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Anthropocentric Habitation of Mars Through Parametric Design

Logan A. Miller[1*]
University of Houston, Houston, TX, 77004

Chris Hisle[2*]
University of Houston, Houston, TX, 77004

Erin Quigley[3]*

University of Houston, Houston, TX, 77004

Chi Lan Huynh[4*]
University of Houston, Houston, TX, 77004

Mars has been a central subject of the space exploration discussion for decades. The Red Planet is an atypical destination, offering humanity a location to study the rudimentary stages of microbial life, as well as implement a greater understanding of how the evolution of the planet's surface can influence the future of our civilization. Conditions on Mars are severe, yet livable. The proposed mission ARES (Architectural Research Expedition of Space) seeks to capitalize on the habitable aspects that the planet offers and develop a sustainable solution regarding humanity's first manned mission to Mars. Comprised of autonomous and human-centered operations, ARES is a thirteen-year expedition with the intent of establishing and constructing a permanent, self-sustaining colony.

A system of three interconnected phases enables ARES to accommodate an initial crew of seven after the proposed site, Valles Marineris, has been readily prepared. Innovation in the 3D printing processes will provide a higher standard of living that limits the effects of radiation while establishing a suite of necessary amenities. This, in conjunction with several preconstructed temporary habitats and greenhouses, provides a system through which Martian crews can conduct a plethora of scientific studies while maintaining a healthy psychological and physiological state. The projected outcome of the mission will see an environmentally protected Martian colony that is prone to expansion and additional crewed missions to Mars.

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[1] Graduate Student, Sasakawa International Center for Space Architecture, 2525 McCue Road.
[2] Graduate Student, Sasakawa International Center for Space Architecture, 1234 Delano St.
[3] Graduate Student, Sasakawa International Center for Space Architecture, 4444 Cullen Blvd.
[4] Graduate Student, Sasakawa International Center for Space Architecture, 4200 Martin Luther King Blvd.
[*] All authors contributed equally

I. Introduction

Architectural Research Expedition of Space (ARES) was formed with the intent to provide a solution for humanity's first self-sustaining colony on the Martian surface, while implementing numerous innovations in the extraterrestrial architectural design process. Mars itself is a suitable location for a long-duration mission due to the scientific interest that the planet intrinsically holds, as well as the degree of accessibility when considering water-ice and hydrated minerals beneath the surface. The proposed mission utilizes new 3D printing technology, advanced hydroponic and fertilization methods, and comprehensive ISRU (*in-situ* resource utilization) strategies to achieve an ideal level of symbiosis. The intricate disposition of ARES naturally yields an unmanageable concept of operations if not handled properly. However, a simplification of the mission into three digestible phases generates a systematic methodology for problem-solving, thereby alleviating a large degree of the mission's complexity.

A thirteen-year mission (Appendix I, Fig. 1) tasked with supporting a crew of seven on the surface of Mars presents a plethora of challenges, as well as opportunities for the advancement of humankind. Provided, the project was conceptualized to be challenging, per the parameters of RASC-AL (Revolutionary Aerospace Systems Concepts Academic Linkage). An institution developed to serve as a threshold between the academic and corporate domains, RASC-AL published a competition with the goal of enabling a crew of at least four individuals to remain on the surface of Mars for a minimum of seven years. The first crew landing is to be scheduled between 2035 and 2040. The mission architecture should be designed around the requirement of demanding no more than 5,000 kg of re-supply cargo every two years after the crewed mission commences.

In response to an extended mission timeline of seven years, crucial information regarding how the human body responds to isolation will be a defining aspect of future psychological and physiological research. Furthermore, continued research on microbial life and the botanical process in extreme conditions will open new avenues of understanding for how life can be sustainable outside of Earth.

A significant amount of research regarding the aforementioned scientific fields has been accomplished in the last century. Dr. Sheryl Bishop's work involving isolated and confined domains has paved the way for a new standard of living for space and arctic habitats in the twenty-first century (1). Dr. Steve Hoffman and space architect Larry Toups' research of Jezero Crater and the surrounding landscape of Mars enabled a successful 2020 Perseverance mission, as well as an elevated perception of how ISRU can be efficiently utilized (2). Yang Ju Im's development in splicing organisms to boost their tolerance in extreme environments has since been used to grow plants on the International Space Station (ISS) with greater consistency (3). Finally, ICON's work in 2020 has opened a new design process when considering analog habitats (4).

The novelty of the ARES program is the scale by which the expedition operates to be successful. There are several elements that contribute to this immense scope: the unprecedented length of time for an extra-planetary mission, the integration of ISRU with imported Earth materials to minimize payload mass, the methods and efficiency of the proposed 3D printing process, and the bioengineering approach to produce a cultivation system needed to sustain a crew on the surface of Mars for seven years.

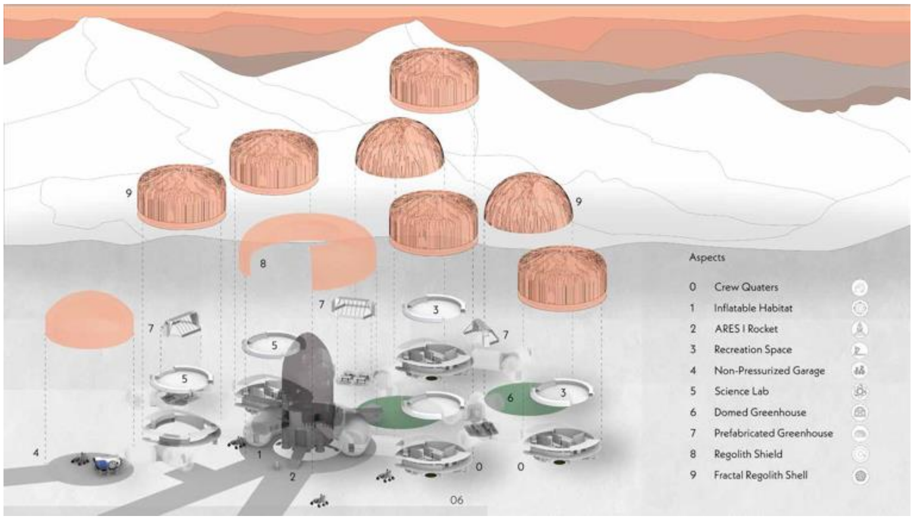

Figure 1. ARES Base

II. Mission Critical Design Considerations

Since no human has spent more than two years in space, an astronaut's mental and physical well-being has driven the majority of the planning and research for this project. Designing from the human factors perspective, especially for a seven-year surface stay on Mars, requires careful attention to the following topics:

1) Radiation Exposure
2) Isolation and Confinement / Distance from Earth
3) Homesickness
4) Hostile Environmental Concerns
5) Gravity Impacts

The ARES mission addresses these issues through design and application. Physical and mental health is addressed most prominently through the permanent surface habitat (Section VI). Thick exterior walls protect the astronauts from radiation exposure and implement biophilic patterns to combat the psychological effects of homesickness. The interior considerations of the habitat tackle the effect of isolation and confinement through flexibility and the personalization of internal space, as well as an integrated circulation system to encourage physical activity. Finally, the impact of a reduced gravitational effect is addressed through the rocket design (Section IV).

An astronaut's sleep could be severely impaired during this mission, causing rifts in their circadian rhythm. Though a Mars day is only 37 minutes longer, compared to that of Earth, the psychological damage this discrepancy could cause on a long-duration mission is immeasurable. Team communication and understanding of one another will be crucial to negate some of these detrimental effects. The habitat design reflects this by introducing communal living that enables each astronaut to have a sense of independence.

