

ABSTRACT

Title of Thesis: DWELLING BEYOND – SUSTAINABLE DESIGN
IN SPACE

Austin Raimond, Master of Architecture, 2016

Thesis Directed By: Mike Binder, Lecturer, School of Architecture,
Planning, and Preservation

In 1620, over the course of 66 days, 102 passengers called the Mayflower their home before arriving and settling in Plymouth, New England. In the years following the Louisiana Purchase of 1803 nearly 7 million people traversed extreme wilderness in covered wagons to found and settle the American West. This year, 2015, the first spaceport has opened in anticipation of sub orbital space flights in 2017 and manned settlement flights to mars by 2026.

This thesis explores the questions: In this next phase of human exploration and settlement, what does it mean to dwell beyond earth? What are the current architectural limitations regarding structure and material sustainability? And, How can architecture elevate the traditionally sterile environments of survival shelters to that of permanent dwellings?

DWELLING BEYOND: SUSTAINABLE DESIGN ON MARS

by

Austin Raimond

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Architecture
2016

Advisory Committee:
Professor Mike Binder Chair
Professor Brian Kelly
Professor Jamie Tilghman

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Preface

What does it mean to dwell beyond earth? This thesis explores themes of extreme condition dwellings, the social and psychological effects of isolation, and site-specific construction methods all set within the context of Mars.

The goal of this thesis is to create a better understanding of architecture's role within the field of space exploration and to facilitate an example of a permanent Martian settlement facility on the surface of Mars.

Dedication

To my parents, Marty and Gina, who filled my childhood with creativity, and to Matt
& Jami, who inspired me to explore the world of high education.

Acknowledgements

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List of Abbreviations

NASA – National Aeronautics and Space Administration

WAVAR – Water Vapor Adsorption Reactor

EVA - Extravehicular Activity

HAB – Habitation

MSL - Mars Science Laboratory

“The surface of the Earth is the shore of the cosmic ocean. From it we have learned most of what we know. Recently, we have waded a little out to sea, enough to dampen our toes or, at most, wet our ankles. The water seems inviting. The ocean calls.”

— *Carl Sagan, Cosmos, 1980*

1. Introduction

Human Settlement on Mars

Since the beginning of civilization humans have explored and settled greater frontiers. Whither it was for new resources, expansion of land, or just curiosity, the human species has been on the move. Now at the start of the 21st century governmental agencies such as NASA along with private companies such as SpaceX, Virgin Galactic, and the Mars One settlement program are seeking to extend humanities present to one of our closest planetary neighbors, Mars. While each of these companies has their own specific set of goals, they all share one commonality, a need for a settlement plan which includes long term dwelling design for Mars's extreme environment.

For the purposes of this thesis and to create clarity within the design intent it is important to define to what scale, permanence, and to what time period the proposed design will take place. Thus this thesis breaks down Martian settlement into three major categories: 1. Near Future: 10–20 years, Non-permanent, Small-scale, Research Dwellings, 2. Close Future: 20-50 years, Permanent, Large-scale, Research Facilities, and 3. Distant Future: 100–500 years, Permanent, Terraforming Operations and Adaptive Settlements. This thesis addresses the second category focusing on a permanent, large-scale research facility.

Thesis Goals

This thesis is a proposal for a permanent research facility for 100 initial settlers and its strategic expansion plan. Through the proposed design the architecture addresses the following questions:

- 1. Internal Vs. External:** When is the design internally limited due to climatic conditions and how can the design provide opportunities for external views.
- 2. Surviving Vs. Dwelling:** How can the design help preserve our humanity (physical, mental, and spiritual health) while living in an otherwise uninhabitable environment?
- 3. Divided Vs. Integrated Systems:** How can integrated vegetation and water systems be used to promote the efforts of the first two goals?

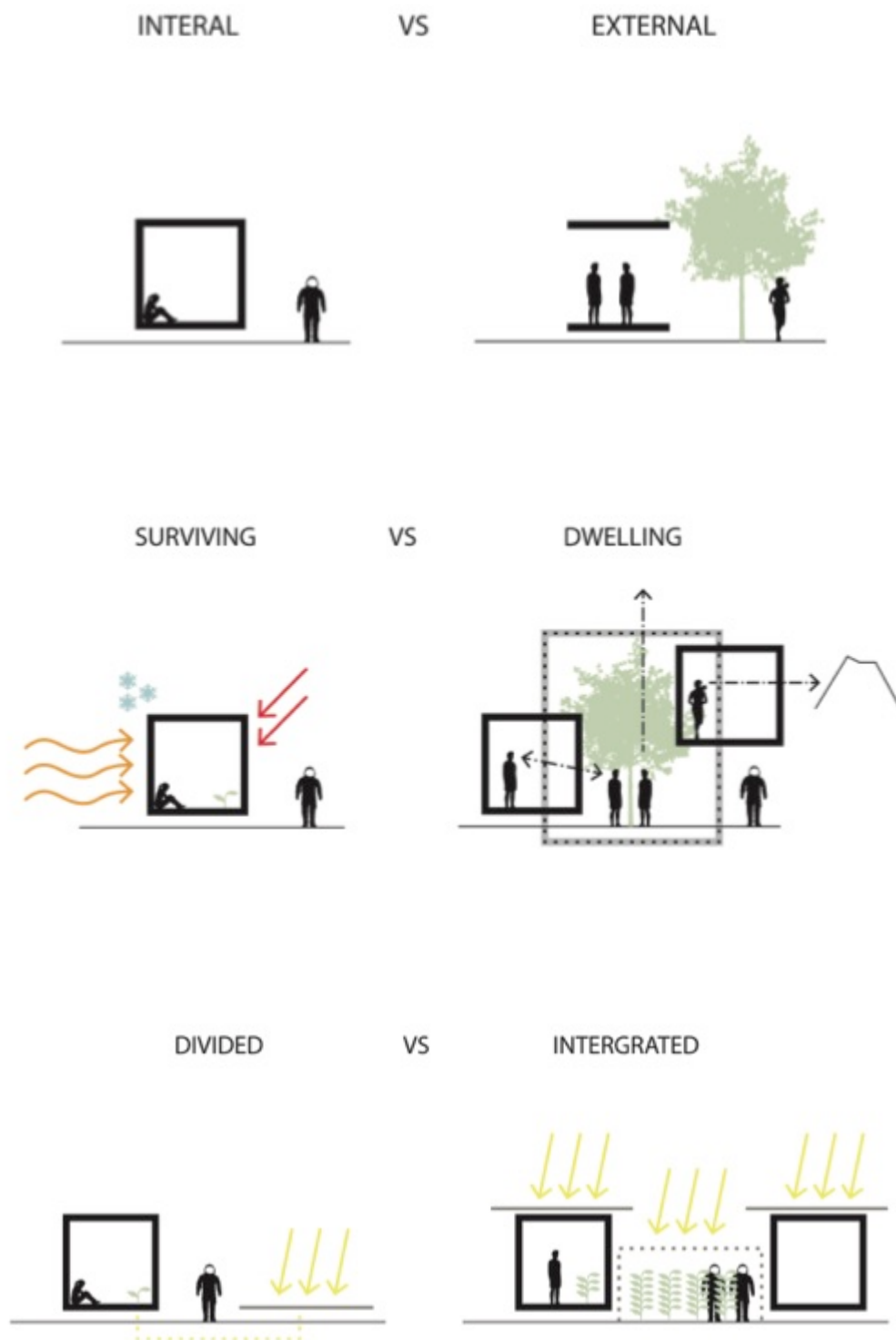


Figure 1. 1: Thesis Goals (image by author)

Settlement Goals

Programmatically the settlement will be modeled off of NASA's 2010 - 2050 strategic goals for exploration/colonization:

NASA's Exploration Strategy Focus¹

1. **Future exploration:** Both human and robotic missions to Mars and beyond.
2. **Accumulate Knowledge:** Pursue questions about earth, the solar system, and the universe, as well as our place in them.
3. **Expanding human civilization:** Extend Civilization beyond Earth
4. **Expanding Economic opportunities:** Expand Earth's economic sphere and conduct activities with benefits to life on Earth
5. **Developing global partnerships:** Strengthen existing global partnerships and create new ones.

Based on the above goals the settlement will support the following programs:

1. Habitation that supports permanent residences (Initial & future growth)
2. Research labs to support the search for past and present life on Mars
3. A central community space to support economic, social, educational, and artistic goods and/or services.

¹ (NASA 2008)

2. Mars

Why Mars?

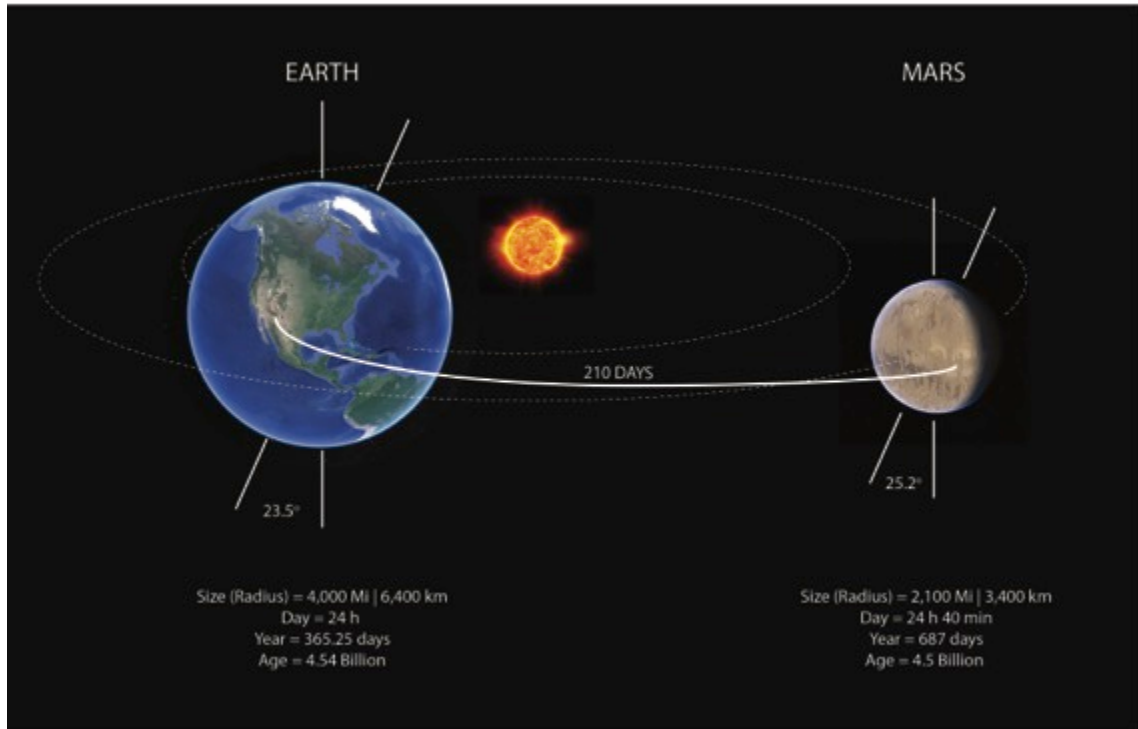


Figure 2. 1: Planetary Comparison (image by author)

Of all of the planets in our solar system, Mars is the most viable for settlement and colonization. This is due to similarities in its physical structure, position within our solar system and economic potential. Physical similarities include: day length (roughly 24 hours), planet age (4.5 billion years old), similarities in geology, the existence of moons (Phobos and Deimos), and a similar rotational tilt (25.2 degrees). Travel between planets is roughly 170 – 225 days making settlement trips possible given current and future projections of aerospace technology. Additionally, Mars could act as an important strategic outpost position for future mining operations,

which could take place on Mars or at our solar system's asteroid belt. Thus as a first step towards colonizing our solar system Mars provides the greatest chance for success. Yet while it is the most viable next step, Mars also has many differences, which will provide unique design challenges. The following section acknowledges those differences and their influence on design.

Earth Vs. Mars: A Planetary Comparative Analysis

A planetary site analysis included a comparative study of Earth and Mars as a means to understand the differences in the physical characteristics of each planet. These particular characteristics were chosen because they would have a direct impact on the design and architectural implications of both the dwelling and its user experience.

Gravity: Mars is 48% smaller and 90% less dense than Earth, this difference in size and density results in a planetary gravity of 3.711m/s^2 or 38% that of Earth's gravity of 9.807m/s^2 . As an example a 165 lbs. Man on Earth would weight 68 lbs. on Mars. Additionally due to the reduced gravity, structural vaulting would be able to span greater distances.

Atmosphere: Mars's atmosphere is made up of 95% Carbon and is about 100 times thinner than Earth's atmosphere which is made up of nitrogen, oxygen, and argon. The lack of oxygen on Mars means survival outside of an oxygen-supplied dwelling would be impossible in its current state. Thus all settlers traveling between

the outside of the facility would need to dawn oxygen-supplied suits.

