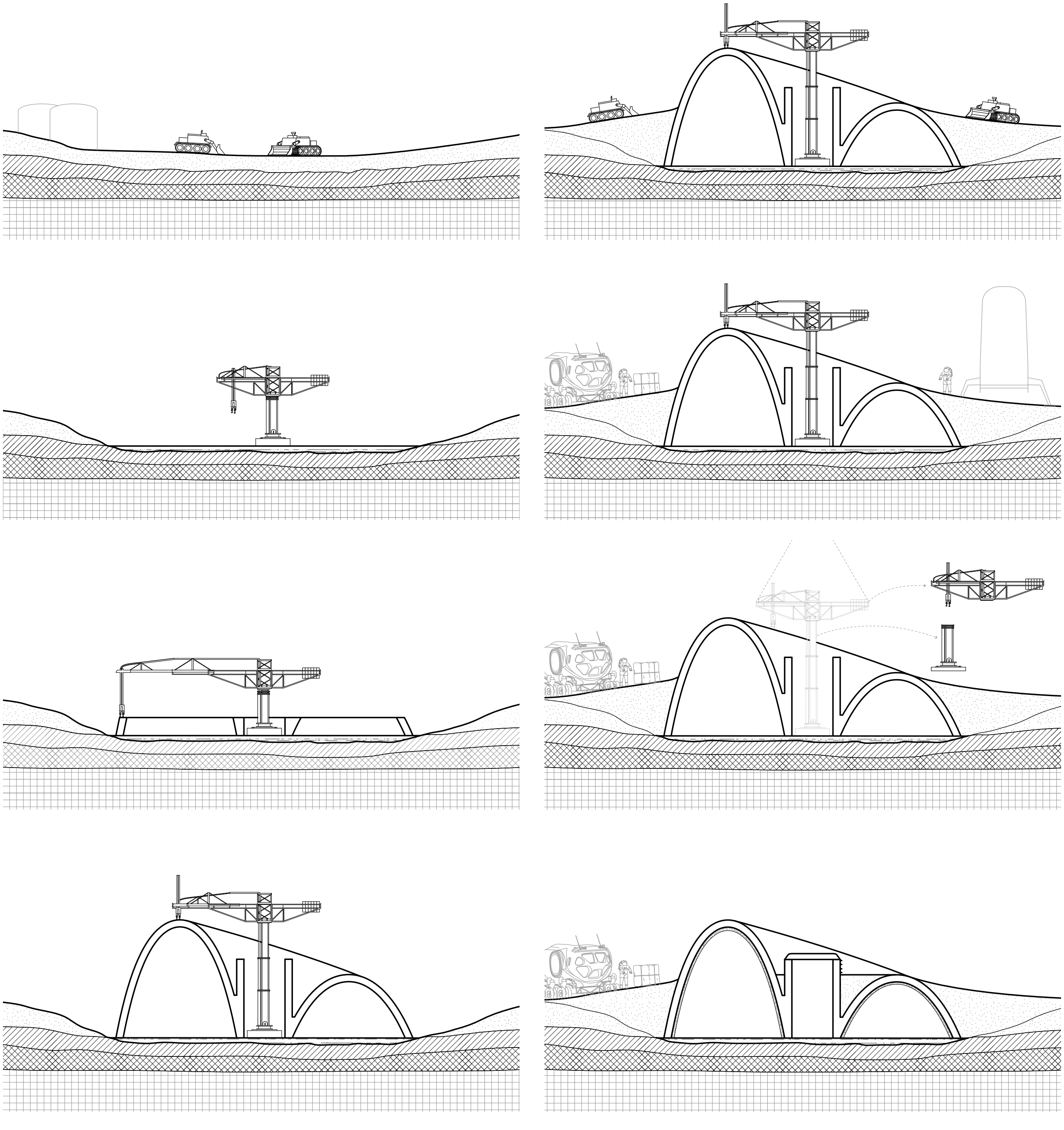


Figure 5.12 - Outpost build up process

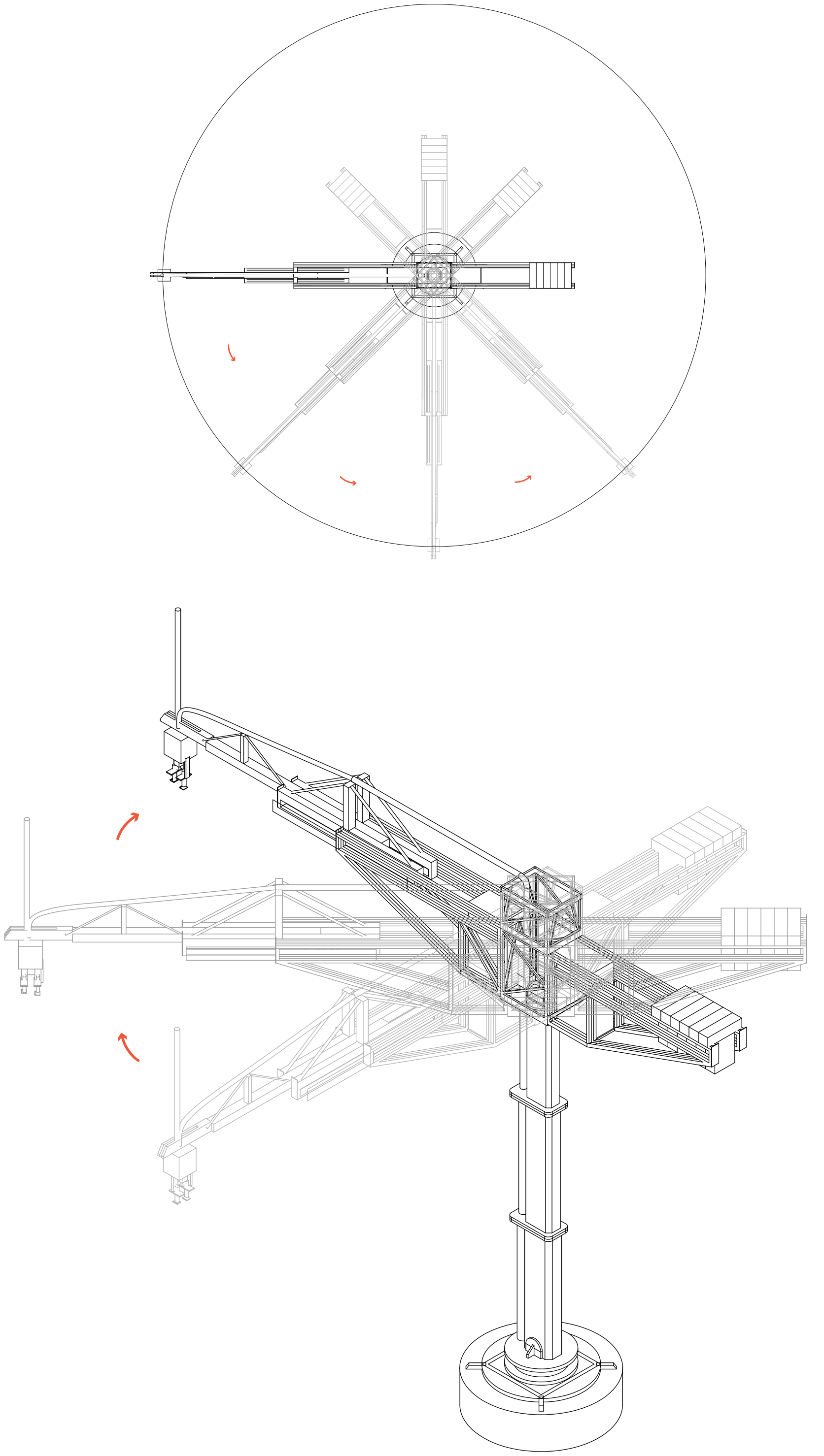


Figure 5.13 - *Large scale 3D printer rotation*

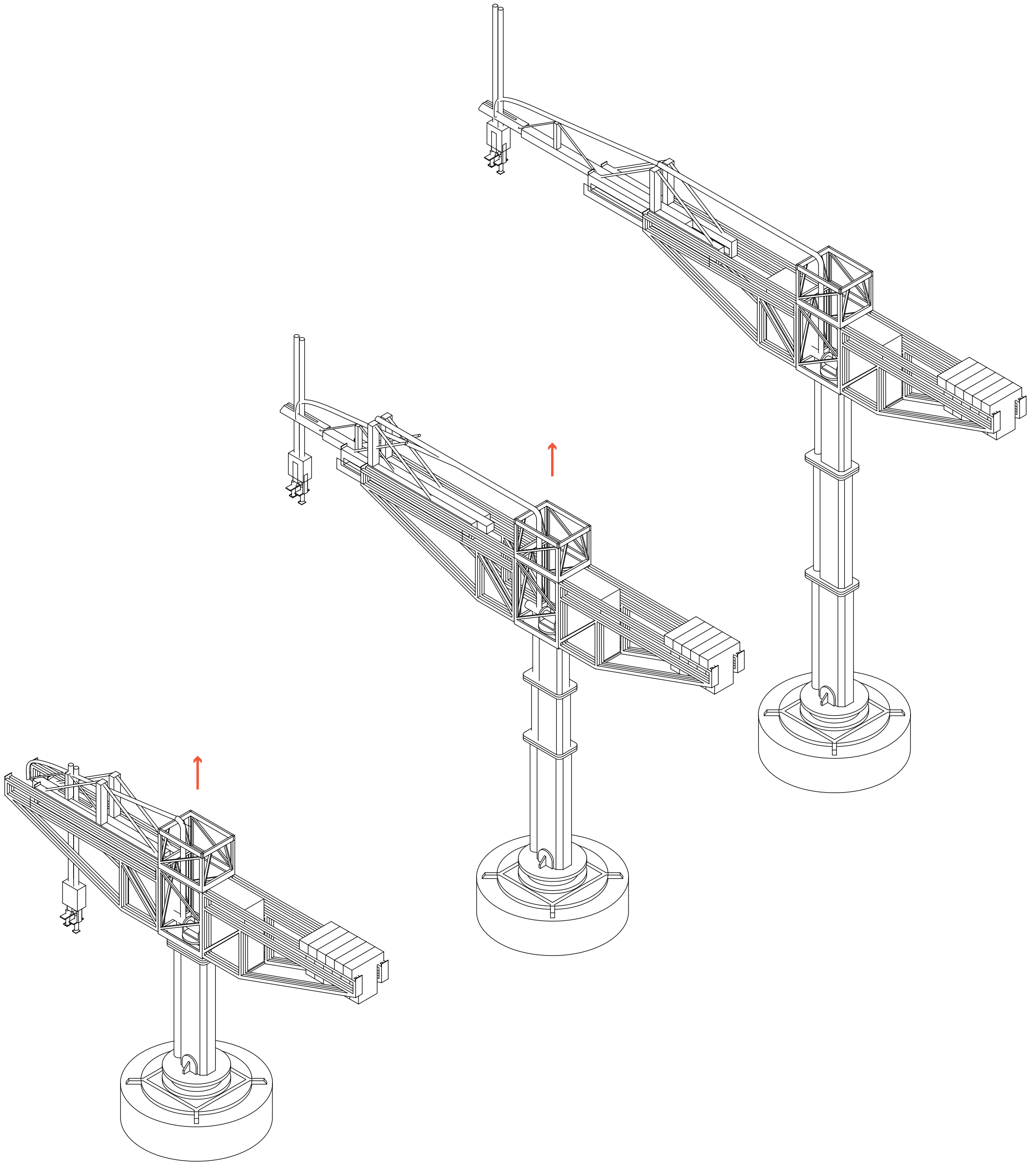
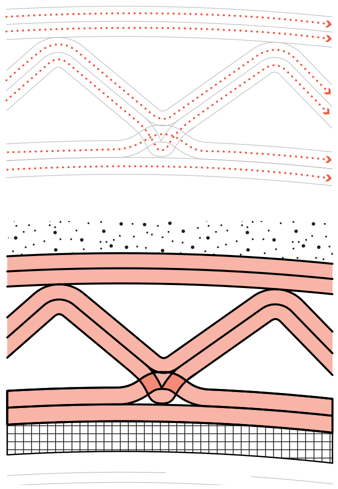


Figure 5.14 - *Example construction method using 3D printer. Large scale 3D printer is placed in the center of a previously excavated site. Material removed in excavation is used to feed the printer. Overtime, the building will be buried, aiding in the radiation shielding.*

The wall assembly of the structures is rather simple since it primarily consists of the Marscrete. A corrugated pattern is used on the interiors of the walls. This has the effect of reducing self weight and the amount of material needed to complete a print. Additionally, the corrugations increase the building's ability to withstand bending similar to a piece of cardboard.

To retain heat, the building will use a form of silica Aerogel insulation. Silica Aerogels are incredibly high in insulative value having approximately 13-16mW/mK thermal conductivity[1]. By comparison, extruded polystyrene has a thermal conductivity of between 30-40 mW/mK (a higher conductivity meaning a greater amount of heat loss)[2]. A product like JIOS AeroVa[3] is a powdered form of silica Aerogel that has approximately 17-22mW/mK thermal conductivity. This material is very lightweight with a density of 0.1g per centimeter cubed - only three times the weight of air.[4] The insulation can also be applied as an airless spray with at an effective temperature of -50°C, or placed as a padding at -100°C.[5] Insulation can be sprayed additively until the required insulation is achieved.

To allow for different materials to be printed simultaneously, multiple nozzles can be used that run different materials. As a concept, a liquid Aerogel insulation can be run through one nozzle adjacent to a nozzle running Mars concrete. Once a few layers of concrete have been set, insulation can be continuously poured into the voids. This way, the insulation will need to be transported alongside the 3D printer. This would allow for the concrete and the insulation to be built up at the same time.



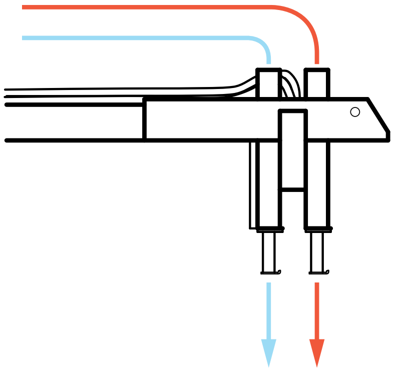


Figure 5.15 - *(top) - Occasional overlap of print path to help tie layers together*

Figure 5.16 - *(bottom) - Double nozzel in 3D printer*

---

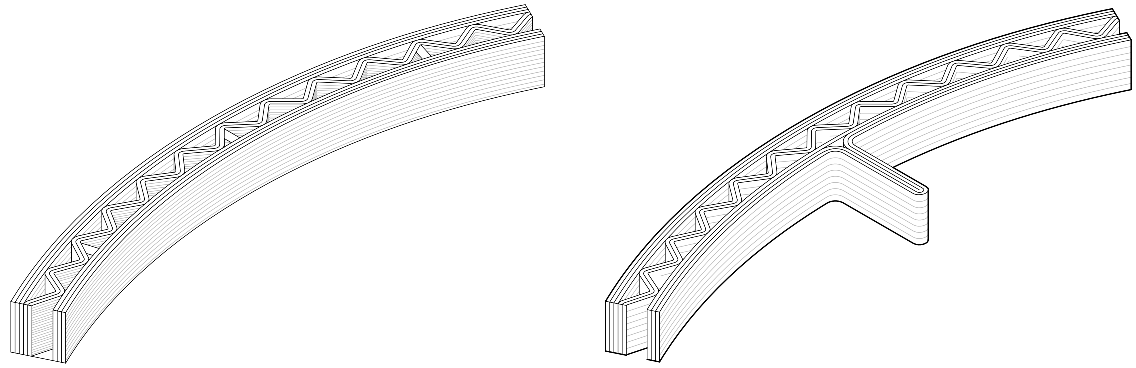
[1] Lang Huang, *FEASIBILITY STUDY OF USING SILICA AEROGEL AS INSULATION FOR BUILDINGS*, Master's thesis, KTH School of Industrial Engineering and Management, 2012, pg 14.

[2] Ibid., pg 21.

[3] "JIOS AeroVa," JIOS Aerogel, accessed March 23, 2018, https://www.jiosaerogel.com/jios-aerova/#Applications.

[4] Ibid.

[5] JIOSaerogel, "JIOS Aerogel - AeroVa Insulation Coating (Airless Spray Method)," YouTube, January 21, 2014, , accessed March 23, 2018, https://www.youtube.com/watch?v=JzEdkTNYvGY.



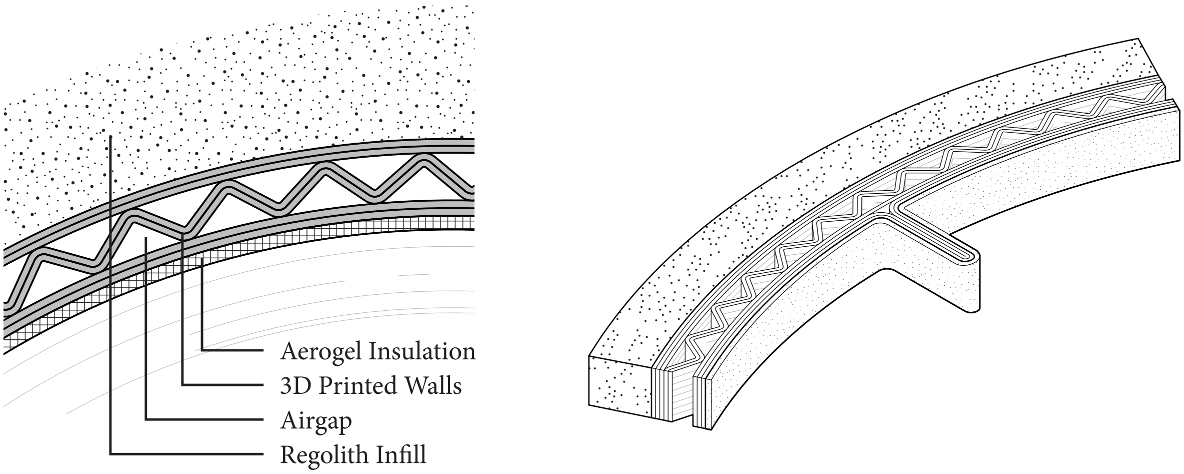


Figure 5.17 - *(top) - Axonometric of exterior wall and a printed interior partition wall.*
Figure 5.18 - *(middle) - Detail plan and Axonometric wall assembly*
Figure 5.19 - *(bottom) - Airless spray application of AeroVa insulation*