Throughout the ARES missions, the crew will experience three distinct gravitational fields: 1g on Earth, microgravity during the transit in space, and one-third gravity on the surface of Mars. On the six to ten-month trip, bone density loss can occur at an average of 1-5% mineral density per month and may not be correctable after rehabilitation. Additional issues, such as impaired vision, will likely occur due to the accumulation of fluids. Kidney stones often spawn due to dehydration and an excess of calcium excretion on the bones. The greenhouse design and food considerations observe how some of the medical concerns, especially dehydration, could be neutralized through proper nutrition (Section VII). Astronauts could experience impaired spatial orientation, poor hand-eye coordination, and motion sickness. Furthermore, crew members can experience post-flight orthostatic intolerance, causing them to faint when standing (5). For this reason, up to two weeks of rest time will be allotted immediately after arrival to Mars, allowing the astronauts to adjust to the new environment.

Mars is an average of 140 million miles from Earth, with communication delays of up to forty minutes. The team will need to be self-sufficient, resolving many issues without the assistance of Mission Control (5). Each member will need to be trained in medical assistance for all basic and life-saving measures. An odd number of astronauts per crew was chosen to prevent any split decision-making, should a conflict arise. The first mission will comprise of one surgeon, one medical professional, one pilot skilled in electrical engineering, one engineer, one pilot skilled in mechanics, and two field scientists skilled in biology and geology, for a total of seven astronauts.

III. Site Selection and 2030 Mission

The process of evaluating and determining a location that will actively contribute to the success of a mission is paramount. Aspects such as average temperature, accessibility of sunlight and water, the probability and severity of dust storms, and regional scientific interest all contribute to the overall grade of a site (Appendix II, Table. 1). After considering these factors, Valles Marineris, the largest canyon in the solar system, has been identified as an ideal landing site and exploration zone for the ARES missions due to the following reasons:

1) Elevated likelihood of water: The discovery of unusually high levels of hydrogen in the center of Valles Marineris by the ESA-Roscosmos ExoMars Trace Gas Orbiter (2021) has led to the theorized existence of water, water ice permafrost, and/or large quantities of highly hydrated minerals buried in the ground of the canyon (6). This is of great significance for the scientific exploration of Mars and it may provide essential information about the planet’s history and evolution, as well as its potential for sustaining life.
2) Sufficient Earth-like lighting conditions: The canyon’s location along the Martian equator provides ample amounts of sunlight for astronauts, a necessary standard of living to achieve psychological well-being during a seven-year mission. Architecture has historically provided adequate lighting in dwellings to give occupants physiological and psychological comfort. In space architecture, the significance of lighting is more critical due to the lack of engagement with the exterior environment (7). The addition of a cupola on the ISS has

given astronauts a feeling of joy and operates as a cradle, a retreat. Moreover, visually observing Earth, a scene that is familiar, combats the feeling of isolation and homesickness (8).

3) Radiation protection: The Martian atmosphere provides various thresholds in terms of shielding the surface from Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE), depending on the elevation level. Valles Marineris capitalizes on the few benefits that a thin atmosphere can provide. As an example, the average surface pressure of the planet is 0.6 kPa, while the pressure in Valles Marineris is over 1.2 kPa (9). Furthermore, Valles Marineris' extreme canyon floor depth of 7 km creates deep shadows and caverns, which provide additional radiation shielding (6). Hydrated regolith present in Valles Marineris also has the capability to provide additional levels of protection (10).

A. Mars 2030 Mission

Phase One is comprised of two uncrewed missions. The first mission, scheduled for launch in December 2030, entails the delivery of three rovers to the designated landing site: the central region of Valles Marineris at approximately 7°S and 72°W. These rovers are to conduct a series of site surveys, verify the presence of water and/or hydrated minerals, and initiate the extraction of water.

Water is an essential component with regards to 3D printing, maintaining a crew, extravehicular activity (EVA), and propellant consumption (9,11). Since the Martian atmosphere is extremely arid and contains less than 0.03% water vapor, extracting water from the Martian regolith should be considered the primary option. This can be achieved through two main steps: excavation and extraction.

The excavation system is based on lunar concepts. The water concentration in the Martian regolith ranges from 3-40% across different regions. Though the regolith in Valles Marineris is believed to be highly hydrated, to be conservative, the amount of regolith needed is approximately 8,438 tons, 3% water content. As of now, the ECLSS recovery rate on the ISS stands at approximately 93.5%. However, for extended missions such as ARES, astronauts will require ECLSS systems that can recover up to 98% of water (12).

The water extraction unit is modeled after the Hydrogen Reduction Reactor for lunar oxygen production. This system includes an inlet/outlet hopper, inlet/outlet auger, two regolith reactors, two gas clean-up modules, and two water condensers. After the regolith has been collected, a temperature of over 330ºC is needed to aid in the desorption process. Subsequently, the water and inert gas mixture are passed through a gas clean-up process, thereby eliminating unwanted contaminants. Finally, the water is collected on a condenser and cooled by a cryocooler (13). A similar process was researched in 2020 by Dr. Hoffman and other NASA scientists, deemed the Rodwell experiment (14).

IV. Mars Ascent and Return Shuttle

The ARES I mission constitutes the second half of Phase One, scheduled to launch in the following three years after the 2030 enterprise. Marsh Ascent and Return Shuttle (MARS) will carry nuclear reactors, deployable robotic systems for 3D printing, preliminary supplies, and prefabricated greenhouses to the selected site (Appendix III, Fig. 1). The primary function of ARES I is to test the safety of the entry and descent (EDL) of MARS before the first manned mission in 2035.

A. ARES I (2033 – 2035)

ARES I, and subsequent missions, will follow a powered Hohmann transfer trajectory from Earth to Mars. Final assembly and check out will be done at Lagrange Point 1 (L1), situated between Earth and its Moon, allowing for a safe installation and testing process of the nuclear reactors. The interplanetary transit will be performed using Nuclear Electric Propulsion (NEP). NEP consists of eight NASA Evolutionary Xenon Thrusters (NEXT-C), a model previously utilized on the Double Asteroid Redirection Test (DART). The performance of eight thrusters working in parallel will produce about 1.9 Newtons of thrust, with a specific impulse of 4,190 seconds (15). A metric that is sufficient to provide the required total impulse in approximately twenty-five days. The ion thruster, NEP, will only be used for interplanetary transit; methane-powered chemical rocket engines will be used to establish a highly elliptical orbit.

The hybrid propulsion method was deemed necessary due to the need to have the thrust for both descent and ascent to and from the Martian surface. Thereby, a chemical rocket engine with an equivalent thrust to weight ratio, as well as the need to reduce fuel mass for the interplanetary cruise, required a highly efficient drive system. The chemical propulsion engines were elected as the best option because of their ascent capability from the surface. Four SpaceX

Raptor engines provide the necessary propulsion to launch the required wet lift mass of the ARES vessel; that being a 4.8 thrust-to-weight ratio at lift off from the Martian surface (16). In addition, the chemical engines will be necessary to avoid the tendency of "spiraling" in and out of Earth and Martian gravity wells, allowing for the NEP to take over at higher orbits. Overall, the chemical propulsion will be responsible for 4 km/s of Δv.

The NEP system takes advantage of the need to have a reliable power source once on Mars; the reactors for this system will be reused as surface power. In transit, the highly efficient gridded ion thrusters provide the remaining 6 km/s of Δv required to make the trip from Earth to Mars. The use here of NEP is not to shorten the transit duration, but rather to reduce the total fuel up-mass of the rocket. The required fuel mass when using the ion thrusters is approximately 1/3 the amount that would be needed for an exclusively chemical rocket. This is what enables a landed payload of 137 metric tons in a single vehicle.