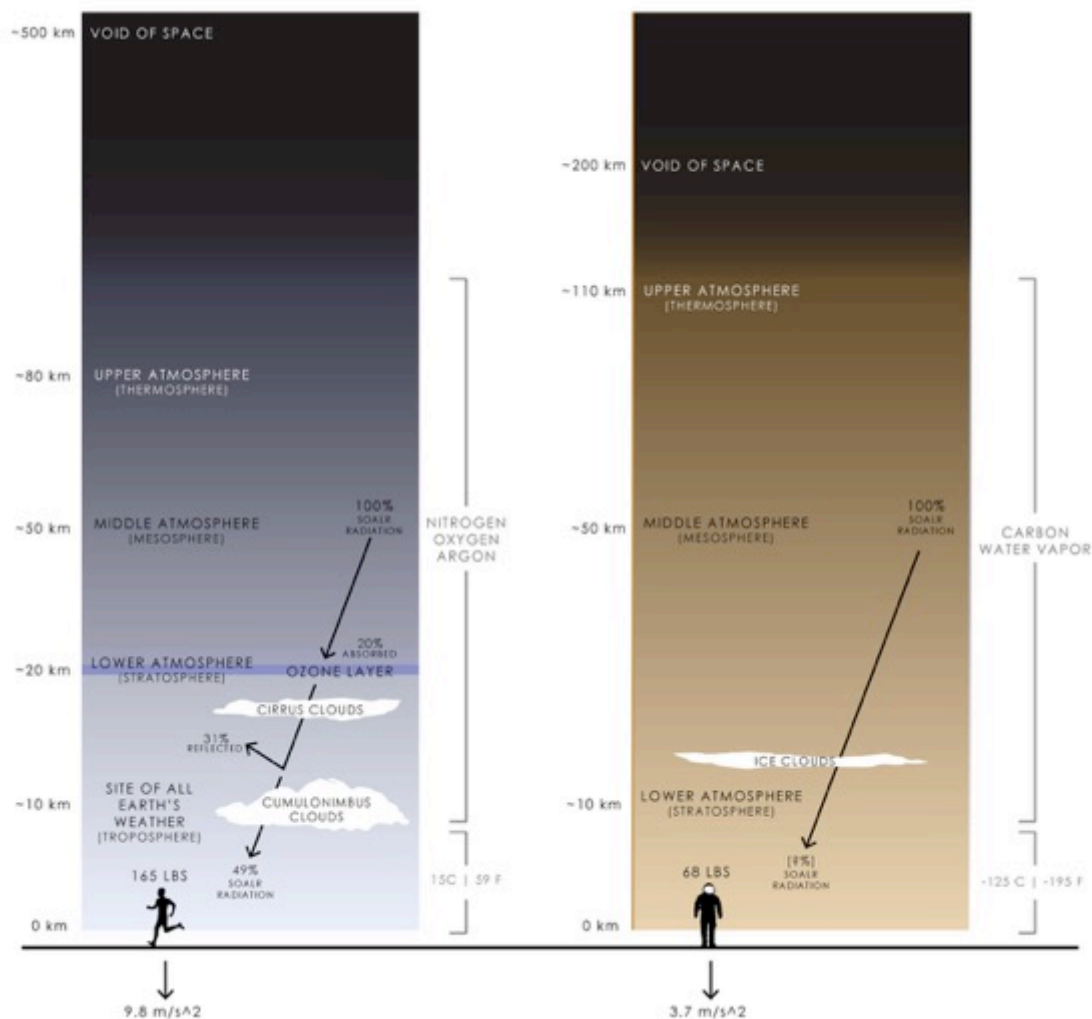


Figure 2.2: Atmospheric Comparison (image by author)

Climate: Unlike Earth, Mars has no oceans to affect weather patterns. Climate and in affect temperature is most directly related to the planet's tilt. The southern hemisphere has the most extreme climatic shifts with the colder winter and hottest summer. The northern hemisphere is more consistent with the most stable region being the northern tropics. The largest difference between Mars and Earth is the lack of available rainfall; Mars gets 0" of rainfall annually. There are however

high levels of embodied hydrogen (potential sub-surface level water sources) within the Martian regolith. Additionally Mar's atmospheric moisture content rises to between 80-100% nightly allowing for the potential to extract moisture from the air.

Temperature: The Average temperature on Mars is -60 C, which is similar to the warmest parts of Antarctica on Earth. The warmest surface temperature on mars is 20C (70F), which only occurs, in direct sunlight during the summer time. The coldest temperature is -125C, which is 25% colder then the coldest temperatures in Antarctica. This climate and temperature data means that any dwelling structure would need to support conditions on average far colder then Antarctica.

Wind Speed: Mars's thin atmosphere causes the wind strength to blow at a rate significantly reduced as compared to earth. The highest recorded wind speed of 100mph on Mars's surface would actually only blow at a strength of a 12mph breeze, that is an 87% reduction from that of Earth.

Solar Radiation:² Mars is 35% farther from the sun then Earth resulting in a 50% reduction in the amount of Solar Flux the surface receives. Solar radiation on the other hand is very extreme. Mars has no magnetic field and lacks an ozone layer causing the Martian surface to be hit with almost 100% of the solar radiation from the sun. The use of protective structures will be necessary to the preservation of human life.

² (George, Chamitoff and Barker 1998)

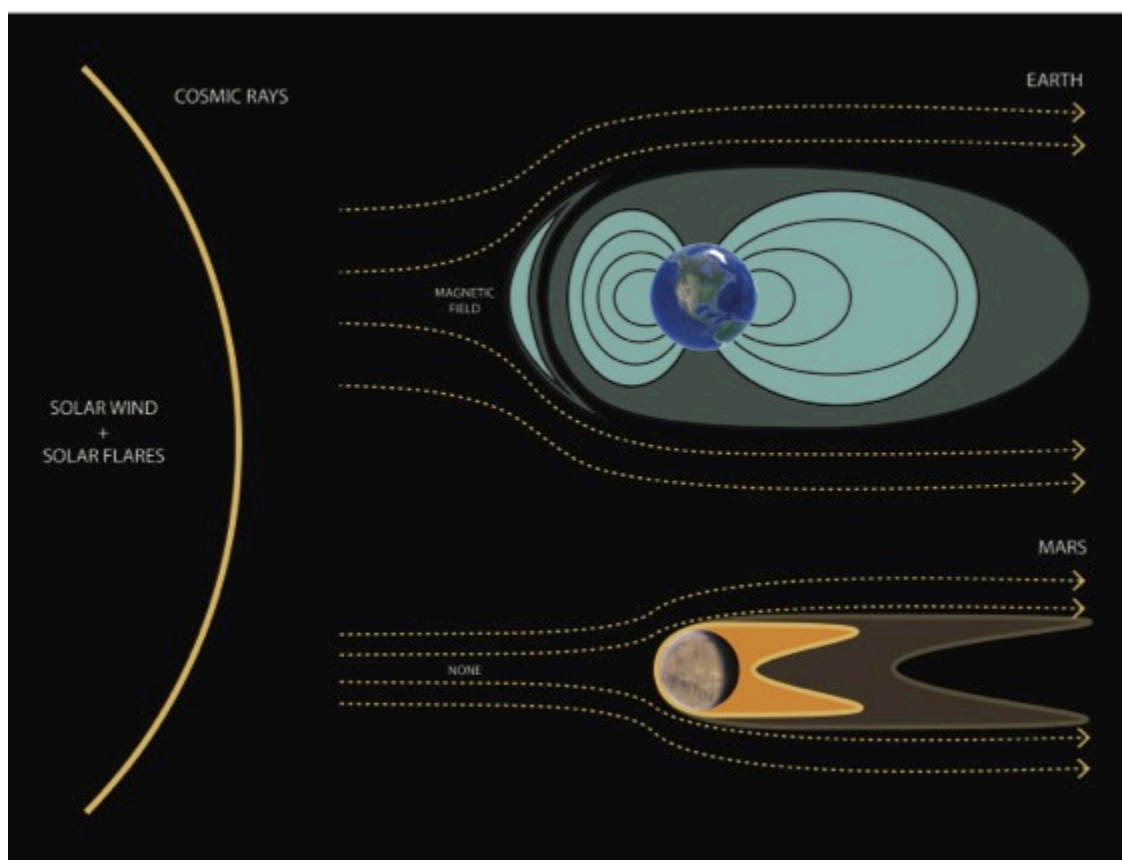


Figure 2. 3: Radiation Sources (image by author)

3. Site Selection

Approach

In order to narrow down the context of Mars into potential settlement sites a selection criteria was created to identify locations which would best support long-term permanent settlements within Mar's current condition. The selection criteria included the following standards: Use of historical NASA interest sites to establish locations of interest, solar exposure to preserve maximum solar energy and temperature levels, locations of historically presence water, and regional site requirements to support settlement goals from chapter one.

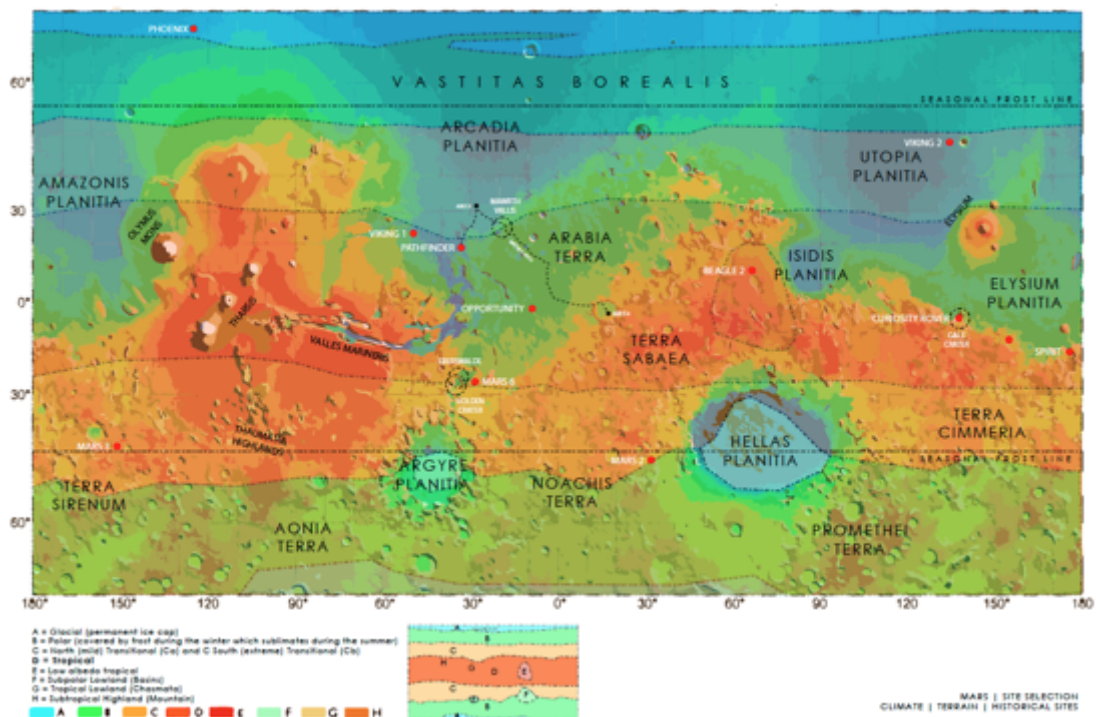


Figure 3. 1: Map of Mars (image by author)

Site Selection - NASA Interest Sites & Tropical Zone Sites

Over the years NASA has generated a list of high priority research locations around Mars. While the most widely documented sites number 58 in total, the most desirable locations for settlement exist within the central tropical zone of the planet. Within this zone solar energy potential and temperature levels are the highest.

With an overarching temperature spectrum of -125C to 20C it was very important to select locations with the most stable temperature ranges. Given the planet's tilt anywhere on Mars's southern and far northern hemisphere would be to extreme. The central tropic zone would offer the greatest degree of temperature stability. Temperatures within this region would be relative to that of Antarctica and during sunny days in the summer could get as hot as 70F.

Additionally, while today Mars is devoid of water, it is speculated that historically this central tropic zone may have once been a transitional zone between the planets singular continent and a northern ocean. As of 2015 seasonal water flows have also been documented on hillsides within this central tropic zone.

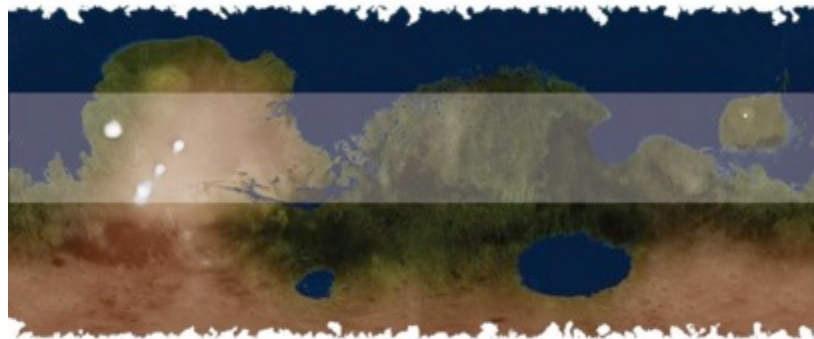


Figure 3. 2: Speculative Maps of Martian Ocean (image edited by author)

Site Selection - Regional

With the scope of site selection narrowed down to NASA approved sites within the central tropical zone a second criteria was used for regional and local site selection. This second site selection criteria addressed primary thesis and settlement goals from chapter one broken down into three categories: Habitat Safety, Research, and Exploration. Within each category, site requirements were given three levels of importance: “Required”, “Desired”, and “Bonus”. If a site failed to fulfill any “Required” requirement it was immediately disqualified. The result of this site selection criteria process yielded five acceptable sites, where three were selected and interrogated for their unique physical characteristics. Ultimately Site 1: Gusev Crater was selected as the final site.