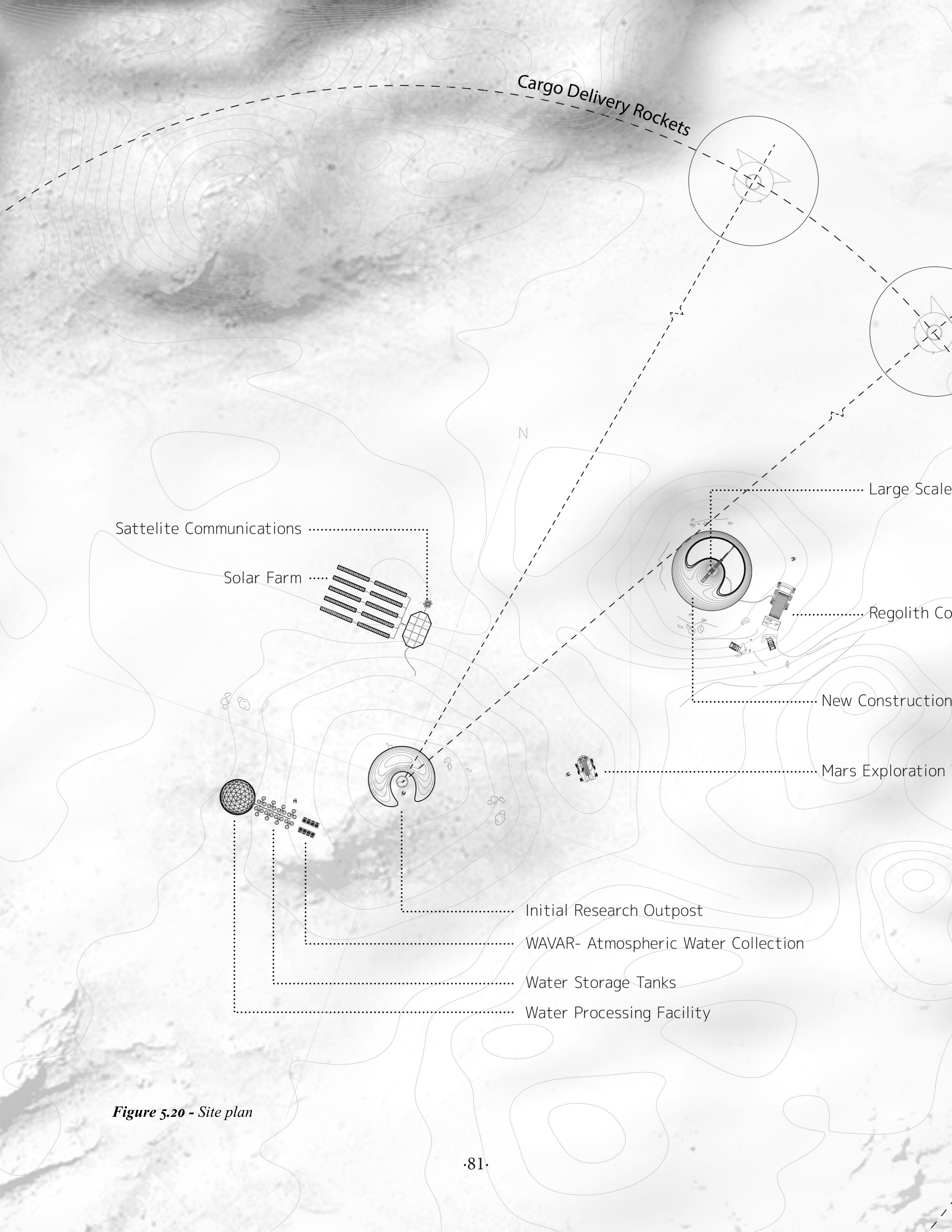
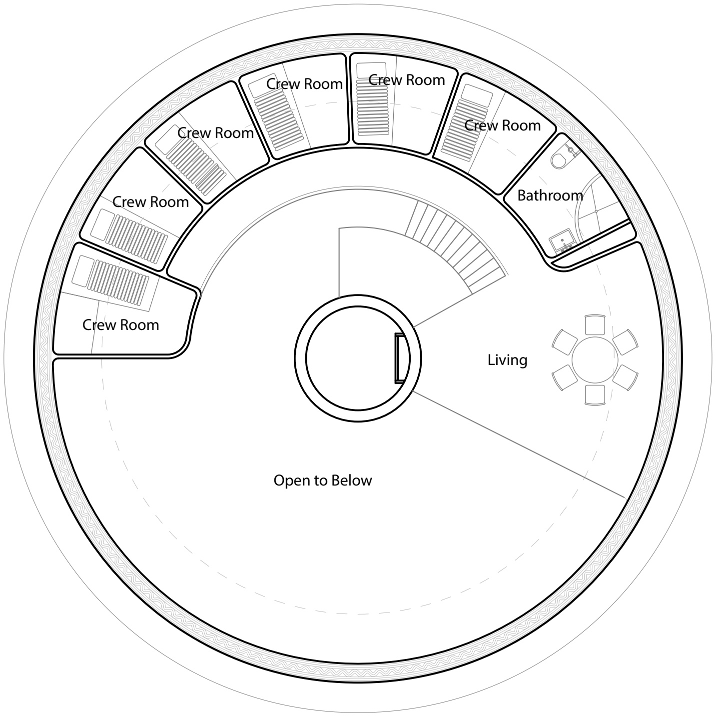


Figure 5.20 - *Site plan*


3D printer
llection
Vehicle



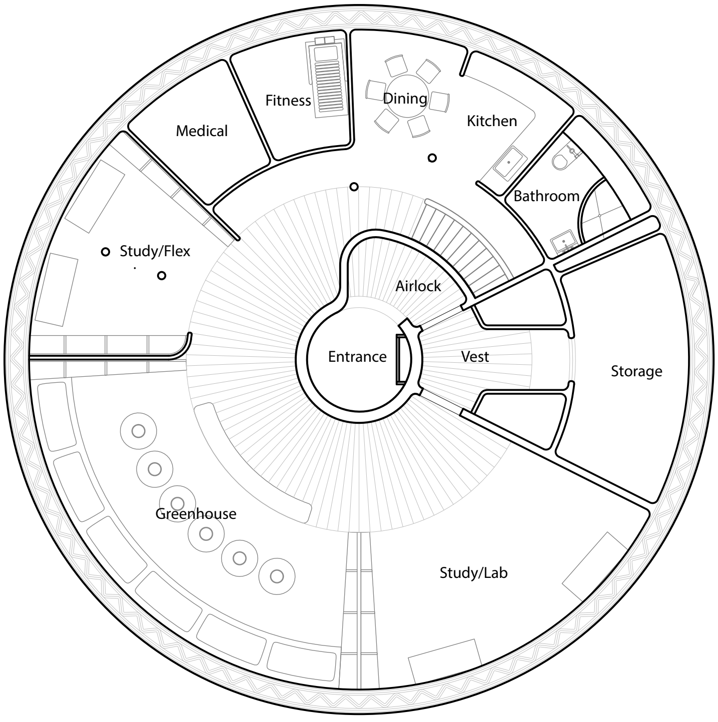


Figure 5.21 - *(bottom) - Ground floor plan*
Figure 5.22 - *(top) - Upper floor plan*

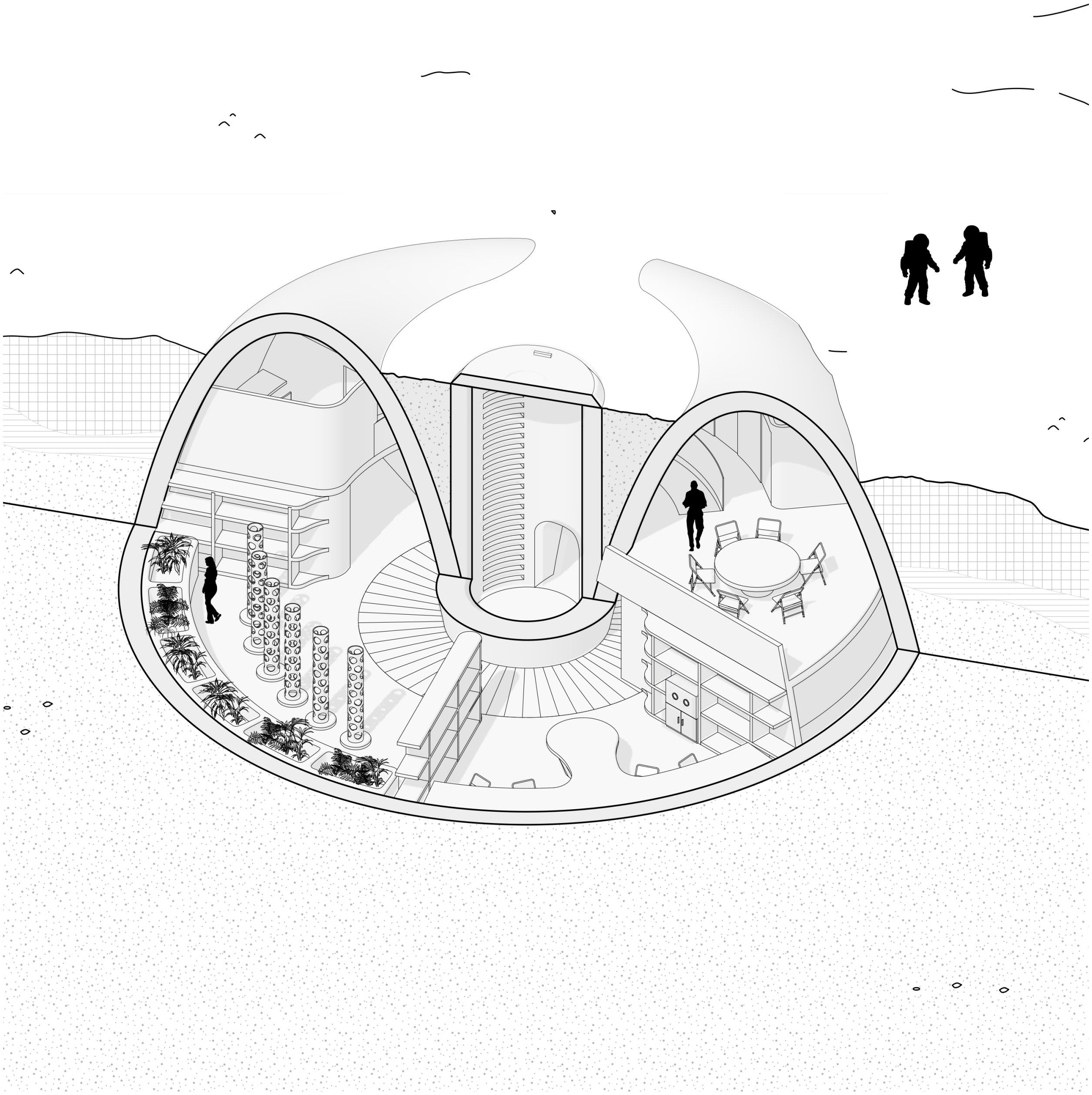


Figure 5.23 - *Interior axometric drawing. Note that this rendering shows a generous and idealized space with floors. 3D printing the the second level may not be possible without additional reinforcing during the print. Architecturally, the second floor adds to the quality of the space, but it is not mandatory. The habitat can be shortened and rearranged to omit the second floor if necessary.*

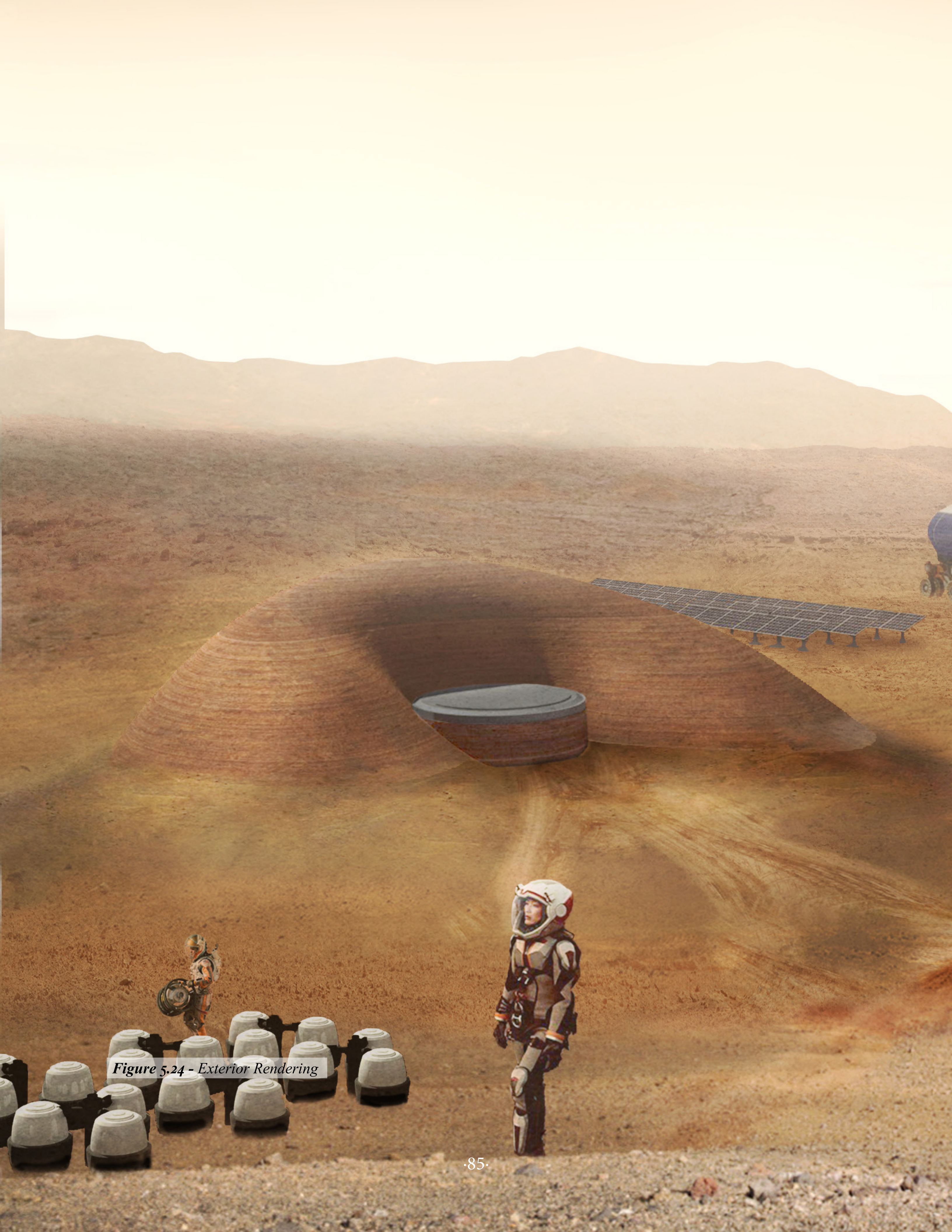


Figure 5.24 - *Exterior Rendering*

Figure 5.25 - Interior Rendering

RESEARCH HUB

Phase 2 - Beginning a Growing Research Colony

The research outpost located at Jezero crater has proven to be a big scientific success. Selected out of a possible 12 probed landing sites across Mars, the base at Jezero is planned to expand into a fully fledged research station and logistics hub.

There is now a higher demand coming from earth for conducting on site research. This base is planned to be able to sustain approximately 150 people, but be capable of expanding even further. The research station can no longer function as a small singular, all-in-one building, but it will instead need a modular, flexible architecture capable of adapting to the evolving needs of the community. Since the physical footprint of the building will need to expand, it will require some changes to the method of construction.

The 3D crane printer has been adapted by attaching it to a similar duplicate. These two machines combine into one gantry printer. The gantry printer is built to be mobile while anchored to the ground at two points. The base is allowed to pivot letting it print segments of a building that string together into a winding floor plan. This gives the building a much larger total floor area. The segmentation has the added benefit of creating different room types based on its shape.

This winding strip could also be printed with intermittent vaults which help short circuit the circulation through the building, and further increase floorspace. To create a path between adjacent vaults, filler pieces would be printed off site and attached post construction. The vaults have an added benefit of laterally reinforcing the structure.

Each base is blocked out on a T shaped spine. Each of these T elements could then link together to similar T's to allow for a continuous and fully enclosed space, reducing the need to exit the building in a space suit.