For ARES I, the primary payload is the materials required for constructing the habitat and greenhouse, including 3D printing equipment, prefabricated greenhouse components, and power distribution instruments.

B. Entry and Descent

Chemical rocket engines will fire to start the entry phase from the parking orbit. Once the ARES rocket approaches the Martian atmosphere, all deployable radiator panels and solar panels will be retracted, allowing for a Hypersonic Inflatable Aerodynamic Decelerator (HIAD) to be deployed and inflated. Thereby protecting the vehicle during its initial entry into the atmosphere.

Once the vehicle has slowed from hypersonic speeds, the HIAD is deflated and retracted back into the spacecraft. Simultaneously, three supersonic parachutes are deployed to slow the rocket and stabilize its trajectory. The primary descent and landing are handled by the four chemical rocket engines, burning from the retraction of the HIAD to touchdown on the surface. From the start of descent to touchdown, approximately 300 metric tons of fuel will be used. The combination of a powered landing and stabilization through a parachute provides a landing accuracy within one hundred meters of the desired site.

C. Temporary Habitat: Power and Energy Outputs

After ARES I lands, secondary solar panels will open to provide power and allow pre-positioned rovers to move the reactors off of the spacecraft towards the reactor farm. The reactor farm is designed to provide power for the initial base construction phase and 3D printing.

The temporary habitat consists of inflatable modules, akin to NASA's TransHab project (17). The system will be decompressed and packed within the ARES I MARS vessel. Upon arrival, the system will be inflated and promptly linked to airlocks aboard the ARES I rocket and future permanent habitat domes. The interior will be equipped with personal crew quarters and essential amenities including hygiene, dining, living, exercise, medical, and scientific laboratories, to ensure a higher quality of living.

The temporary habitat will present the crew with interior pressure conditions comparable to that on Earth, five to ten tons per meter squared (50 to 100 kPa). Following the inflatable portion of establishing the temporary habitat, a thick layer of Martian regolith will be spread across the surface of the structure to provide additional radiation shielding. Martian regolith has a density of approximately 1,500 kg/m3, equivalent to 523 kg of soil pressure per square meter. As a result, the inflatable habitat can support up to 19 meters of Martian regolith (17). Supplementary research has revealed that a meter of regolith can provide adequate shielding against both SPE and GCR (17). Once deployed, the robotic arm equipped on the ARES I rocket will begin to 3D print a 1.5-meter regolith shield over the temporary habit. The crew will continue to live in the ARES MARS vessel during this time period of two to four weeks. Once constructed, the crew will expand their base of operations by over two hundred percent in total area. The temporary habitat will serve as the crew's home for over six months, as the permanent habitats will continue to be constructed during this period.

The ground systems for the habitat will initially consist of communications and 3D printing apparatuses. Once occupied, the habitat will be supporting a crew of seven, similar in size to the current International Space Station, which requires 76 kW in normal operation (18). The operation of the 3D printing technology by itself can be assumed to require less than the life support systems. This power will be provided by the eight nuclear reactors aboard ARES I. The selected reactors for the ARES vehicle, and subsequently for power production on the surface, is the Kilopower Reactor Using Stirling technology (KRUSTY), which will provide 10 kW of electrical power per unit (19). Prior to the crew occupying the base of operations, reactors will need to be transported to a remote site for safety protocol. These reactors will ultimately be added onto by the set of reactors carried on-board the ARES II flight. This will eventually provide a full 80 kW of power for surface operations. The reactors will be deployed a minimum of 500 meters away from the habitat location, with a distribution box deployed to connect the reactors to a grid. This is an essential step that generates the ability to transmit power back to the base of operations along a 500-meter cable. This cable will be put in position by a rover on its return trip to the base. Further study is required to determine whether the reactors can be operated at the base while it is uncrewed, or if the relocation must happen remotely before crew occupation. Supplies from ARES I will consist of materials and equipment for habitat construction; as a preceding mission, no food will be on board apart from one year's worth of emergency rations for a crew of seven (shelf stable rations similar to survival food on Earth). All cargo volume and mass not consumed by the construction equipment and additional materials will be used for spare parts as well as additional spares for the life critical equipment on board Ares I.

V. 3D Printing Techniques

Surviving sustained radiation exposure is the primary roadblock when pioneering life on Mars. NASA implements ALARA (As Low as Reasonably Achievable) as the standard of limiting radiation exposure, with a career maximum of 600 mSv (9). The CO_2 in the atmosphere of Mars may provide sufficient protection from Galactic Cosmic Rays and solar flare protons (20). However, astronauts bound for Mars will still experience a substantial amount of radiation exposure during the six-month transit from Earth to Mars, thereby effectively reducing the amount of radiation that can safely be absorbed while living on the planet's surface to a maximum of 300 mSv (21). For this reason, additional radiation shielding is necessary, particularly for long-term settlement. Local resources, such as Martian regolith, can serve that supplementary role. Combining functionally graded materials (FGM) with regolith will produce an inherently robust compound that can be 3D printed.

FGMs add natural illumination to a structure through the properties of their chemical makeup, which consists of a ceramized geopolymer concrete (GP) that shares structural properties comparable to that of transparent glass. Mechanical joints and chemical bonds of traditional adhesives do not guarantee a seamless seal, an aspect that is crucial for pressurized habitats. Furthermore, FGMs will not require leakage maintenance.

Researchers at Penn State University conducted experiments on improving FGMs in 2018. Their studies mixed GP pastes with glass sheets and aqueous activators, heating the formed material to 850ºC (Appendix II, Table. 2) (22). The results indicated that the interface between the concrete and transparent glass was smoother when the initial materials had similar coefficients of thermal expansion (CTE). Additionally, the tests found by increasing the number of layers for a given length of a structure, while making precise incremental changes to the material composition, the significant volume expansion between layers can be reduced, thereby minimizing the likelihood of crack formation (22). The research also found that by adding trace amounts of glass powder, a minimum of 5%, to the GP-rich layers, additional strength can be garnered to further prevent cracking between surfaces (22). The majority of components of the GP paste are SiO_2, Al_2O_3, CaO, Fe_2O_3, MgO, and SO_3, which are available for harvest on Mars' surface (10).

A. Printing Method

Printing of the first habitat dome will begin prior to the astronaut's arrival to reduce the dwelling period in the temporary habitat. The ARES I rocket carries a detachable robotic arm that has been designed to independently reach a maximum distance of 25.85 meters from the rocket with no external assistance. This distance is sufficient for the outer bounds of the habitat domes. The robotic arm contains two separate nozzles. One nozzle releases regolith mixture one (M1), while the other releases regolith mixture two (M2). A predetermined pattern that emulates fractal geometry found in nature is encoded in the 3D printer's algorithm (Appendix IV, Fig. 2). The interlacing regolith mixture boasts intrinsic transparent qualities that allow the passage of ambient light to filter through the constructed dome. Fractal-like patterns create the illusion of a tree canopy, with tree-like trunks descending along the vertical sides. The biophilic pattern provides astronauts with a form of relief from the desolate landscape by introducing organic forms that they are accustomed to on Earth.

Each regolith mixture requires a different infill methodology. Using parameters for 3D construction methods for Earth homes, the nozzles will have the capacity to print a layer width of 30-300 mm. The thickness of the dome wall was determined to be 1.5 meters for optimal radiation shielding. This would indicate needing five to fifty horizontal layers per vertical layer. The opaque regolith mixture (M1) will print the outer and inner shell surfaces connected by a minimal, yet structurally sound, lattice pattern. The voided space will then be infilled with loose regolith that has been ground, but not processed, with the binding material. The more translucent regolith mixture (M2), however, will be printed with the full five to fifty iterations depending on the size of the nozzle, so as to not interfere with the translucent properties.