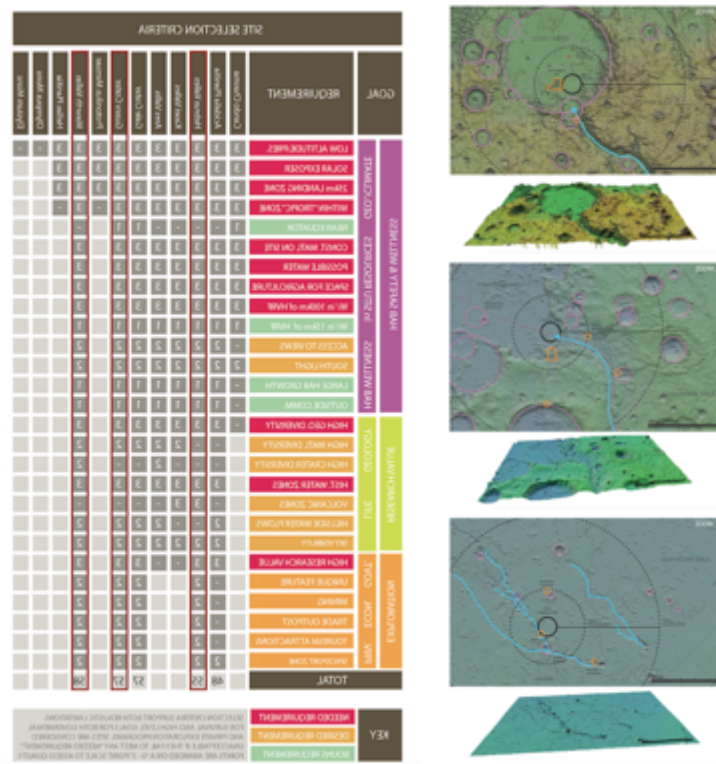


Figure 3. 3: Site Selection Criteria Overview (images by author)

SITE SELECTION CRITERIA															
GOAL		REQUIREMENT	Cando Chasma	Acidalia Planitia	Hebrus Valles	Kasei Valles	Ares Vallis	Gale Crater	Gusev Crater	Protonilus Mensae	Mawrth Vallis	Heillas Planitia	Olympus Mons	Elysium Mons	
HAB SAFETY & WELLNESS	GEO/CLIMATE	LOW ALTITUDE/PRES.	3	3	3	3	3	3	3	3	3	3	-		
		SOLAR EXPOSER	3	3	3	3	3	3	3	3	3	3			
		25km LANDING ZONE	3	3	3	3	3	3	3	3	3	3			
		WITHIN "TROPIC" ZONE	3	3	3	3	3	3	3	-	3	-			
		NEAR EQUATOR	1	-	-	-	-	1	1		-				
	In Situ Resources	CONST. MATL ON SITE	3	3	3	3	3	3	3	3		3			
		POSSIBLE WATER	3	3	3	3	3	3	3	3		3			
		SPACE FOR AGRICULTURE	3	3	3	3	3	3	3	3		3			
		W/ in 100km of HVRF	3	3	3	3	3	3	3	3		3			
		W/ in 15km of HVRF	1	1	1	1	1	1	1	1		1			
		ACCESS TO VIEWS	-	2	2	2	2	2	2	2		2			
		SOUTH LIGHT	2	2	2	2	2	2	2	2		2			
		LARGE HAB GROWTH	-	1	1	1	1	1	1	1		1			
		OUTSIDE COMM.	-	1	1	1	1	1	1	1		1			
		RESEARCH VALUE	GEOLOGY	HIGH GEO. DIVERSITY	-	3	3	3	3	3	3		3		
HIGH MATL DIVERSITY				-	-	2	2	2	2		2				
HIGH CRATER DIVERSITY				-	-	-	2	-	-		2				
HIST. WATER ZONES				3	3	3	3	3	3		3				
LIFE	VOLCANIC ZONES			-	3	3	-	-	-		-				
	HILLSIDE WATER FLOWS			2	-	-	2	2	2		2				
	SKY VISIBILITY			2	2	2	2	2	2		2				
EXPLORATION	GOVT.	HIGH RESEARCH VALUE	3	3	-	-	3	3		3					
		UNIQUE FEATURE	-	2			2	2		2					
	PRIV.	MINING	-	2			2	2		2					
		TRADE OUTPOST	-	2			2	2		2					
		TOURISM ATTRACTIONS	-	2			2	2		2					
		SPACEPORT ZONE		2	2			2	2		2				
TOTAL			48	55			57	57		58					
KEY	NEEDED REQUIREMENT		SELECTION CRITERIA SUPPORT BOTH REALISTIC LIMITATIONS FOR SURVIVAL AND HIGH LEVEL GOALS FOR BOTH GOVERNMENTAL AND PRIVATE EXPLORATION PROGRAMS. SITES ARE CONSIDERED UNACCEPTABLE IF THEY FAIL TO MEET ANY "NEEDED REQUIREMENT". POINTS ARE AWARDED ON A "0 - 3" POINT SCALE TO ASSESS QUALITY.												
	DESIRED REQUIREMENT														
	BOUNS REQUIREMENT														

Figure 3. 4: Site Selection Criteria Chart (image by author)

Site 1: Gusev Crater – Crafter site with a historical rover landing and river delta.

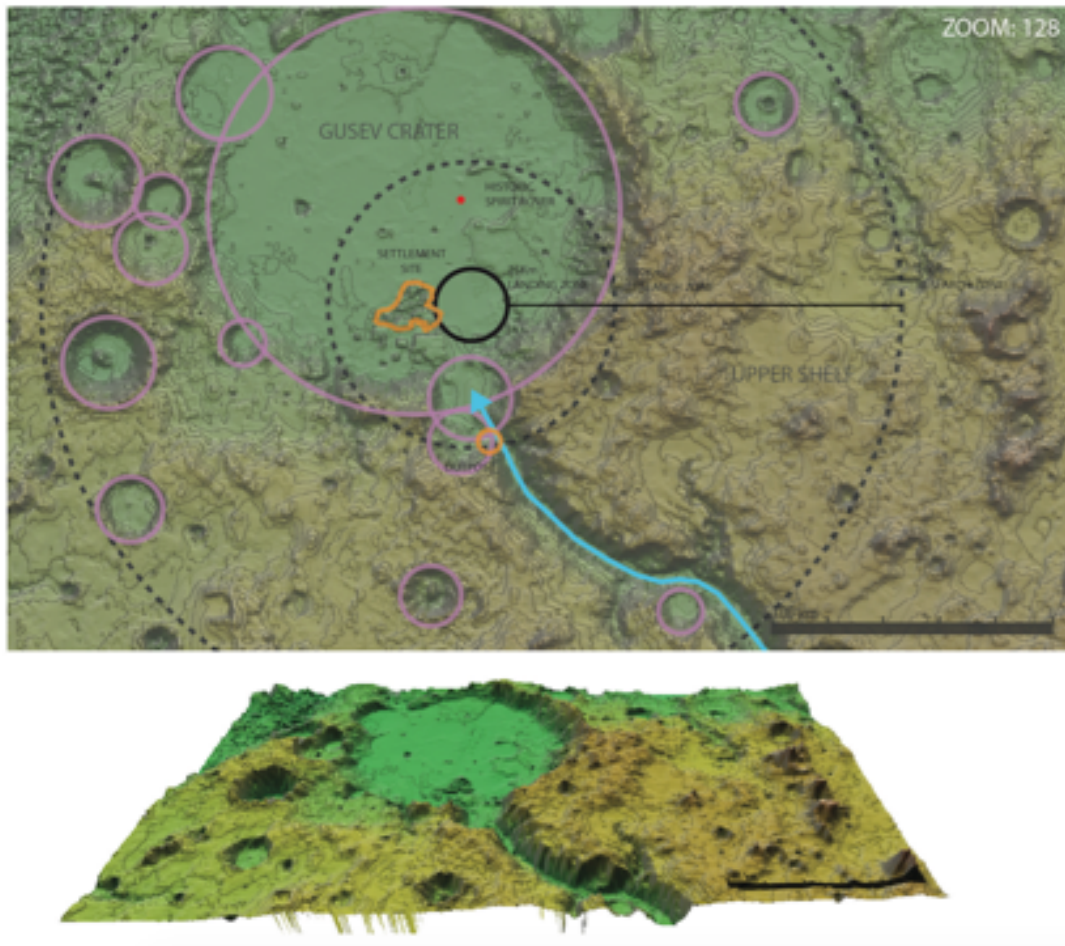


Figure 3. 5: Gusev Crater Site - Selection Analysis (image by author)

Site 2: Mawrth Vallis – Hill site between the middle and lower planet shelves.

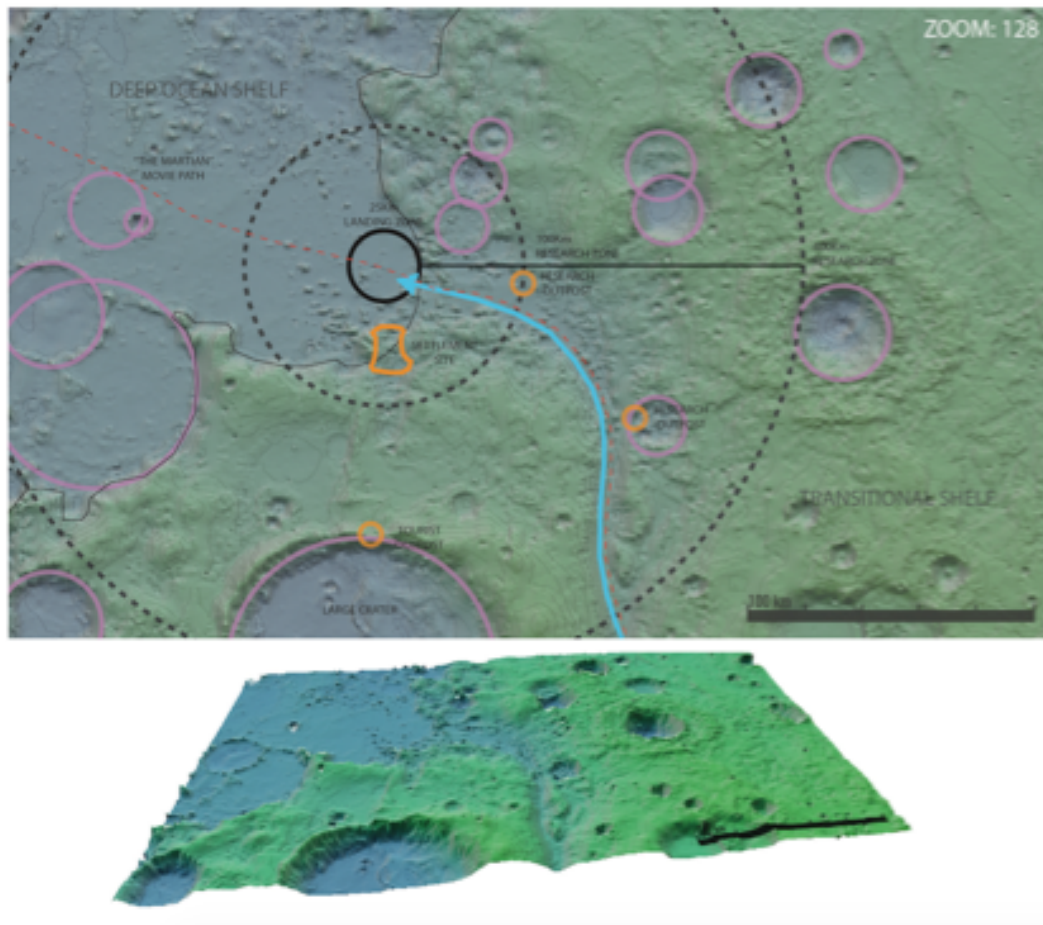


Figure 3. 6: Mawrth Vallis Site - Selection Analysis (image by author)

Site 3: Hebrus Vallis – Lava tube site located along series of canyons.

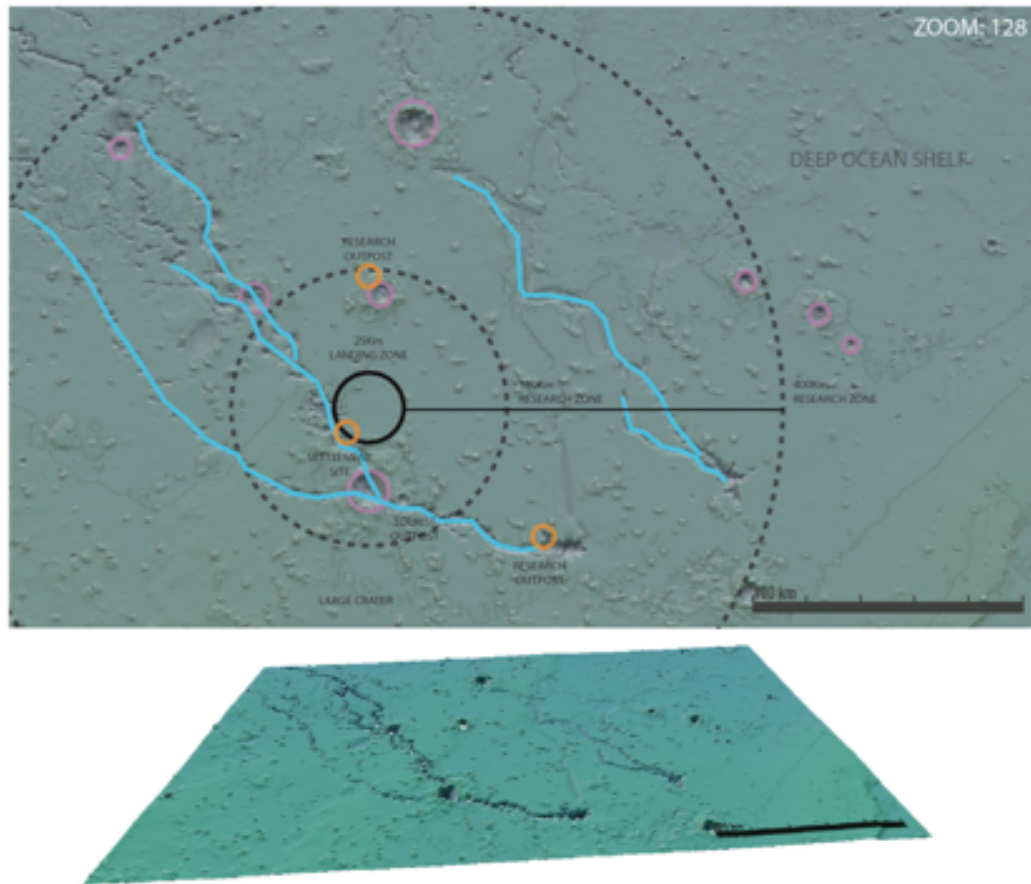


Figure 3. 7: Herbrus Vallis Site - Selection Analysis (image by author)

4. Site Analysis – Gusev Crater

Approach

Site analysis was conducted in concert with several master-planning exercises at three different scales: Regional, Local, and Direct. These were done as a means to position the settlement within the context of naturally occurring geographic features. This process additionally involved the naming of those specific geographic features to both anchor the settlement among tangibly identifiable places and to create a larger narrative for the settlement's foundational story. The Latin name Mosa Vallis, meaning mesa valley was given to the settlement as a whole derived from the site's collection of mesas, which surround the settlements central valley. Additionally multiple comparative graphics were produced as a means to frame these Martian geographic features within the context of identifiable forms.