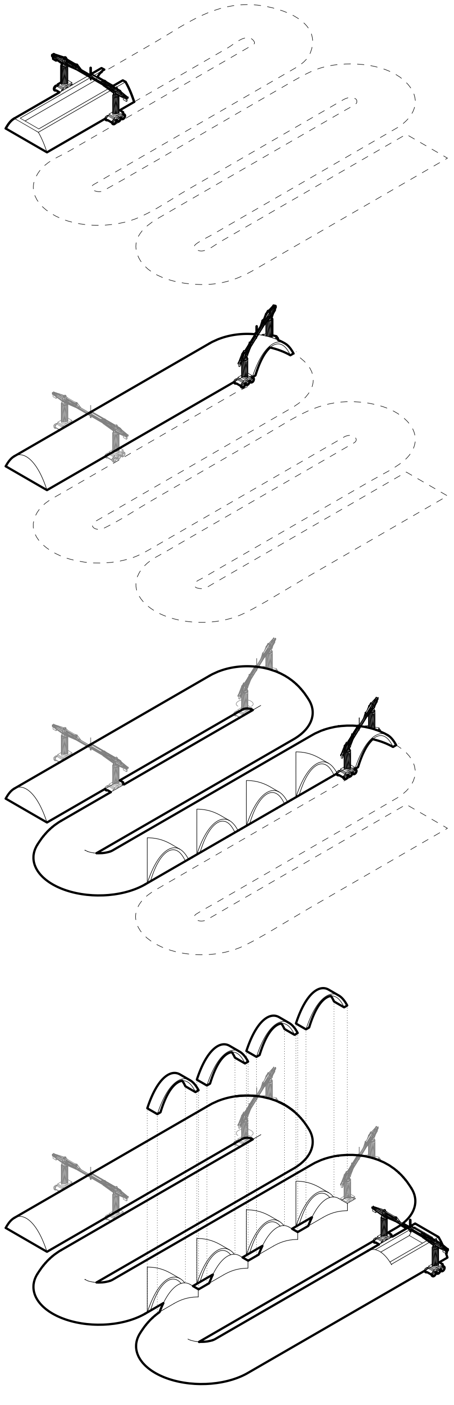


Figure 5.26 - *Research station build up*

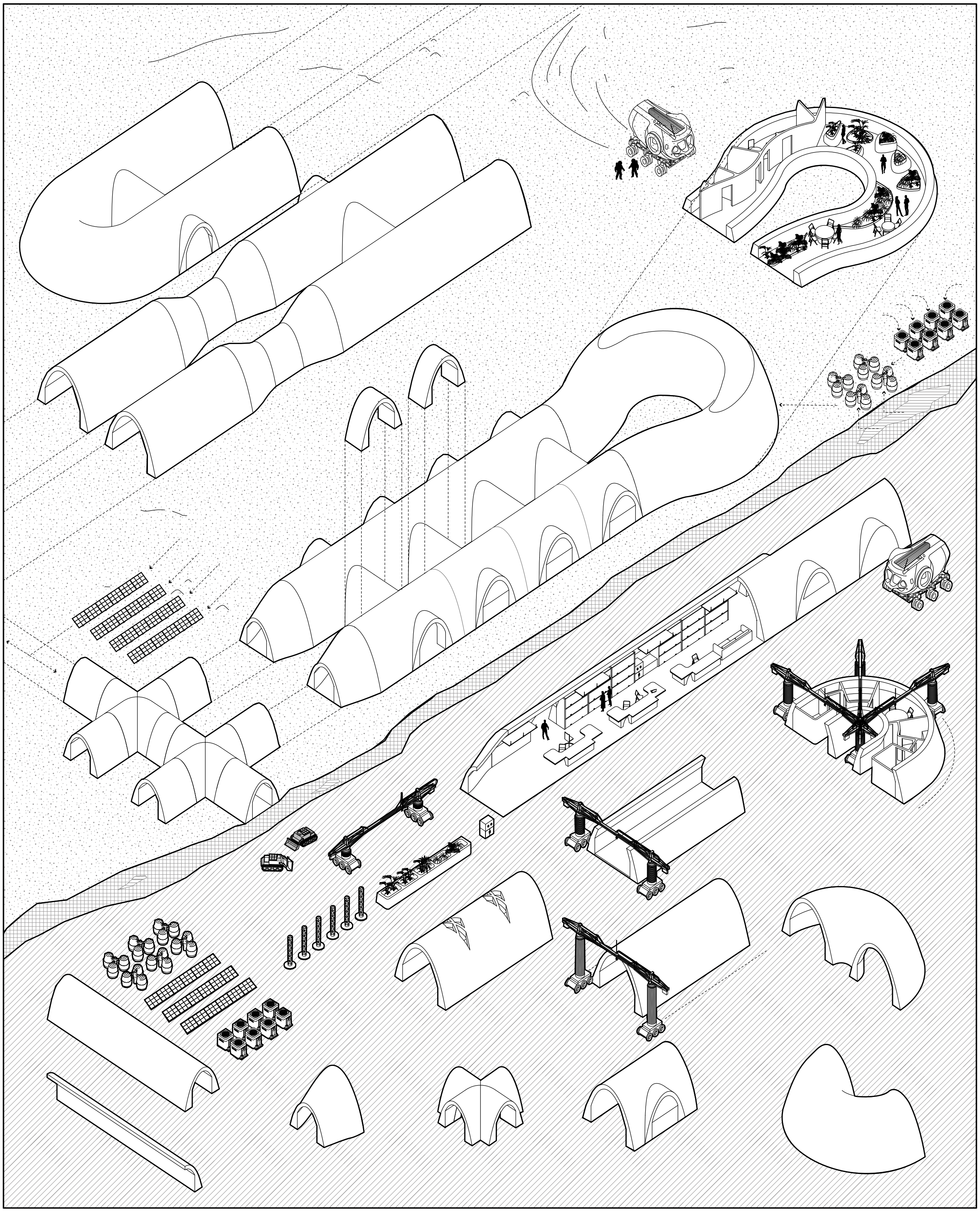


Figure 5.27 - Individual building segments and their connections

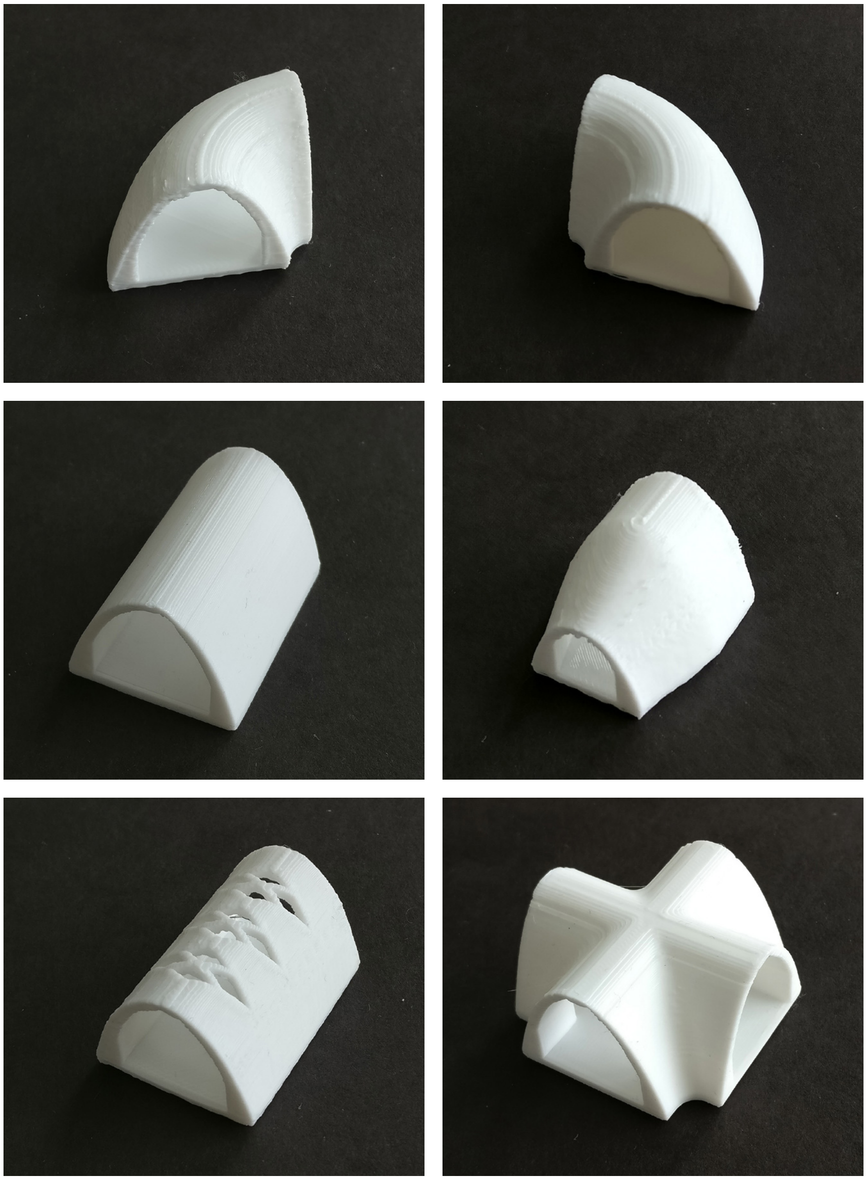


Figure 5.28 - *Segment 3D printed Model Tests*

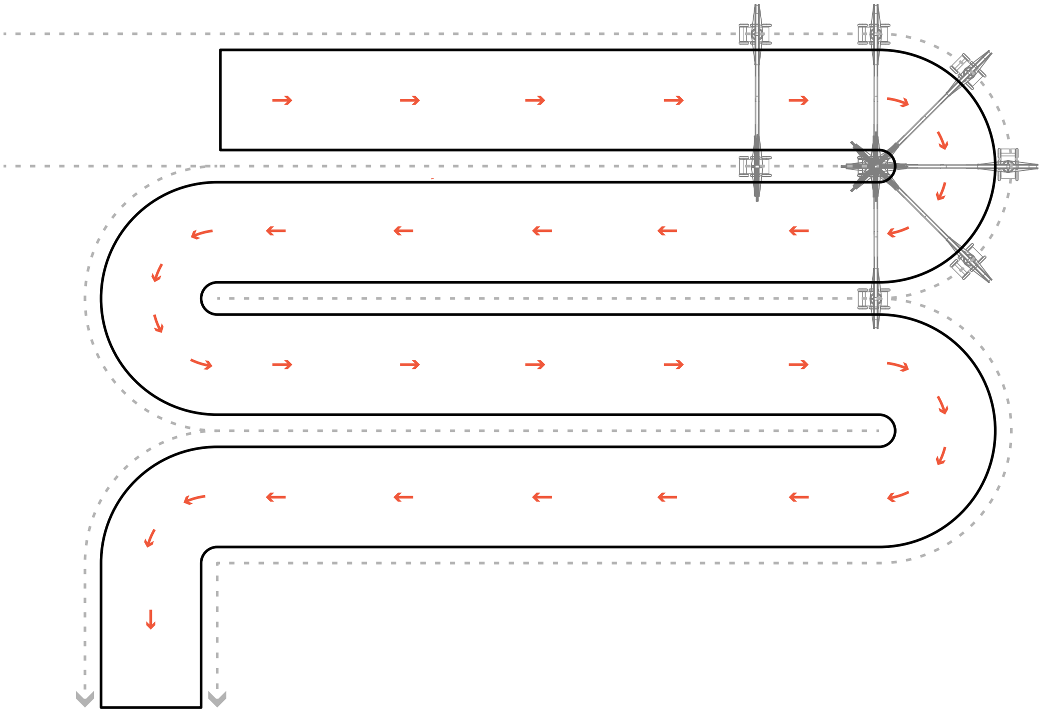


Figure 5.29 *- Printer creating a continuous plan*

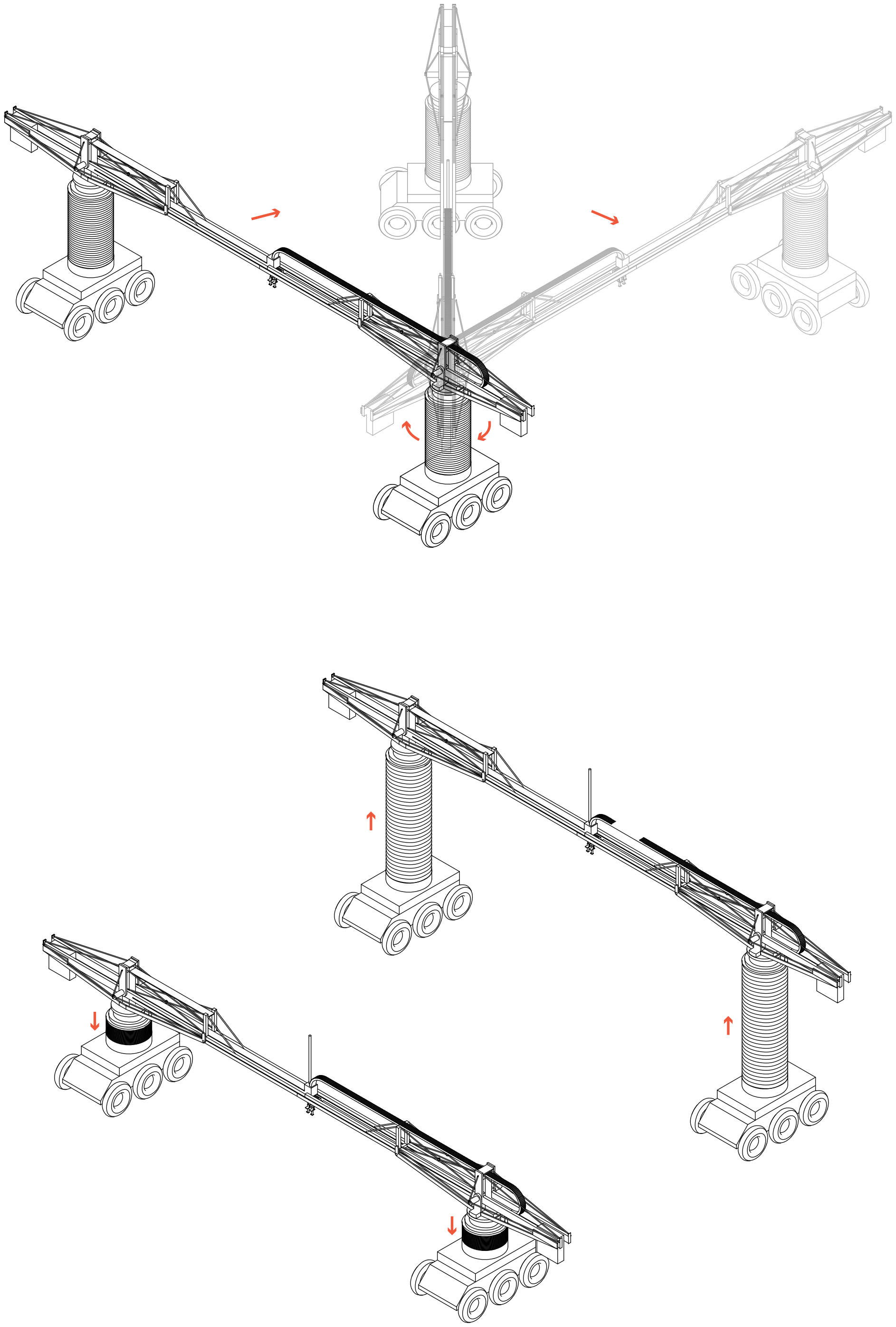


***Figure 5.30 -** Gantry printer movement*

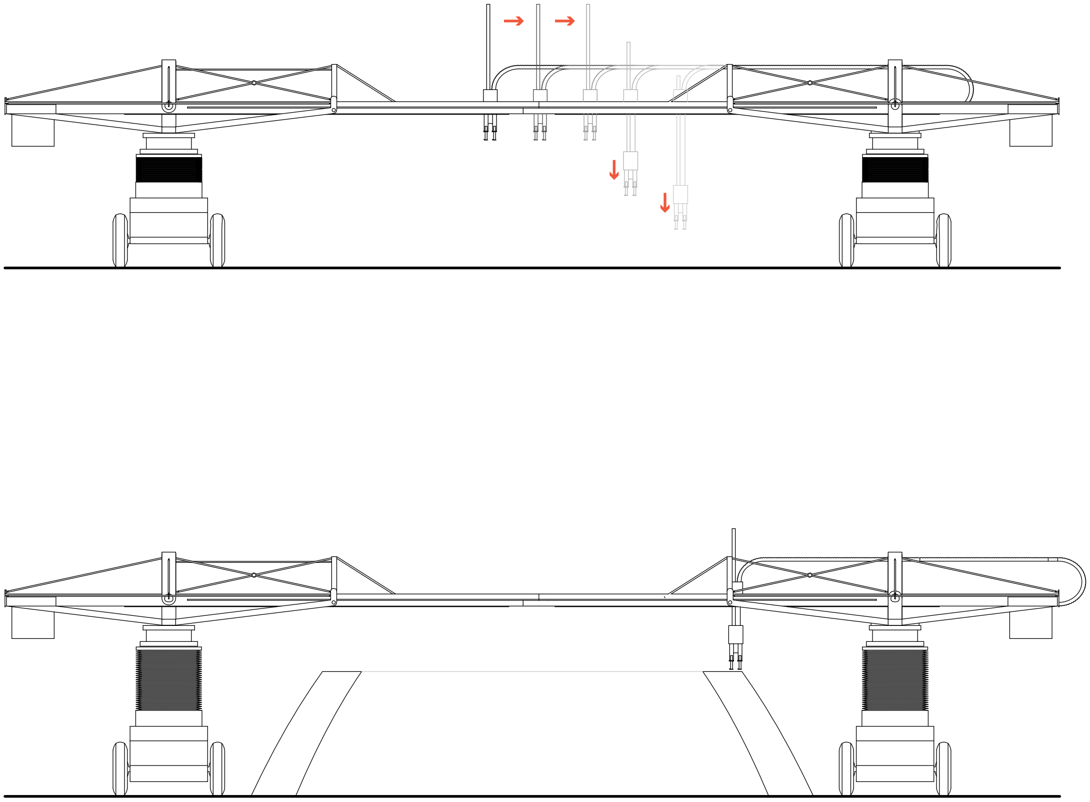


***Figure 5.31 -** Gantry printer movement elevation*

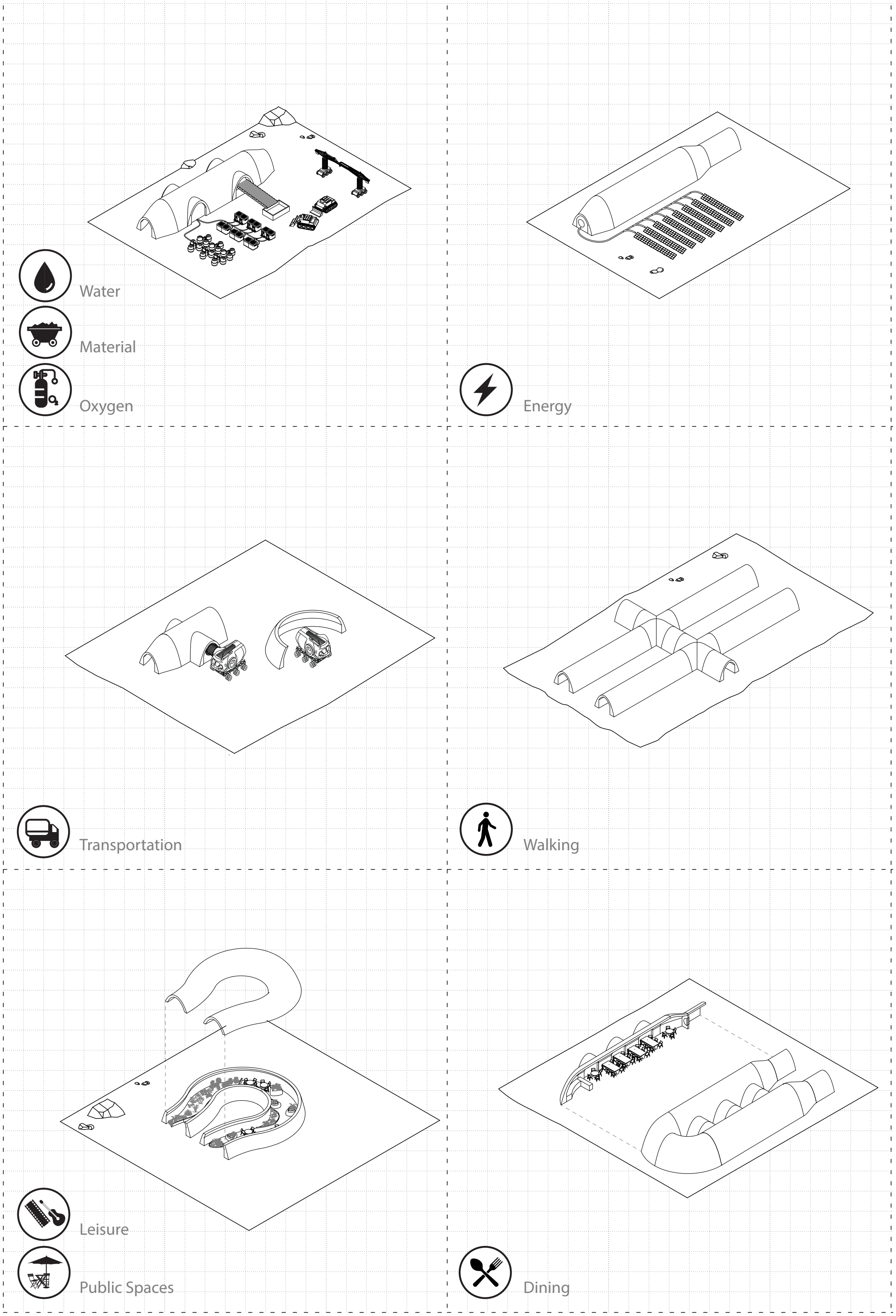