The rover will excavate the regolith material and transport it to a specialized refining assembly. Once there, the regolith will undergo a process, whereby large chunks are to be broken down into a finer material. Finally, the refined regolith mixture will be transported to an electric mixer stationed in the ARES I rocket. The mixer utilizes concentrated microwaves to blend the regolith mixture to the desired consistency before being pumped up to the location of the 3D printing nozzles. A series of programming languages will be employed to remotely control the 3D printing system from Earth, as well as predetermining the complex toolpath for the robotic arm (23). Given the significant delay in communication with Earth, the process will proceed at a measured pace.

VI. Erecting a Permanent Habitat

Phase Two begins with the inaugural manned mission to Mars, ARES II in 2035. The second ARES mission is scheduled to land 1.5 km southeast of the designated ARES I location. After the crew arrives, the initial habitat connected to MARS will serve as the base of operations for the first several months. The walkable distance of 1.5 km provides the crew with maximum flexibility and redundancy. If the pressurized rover fails to operate as expected, the crew can walk to the designated habitat location.

The presence of humans on site will expedite the construction process for the permanent habitat. The crew outfits the first regolith dome and assembles airlocks, eventually moving into their new Martian home. The initial temporary habitat is turned into a scientific laboratory, while the rocket will be the main central hub for restrooms, storage, and experimental spaces. The crew is not encouraged to spend much time in the rocket as aluminum and polyethylene become less effective methods of radiation shielding on Mars' surface (24).

The diameter of each dome derives from the constraints of the robotic 3D printing arm. Since printing begins before the arrival of the crew, the arm needs to reach the outer boundary of the dome without assistance. Therefore, each dome is 18 m in diameter. One and a half meter thick regolith walls allow for 14 m, in diameter, or 153.94 m^2, of livable space. The floor is recessed into the surface by 1.5 m for additional structural supports and stands at 8.2 m above the surface. The three main drivers of habitat design were nature, circulation, and functionality (Appendix IV, Fig. 4).

A. Circulation

Typical planetary schedules include four Extra Vehicular Activities (EVA) a day, at 45 minutes each (25). This equates to 23%, on average, of crew members' active hours, assuming eight hours of sleep. An individual's schedule will vary over time, with mission planning accounting for 24 hours of EVA per week (25). Ultimately, this leaves 112 hours to be allocated inside the proposed habitat space. Extended circulation routes were integrated into the design of the permanent habitats to combat cabin fever. The circulation inside the dome creates a space that enables varied pathways, promoting physical and mental well-being. The flexibility of interior space is crucial for a mission whose duration is multiple years. Priorities of the mission will inevitably change over time, allowing the surrounding environment to adapt, along with the crew members themselves.

The layout of the typical dome (Appendix III Fig. 3) consists of two full height floors and one mezzanine. The mezzanine provides three points of egress leading towards another habitat dome, greenhouse, or a safe means to exit onto the surface of Mars. Horizontal and diagonal notches are designed to be left vacant in the interior wall section to allow for multiple configurations of the ramp system. This system is intended to provide the crew with multiple levels of egress within the dome itself. The circulation ramps can be laid in multiple configurations due to the aforementioned notches. Thereby enabling an additional level of flexibility to suit the unique needs of each dome. The inner wall promotes the primary circulation route, emphasizing the 3D printed fractal patterns, thereby giving crew members the impression of a leisurely walk in nature.

The circulation design driver challenges the traditional approach of configuring the standard geodesic domed massing of previous extraterrestrial habitation designs. Through elevation, a series of iterations assesses the pressurization of the volume. That being methods of standardized domed masonry and the vertical space required for a walking path. The ideal form for a habitat is a half sphere resting atop the surface of the landscape. A perfect sphere, however, limits the extent through which the circulation ramp can access the upper levels. This is due to the walls' innate desire to curve at a steep angle. Instead, vertical walls that support a domed roof help to maintain the proper level of pressurization, while providing adequate space for creative measures, such as a circulation ramp, to succeed (Appendix IV Fig. 3).

B. Interior Considerations

The lower level of the habitat consists of four private quarters. A single corridor separates the center of the space into two groups. Each room has three walls: the curved exterior wall, a fixed wall, and a flexible wall (flex wall) separating the room from the corridor (26). The flex walls enable breathability, as well as a level of variability within private spaces. Should all the walls be fixed, the effects of claustrophobia could be substantially amplified, negatively impacting the mental health of the crew. Furthermore, flex walls invite the aspect of individuality within each crew members' room. Subtle shifts in the physical makeup of a space have the tendency to disrupt the monotony of linear circulation paths. Another way that the mental health of crew members can be elevated. The flex walls are attached to a prefabricated grid below the ceiling, enabling a wide degree of freedom within the grid lines. Fixed walls are placed between the rooms to significantly reduce the possibility of tensions over allocated space. Finally, the outer curved walls provide a splash of ambient light into each of the rooms.

The furniture for each room comes prefabricated from a standard ISS rack. A single rack will be emptied and reused as a door and as an anchor for the flex and fixed walls (Appendix 3, Fig. 4). In total, four racks will be used for each dome. Each room will have two ISS racks, which are then reused to assemble the furniture pieces into a bed and desk. The arrangement of which is dependent on suiting the needs of each crew member (Appendix 3, Fig. 5). An additional eight racks will be used for each dome, for a total of twelve racks per dome.

The upper level is a multi-use space for recreation and activities. The outer domed ceiling allows for fractal patterns of ambient light to trickle through the space during the daylight hours. Ample storage cabinets line the outer edges of the upper level. These can be opened on the mezzanine or upper level itself, pending the configuration of the ramp. This meeting space promotes team building, as well as physical and mental health.

VII. Cultivation Framework

The fundamental purpose of establishing a greenhouse environment for the ARES mission is to enable and sustain a level of autonomy from Earth. Crops that will be grown on Mars serve three functions: produce supplementary oxygen, reduce CO_2 levels, and generate nutritional value for the crew and other greenery. The Russian Salyut Missions, an evolution from their forerunner, the Soyuz Missions, were a series of Soviet Space Stations launched between the years 1971 and 1982 (27). Although fostering a domain to research information on vegetational growth patterns in micro-gravity was not the primary focus of the Russians during this period, valuable information was still obtained regarding this matter:

1) Effects of spaceflight exposures on seeds and plants in natural dormancy or activation
2) gravitational perception and growth of plants in weightlessness
3) plant cultivation technologies
4) selection of plant sets for bio-technical life support systems

Further studies have been conducted more recently aboard the ISS and in environments designed to replicate the Martian soil (28). The data from these studies are intriguing, yet they do not attempt to solve the problems that an acidic and low-gravity environment, such as Mars, possesses. These problems are as follows:

1) A lack of sustainable nutrients for the crew and plants themselves
2) A lack of naturally occurring habitable conditions (growth space, soil, air temperature and pressure)
3) A lack of water and natural sunlight

The following vector optimization methods seek to provide solutions to said problems:

1) Nutritional Enhancements: Martian regolith (Appendix V, Fig. 1) will need to act as a solvent, absorbing additional nutritional enhancements to alter its chemical pH level. Due to the higher levels of Iron, an alkaline metal, the pH level of the soil on Mars is higher than that on Earth, which has an average level of 7.2. Introducing ammonium-containing fertilizers will lower the pH level of the soil over time, a substance that can easily be fabricated using compost.
2) Nitrogen Fixation: Introducing secondary doses of Nitrogen through ammonium-containing fertilizers can strategically boost the Martian regolith to the necessary level needed to sustain the Nitrogen Fixation process. Without Nitrogen Fixation, plants, and other organisms will not be able to grow adequately. Microorganisms such as diazotrophs naturally conduct this procedure, thereby expediting the bio-synthetic portion of the Nitrogen Fixation cycle, an essential aspect of cultivating organic compounds (29). Additional nutrients can be incorporated into an ammonium-containing fertilizer to further develop the number of vitamins that can be provided to the plants in Martian greenhouses. Vegetation that is more comfortable in extreme conditions,

such as Alfalfa, is an excellent way to supercharge the regolith, resulting in healthier and more tenacious plants.