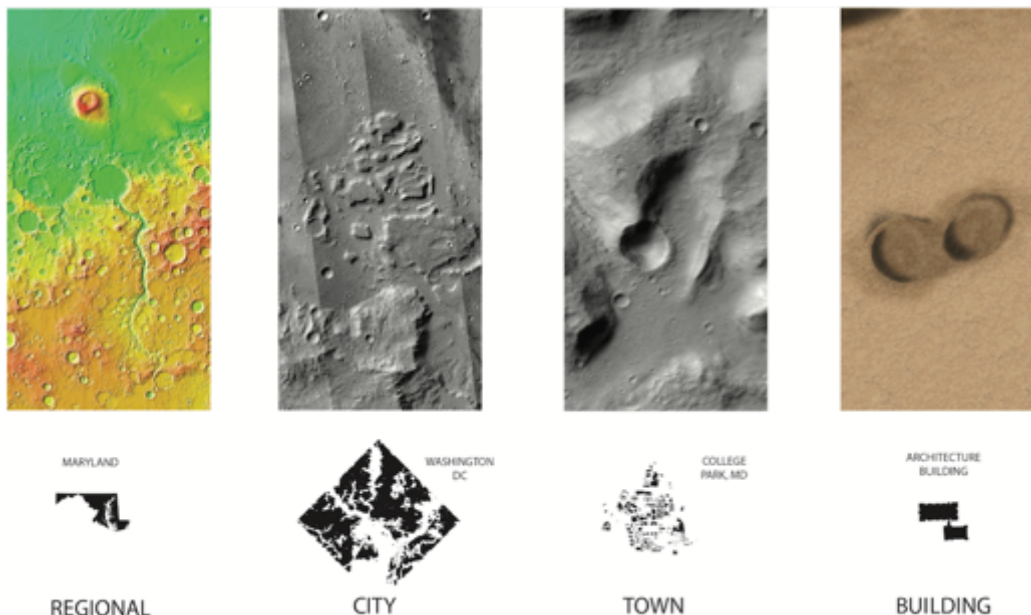


Figure 4. 1: Comparative Graphics (image by author)

Site Introduction

Gusev Crater is located on the southern edge of the planet's tropic region between Elysium Planitia and Terra Cimmeria. Between 2004 and 2010 it was the active location of NASA's spirit rover. NASA describes spirit's findings there as such:

*“Spirit landed on the opposite side of Mars from its twin, Opportunity, in Gusev crater, a 170 km diameter crater which formed three to four billion years ago. A channel system drains into the crater that likely carried liquid water, or a combination of water and ice, at some point in Mars' past. The crater appears to be an old lakebed filled with sediments. It was hoped that sedimentary material from this early era could be studied, although at first the region proved disappointing in its lack of available bedrock on the flat lava plains of the crater. Spirit eventually made its way to the Columbia Hills, a small group of low-lying hills about 3 km from the landing site, and rocks examined there do show evidence of interaction with small amounts of briny (salty) water.”*³

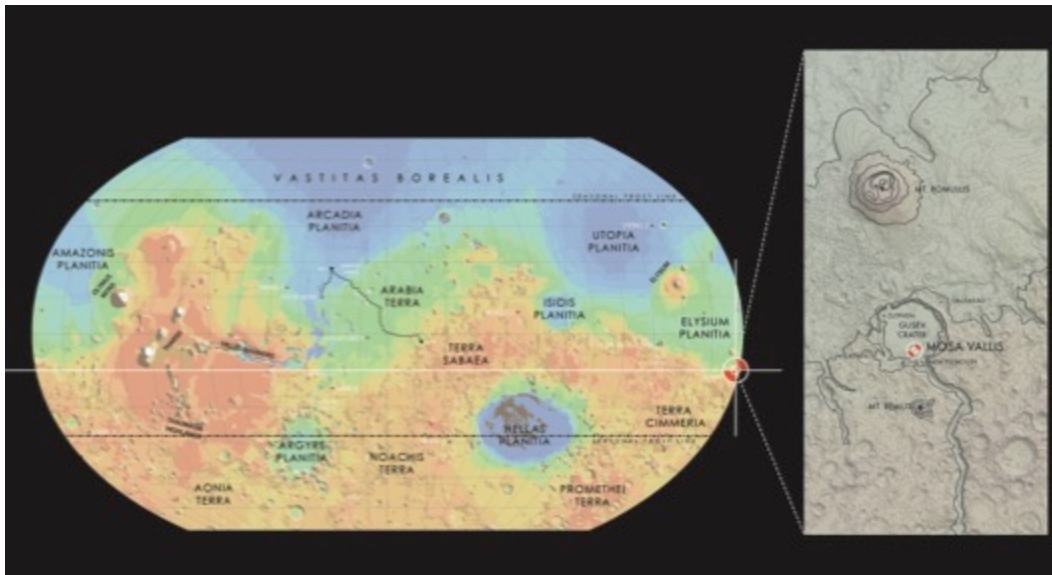


Figure 4. 2: Mosa Vallis Site Location (image by author)

Site Analysis - Regional

Regionally Gusev Crater is located on a transitional boundary between Mar's highland continent and midland shelves. Located slightly off due north and due south from Gusev Crater are two Mount Everest sized (in height) mountains. These mountains have been given the names Mount Romulus (North) and Mount Remus (South) based after the myth of twin brothers linked with the founding of Rome. These two mountain ranges additionally share an axial relationship with a naturally occurring collection of mesas, which has been selected as the settlement's local site. Additionally throughout the regional landscape, unique topographic formations were identified as potential sites for independent research outposts.

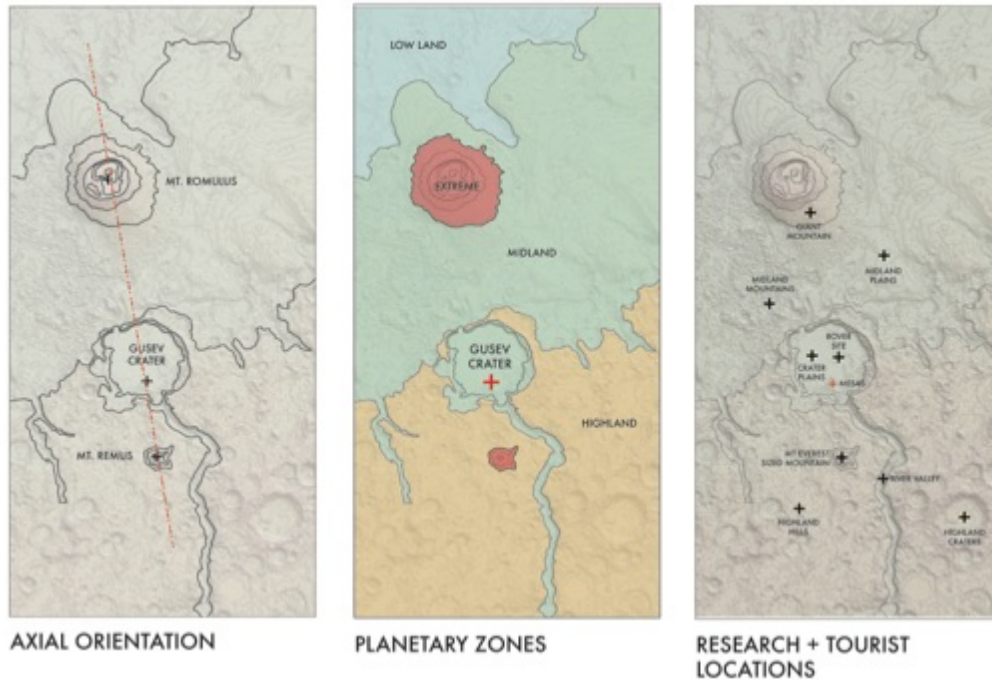


Figure 4. 3: Regional Site Context (image by author)

Site Analysis - Local

Within the mesa valley itself a second naming exercise was conducted to link geographic features with specific programmatic elements. The follow list explains each location's significance within the local site:

EOS – Greek for Dawn - Mesa oriented to the rising sun

ASTRA – Greek for Dusk - Mesa oriented to the setting sun

ELYSIAN VALLEY – Location selected for community gravesite

THE VALE – Shadowed valley corridor leading to off site gravesite

SELENE – Greek for Moon - Mesa representational of Mar's Moons

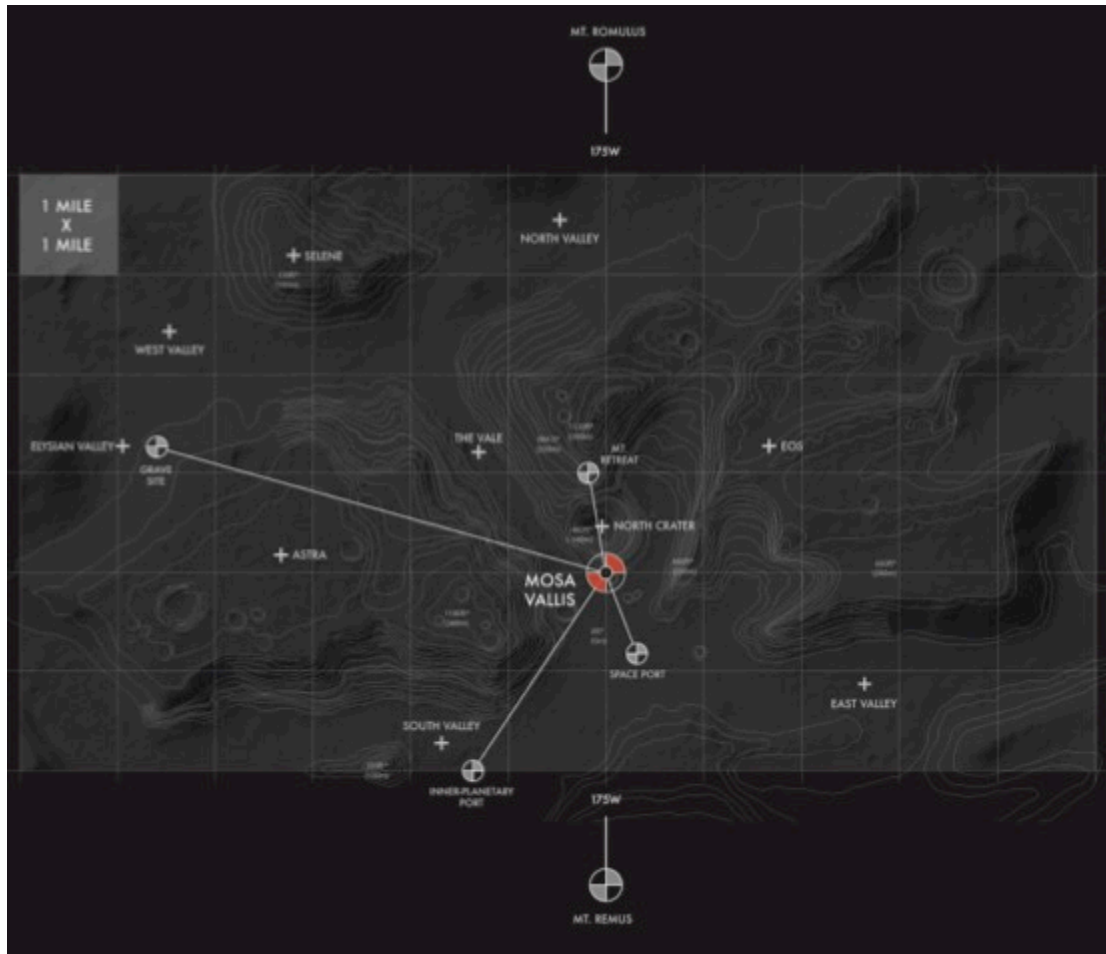


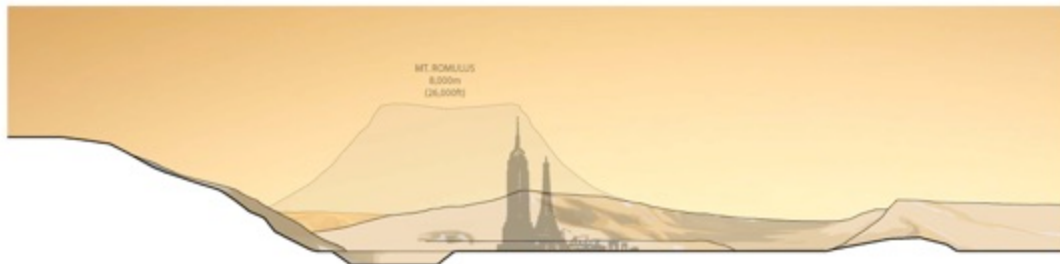
Figure 4. 4: Local Site Context (image by author)

As an organized element the local site is also oriented in connection with the north-south axis established by Mount Romulus and Mount Remus. Proportionally the settlement would have an experiential relationship to the two mountains similar to that of Mount Fuji viewed from Tokyo. Depending on dust conditions the views to these two mountains would range between full clarity and distant blur. To the east and west the twin mesas of EOS and ASTRA would both welcome the rising sun and cradle the setting sun each day.



1" = 100m = 320 ft

SITE - LOOKING SOUTH (A)



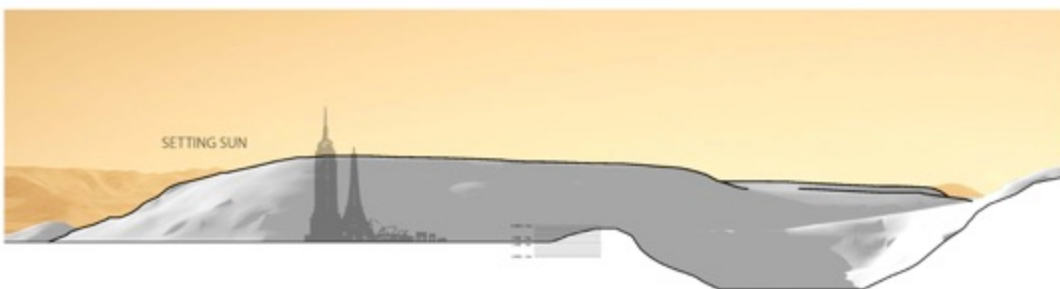
1" = 100m = 320 ft

SITE - LOOKING NORTH (B)



1" = 100m = 320 ft

SITE - LOOKING EAST (C)



1" = 100m = 320 ft

SITE - LOOKING WEST (D)

Figure 4. 5: Local Site Sections (image by author)

Site Analysis - Direct

The direct site consists of an open field condition within the mesa valley and includes several unique crater features most notably “North Crater” – a 140m deep crater directly north of the center of the site. To assist in the selection of the building’s constructed location the major geographic features were organized along two major axial paths: a north-south cardo axis and an east-west decumanus maximus. As a strategy the central crossing “Middle Field” was selected for its flat topography. This flat surface would be ideal for a large-scale solar array, which would be needed to provide power to the settlement.

Ultimately the dwelling constructed location was chosen exist on the southern “Levy” of “North Crater”. Building into the crafters edge would both allow for the collection and re-utilization of the craters regolith as a construction material along with positioning the building on the main north-south axis which has been held as an organizing line within the site respective scales of influence.