Figure 5.32 **-** *Building segment program morphologies*

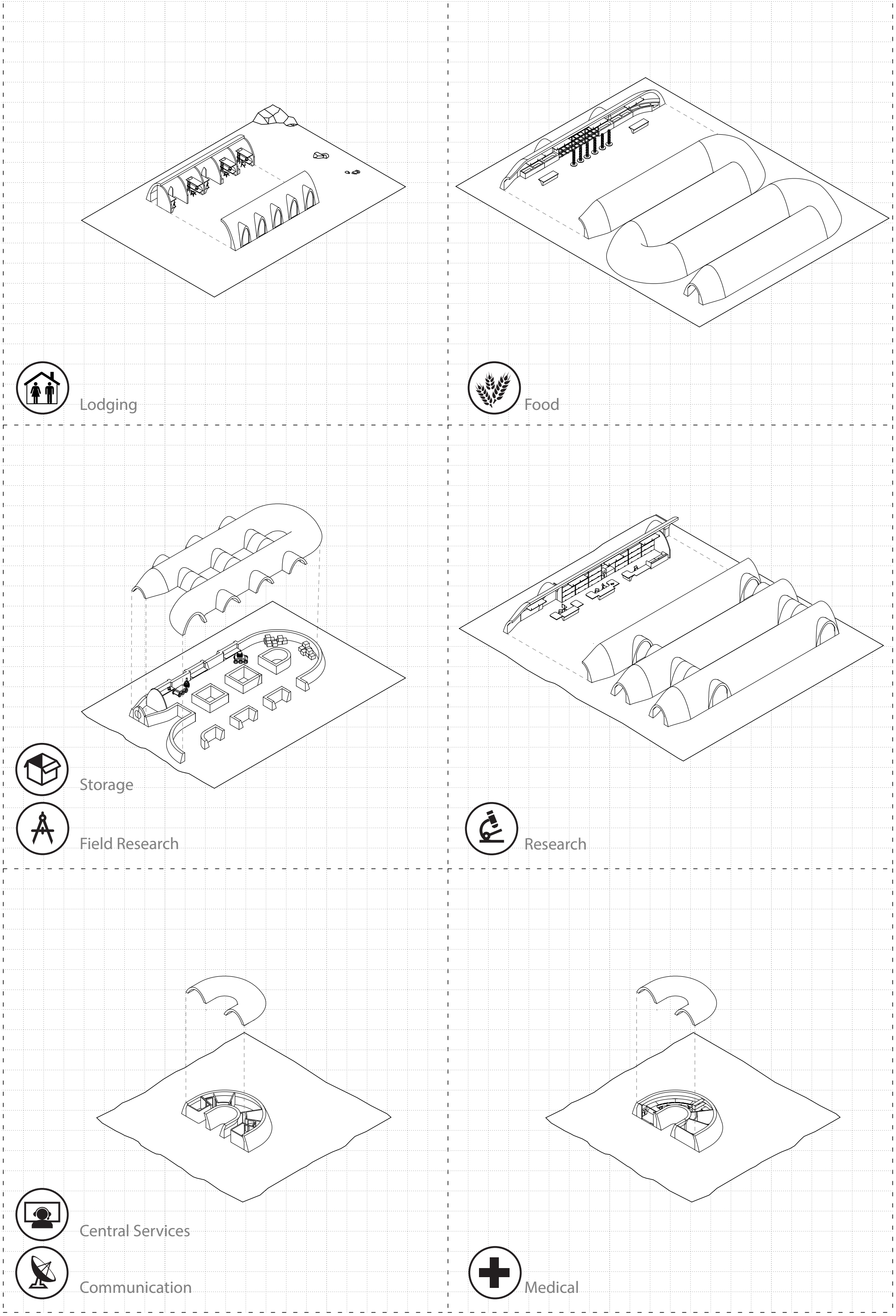


Figure 5.33 - *Building segment program morphologies*

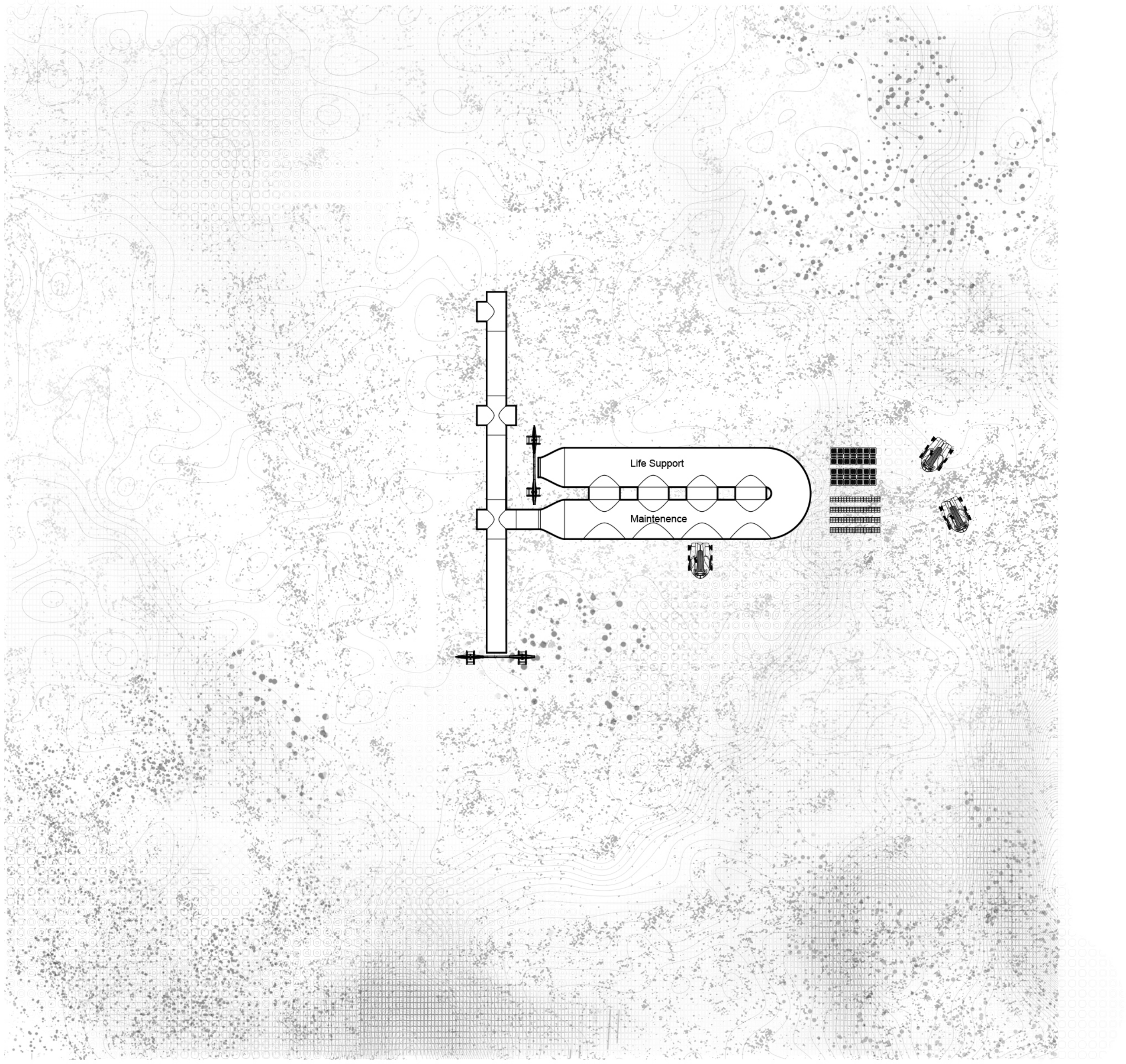


Figure 5.34 - Site plan 1, progressional build up of architecture

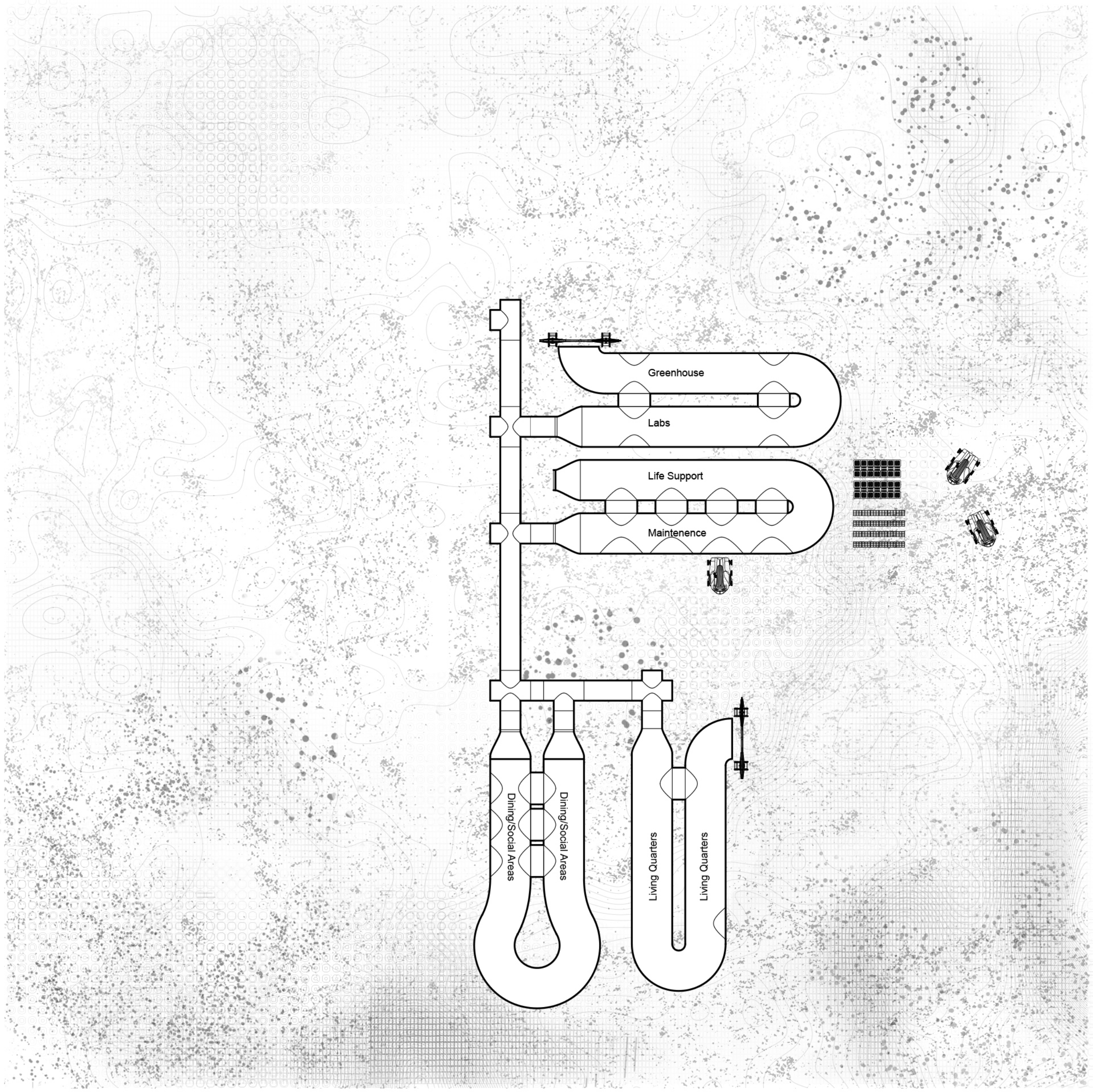


Figure 5.35 - *Site plan 2, progressional build up of architecture*

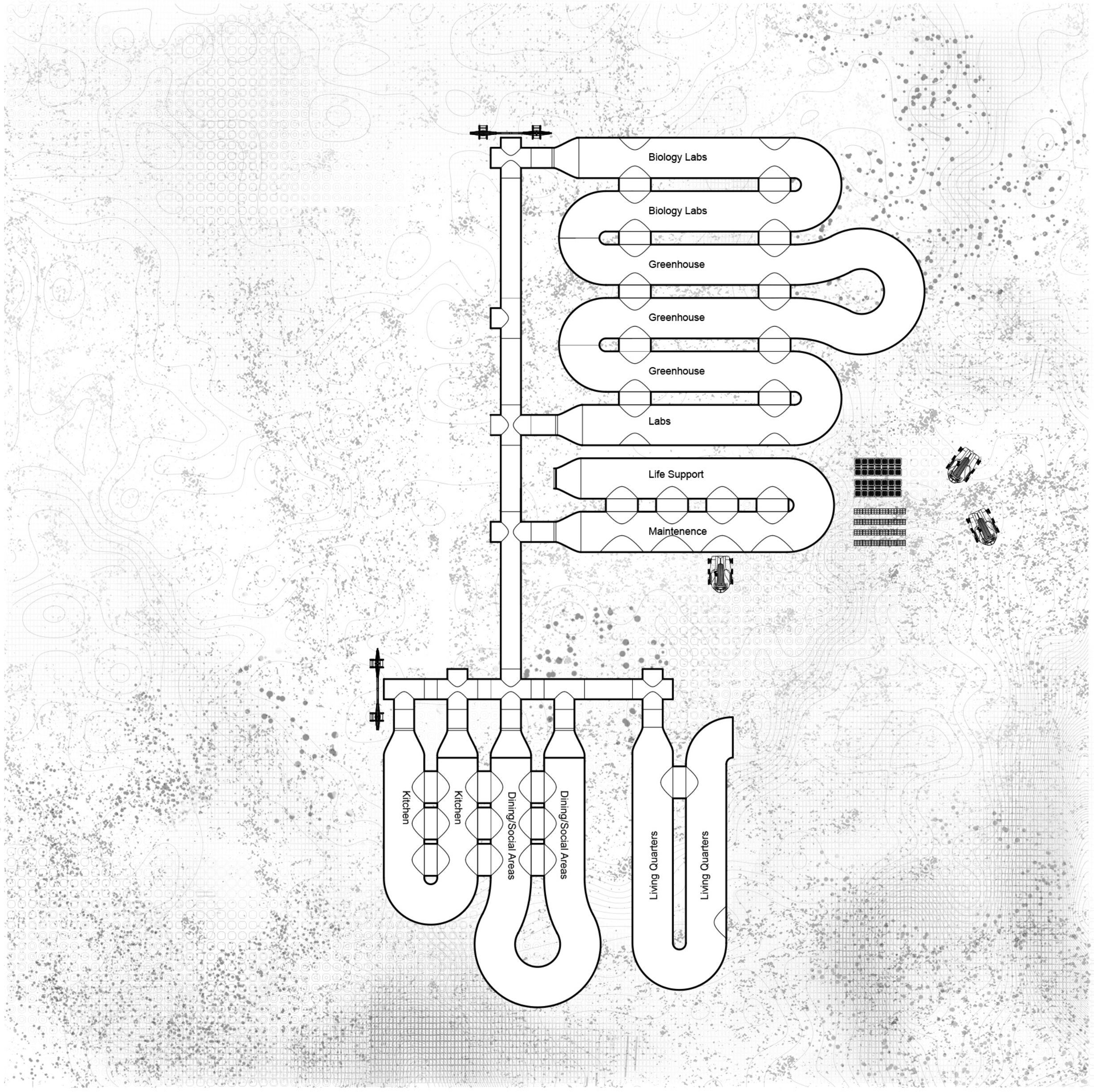


Figure 5.36 - *Site plan 3, progressional build up of architecture*

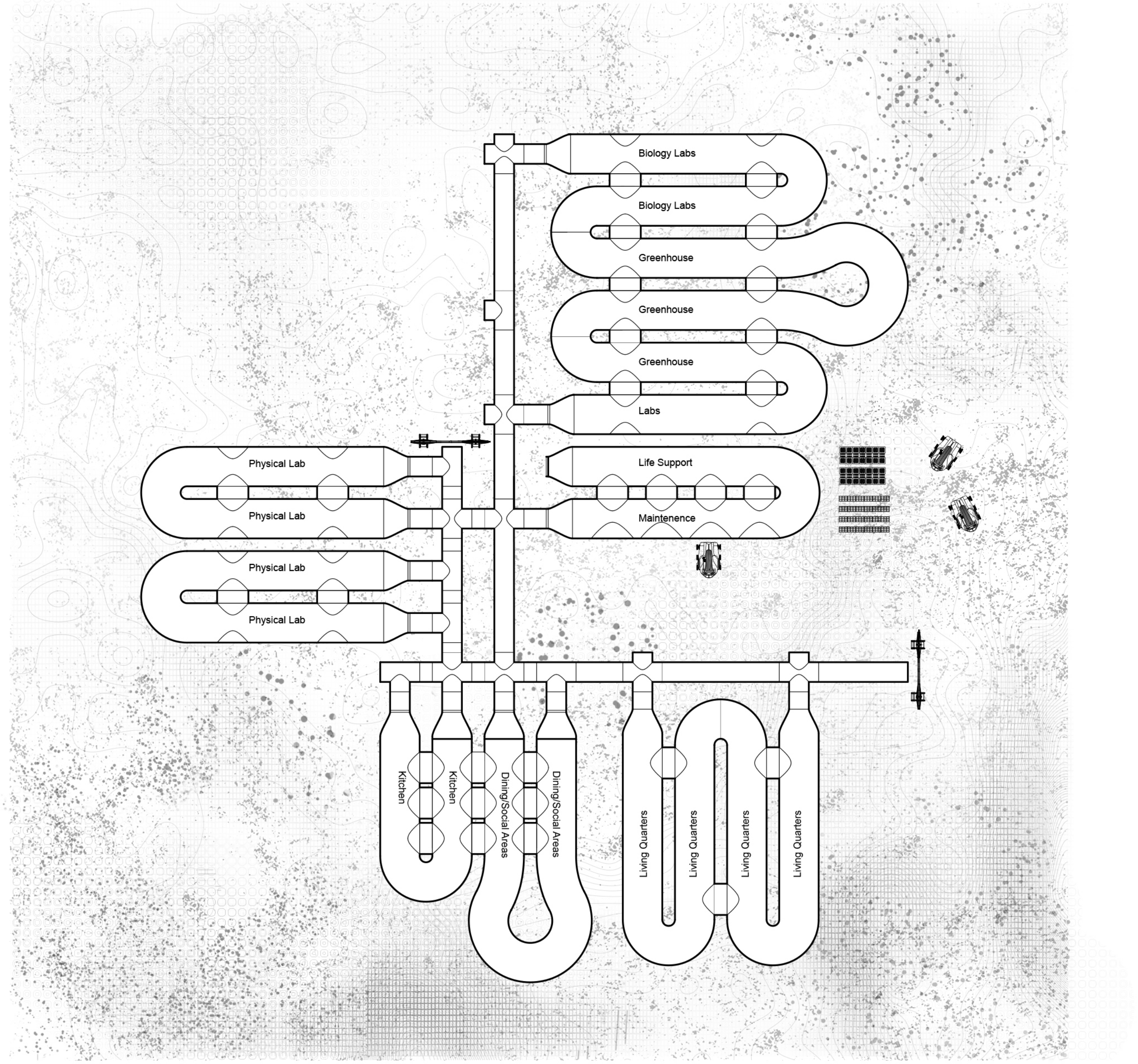