3) Addition of Extremophiles: Extremophiles are microscopic organisms that have significant biological characteristics, allowing them to survive in extreme conditions. Although there are millions of genetic strands among billions of organisms, a select few traits could be revolutionary. A series of experiments, involving bio-domes as a constant, revealed two key genes as being highly useful. Those being pyrococcus furiosus + superoxide reductase (30). A process of gene splicing these two specified genes into the selected plants' biochemical makeup would allow a higher level of resistance to cold temperatures, as well as introduce a tendency for the plant to rely less on consistent watering practices. This is possible through synthetically reducing cytosolic Reactive Oxygen Species (ROS), which if left unintended will result in cell death due to a high level of stress (30). Both traits would be considered necessary to make a sustainable colony in the Martian environment.
4) Soil: The Martian soil differs throughout the varying regions of the planet, but generally is a clay-based material that is dense and thick. Implementing strategies in order to transform the soil into a sandy loam-like consistency will pay dividends for the future of a Martian colony. This process is designed around growing two separate plants within a confined region of regolith. The difference in growth patterns between the two plants harrows the soil after several growing cycles, resulting in a basin that future rotations of crops adapt to more effectively. Additional components can be brought from Earth such as charcoal and trace amounts of organic matter to replicate the fertile success observed in terra preta (31). Pottery fragments also have a direct positive correlation with the level of fertility in compost soil akin to terra preta, a practice that will more than likely naturally develop for habitual use.
5) Lighting: High-efficiency LED lights will be a staple in Martian greenhouses due to the lack of natural sunlight. An individualized lighting system allows for each section of a greenhouse to be customized for the specific plants being grown. A wide variety of commercial grow lights are applicable in this scenario. Recent studies on vertical farming and hydroponic research have shown that DC Lighting apparatuses have a higher yield percentage, while also supplying the plants with a healthier source of energy (32). Technology demonstrated in vertical farms constructed by Kalera showcases this interaction on Earth, potentially leading to promising results on Mars. In addition to an efficient lighting system, heating filaments installed under the greenhouse will provide further warmth, a necessary aspect when the average temperature of Mars around the equator is 0°C.

A. Vegetational Analysis and Algorithmic Studies

A human's daily nutritional values define the stipulations for the required yield of each type of nutrient. In conjunction with the principle of required diversity, an algorithm can be fabricated to produce a list of plants that have the potential to successfully grow in extreme environments (Appendix V, Table 1). The resulting list of plants, when combined with the previously discussed set of strategies and data from the ISS and Salyut missions research, will allow the pioneers of Mars to become Earth-independent. The basis of the algorithmic process can be simplified into a few equations:

1) The list of plants generated from the initial data input (R)

$$R = \{r_i, iE1, n\} \tag{1}$$

n = Number of Plants

2) The list of vitamins (V)

$$V = \{v_j, jE1, m\} \tag{2}$$

$m = m0 + mi$; m, a number of vitamins; $m0$, a number of major vitamins; mi, a number of representative vitamins

3) Daily requirements for plant mass (Q)

$$Q = \{Qi, iE1, n\} \tag{3}$$

The daily requirements for plant mass were categorized into quantitative and qualitative parameters (Table 2).

Quantitative Demands	Qualitative Demands	Quantitative Outputs	Qualitative Outputs
Proteins Carbohydrates Lipids Vitamins Salts Productivity Caloric Value	Stability Assimilation Nutritional Value Thermal Demands	Cellulose Transpiration Photosynthetic Output Compact Sowing Percentage of Edible Portion	Morphology Simplicity to Cook Simplicity to Cultivate Acceptance Rate

Table 2. Daily Requirements for Plant Mass

Table 1 (Appendix V) is the result of this algorithmic process and is a comprehensive list of the biochemical characteristics of the plants that were found suitable to grow in extreme environments. This data can be used to narrow down the specific function of each individual plant, thereby allowing for the introduction of an expanded plan for a greenhouse design. Variables such as how much space, energy, and water each crop needs can be categorically assigned to a specific zone in order to maximize efficiency.

Ten of the twenty-seven plants from Table 1 (Appendix V) were chosen for the ARES mission. Seven of the ten selected plants were chosen primarily for their nutritional benefits with regards to the first two years of the mission. Three additional plants, Lupinus lepidus, Alfalfa, and Asteraceae, were selected for their psychological and fertilization effects, for a total of thirteen crops.

B. Cultivation Output and Data Application

The architectural concept of the prefabricated greenhouse is a direct reflection of the data gained through the vegetational analysis process. In this way, each of the three prefabricated greenhouses (Appendix V, Fig. 2) will need to provide enough nutritional support for the first two years of the mission. The two-year mark designates the predicted timeline of when a larger, 3D printed, greenhouse will be able to be fabricated on-site. Each of the prefabricated greenhouses contains twelve planter boxes, with a total of 96.363 square meters of growable area. Table 3 demonstrates the productivity levels of each of the prescribed plants in the prefabricated greenhouses.

Plant	Maturation Period	Pounds/ Square Foot	Designated Space	Daily Intake	Daily Crew Intake	Required Output	Actual Output
			Total Area (Sq. M.)	Grams	Crew Size of 7	Kilograms	Kilograms
Chives	4-6 Weeks	2.42	4.5	200	1,400	39.2	52.7
Lettuce	6-8 Weeks	0.5	13.1	90	630	30.9	31.8
Potatoes	16 Weeks	1.5	30.1	275	1,925	215.6	220.5
Radish	4 Weeks	0.1	4.5	10	70	2.1	2.2
Soybeans	8-12 Weeks	0.34	9.9	30	210	14.7	16.3
Tomatoes	3-4 Weeks	1.65	4.5	200	1,400	35.1	36.3
Turnips	4-6 Weeks	1.0	4.5	65	455	20.5	21.8

Table 3. Cultivation Outputs

1 lb = 453.59237 g

Daily Crew Intake (7) (Maturation Period) = Required Output

Designated Space (Pounds/ square meter) (453.59237) = Actual Output

In total, the three prefabricated greenhouses deployed on the surface of Mars, pertaining to a crew size of seven, can produce 870/1,300 grams needed to sustain an individual's personal biomass intake. For the first two years of residency, the remaining 430 grams will have to be supplemented through pre-packaged freeze-dried food. Upon the crew developing and expanding their colony at the two-year mark, larger 3D printed greenhouses can be constructed. Thereby allowing for the growth of more land-intensive plants, such as cress, quinoa, and rye. This greenhouse expansion will also allow the former prefabricated greenhouses to harbor other types of plants selected for this mission such as alfalfa, asteraceae, and lupinus lepidus. The successful construction of an ISRU greenhouse will enable the ARES mission to be self-sustainable, no longer relying on supplementary cargo missions to fulfill daily human nutritional needs.

C. Fabrication Method

The prefabricated greenhouse modules will be constructed on Earth and shipped to the Martian surface aboard MARS. The cargo bay present in the rocket is designed to hold one hundred tons of contents within a 512 cubic meter chamber. More than enough space is available to transport and deliver two prefabricated greenhouse modules in each rocket. Thereby allowing three fully functional prefabricated greenhouses to be available for use on-site when the manned ARES II mission touches down in 2035.