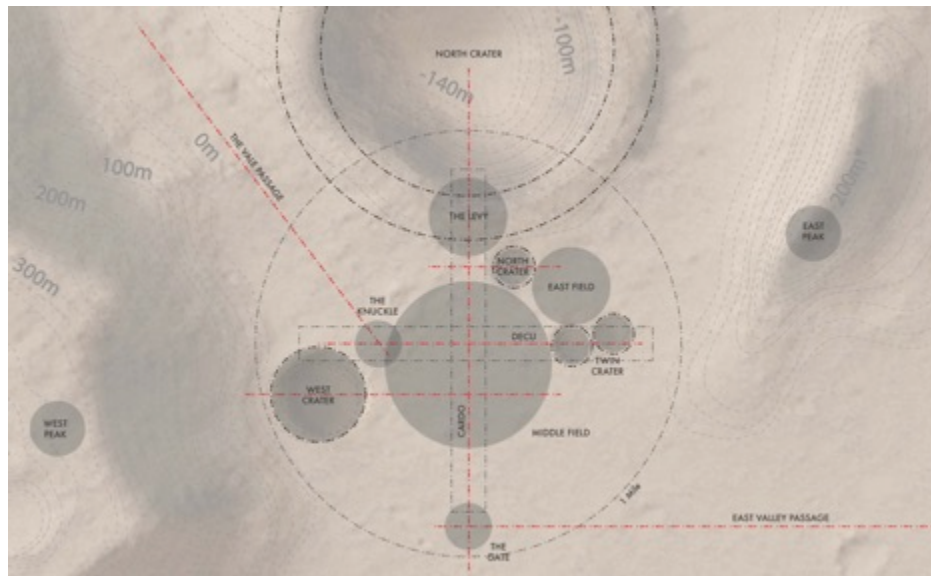


Figure 4. 6: Direct Site Context (image by author)

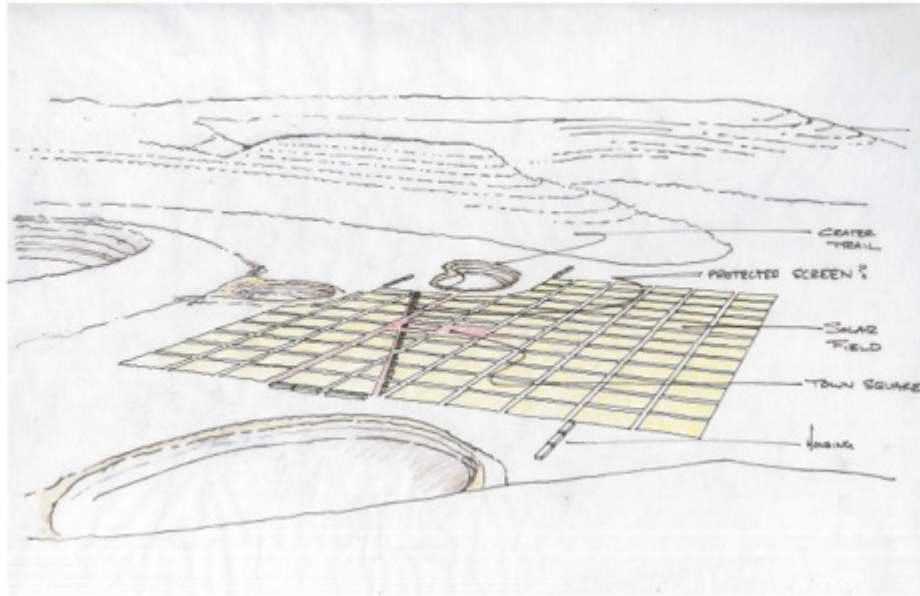


Figure 4. 7: Solar Field Concept Image (image by author)

5. Program

Approach

Three types of programmatic areas will support the settlement's goals from chapter one:

1. Habitation that supports permanent residences (Initial & future growth)
2. Research labs for searching for past and present life on Mars
3. A central community space to support economic, social, educational, and artistic goods and/or services.

To better understand the program size a series of precedent studies were conducted to inform both the typical settlement users and their spatial requirements. As a sizing process the following equation was used:

Total Users = Total Beds = Food & Oxygen Requirements = Approximate HAB Size

Program – User Analysis

To understand the users and their settlement roles a passenger study was conducted using the Santa Maria and Mayflower discovery and settlement ships; the resultant roles were:

- Ship Crew
 - Command
 - Support
 - Crew
- Passengers
 - Resource Collection
 - Production
 - Trade
 - General Workers
 - Communication
 - Child Rearing
 - Children

Next using the NASA Mars reference mission – A 2009 proposal for a research lab on Mars, a population extrapolation was conducted. The resultant was an initial foundational research group of 12 people followed by a 48-person settlement group. Adjustments include a reduction in adult passengers to support 2015 life support systems and a reduction of children based on 2015 standards of children per family unit.

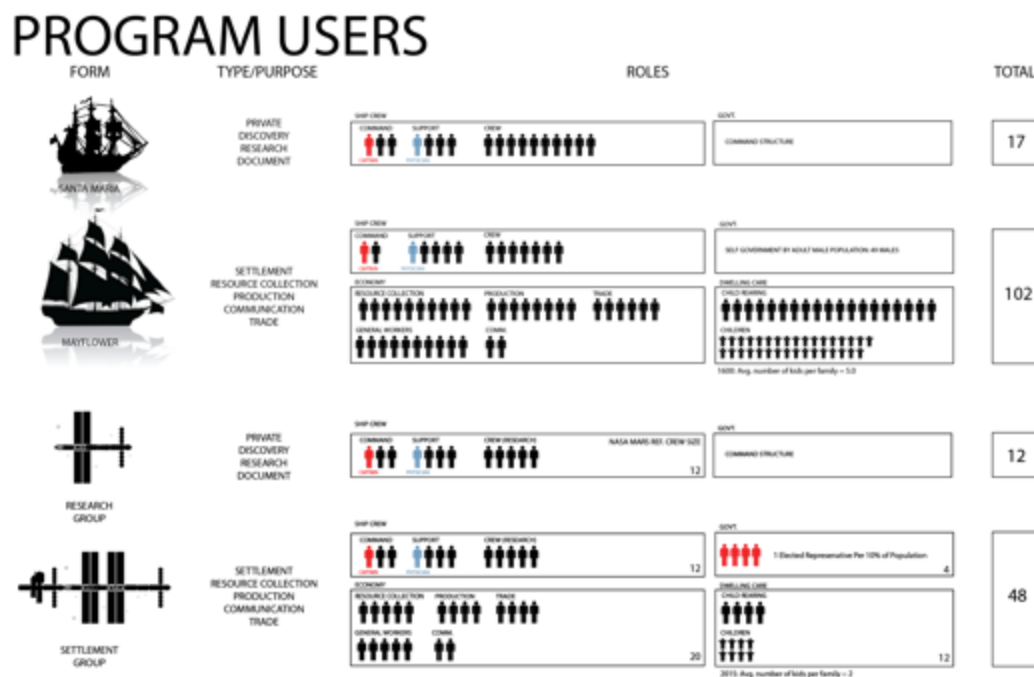


Figure 5. 1: Program User Analysis (image by author)

It is expected that the settlement population will grow over time with each subsequent group of settlers (not including on site births). Thus a 10-year population timeline yields a total population of around 168 adults and children combined. For the purpose of this thesis the settlement will use the standard number of 100 inhabitants as a means to size the initial structure. To that affect the architectural response described in Chapter 9 details how the building will accommodate future growth.

PROGRAM TIMELINE

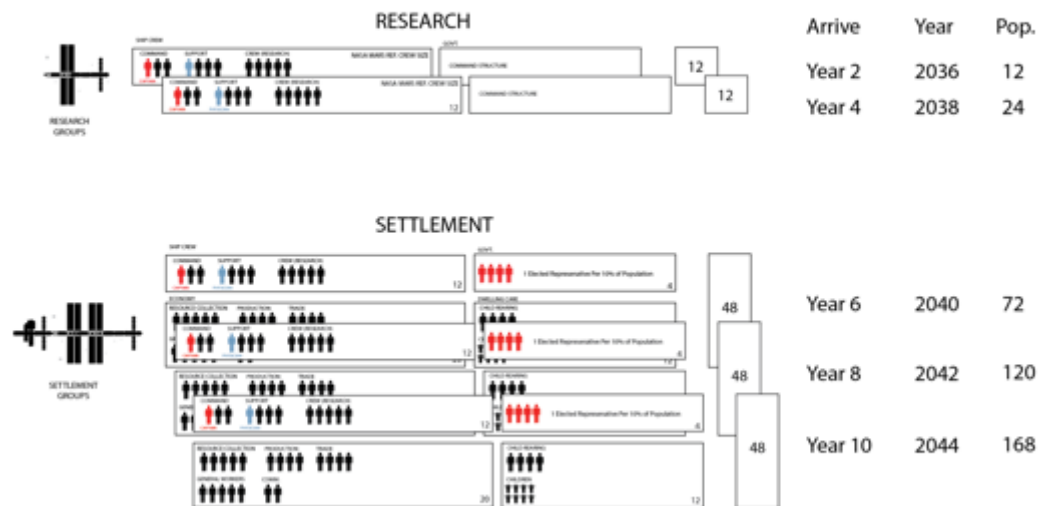


Figure 5. 2: Program Timeline (image by author)

Program - Precedent Analysis

NASA and Russian Missions

NASA and Russian reference documents were used to examine power, food and oxygen requirements needed to support both the settlement.

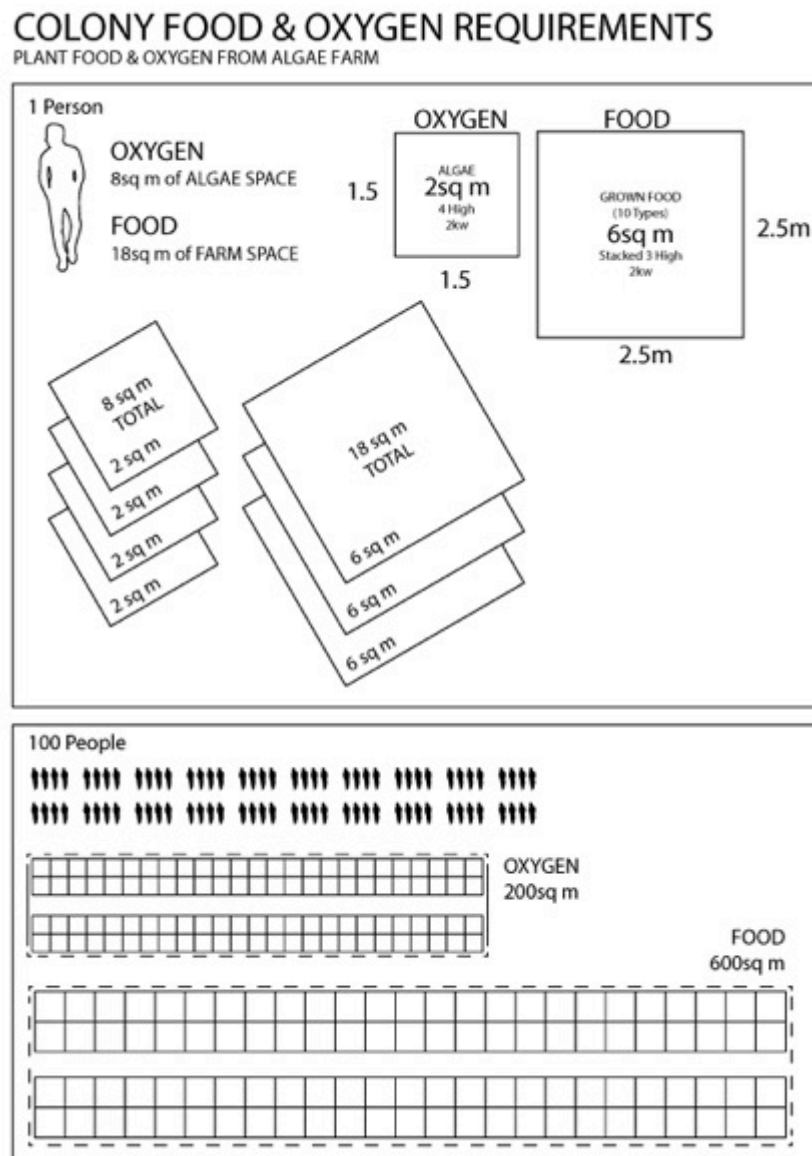


Figure 5. 3: Food Production and Oxygen Requirements (image by author)

COLONY POWER REQUIREMENT

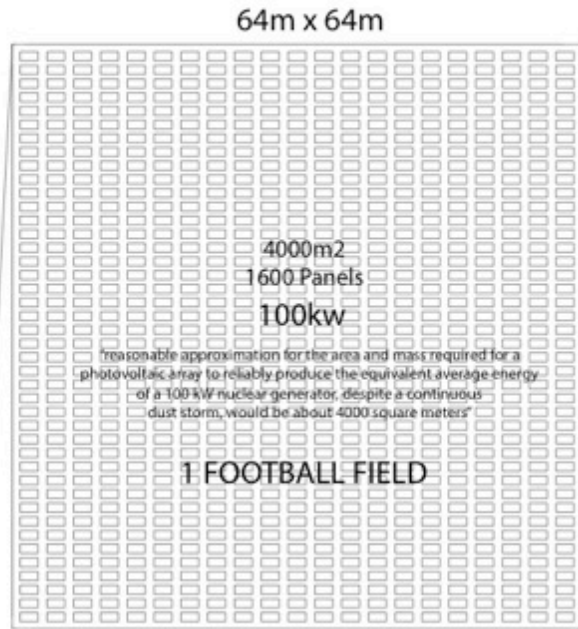
PV Solar Solution



25 kw Per Person
Biosphere 2: 100kw
Japanese Study: 20 - 50kw
NASA: 10 - 30 kw
400 SOLAR PANELS



4 People
||||



100 People
.....

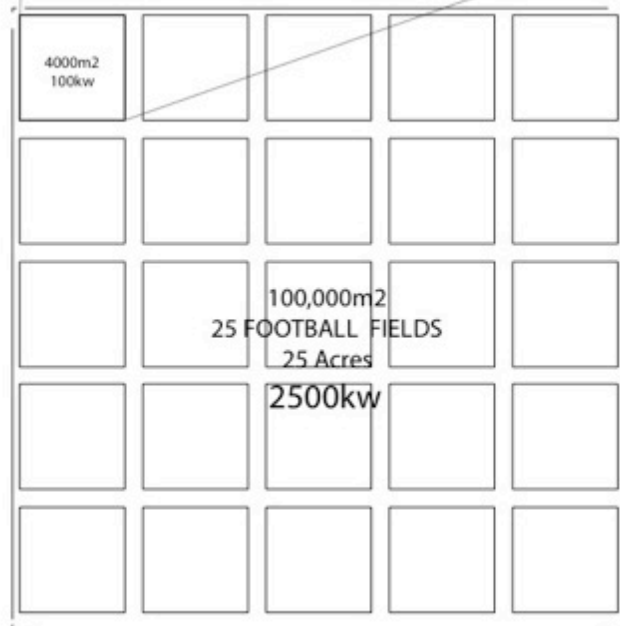


Figure 5. 4: Solar Energy Requirements (image by author)

Biosphere 2

Biosphere 2, an Earth systems science research facility located in Oracle, Arizona was used as a precedent for closed loop ecosystems. The building was designed to allow a team of 8 researches to survive in isolation with all of the physical ecological systems needed to support and maintain human life.