Figure 5.37 - *Site plan 4, progressional build up of architecture*

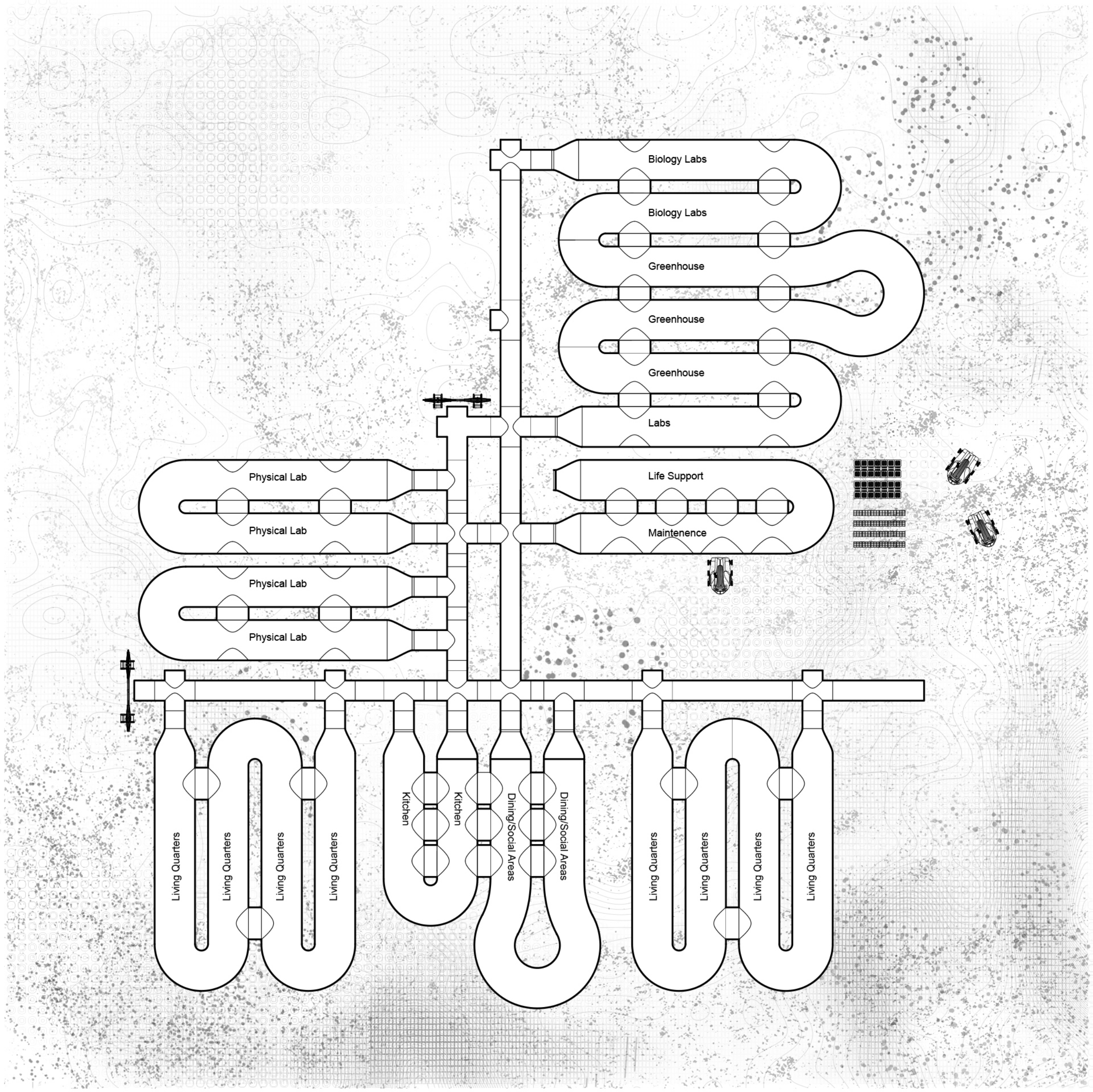


Figure 5.38 - *Site plan 5, progressional build up of architecture*

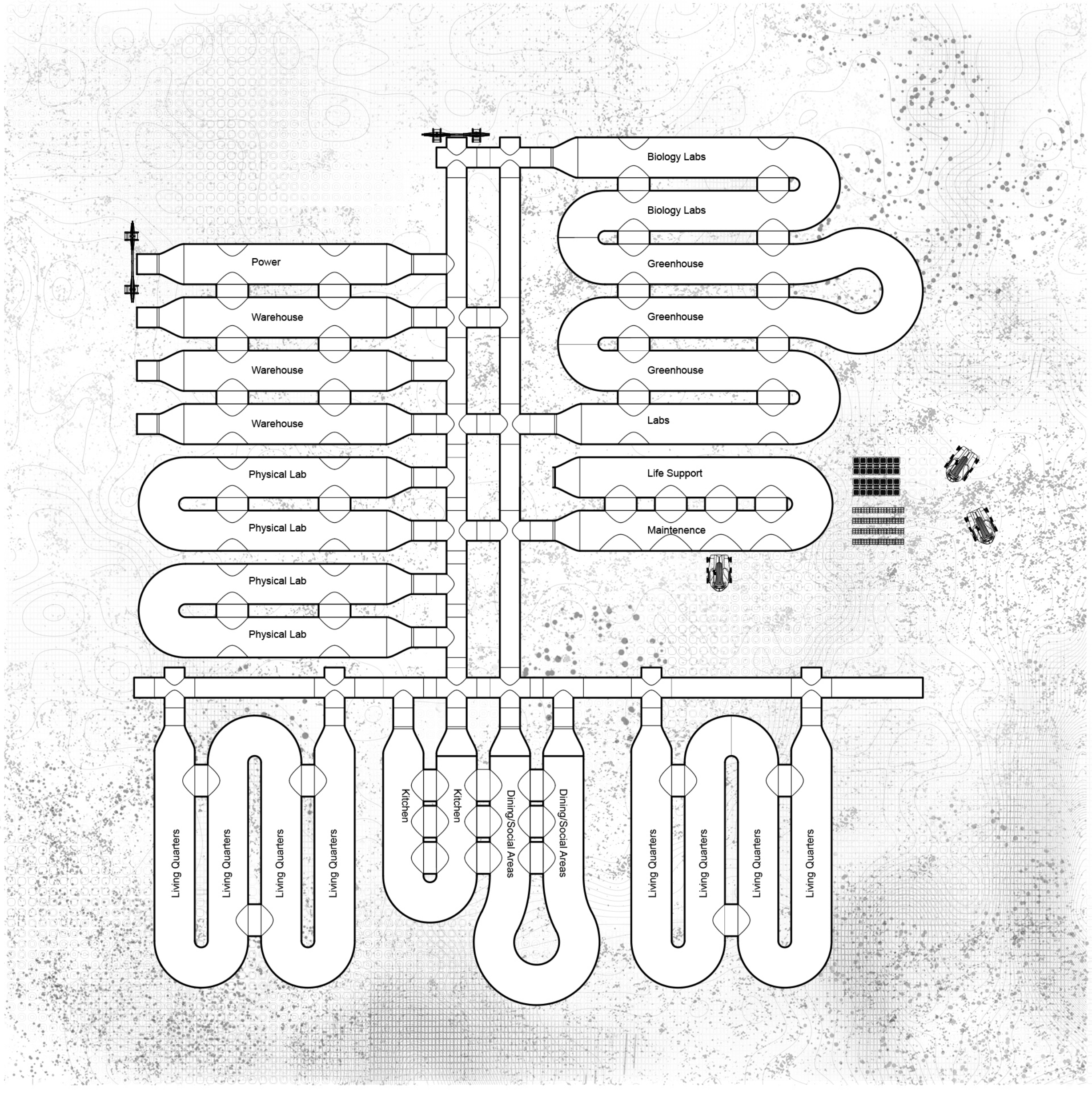


Figure 5.39 *- Site plan 6, progressional build up of architecture*

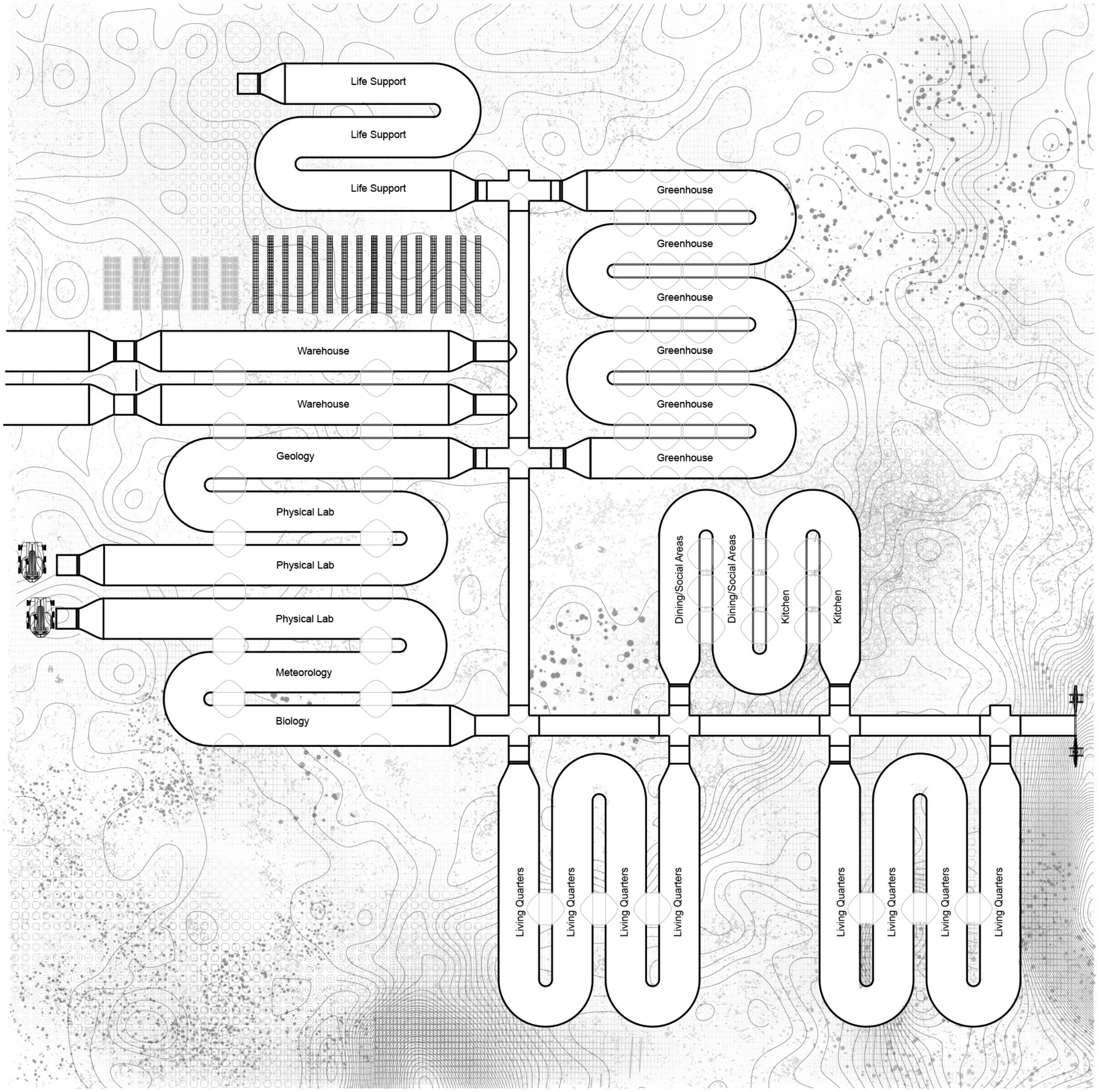


Figure 5.40 - *Alternate Site Layout*

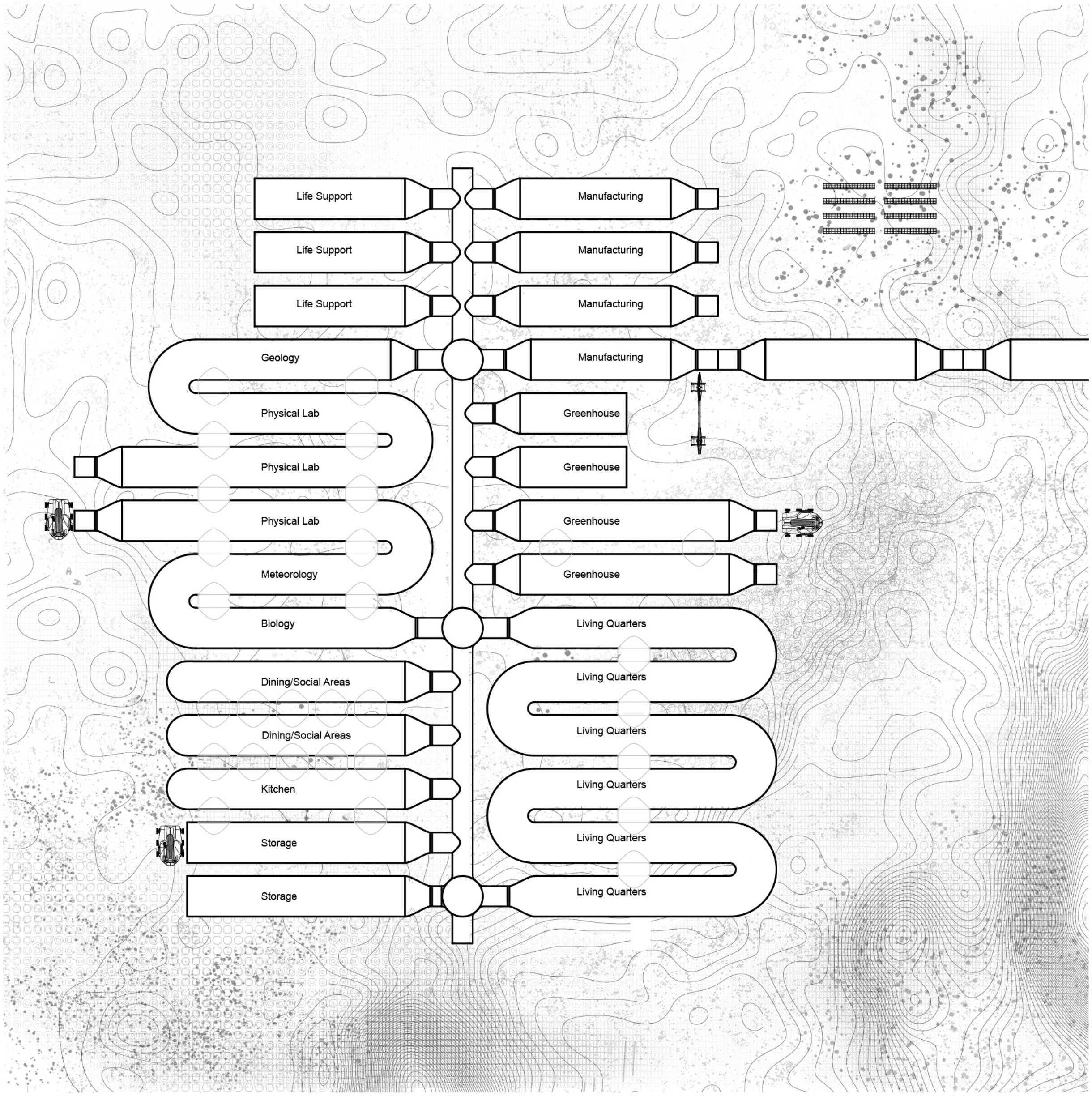


Figure 5.41 - *Alternate Site Layout*

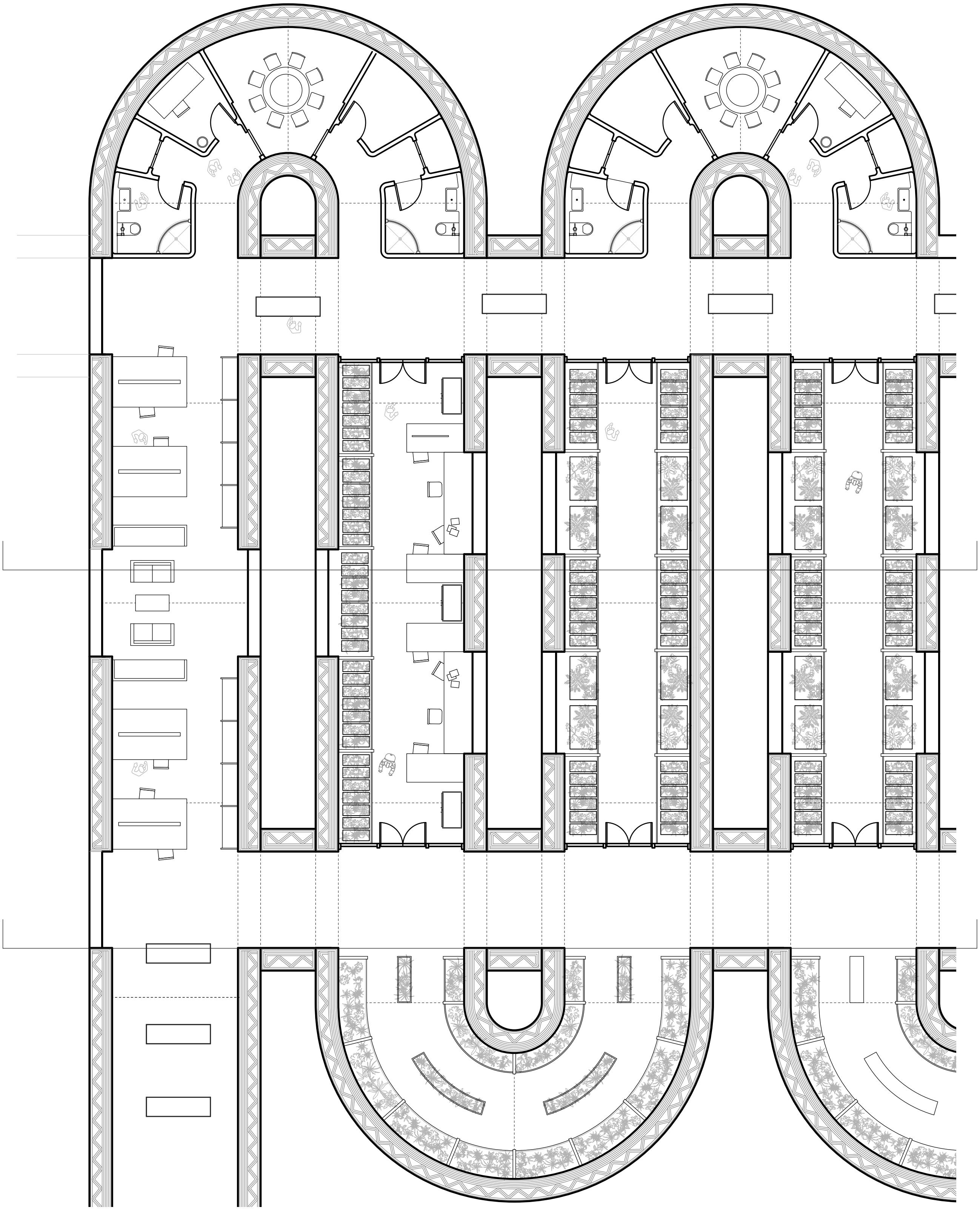
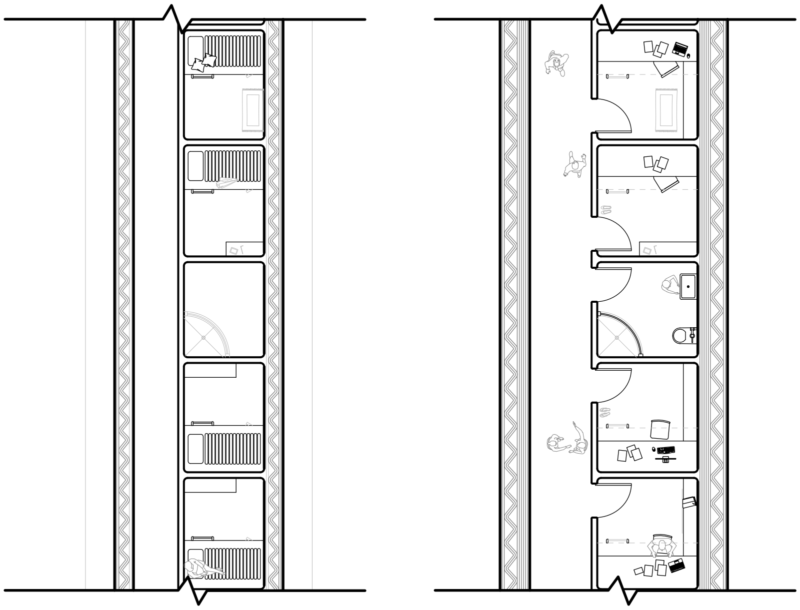