The prefabricated greenhouses themselves are designed in a simple manner, engineered to promote an effortless repair process. Silicon caulk is utilized to minimize the risk of external air infiltration into the interior space, while a series of galvanized steel screws meld the structural members together, resulting in a finished architectural shell. The screws and joints used in the design process can be replicated and 3D printed on site if need be.

Thermo-insulating pads are installed on top of a two-piece foundation, which can be readily accessed through the removal of an aluminum grated floor. Solar trees and secondary level supports are easily dismantled if access is needed, allowing for maintenance and cleaning of the fiberglass planter boxes. Finally, exterior solar panels and hanging DC LED lights complete the space. The 3D printed greenhouses will be constructed in the same manner as the shell of the permanent habitats.

VIII. The Future of ARES

Phase Three welcomes the second crew aboard the ARES III mission, scheduled for arrival in 2040. Crew two continues to complete their own permanent habitat and greenhouses using robotic systems, lessons, and experiences gained through crew one. Furthermore, crew two will use an exploration helicopter from the previous re-supply cargo mission to continue ARES exploration efforts and establish research outposts. Future expansion into the canyon and valley will maximize the beneficial effects of radiation shielding, as well as enable further research of scientific regions.

A. ARES III (2039 – 2043)

During the February 1956 flare event, the radiation protection capabilities of a Space Station Freedom module with a length of 8.2 meters and a diameter of 4.45 meters covered by Martian regolith in various thicknesses were examined (33). The cliff scenario was considered in parallel when the same module was placed two meters from a ten-meter-high cliff. A series of calculations indicated that the regolith thickness change did not improve radiation protection levels, rather positioning the module near the cliff reduced the BFO (Blood Forming Organ) dose by 20 mSv to 25 mSv for both the GCR and solar flare protons. Therefore, locating the future habitat next to the cliff is a practical method to gain additional radiation shielding (33). Cliff architecture can simplify the built form, as well as, the use of materials, and components (34).

B. Technology Readiness Levels (TRL) Assessment

Each component of ARES has been assessed and estimated using the NASA Technology Readiness Levels (TRL).

1. Permanent Habitat: (a) Interior elements: walls and furniture are available on Earth in terrestrial domains. Further studies to adjust interior elements for a one third gravity differential may be required, but their

availability and functionality has readily been tested. (b) The NASA Centennial Competition (3D-printed Habitat Challenge) has motivated more research for 3D-printing on Mars, including Penn State University's research on FGMs (23). The team at Penn State University has successfully 3D-printed 50 mm by 400 mm columns of FGMs (22). More experiments are required, but the potential is promising.

2. Prefabricated Greenhouse: Components of each prefabricated greenhouse would be manufactured on Earth, packed and delivered to Mars. Simulation and demonstration could be proven on Earth before flight.
3. Martian-Constructed Greenhouse: The exterior shell would require the same 3D printing techniques as the permanent habitat. Experience and studies of growing food on Mars from the prefabricated greenhouse can be applied.
4. Initial Inflatable Habitat: The cases of TransHab and Bigelow Expandable Activity Module (BEAM) would require additional study to adjust for the surface of Mars.
5. Non-Pressurized Regolith Garage: In accordance with the permanent habitat and Martian-constructed greenhouse, the exterior would also apply the same 3D-printing techniques.
6. Airlocks: Airlocks would be manufactured on Earth with the same approach as those deployed in the ISS.
7. MARS (Mars Ascent and Return Shuttle): The NEP system has been successfully tested on ground, leading to the projected success of any spacecraft utilizing the same propulsion methods. The payload requirements for the MARS vessel are more than achievable, as seen with the project payload of Starship being close to one-hundred tons. Further advancement in technology and continued testing will provide a better understanding for how precise landing larger payloads on extraplanetary surfaces can be.

Component	Earth/Mars	Volume	Mass	Technology Readiness Levels (TRL)
Permanent habitat:				
Interior elements (walls, furniture)	Earth	1,175 m^3 x 5	2,184 kg	TRL 9
Exterior walls with Functionally-graded Materials (FGM)	Mars	750 m^3		TRL 5
Prefabricated greenhouse	Earth	85 m^3 x 3	120 kg	TRL 6
Martian-constructed greenhouse		1,175 m^3 interior x 2		
Exterior walls with Functionally-graded Materials (FGM)	Mars	750 m^3 x 2		TRL 5
Initial inflatable habitat	Earth	725 m^3 interior	25,000 kg	TRL 6
Non-pressurized regolith garage	Mars	1,175 m^3 interior 750 m^3 exterior		TRL 5
Airlocks	Earth	40 m^3 x 22	6,500 kg	TRL 6
MARS (Mars Ascent and Return Shuttle)	Earth	1,100 m^3 for payloads	4,400 tons launch mass 100 tons for payloads	TRL 6

Table 4. TRL Assessment of the ARES Base

C. Conclusion

The methods utilized in ARES will be essential for the future of human exploration. New strategies regarding 3D-printing technology are constantly being innovated upon, leading to perpetual shifts in the design approach. More efficient procedures will inevitably push the boundaries of what is possible in the mission planning process. This includes development in the robotic, biophilic, cultivation, psychological, architectural, and propulsion systems.

Advancements in each of these fields enable longer duration missions in more extreme environments. Mars is an unforgiving landscape and ARES is an attempt to push the envelope of what is possible there.

Challenges are created to elevate the threshold of what is reasonably achievable in the near future. ARES is a mission tasked with a seemingly un-accomplishable goal to maintain human life on a foreign planet consecutively for over seven years. The set parameters have forced the habitat to be constructed in a more robust manner. Certain design decisions took precedence over others, such as prioritizing new methods and material compositions to reduce the amount of harmful radiation exposure. This, as well as developing an architectural plan that is easy to physically construct using 3D-printing equipment while allowing a high degree of *in-situ* flexibility, is what sets this proposal apart.

Space exploration is going to be the focal point of human civilization this century. Establishing a research station on the moon is obtainable in this decade. Mars is next, but the set of challenges attached to conquering the red planet, from a scientific achievement standpoint, are much more challenging. The distance from Earth results in a mission to Mars consuming more fuel, having a longer transit time, and experiencing longer communication delays. The average temperature of the Red Planet, paired with the scarcity of water, limits the amount of feasible site locations. The lack of a potent atmosphere increases the need for radiation shielding. Homesickness, sandstorms, lack of light, unsuitable pressure levels, isolation confinement, lower gravity, and an abundance of other problems await the first crew to Mars. These are all obstacles that can be overcome with proper preparation and high-level human-centered designs.

The beauty of ARES lies in the grandeur of its expeditionary scale, essential for its triumph. Numerous facets converge to create this awe-inspiring magnitude: an extraordinary duration surpassing all previous interplanetary missions, the fusion of ISRU with Earth materials for minimal payload mass, the ingenuity and effectiveness of the proposed 3D printing techniques, and a revolutionary bioengineering strategy to cultivate a self-sustaining system capable of nurturing a crew on the Martian surface for seven remarkable years.

ARES has proposed innovations for solutions to all of the challenges that Mars presents. Future projects will look to improve on the foundation that ARES and other research-based proposals have built, as the quest to inhabit Mars continues to grow closer.