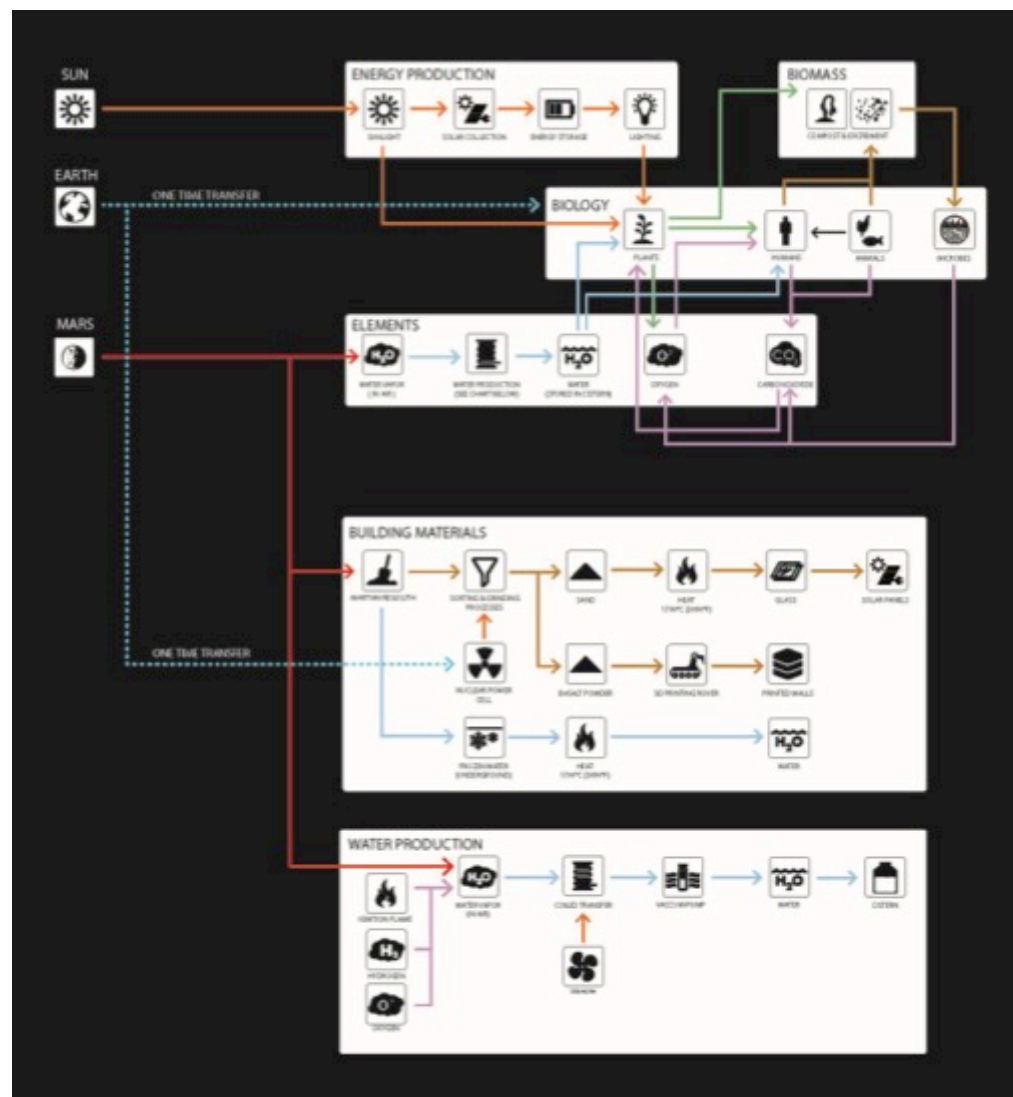


Figure 5. 5: Closed Loop System Structure (image by author)

Conceptual Martian Dwellings

Multiple conceptual Martian dwelling proposals were examined to explore the idea of 3D printed structures on mars. These projects include the following: Norman Foster's 3D printed Martian Dwelling which uses a team of regolith fusing drones to construct a monolithic shell around the structure. SEArch (Space Exploration Architecture) and Clouds AO (Clouds Architecture Office) proposal for a ice printed dwelling called Mars Ice House which uses radiation neutralizing gas to allow for glassed opening in their façade.

Program – Proposed Spaces

Program Area 1 – Residential Dwellings

Private Suites

- Kitchen
- Dining
- Living Room
- Exercise/Meditation
- Shared Bathroom

Social Courtyard

- Common Lounges
- Entertainment/Multimedia
- Agricultural Fields
 - Vertical Oxygen Walls
 - Horizontal Planting Beds

Program Area 2 – Research Facilities

Educational/Governmental Meetings Spaces

- Multipurpose Room Small
- Multipurpose Room Large

Work

- Labs
- Command
- Conference
- Medical

Maintenance & Utilities

- Interior Air, Water, Chemical Plants
- EVA Rooms
- Garage
- Fabrication Shop

Program Area 3 – Community Center

Social

- Public Plaza
- Running / Workout Facilities

Work

- Fishery
- Market Stalls

Play

- Gym
- Walking Park
- Recreational Field

6. Social and Psychological Challenges

Approach

In order to elevate the physical, mental, and emotional experience within the settlement from a state of survival to that of dwelling it was important to both define and quantify what creates a desirable living environment. Using collected information from both the World Health Organization and the UK government's Foresight project the following chapter details those elements and spaces which best promote ideal environments for physical and mental well being.

*Surviving Vs. Dwelling*³

“The World Health Organization now defines health not as the absence of ill-health but as “a state of complete physical, mental and social well-being ... In the field of sustainable development, reference is often made to the ‘triple bottom line’ of physical, economic and social. The health and well-being triple bottom line could be summarized as health, comfort and happiness.”

I	Firmness (health)
II	Commodity (comfort)
III	Delight (happiness)

³ (Steemers 2015)

“UK Government’s ‘Foresight’ project, related to well-being, provides the critical mass of evidence that led to the definition of the Five Ways to Well-Being”

I - Connect: The quantity and quality of social connections

II - Keep Active: Physical activity

III - Take Notice: Paying attention to external environment and internal self

IV - Keep Learning: Higher aspirations lead to better lifestyles

V - Give: Pro-social rather than self-centered behavior impact happiness.

I - Connect

Public Spaces create opportunities for people to connect between individuals and their wider community.

Key qualities include:

Location - Proximity to communal resources to support casual encounters

Places to stop and sit - bench or café table, to encourage extended encounters

Adaptability – Spaces without specific or prescribed functions

Homeliness – a sense of safety and familiarity;

Pleasantness – clean and peaceful, or bustling and lively;

Specialness – Unique qualities, aesthetics, or subjective memories.

II - Keep Active

Physical activity (walking, cycling, sports, etc.) is widely associated with reducing symptoms of mental and physical ill health.

Design characteristics - Outdoors

Facilities - Access to physical activity facilities

Destinations – Proximity to destinations (work, school, public transport)

Density - Residential density is associated with greater proximity to facilities

Land use - Mixed use is desirable

Walkability - Convenient and safe access

Design strategies - Indoor Physical

Shared Exercise Space - Shared exercise space provided

Promote Stairs - Encouraging use of stairs

Attractive Circulation - Attractive experiences such as views, art, daylight, and greenery

III – Take Notice

Design features that lead to people stopping and taking notice have been linked with increased happiness:

Features Include:

Art

Planting and Landscaping

Wildlife Features (e.g. insect boxes)

Seating

Spaces Include:

Diverse Spaces - combining green as well as hard landscaping

Open spaces - views to outside

Mostly Public - Higher relative proportion of public to private space

IV – Keep Learning

The physical environment of the homes and classrooms contain mediating variables that influence intellectual development.

Features

Clean - Clean and uncluttered

Safe - Safe for play and is not dark or monotonous.

Arrangement – Seat orientation (Semi Circle = Good vs Adjacent = Less So)

Clear Visibility - Unobstructed eye contact

Comfort - Physically and thermally comfortable, safe, well-lit, quiet, clean air

Level of Quality

Poor environment vs Adequate one = Large Difference

Adequate vs extravagant facilities = Little Improvement

V - Give

Giving has been associated with increased happiness. Altruism increases with the presence of first four conditions present.

7. Structural Considerations

*Engineering Challenges*⁴⁵⁶⁷⁸⁹

Low Atmospheric pressure: Mars's atmosphere is 100 times thinner than Earth's atmosphere. To maintain a hospitable environment the habitation will need to be pressurized. The resulting pressurization will require the structure to withstand outward forces around 60 kPa (8.7 si)

Health & Safety (Redundancies): To ensure the safety of the inhabitants most if not all of the systems should be redundantly designed. The facility should be comprised of airlocks and interconnected segments, which can be evacuated and sealed in the case of an emergency due to fire or pressure loss. Additionally spaces should be provided for bacterial cleansing for individuals arriving and leaving the facility.

Radiation: Mars's lack of an ozone layer makes inhabitants susceptible to solar and galactic radiation. All habitable spaces should be shielded from radiation rays. The simplest solution is to cover the structure with regolith. On Average sixteen

⁴ (Petrov 2004)

⁵ (Marwaha 2014)

⁶ (NASA 2009)

⁷ (NASA 2015)

⁸ (Lunar and Planetary Institute n.d.)

⁹ (NASA n.d.)

feet (5 meters) of Martian regolith should provide the equivalent protection to Earth's atmosphere.

Distance from Earth: Due to the cost associated with transporting materials, aside from initial survival structures most construction materials should be locally acquired or produced. The use of Martian regolith as both a building material and/or for 3D printed parts would be the simplest to acquire. Additionally communication with earth is delayed between 3 and 22 mins to travel each way.

Dust Storms: Mars is prone to seasonal dust storms. The strongest of these storms top out around 60 miles per hour however due to the planet's thin atmosphere the power of these storms is insignificant. While storm forces aren't much of a problem, the dust particles carried within can coat solar panels requiring regular cleaning.

Gravity: The surface gravity on Mars is 38% that of Earth. While it is possible that the human body will adapt to the new condition over time, it is almost certain that adapting back to Earth's gravity would be impossible. This issue could be avoided altogether via artificial gravity

Energy Systems: Mars science laboratory uses a radioisotope power system – a generator that produces electricity from the natural decay of plutonium-238. NASA/DOE is currently developing small-scale nuclear reactors. These types of power systems have a limited life span requiring resupplying from earth.

Water Systems: The use of a water vapor adsorption reactor (WAVAR), extracts water vapor from the Martian atmosphere.

Oxygen: The lack of oxygen on mars means survival outside of an oxygen-supplied dwelling would be impossible in its current state. An Oxygen Generation System, which replaces water with breathable air, will be used within the facility. The system creates oxygen through a process called electrolysis, which splits water molecules into their component oxygen and hydrogen atoms. Oxygen is released into the air while a hydrogen by-product is recycled into the facilities systems.

Proposed Construction Method

Due to the multiple physical constraints imposed on the building a particular set of construction processes and structures would be required to meet all of the settlements health and safety requirements. This process would include:

1. The production and inflation and or sealing of an internal pressured chamber.
2. The application of a structural framework constructed over the pressurized chamber using local building materials. This would be accomplished by fusing Martian regolith together as a monolithic build.
3. The application of a covering layer of loose Martian regolith as a protective layer from harmful solar radiation.

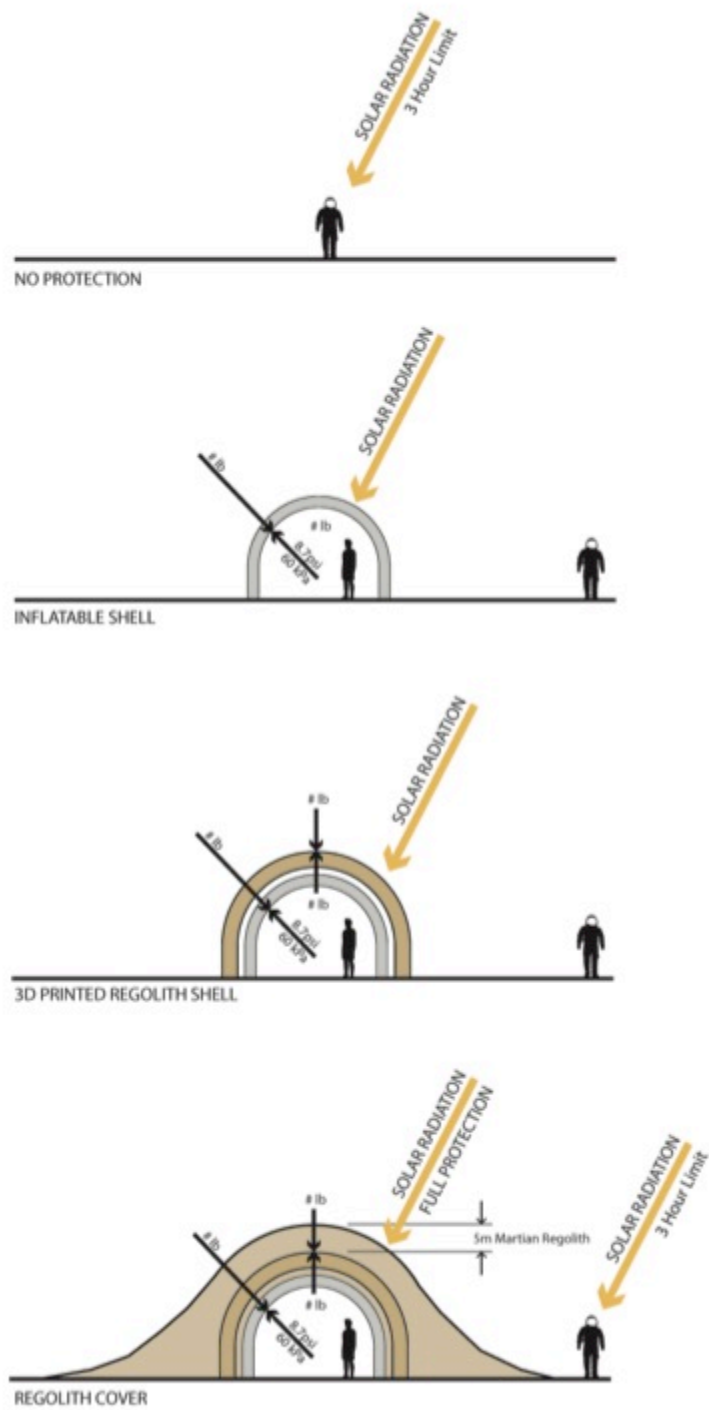


Figure 7. 1: Proposed Construction Process (image by author)

8. Design Strategies

Approach

To assist in the design of a Martian settlement a series of different issues were considered, each using a set of precedents as a guide towards a synthesized solution. These issues range from large-scale organizational principles to more detailed life support systems.