***Figure 5.42 -** Building plan of research and greenhouse spaces*



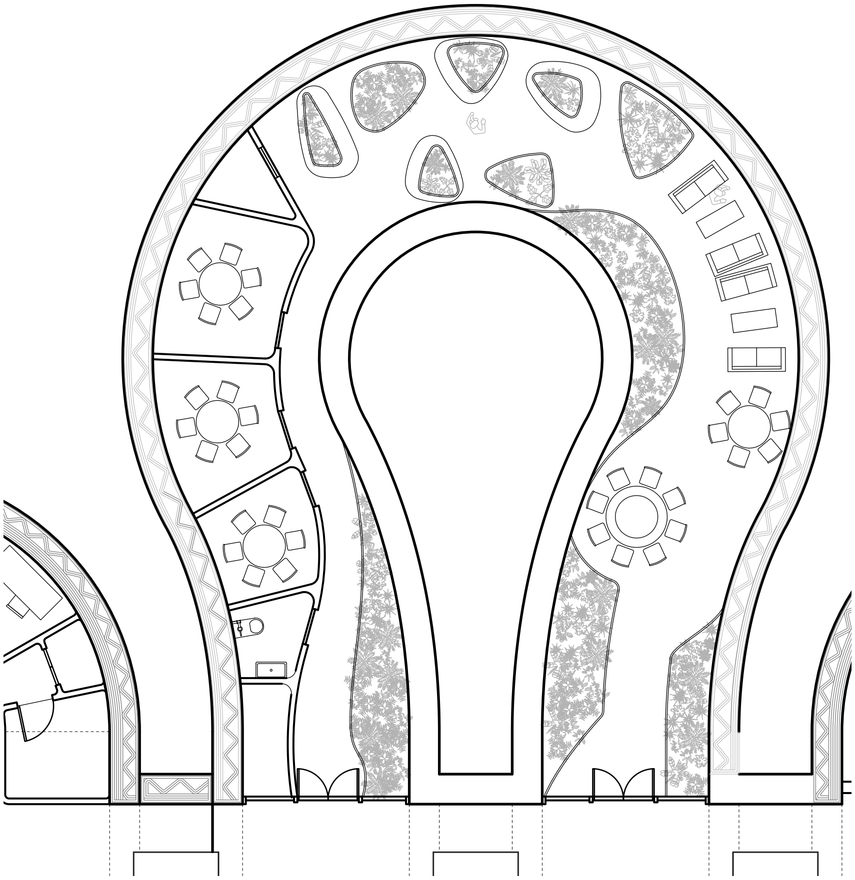


Figure 5.43 - *(top) - Bedroom Layouts*
Figure 5.44 - *(bottom) - Meeting rooms and garden layout*

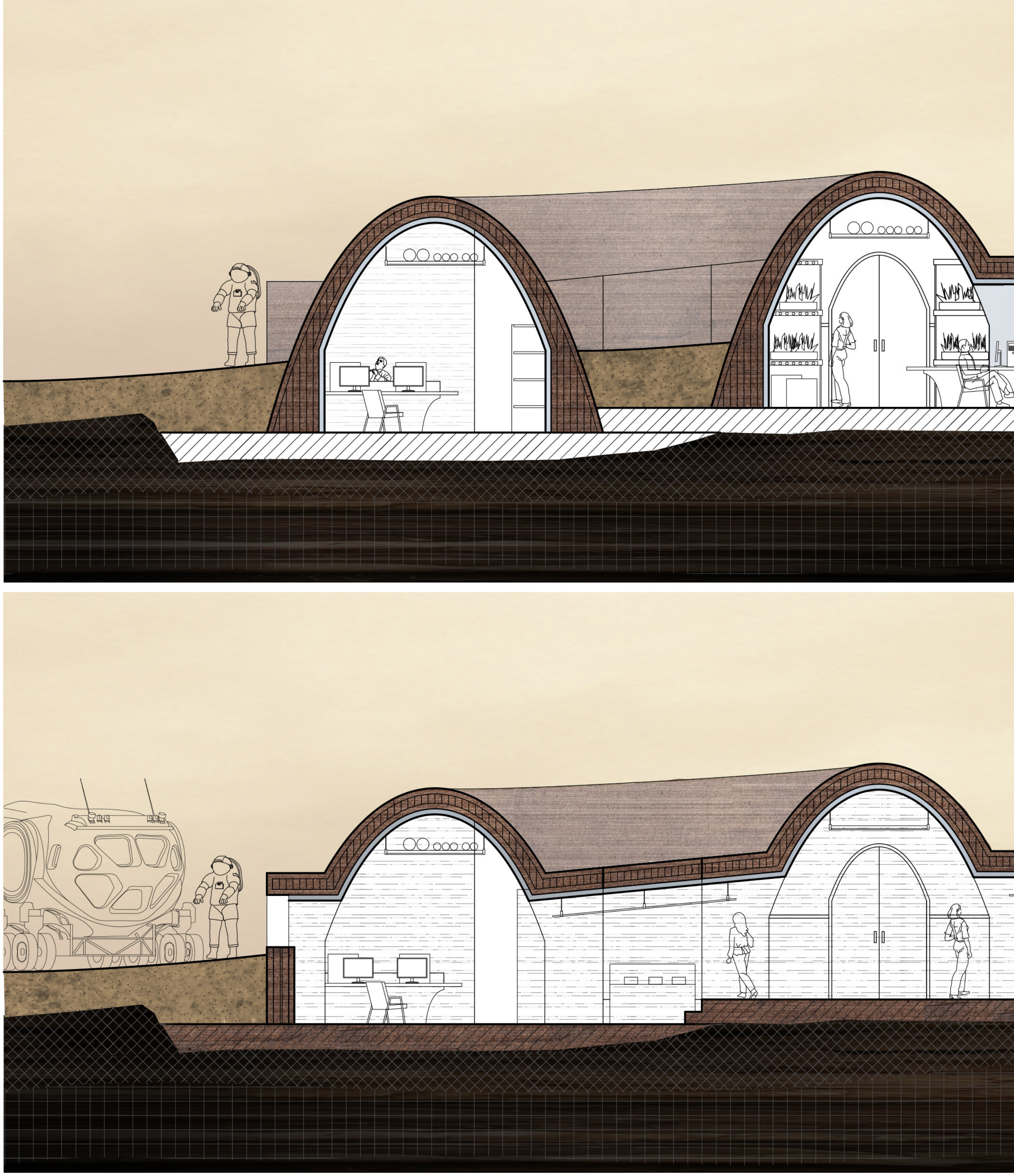
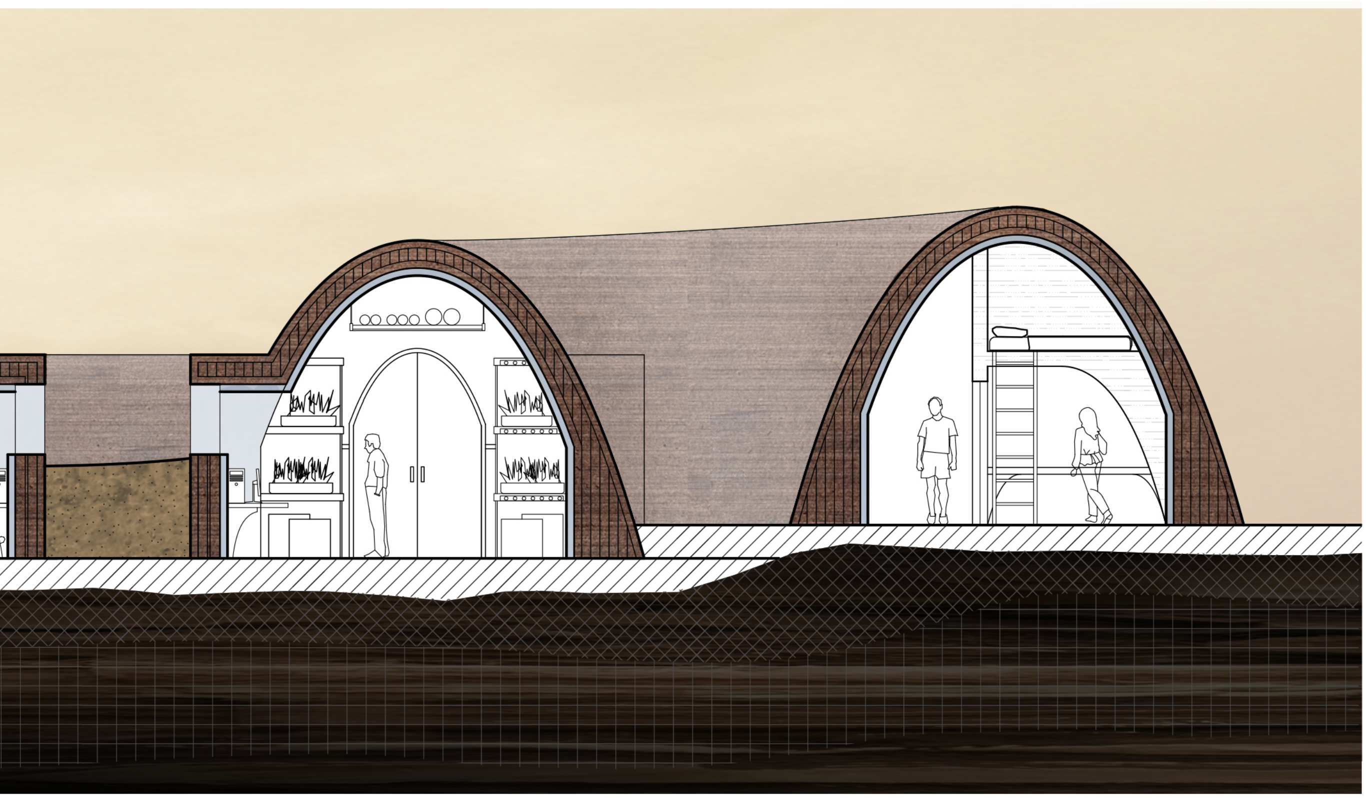
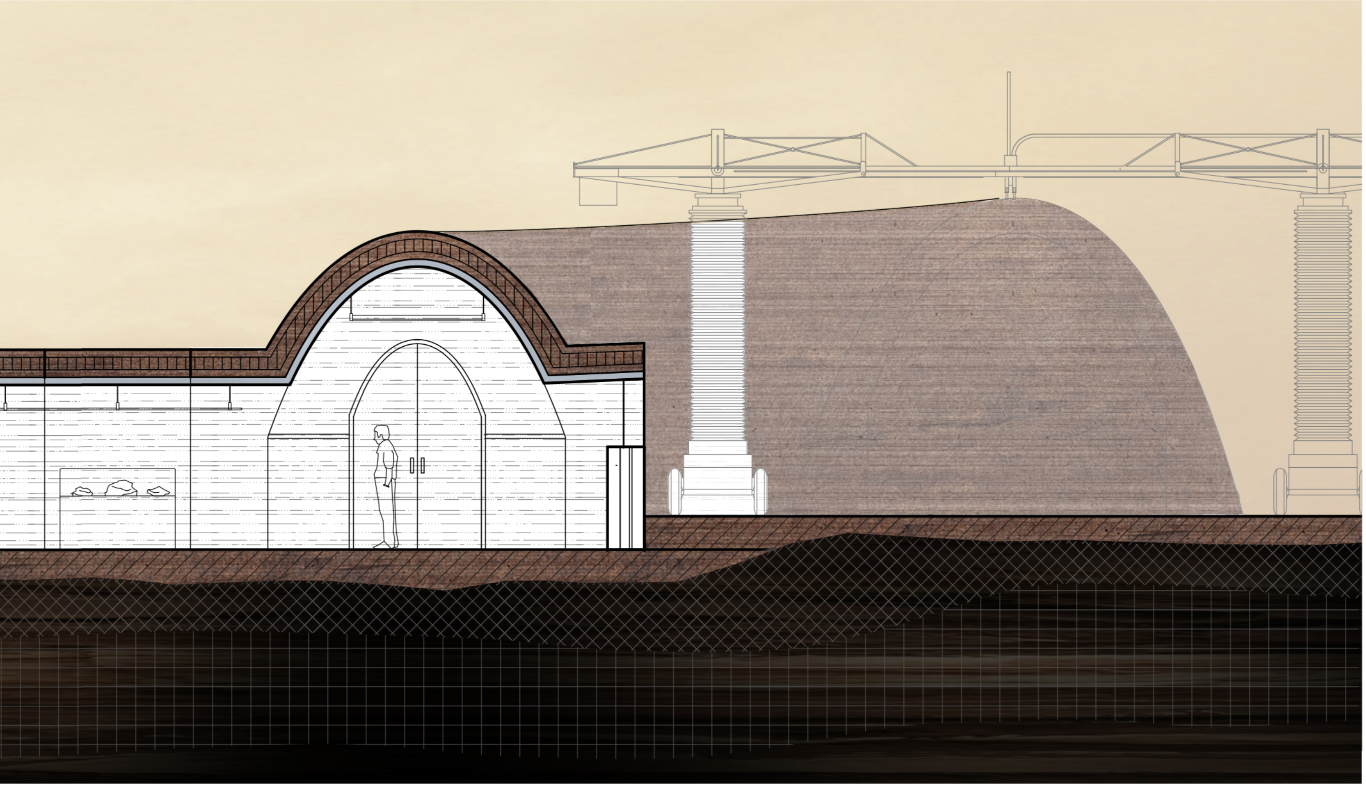