Appendix I

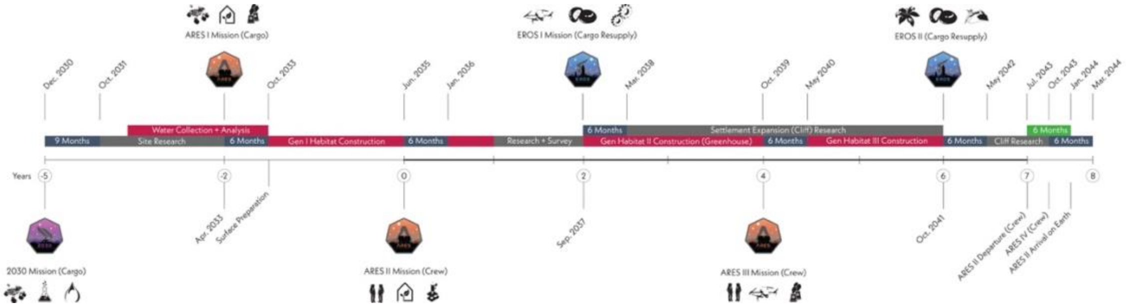

Fig. 1 ARES Mission Timeline

Appendix II

Site	**Jezero Crater**	**Gale Crater**	**Valles Marineris**	**Elysium Planitia**	**Acidalia Planitia**	**Utopia Planitia**
Location	18^{o}N, 77^{o}E 45 km in diameter	5.4^{o}S, 137.8^{o}E 154 km in diameter 4.4 km deep 5.5 km high (Mount Sharp)	13^{o}S, 59^{o}W 4000 km long 200 km wide 7km deep	3^{o}N, 154.7^{o}E 1700 - 2400 km	49.8^{o}N, 339.3^{o}E Vast plain	46.7^{o}N, 117.5^{o}E 3300 km in diameter
Temperatures	-55^{o}C in average	-90^{o}C to 0^{o}C	-125^{o}C to 37^{o}C	-53^{o}C in average	-96^{o}C in average	-79^{o}C in average
Pressure	705 - 735 Pa	650 - 1000 Pa	Over 1200 Pa	630 Pa	610 Pa	730 to 1080 Pa
Atmosphere	Medium	Thick	Dense	Dense	Thin	Thin
Radiation Level	High	High	Low	High	Low	Low
Dust Storms	High	Medium	Significant	Significant	High, large but the moving speed decreases	High, large but the moving speed decreases
Existing Water?	No	No	Potentially Yes	Maybe Yes	No	Yes (confirmed)
Mobility	Sand dunes, steep slopes, lots of scattered rocks	Fairly smooth and plain	Various sites	Plain	Plain	Plain
Rover or Lander	Perseverance (2020-present)	Curiosity (2012-present)		InSight (2018-2022)	Pathfinder (1997) in Ares Valley, 1475 miles away	Viking II (1976-1980)

Table 1. Martian Site Comparison

Oxides	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	SO_3	Na_2O_{eq}	LOI	Sp. Gr.
Fly ash	46.69	22.44	4.99	19.43	1.04	0.76	1.74	2.00	2.64
Slag	30.80	11.45	47.50	2.26	3.65	3.03	0.27	2.56	2.85
Glass chunks	63.8	14.4	4.4						

Table 2. Solid Materials for GP Pastes (22)