*Settlement & Expansion Strategy*¹⁰

As a permanent research facility, the need to consider expansion due to population growth is imperative. Not only will new residents arrive every 2-4 years but resident families will also have children who will one day seek out their own private homes within and outside the original facility. While there have been multiple examples of settlement communities throughout history one example, the ‘**Law of the Indies**’ - a set of rules for Spanish Colonization has been very influential.

As an urban strategy each colonial city was organized as a square grid rotated at 45 degrees from north to maximize sunlight to the street grid. A central plaza would contain all the public buildings such as religious, civic, and leadership buildings. The street grid extends off the main plaza with residential dwellings organized as blocks.

While the original text details 148 specific rules for establishing a settlement, 21 of these rules helped influence both site selection and the overarching settlement

¹⁰ (Mundigo and Crouch 1977)

spatial organization. Most notably the rules pertaining to: a settlement's location near major resources, orientation to maximize sunlight, centralized public buildings and spaces, and dwellings units organized along major pathways.

Law of the Indies: Urban Planning Rules: (Paraphrased as core ideas)
Rule 39: Site located near water, local materials, land for farming, cultivation, and pasturation.
Rule 40: Do not select high land affected by winds or unhealthy low lands. Rather select medium elevations that get good air and sunlight. Settle town east of any body of water.
Rule 42: Consider adjacent site conditions to be subjected and incorporated into the town's jurisdiction.
Rule 43: Determine size as City, Town, or Village and staff leadership accordantly
Rule 90: First set aside required land for housing. Next, set aside required land for farming and pasturation. Then divide land into four parts: $\frac{1}{4}$ for leadership $\frac{3}{4}$ as 30 plots of land of the town.
Rule 112: Main plaza to be center of town. Either center if landlocked or at waters edge near port if coastal (Plaza to be square or rectangular).
Rule 113: Plaza size is proportional to the number of inhabitants.
Rule 114: Plaza shall have four principal streets, one from each side and two streets from each corner. The entire grid is rotated 45 degrees to minimize extreme winds and maximize street sunlight.
Rule 115: Along four principal streets shall be retail.
Rule 116: Adjust street width for more sun in cold regions and narrower for defense.
Rule 117: Streets from main plaza to maintain axis to assist in urban growth.
Rule 118: Smaller plazas may exist throughout the city.
Rule 119: Temple, Church, or Monastery located off main plaza as its own block.
Rule 120: Leadership and Civic buildings (such as hospital) shall be located off main plaza.
Rule 121: Buildings that produce filth shall be located to accommodate the ease of filth removal.
Rule 126: No building around plaza shall be for private use only public use.
Rule 127: Homes shall be assigned via lottery to settlers starting near the plaza and working outwards.
Rule 129: Inclusion of a town commons for recreation.
Rule 134: Consistency of building types for beauty of the town.
Rule 139: Establish trust amongst diversity of nations, languages, sects and prejudices through acts of friendship and the sharing of beliefs.
Rule 140: Provide access to all individuals to churches and ritualistic spaces to facilitate spiritual growth.

Figure 8. 1: Selected Rules from Law of the Indies (image by author)

9. Architectural Response

Conceptual Design Development

Early conceptual design proposals explored the building forms in both the field and hillside condition. Goals included maintaining a central community space, which could be accessed by individual dwelling units, the inclusion of either a solar or regolith shielding skin, and ways to create external views. Ultimately these design explorations lead to the simple conclusion that a hillside parti would produce the greatest benefits regarding constructability. Using the extracted material from the hill the Martian regolith could be filtered, treated, and re-used as a 3D printing material throughout construction.

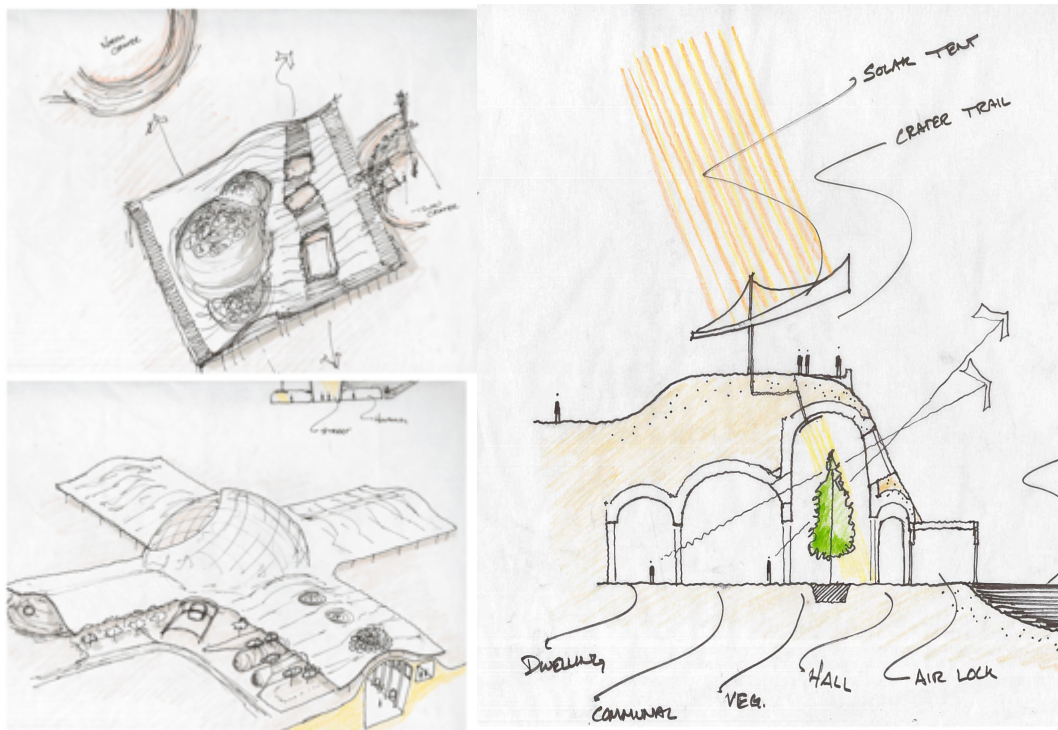


Figure 9. 1: Concept Sketches (images by author)

Within the structure itself the community center was conceived as the social, economic, and recreational hub for the entire settlement. Facilities would include multiple walking parks for physical and mental stimulation, a communal fishery as a source for protein, and a central market plaza with pop-up stall space for trade.

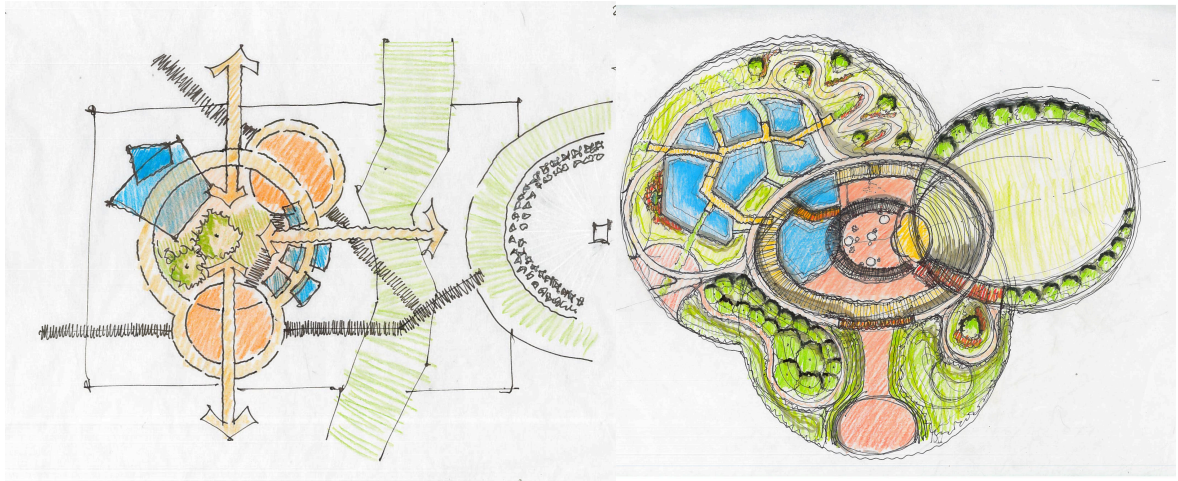


Figure 9. 2: Concept Sketches (images by author)

Sublime Landscapes

Outside the physical dwelling itself the exterior experience was constructed to create a self-referential identity based on environmental themes of the sublime.

Within the context of the mesa valley itself the building supports a visual language of being in concert with the surrounding hills. Settlers will be able to find comfort in knowing their dwelling is proportionally equivalent in visual size to the landscape surrounding it. The surrounding hills on the other hand offer the opposite experience. When walking through the hills the experience is that of a landscape dominated

environment where settlers sublime landscape and distant mountains reminiscent of paintings harking back to westward expansion within the United States.

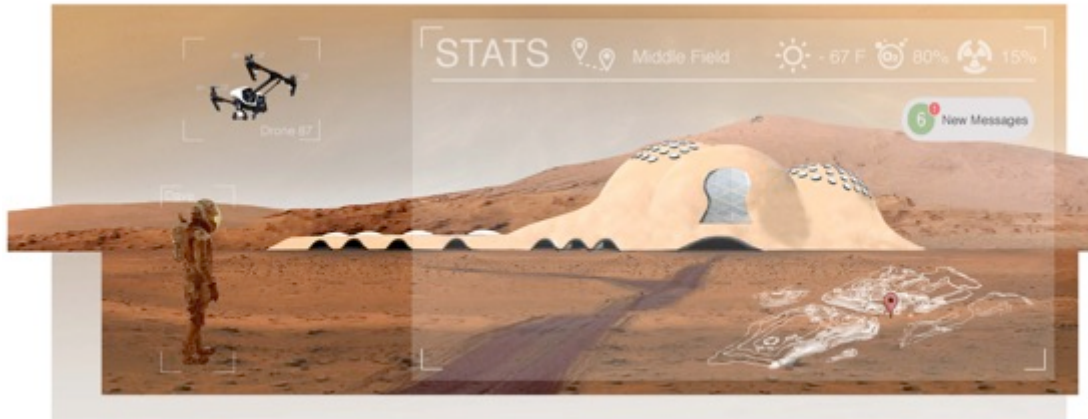


Figure 9. 3: View from Middle Field (image by author)



Figure 9. 4: View looking south over North Crater (image by author)

Design Proposal – Master Plan

The master plan of the main settlement building illustrates both the connectivity and the segregated nature of the different programmatic elements. The main community hub acts as both the receiving anchor from the building's main entrance and a central connection to both the dwelling and working spaces within the building. The southern wing of the building includes a series of research laboratories, vehicle bay, and fabrication shop, all of which can double as both working and educational spaces within their respective disciplines. The northwestern extension is made up of a series of vertically sunken courtyard apartments, which serve as both the main living and food production spaces within the settlement.