Figure 5.45 - Building section of research and greenhouse spaces





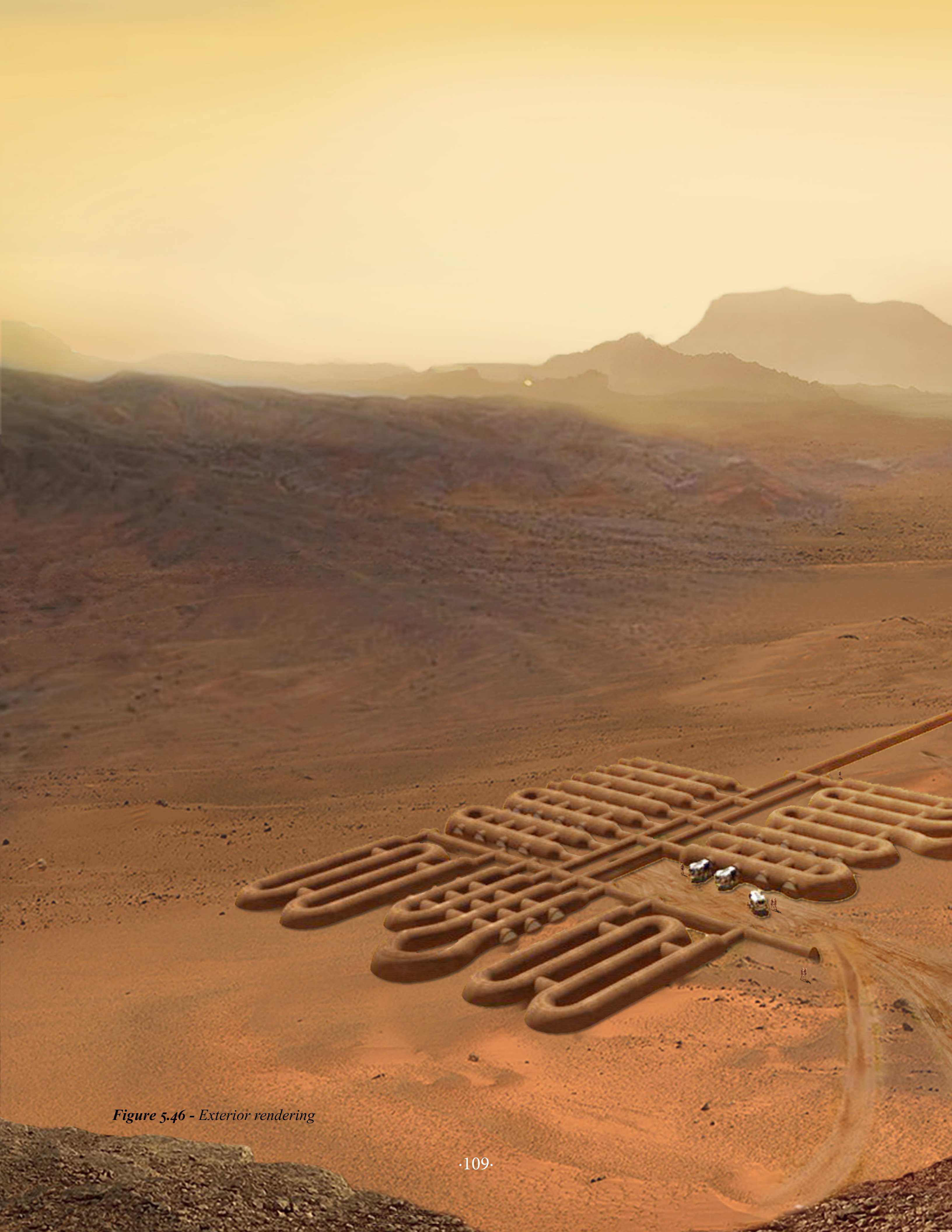


Figure 5.46 - Exterior rendering

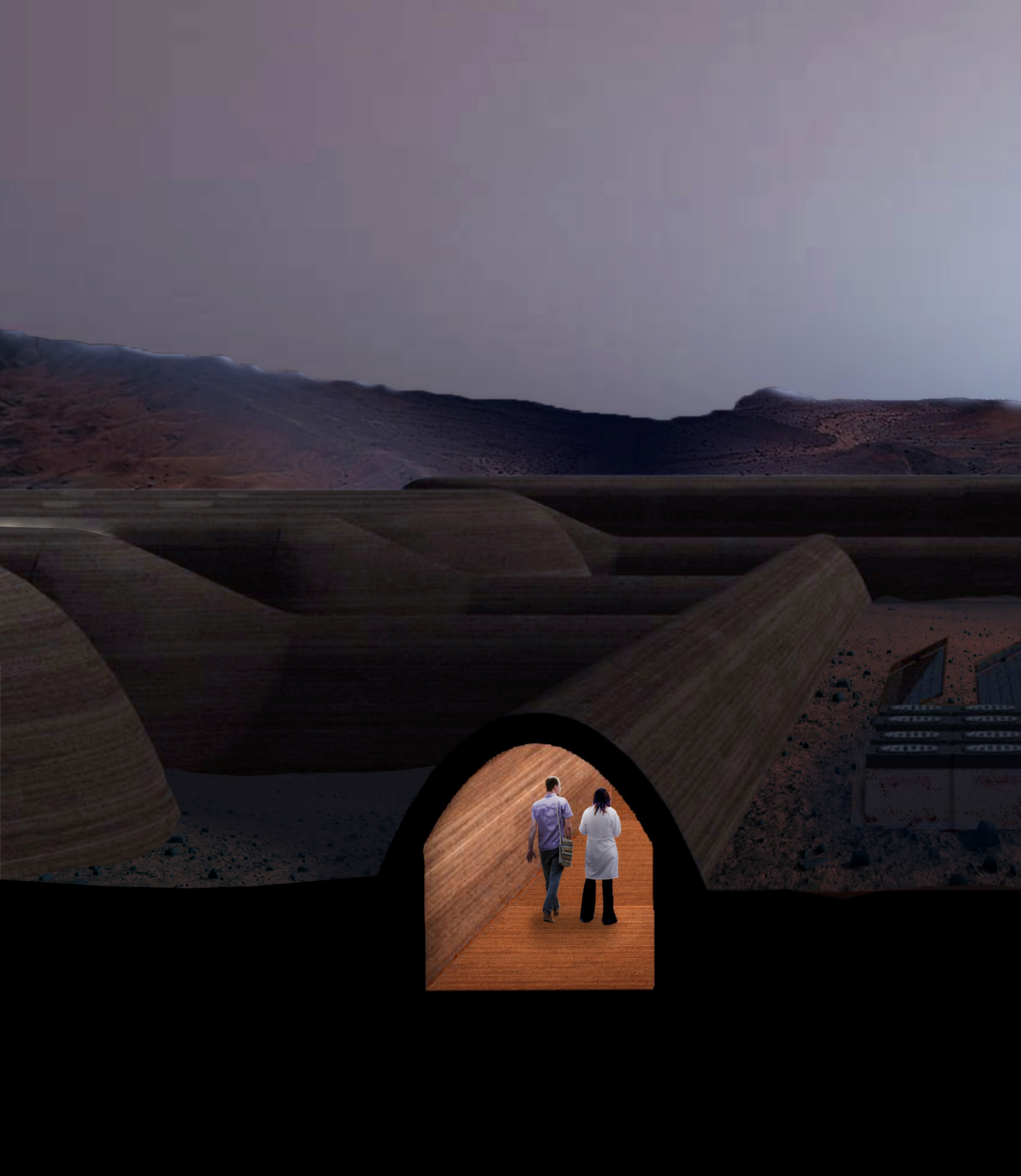


Figure 5.47 - Projected Section Rendering

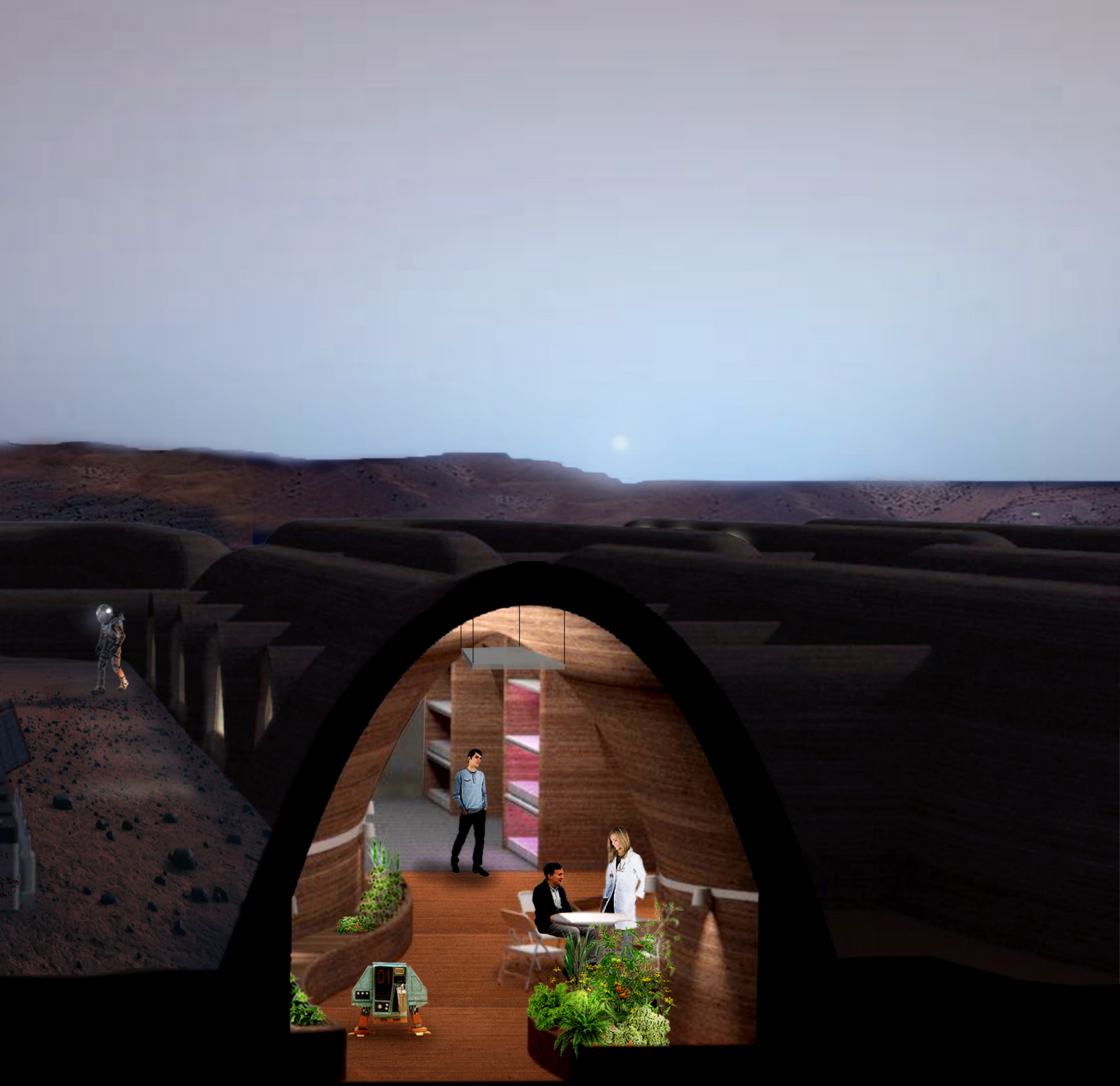


Figure 5.48 - *Interior Research Lab rendering*

- PART SIX -

TECHNICAL CHALLENGES

TESTING, RETESTING

The designs created in the previous sections are not perfect. By nature, the speculative design uses a level of assumption and idealization. There are a number of things in these designs that have not or cannot be tested in full, for either lack of means or lack of available information. This section will look at where these gaps are and suggest possible solutions to each.

The geometries used in the designs were tested iteratively though fused deposition modelling (FDM) 3D printing. The printer was a MakerGear M2 printer with PLA filament (figure 6.1). FDM most closely mimicked the contour crafting method that would be used in reality. Although the designed method is more similar to figure 6.2, access to that machine was not available and therefore not used.

The initial geometry tests for the Outpost show a catenary torus able be printed in full without any supports. Although successful, the actual qualities of the print may not work when scaled up to a 1:1 scale. The material is not the same. 3D printing with Wan's Marscrete[1] will not have the same properties as PLA. At a small scale, PLA is able to print cantilevers with a passable degree of accuracy, whereas concrete cannot. Figure 6.14 shows the areas at the peak of the arches of the Outpost most likely to have complications. To combat this, the cross section of the structure may need to change to a shape that is more concrete friendly like a Gothic arch which meets at the top at a point (see figure 6.3).

Concrete curing times can also present another issue. As shown in Akke Suiker's paper,[2] concrete printed walls can buckle during printing as a result of the speed at which the concrete cures during print. "Unlike conventional concrete construction

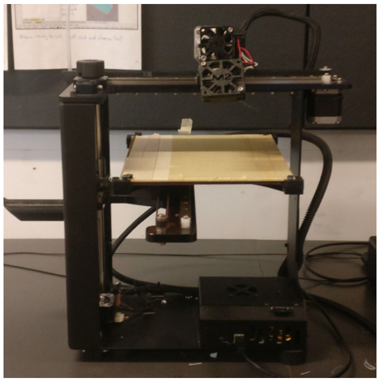


Figure 6.1 - *(previous page) Outpost design print testing*

Figure 6.2 - *(top) - MakerGear Printers used in testing*

Figure 6.3 - *(middle) - Potterbot XLS-1, rotational ceramic printer*

Figure 6.4 - *(bottom) - 3D printed concrete gothic window*

---

[1] Lin Wan, Roman Wendner, and Gianluca Cusatis, "A novel material for in situ construction on Mars: experiments and numerical simulations," Construction and Building Materials 120 (2016): , doi:10.1016/j.conbuildmat.2016.05.046.

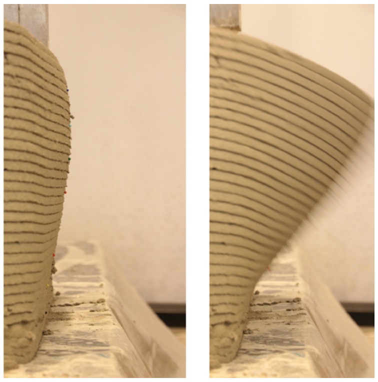
[2] A.s.j. Suiker, "Mechanical Performance of Wall Structures in 3D Printing Processes: Theory, Design Tools and Experiments," International Journal of Mechanical Sciences 137 (2018): , doi:10.1016/j.ijmecsci.2018.01.010.

processes, concrete 3D printing does not allow layers to dry before another one is deposited over it."[3] Suiker considered two failure principles; elastic buckling and plastic collapse, testing it against a 3D printed free wall, simply supported wall, and a fully clamped wall. What was produced is a means for engineers "to determine the necessary parameters to print stable walls that neither buckle nor collapses fully during manufacturing."[4]

The printed tests of the Research Hub show more complications. Since the prints are created in segments with different geometries that link together, they will also print with unique results requiring its own forms of support. For example, the most problematic segments were the vaults which printed with rough faces, indicating signs of movement during the print (figure 6.8-6.10). This inconsistency in positioning of the object can cause problems during 1:1 printing.

There are a couple likely causes of these problems. Firstly, the vaults meet the ground with a small surface area. As the print progresses, the upper portions of the vault begin to become top heavy, causing it to topple slightly, resulting in failure or roughness. To counter this, the print was redone to include the floor. Printing with the floor increases the area of which the print touches the ground, thereby adding stability and decreasing movement. Secondly, similar to the Outpost, the cross section of the print is altered to allow more area to meet the ground. Finally, the corners of the vault are rounded to both add stability from toppling, and to allow the printed head to move more smoothly around a corner.

Part of the problem might also be because of the printer itself. The Makergear printers moved both the bed and the nozzle to position the material in the correct area, this caused some rigorous shaking of the model and in combination to the previous factors, perhaps contributed to the unbalanced nature of the model. It was noted that of the two printers used, one created more stable and consistent models (see comparison figure 6.5-6.7). In actual practice, effort will need to be put to ensure the consistency of the printers used. Outside



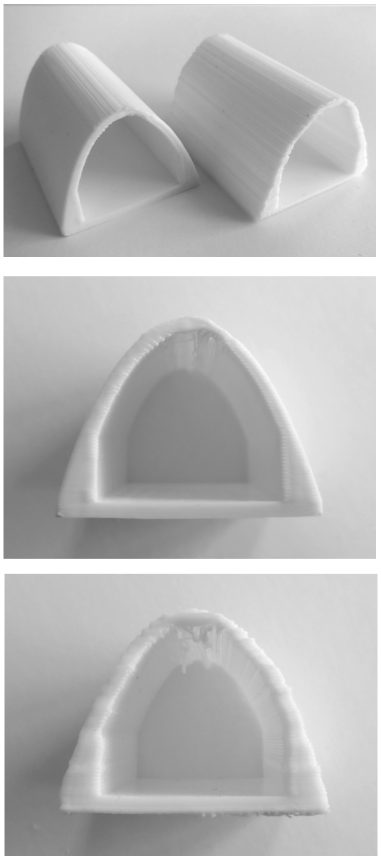


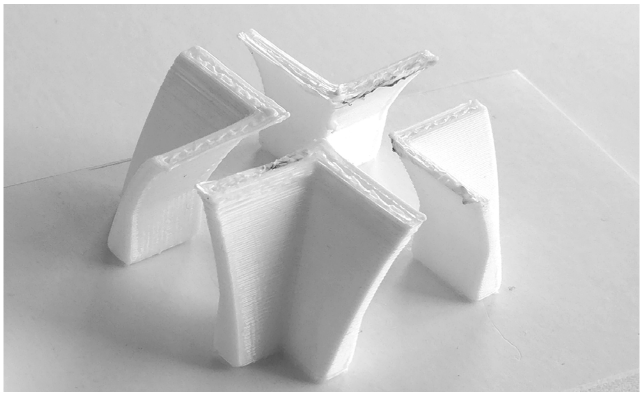
Figure 6.5 - *(top) - Suiker's 3DP wall testing showing the onset of buckling and during buckling*

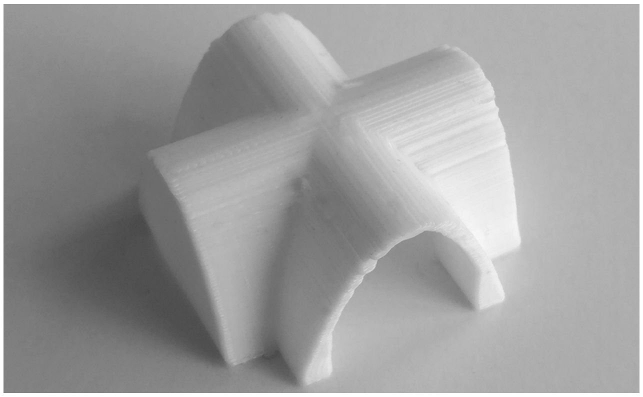
Figure 6.6 - *(middle - bottom) Quality difference between printers*

---

[3] Rushabh Haria, "Code of 3D Printed Houses Cracked by TU Eindhoven Professor's Equations," 3D Printing Industry, February 15, 2018, https://3dprintingindustry.com/news/tu-eindhoven-professors-equations-solve-problems-3d-printed-concrete-128969/.

[4] Ibid.





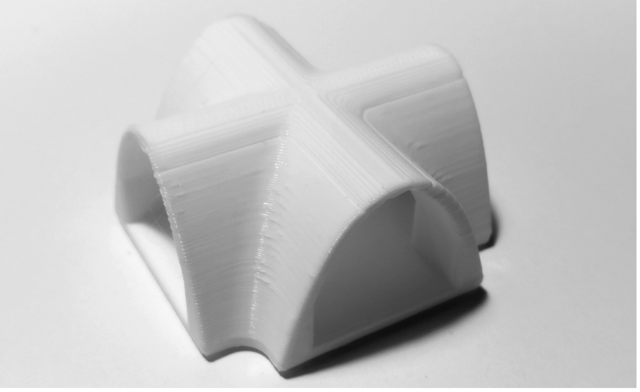
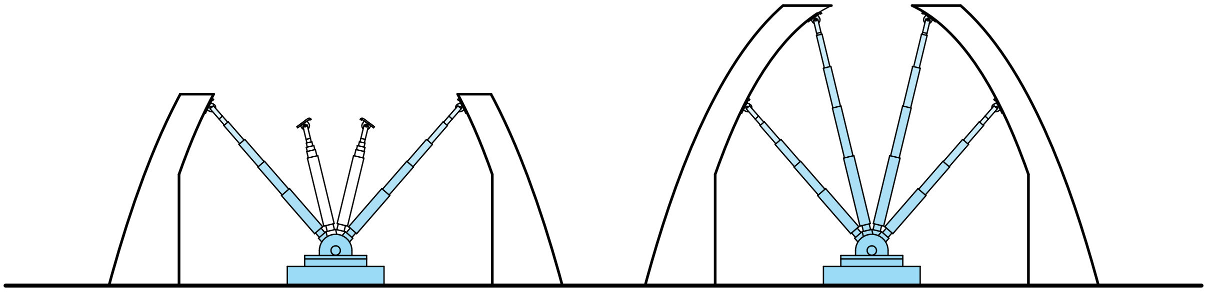
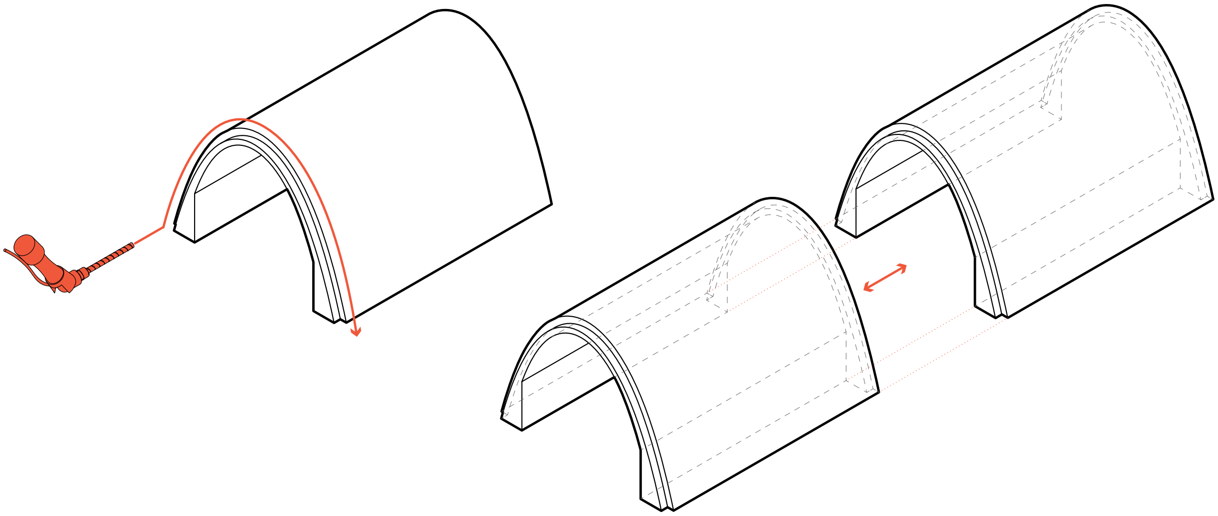


Figure 6.7 - *Failed 1:200 research station splitting during printing process when detaching from printing bed*

Figure 6.8 - *1:200 3D printed vault successful print with rough edges*

Figure 6.9 - *Adjusted 3D print vault segment to use curved edges at the base, and include floor and foundation for support.*





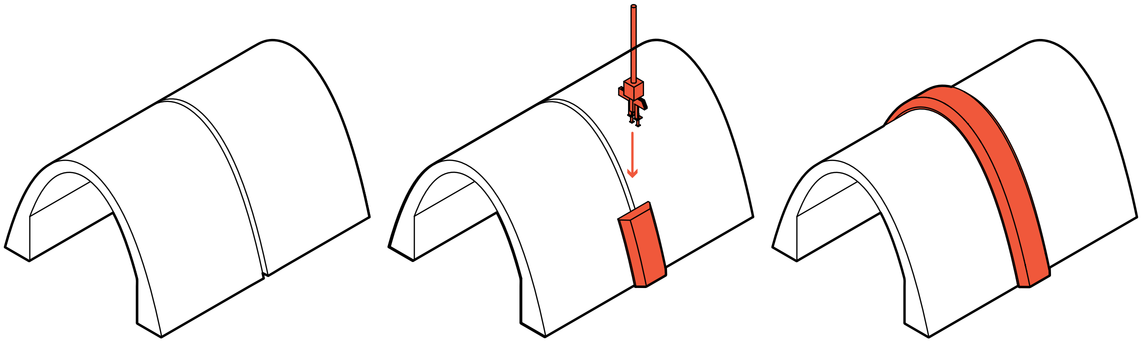


Figure 6.10 - *Telescoping temporary supports for prints*

Figure 6.11 - *Notch creation and insertion*

Figure 6.12 - *Segment connector*

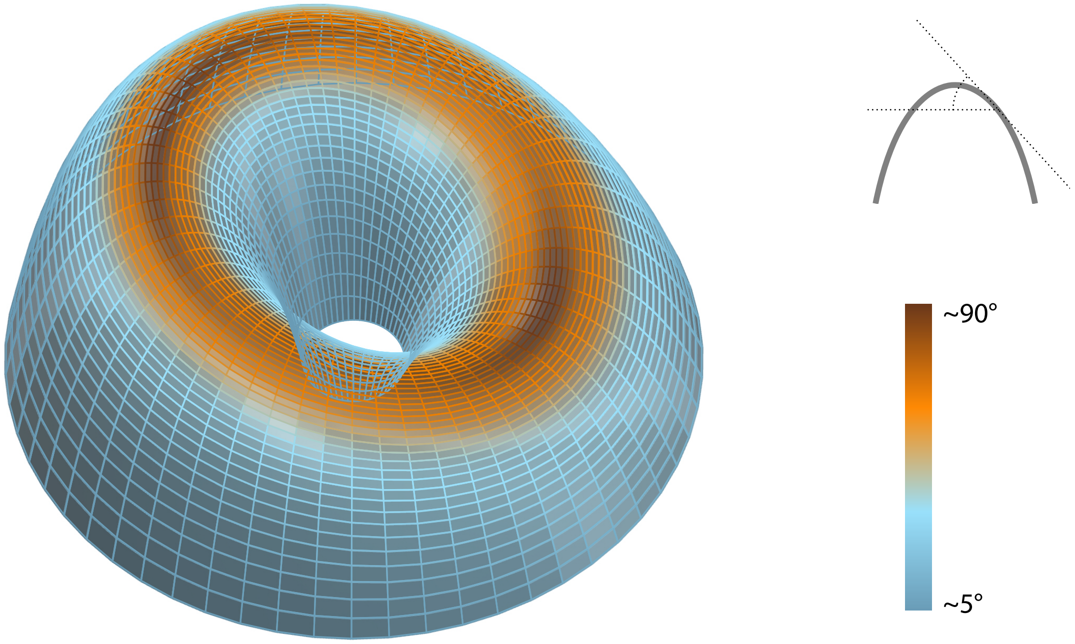


Figure 6.13 - *Areas of extreme printing overhang potentially resulting in problems during the printing process.*

intervention can be used as well. In terms of mission timing, the Research Hub would undergo construction after a livable outpost is constructed. Because of this, a system of temporary reinforcements can be used to support the arches (figure 6.11).