Figure 9. 5: Social Gathering Locations (image by author)

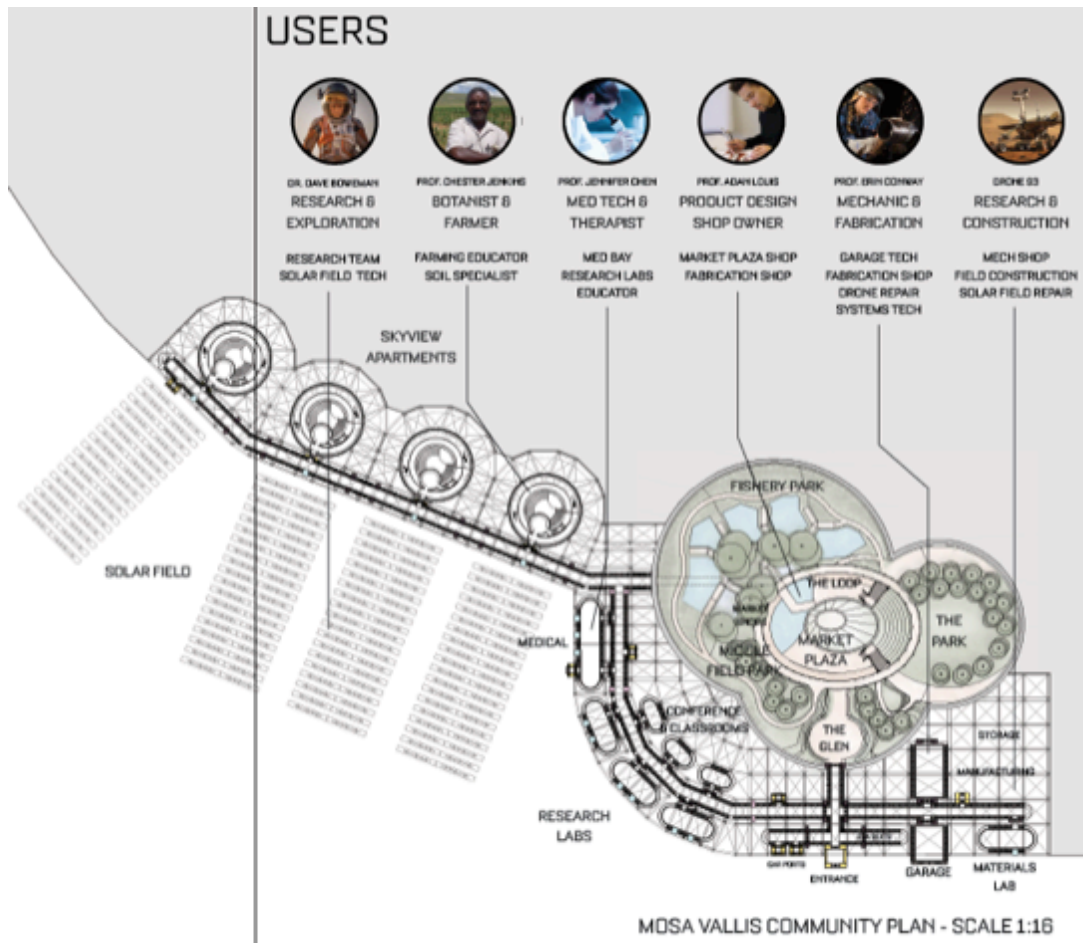


Figure 9. 6: Settlement Main Building Plan (image by author)

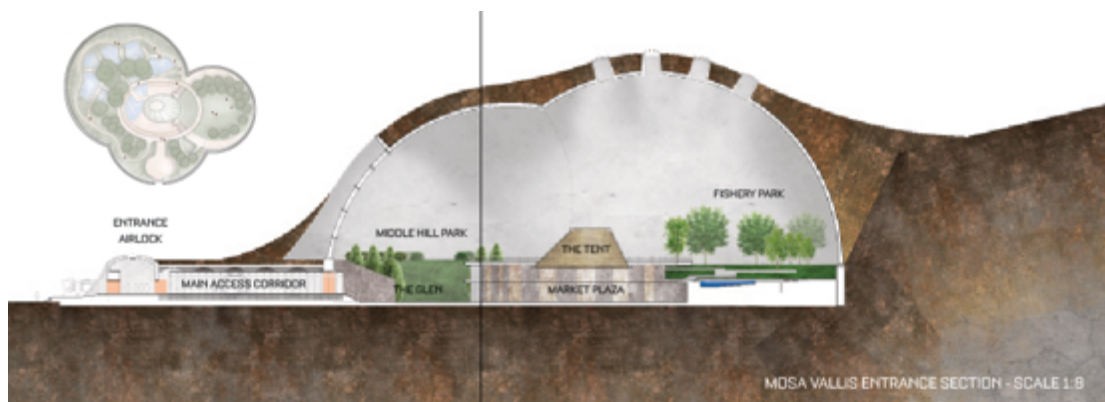


Figure 9. 7: Settlement Main Building Section (image by author)

Design Proposal – Dwelling Design

The residential dwelling design itself is organized to accomplish three major goals: to create a sub-surface structure to protect against radiation, to provide a communal farming location allowing residents to take ownership over their food production and to provide multiple spaces for social interaction both within and around the farm itself.

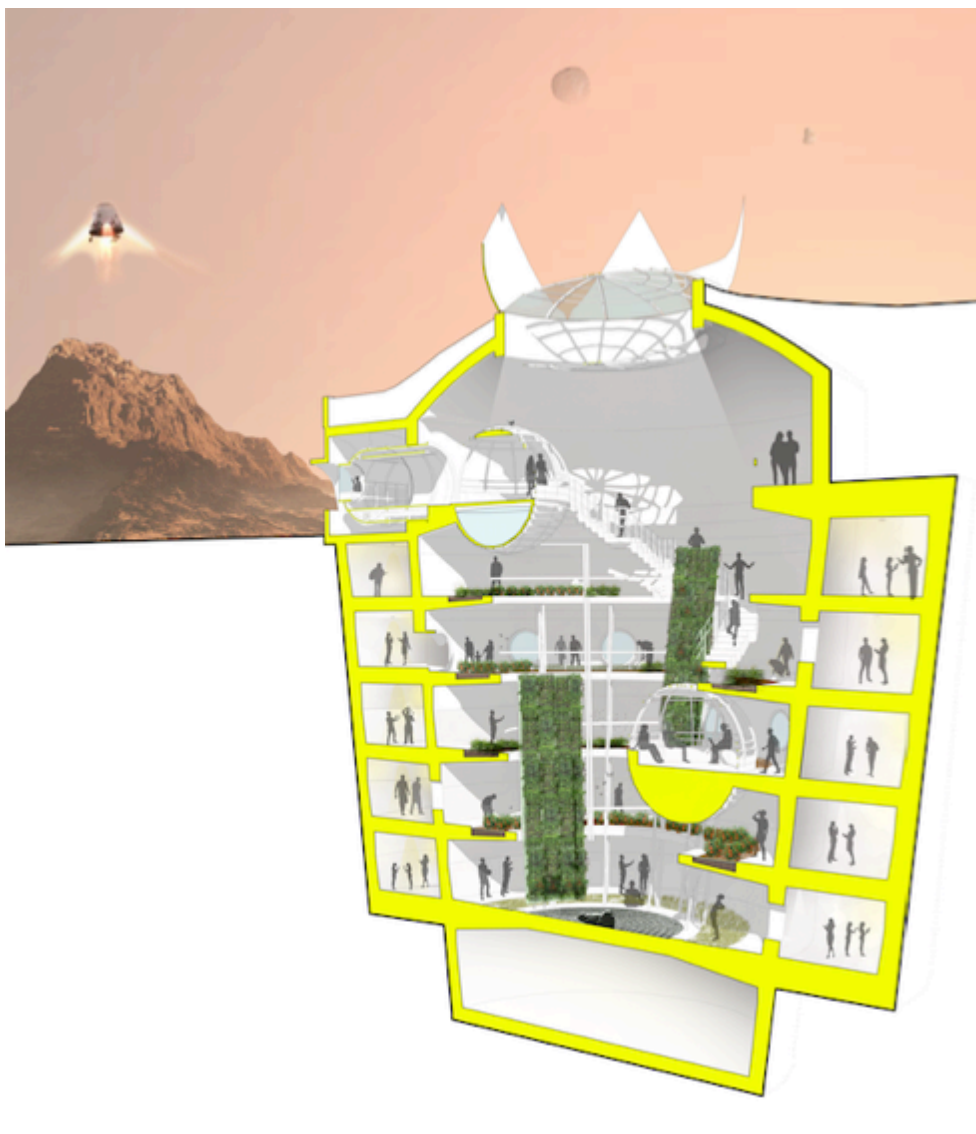


Figure 9. 8: Residential Dwelling Section Perspective (image by author)

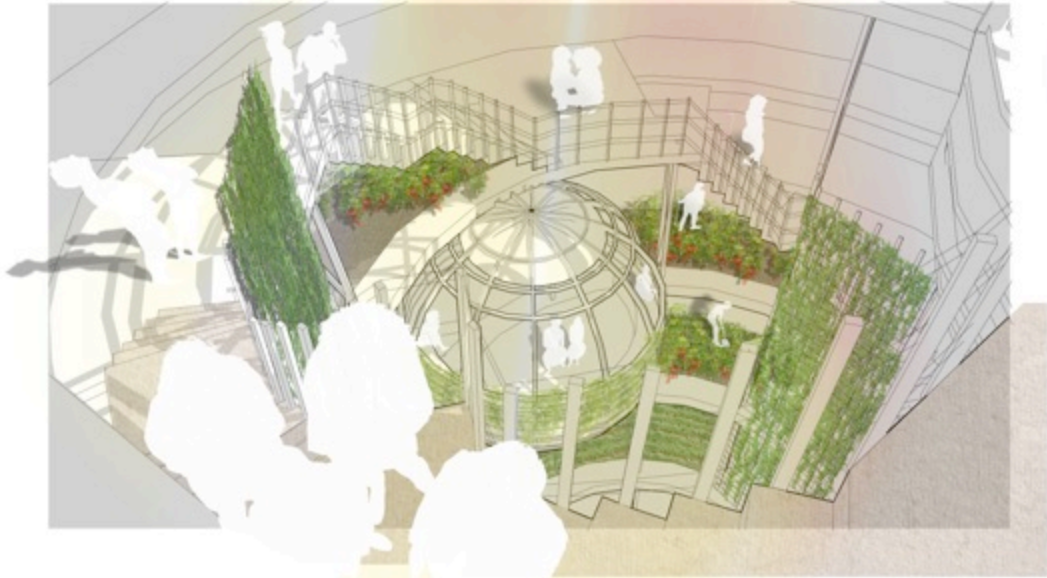


Figure 9. 9: View Looking Into Vertical Farm Courtyard (image by author)

A central ramping surface spiraling around the main courtyard serves as both vertical circulation and over 9000sq ft of farmable surface area. Within the central space a main access stair meanders between vertical structural trestles allow high oxygen producing plants to produce breathable air for the settlement. Cool air circulates along the ramp itself being blown out over the plants. This creates both resilience with in the plants themselves and creates the illusion of natural breezes, a calming element for the settlers mental health. Hot air flows up towards the space's main solar skylight before being processed through returns. The skylight itself is constructed as a double paneled oculus, which is filled with radiation neutralizing gas allowing for constant

views out into the sky. Above the skylight itself four large petals act as a sealable cover which will protect the glass in the event of a dust storms. On clear nights the petals will remain open allowing settlers to stargaze.

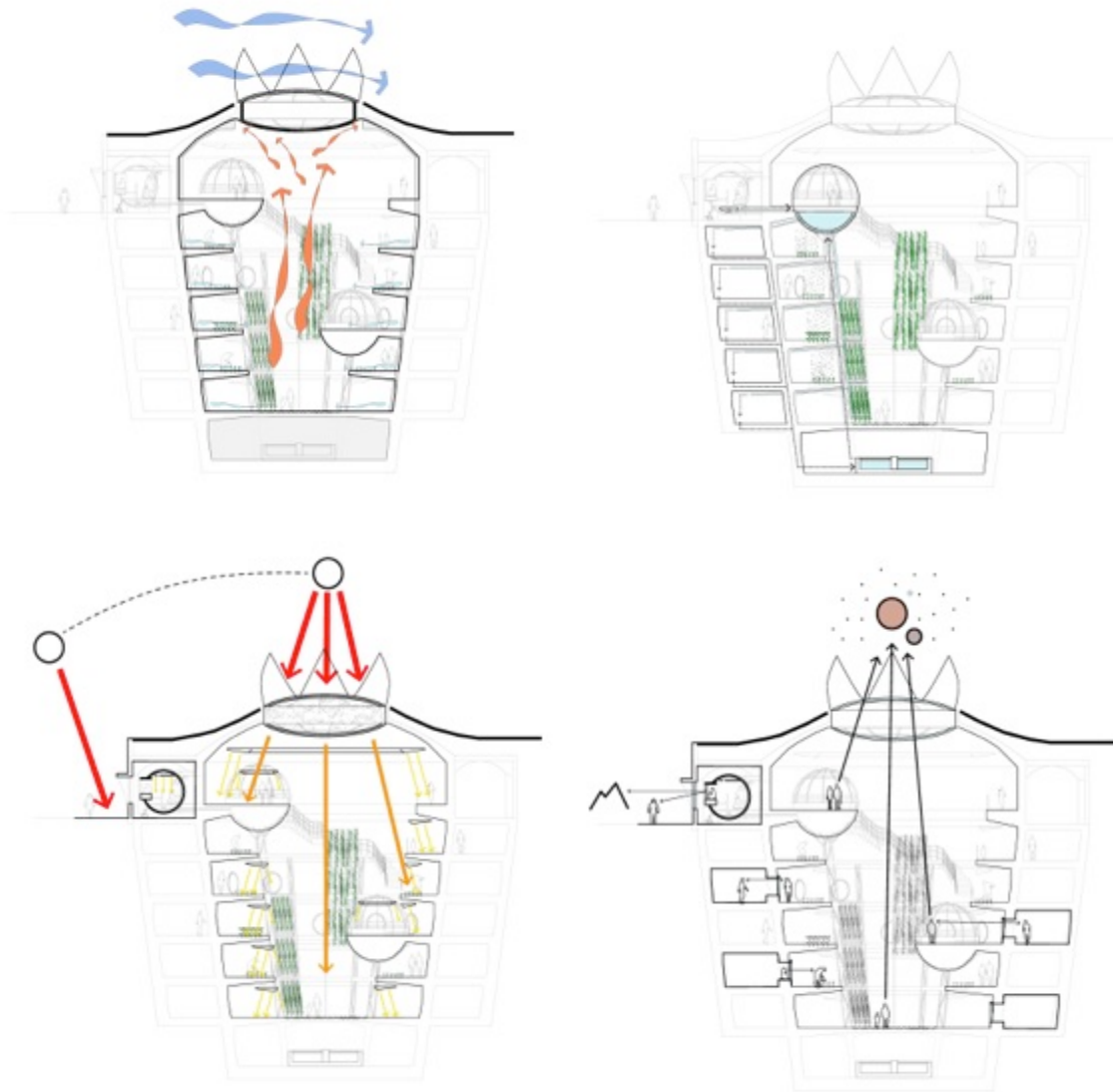


Figure 9. 10: Residential Systems Design (image by author)

10. Conclusions

Design Conclusions

Designing for a permanent settlement on mars is a multiple faceted undertaking. It requires the holistic application of an environmentally shielded skin and structure, a closed loop ecological system, and the development of multiple levels of private and socially activated spaces. It is only with this combination of both embodied system design and attention to social and emotional needs that a permanent settlement on mars could activity sustain and thrive.

Presentation Conclusions

As a concluding aside during the final public review of this thesis multiple points were raised about what the style of the internal environment of the main community plaza. Positions were taken for both an extremely minimalistic environment made to harden the resolve of the settlers and that of a paradise garden. It is the position of this thesis that it is not one or the other but rather both. That in addition to the importance of a centralized community space there is the potential for a series of emotionally and physically “hardening” and “softening” environments meant to assistant in the conditioning of settlers.

Glossary

Regolith – The layer of unconsolidated rocky material covering bedrock.

In-Situ (Material) – Material mined or collected in its original place.

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