There is also an issue of connecting segments. There needs to be a system for which the segments can interlock together to close the gap between individual pieces. There are a couple possible ways in which this can be done. One way is to use a drill bit to remove parts of a completed print to allow the prints to insert into one another (figure 6.12). Another option is to go back over top of the completed print with an extended nozzle and print a connecting piece, perhaps filling it with mortar, similar to how bricks are laid (figure 6.13).

Siting is another factor that must be researched more closely. A design on Mars, by nature will require some level of assumptions about the site conditions. Without a determinate landing site, or ample knowledge of the ground conditions, there will always be some assumptions to the site.

As stated before, Martian temperatures can drop as low as -129°C while the Apis Cor 3D printer has only been tested to be successful at temperatures above -35°C. By and large it seems that the 3D printing strategy may run into issues because of the weather. One possible strategy is to time the construction to more advantageous seasons in the Martian year, namely during the summers, where temperatures can rise to as high as 30°C. If the weather conditions are still unfavourable however, another solution could be to create a temporary shelter while the print occurs.

Additionally, there is an assumption in these designs that the equipment will work. Sending these 3D printers is a substantial investment. If there are malfunctions or mistakes, it can mean a big waste of resources. One of the best ways to tackle this issue is to have redundancy in the machinery - meaning sending multiple 3D printers. As a next step, prototyping and further development of this machinery would allow us to judge the pros and cons more effectively.

Finally, the last notable area that is not fully explored in this thesis is the implication of air and pressurization. The air pressure inside the base will be greater than the outside, therefore exerting an outwards force on the walls. This is not ideal since concretes are not strong in tension. However, in Zubrin's *A Case For Mars*, he states with Roman style vaults with an interior pressure of 5 psi can be maintained if they are buried with about 2.5m of regolith (this depth already compensates for the reduced gravity)[5].

Another a strategy that can be adopted is to use a balloon made from plastics like ETFE. This balloon can be made to withstand the pressure and brought to Mars, and on arrival inflated inside the preconstructed shell. Alternatively, it can be inflated beforehand and can act as support during printing (figure 6.15). Although at first these plastics must be imported, there is potential for them to be made using Mars resources. Zubrin outlines that Mars is abundant with Carbon and Hydrogen. Since plastics require ethylene (C2H4) as a key ingredient, plastics can be made.[6] Fluorine has also been found on Mars[7], perhaps allowing for ETFE (C4H4F4) plastics to be made.

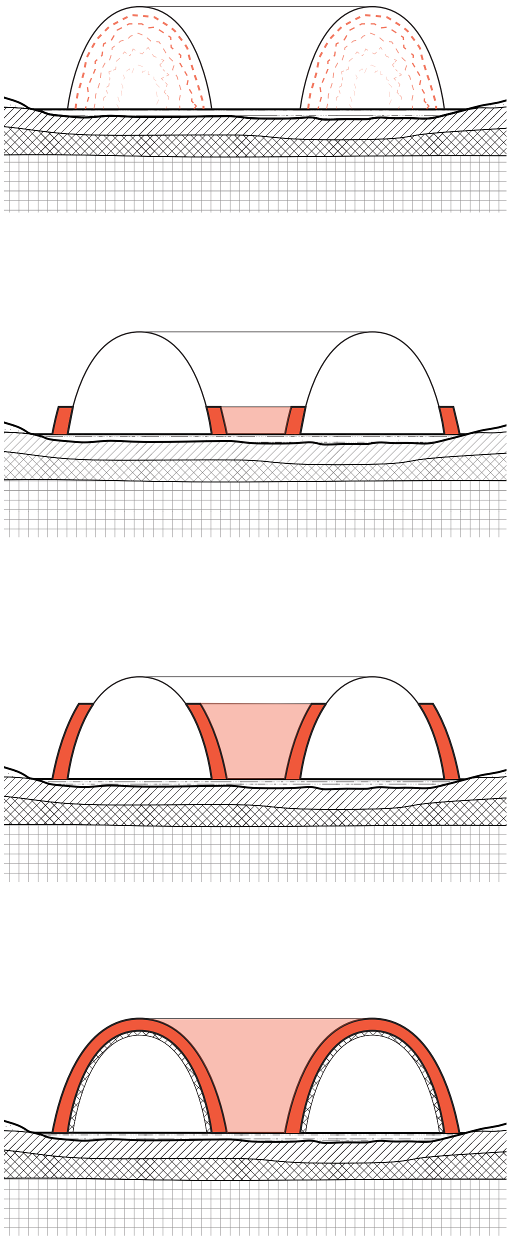


Figure 6.14* - *Build up diagram showing the inflation of a pressurized balloon followed by 3D printing a shell

---

[5] Zubrin, pg 191.

[6] Ibid., pg 197-200.

[7] O. Forni and Et. Al., "First Fluorine Detection on Mars: Implications for Gale Crater's Geochemistry," Geophysical Research Letters 42 (2015): doi:10.1002/2014GL062742.

ONWARDS

Having humans on Mars is something that will likely happen in most of our lifetimes. It is an exciting prospect which will no doubt have a profound effect on our species, making humanity into a space faring race. Just like the river, the ocean, or the sky, space is just another obstacle to overcome.

For all our efforts, if our existence on Mars is not to be just a fleeting singular visit, our architecture must change to suit our long-term needs.

To survive for an extended period of time in space, we cannot afford to use wasteful, single-use methods of construction; the old model of tuna can pods cannot be considered a viable long-term option. Without meaningful built precedent, it is understandable why we reflexively imagine this building typology as our future. Although they may work in Earth's orbit, the cost of sending bulk material to Mars is far too high to practice long term. Instead, the resources available on Mars should be exploited to use 3D printing as an in-situ construction method.

The research station and outpost rendered in this thesis are not necessarily a finished solution that will resolve all the problems faced on Mars. Instead, it is a design speculation on creating a process of procuring buildings that can adapt to the needs of multiple generations of occupants.

What comes from these designs is the realization that an additive manufacturing technique is imperative for constructing livable habitats on Mars. Additive manufacturing only inputs energy to directly manipulate previously unusable in-situ raw materials to create a building. This contrasts with subtractive manufacturing in which a large mass of raw material is chipped away to leave the building, resulting in excess waste materials leftover that must be removed. With a greater investment into advancing large scale 3D print technology, it has the potential to overcome the physical constraints and thus offer a hands-off, cheaper method than simply shipping buildings to earth.

In addition to energy savings, the designs of the outpost and the research station are a needed step into the right direction for creating architectural spaces on Mars. Considering Vitruvius's[1] three rules for what make good architecture, buildings must have function, permanence, and beauty . The pod designs that are abundant today generally focus almost entirely on the function and utility of a building. This is not necessarily a fault for the designers; when designing in these environments, it is critical to engineer a functional building. The 3D printed outpost and research station help improve on these designs in that they also account for the second factor of permanence: a sense of robustness, safety, and fortitude. However, as a result of building in such an extreme environment, where the designs are open for improvement is perhaps in Vitruvius's last rule, beauty.

These designs represented the greatest amount of floor area and height in an effort to show the maximum potential of each printer. Furthermore, it prioritized simplicity of form for ease of construction and predominately utilized one type of material. Though not directly explored in this thesis, now knowing the printers max capacity, beauty and the topology of spaces can be improved on in a subsequent iteration of the design. Furthermore, the pallet of 3D printable materials can begin to expand beyond just concrete as well, opening up the potential for newer qualities of space and light.

The perception of living and working on Mars has typically been something that is tied closely to fantasy. Although previously dismissed as fiction, it has now begun to shift closer to reality. With this transformation comes a viable and necessary change in the design vernacular of extreme architecture on Mars, Earth or beyond.

---

[1] Vitruvius Pollio and Morris H. Morgan, Vitruvius: The Ten Books on Architecture (New York: Dover Publications, 1960), pg 17.

Figure 6.15 - *View of Earth from Mars*

BIBLIOGRAPHY

2001: a space odyssey. Directed by Stanley Kubrick.

Aelita. Directed by Yakov Protazanov. Produced by Sergei Kozlovsky, Alexandra Exter, Isaac Rabinovich, and Victor Simov. Performed by Valentina Kuinzh, Nikolai Tseretelli, Konstantin Eggert, Yulia Solntseva, Igor Ilinsky, and Nikolai Batalov. U.S.S.R.: Publisher not identified, 1924. https://www.youtube.com/watch?v=je1bIhS-7G8.

"Antarctic weather." Australian Government, Department of the Environment and Energy, Australian Antarctic Division. March 01, 2012. http://www.antarctica.gov.au/about-antarctica/environment/weather.

Bruckner, Adam, Kirsten Carpenter, Laila Elias, Rob Grover, Mark Hilstad, Chris Hoffman, Matt Schneider, and Sergio Adan-Plaza. "Extraction of Atmospheric Water on Mars for the Mars Reference Mission." *Lunar Planetary Institute Contribution No. 955*, December 1997, 171-94.

Cesaretti, Giovanni, Enrico Dini, Xavier De Kestelier, Valentina Colla, and Laurent Pambaguian. "Building components for an outpost on the Lunar soil by means of a novel 3D printing technology." *Acta Astronautica* 93 (January 2014): 430-50. Accessed December 3, 2017. doi:10.1016/j.actaastro.2013.07.034.

Collis, Christy, and Quentin Stevens. "Cold colonies: Antarctic spatialities at Mawson and McMurdo stations." *Cultural geographies* 14, no. 2 (2007): 234-54. doi:10.1177/1474474007075356.

Davis, Georgina A. "A history of McMurdo Station through its architecture." *Polar Record* 53, no. 02 (2017): 167-85. doi:10.1017/s0032247416000747.

Drake, Bret G., ed. *Human Exploration of Mars Design Reference Architecture*. Report no. 5.0. Mars Architecture Steering Group, National Aeronautics and Space Administration. Houston, TX: NASA Johnson Space Center, 2009. 47-48.

Dunbar, Brian. "Follow the Water: Finding a Perfect Match for Life." NASA. Accessed January 04, 2018. https://www.nasa.gov/vision/earth/everydaylife/jamestown-water-fs.html.

"Mars 2020 Landing Sites." Kenneth A. Farley and Kenneth H. Williford to Dr. Michael Meyer. February 13, 2017. Accessed January 5, 2018. https://marsnext.jpl.nasa.gov/documents/Mars%202020%20landing%20site%20down-select%20Feb%202017.pdf.

Field, Francis, Jon Goodbun, and Victoria Watson. "Space-Time and Architecture."

Journal of the British Interplanetary Society 67 (2014): 322-31.

Fisher, Gary C. “Torus Or Dome: Which Makes The Better Martian Home.” 1999. Accessed March 18, 2018. http://www.marshome.org/files2/Fisher.pdf.

Fraser, Douglas. *Village planning in the primitive world*. S.l.: S.n., 1986.

Garner, Rob. “How to Protect Astronauts from Space Radiation on Mars.” NASA. September 30, 2015. Accessed January 04, 2018. https://www.nasa.gov/feature/goddard/real-martians-how-to-protect-astronauts-from-space-radiation-on-mars.

Howard, Ron, writer. “Power.” In *Mars*, directed by Everado Gout, produced by Brian Grazer. National Geographic. December 5, 2016.

Grazer, Brian , and Ron Howard. “What Does Colonizing Mars Look Like? | MARS.” National Geographic. December 05, 2016. http://channel.nationalgeographic.com/mars/videos/what-does-colonizing-mars-look-like/?_ga=2.131282447.1653228695.1513219728-214944302.1513219728.

Gushanas, Timothy. “About Analog Missions.” NASA. February 17, 2016. Accessed December 16, 2017. https://www.nasa.gov/analogs/what-are-analog-missions.

The New YorkTimes. “How McMurdo Station Is Run On The Least Habitable Continent.” YouTube. June 03, 2017. Accessed January 11, 2018. https://www.youtube.com/watch?v=nZr5MJuNcXU&t=19s.

Huang, Lang. *FEASIBILITY STUDY OF USING SILICA AEROGEL AS INSULATION FOR BUILDINGS*. Master’s thesis, KTH School of Industrial Engineering and Management, 2012.

Jakus, Adam E., Katie D. Koube, Nicholas R. Geisendorfer, and Ramille N. Shah. “Robust and Elastic Lunar and Martian Structures from 3D-Printed Regolith Inks.” *Scientific Reports* 7 (March 20, 2017): 44931. doi:10.1038/srep44931.

JIOSaerogel. “JIOS Aerogel - AeroVa Insulation Coating (Airless Spray Method).” YouTube. January 21, 2014. Accessed March 23, 2018. https://www.youtube.com/watch?v=JzEdkTNYvGY.

“JIOS AeroVa.” JIOS Aerogel. Accessed March 23, 2018. https://www.jiosaerogel.com/jios-aerova/#Applications.

Kading, Benjamin, and Jeremy Straub. “Utilizing in-situ resources and 3D printing structures for a manned Mars mission.” *Acta Astronautica* 107 (March 2015): 317-26. Accessed December 3, 2017. doi:10.1016/j.actaastro.2014.11.036.

Kaplan, Gail. “The Catenary: Art, Architecture, History, and Mathematics.” In *Bridges Leeuwarden: Mathematics, Music, Art, Architecture, Culture*, 47-54. Tarquin Publications, 2008.

Available online at http://archive.bridgesmathart.org/2008/bridges2008-47.html

Keating, Steven J., Julian C. Leland, Levi Cai, and Neri Oxman. "Toward site-specific and self-sufficient robotic fabrication on architectural scales." *Science Robotics* 2, no. 5 (2017). doi:10.1126/scirobotics.aam8986.

"Landing Site - Mars 2020 Rover." NASA. Accessed January 05, 2018. https://mars.nasa.gov/mars2020/mission/timeline/prelaunch/landing-site-selection/.

Legler, Gretchen. *On the ice: an intimate portrait of life in McMurdo Station, Antarctica*. Minneapolis: Milkweed Editions, 2005.

"Mars Facts | Mars Exploration Program." NASA. Accessed December 31, 2017. https://mars.nasa.gov/allaboutmars/facts/#?c=inspace&s=distance.

SEArch, and Clouds AO. "MARS ICE HOUSE." Accessed January 04, 2018. http://www.marsicehouse.com/.

NSF, Antarctic Support Contract, and United States Antarctic Program. *McMurdo Station Master Plan 2.1*. December 16, 2015.

Morris, Mars S. "Galaxy Gadgeteers: Architects in Space." *Journal of the British Interplanetary Society* 67 (2014): 272-78.

Musk, Elon. "Making Humans a Multiplanetary Species." Lecture. Accessed March 19, 2018. https://www.youtube.com/watch?v=H7Uyfqi_TE8.

Petranek, Stephen . "Your kids might live on Mars. Here's how they'll survive." Speech, TED2015, Canada, Vancouver. March 2015. https://www.ted.com/talks/stephen_petranek_your_kids_might_live_on_mars_here_s_how_they_ll_survive.

Pollio, Vitruvius, and M. H. Morgan. *The ten books on architecture*. New Delhi: Kaveri Books, 2016.

RBSystems. "NASA 3D-PRINTED HABITAT CHALLENGE." Accessed March 20, 2018. http://www.rb-systems.us/projects/#/new-gallery-58/.

Silent Running. Directed by Douglas Trumbull. United States: Universal Pictures, 1972.

The Martian. Directed by Ridley Scott. By Andy Weir. United States: 20th Century Fox, 2015. Film.

Wan, Lin, Roman Wendner, and Gianluca Cusatis. "A novel material for in situ construction on Mars: experiments and numerical simulations." *Construction and Building Materials* 120 (2016): 222-31. doi:10.1016/j.conbuildmat.2016.05.046.

Warren, Stephen G., Richard E. Brandt, and Thomas C. Grenfell. "Visible and Near-ultraviolet Absorption Spectrum of Ice from Transmission of Solar

Radiation into Snow." *Applied Optics* 45, no. 21 (2006): 5320. doi:10.1364/ao.45.005320.

Williams, D., A. Kuipers, C. Mukai, and R. Thirsk. "Acclimation during space flight: effects on human physiology." *Canadian Medical Association Journal* 180, no. 13 (2009): 1317-323. doi:10.1503/cmaj.090628.

JIOSaerogel. YouTube. January 21, 2014. Accessed March 23, 2018. https://www.youtube.com/watch?v=JzEdkTNYvGY.

Derzhiarbuz. YouTube. October 19, 2017. Accessed March 20, 2018. https://www.youtube.com/watch?v=pSUEcM-JPos.

Zubrin, Robert. *The case for Mars: the plan to settle the red planet and why we must*. New York: Free Press, 2011.