Appendix III

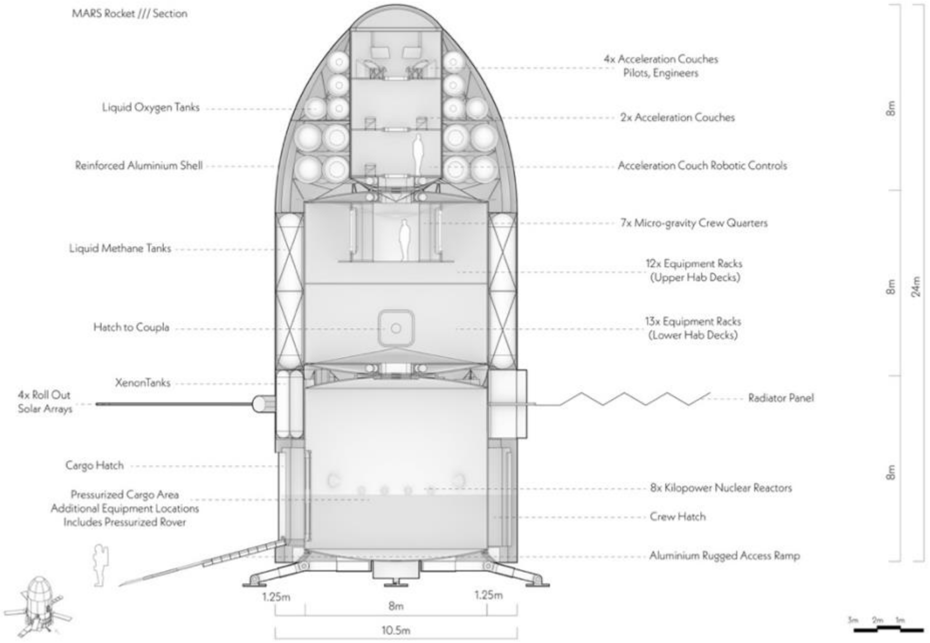

Fig 1. MARS Rocket Section

Appendix IV

Fig 1. Biophilic fractal pattern of interwoven regolith mixtures for the Habitat

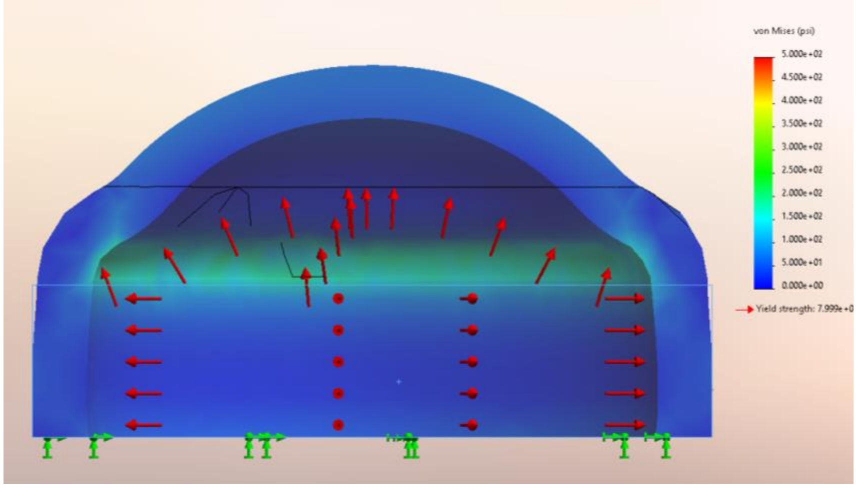

Fig 2. Habitat Pressurization Analysis

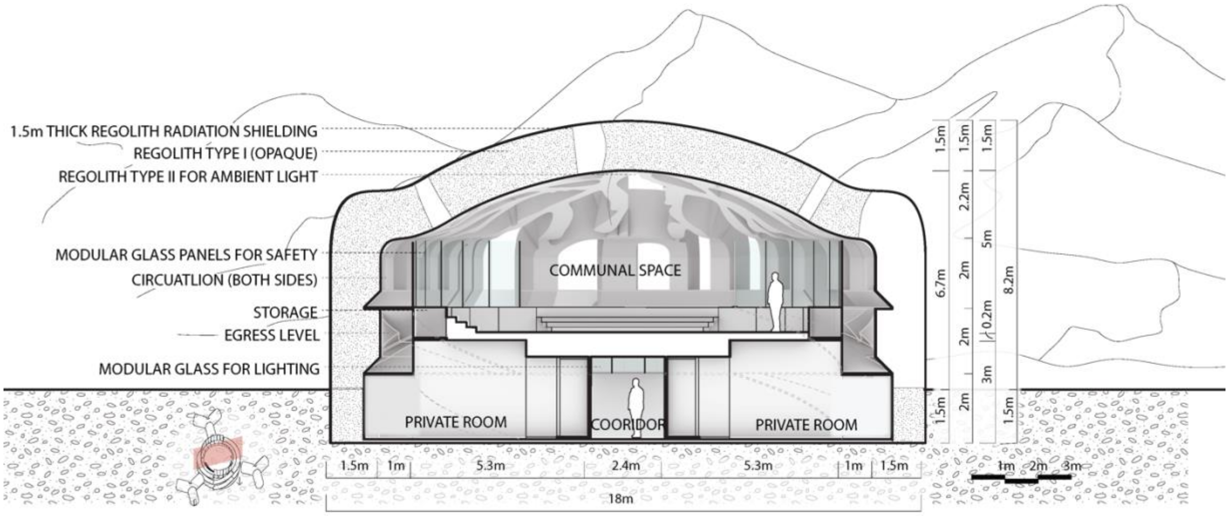

Fig 3. Typical Habitat

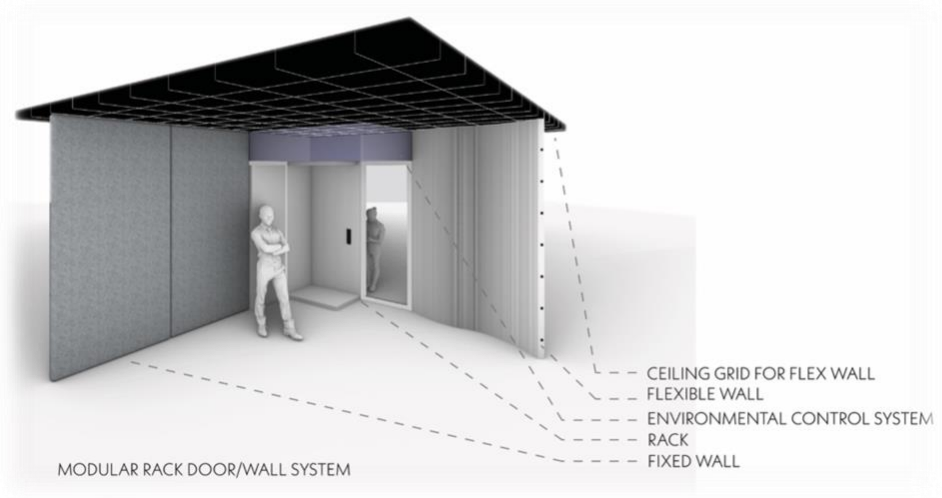

Fig 4. Modular Door/wall system for a private room

Fig 5. Modular Furniture Configurations

Appendix V

Plant	Group	Proteins	Lipids	Carbs	Vitamins	Minerals
			Grams			
Wheat	Cereals	12.0	1.70	68.70	6.40	0.850
Rice		7.6	1.0	75.80	2.350	0.240
Peanuts		27.50	48.50	16.0	14.60	1.20
Soybeans	Legumes	34.0	18.40	24.60	3.40	2.90
Peas		23.40	2.40	53.10	3.750	1.420
Beans		23.0	2.10	53.80	3.150	1.940
Chives	Tubers	9.0	28.0	41.0	- -	- -
Potatoes		2.0	0.10	21.0	3.80	0.650
Sweet Potatoes		2.0	1.0	24.30	3.350	0.510
Carrots	Root Crops	1.50	0.170	8.0	10.10	0.260
Radishes		1.20	0.170	4.0	2.350	0.320
Turnips		3.30	0.170	10.0	7.350	0.420
Table Beets		2.0	0.170	10.80	4.50	0.290
Swede		2.0	0.40	11.0	1.10	0.330
Sweet Pepper	Fruit Vegetables	1.30	0.40	4.70	36.30	0.180
Tomatoes		0.60	0.40	4.20	6.60	0.230
Cucumbers		0.80	0.10	3.0	0.850	0.210
Kolrabi	Leaves	3.0	0.30	8.30	5.80	0.50
White Cabbage		2.70	0.180	5.40	5.70	0.280
Cauliflower		2.50	0.340	4.90	12.40	0.30
Brussel Sprouts		6.90	0.460	6.70	19.40	0.530
Green Onions	Greens	3.0	0.30	7.30	6.40	0.350
Garden Cress		2.20	0.30	3.70	15.50	0.360
Parsley		3.70	0.30	8.10	26.80	1.590
Spinach		2.90	0.30	2.30	21.30	1.0
Lettuce		1.50	0.30	2.30	16.0	0.350
Quinoa		2.60	0.30	5.30	14.60	0.630

Table 1. Vegetational Analysis

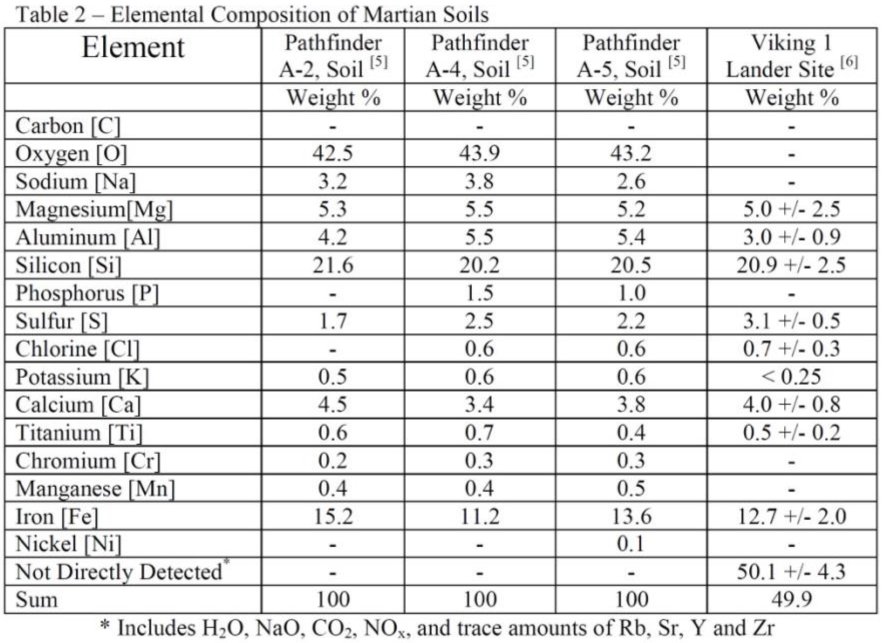

Table 2 – Elemental Composition of Martian Soils

Element	Pathfinder A-2, Soil [5]	Pathfinder A-4, Soil [5]	Pathfinder A-5, Soil [5]	Viking 1 Lander Site [6]
	Weight %	Weight %	Weight %	Weight %
Carbon [C]	-	-	-	-
Oxygen [O]	42.5	43.9	43.2	-
Sodium [Na]	3.2	3.8	2.6	-
Magnesium[Mg]	5.3	5.5	5.2	5.0 +/- 2.5
Aluminum [Al]	4.2	5.5	5.4	3.0 +/- 0.9
Silicon [Si]	21.6	20.2	20.5	20.9 +/- 2.5
Phosphorus [P]	-	1.5	1.0	-
Sulfur [S]	1.7	2.5	2.2	3.1 +/- 0.5
Chlorine [Cl]	-	0.6	0.6	0.7 +/- 0.3
Potassium [K]	0.5	0.6	0.6	< 0.25
Calcium [Ca]	4.5	3.4	3.8	4.0 +/- 0.8
Titanium [Ti]	0.6	0.7	0.4	0.5 +/- 0.2
Chromium [Cr]	0.2	0.3	0.3	-
Manganese [Mn]	0.4	0.4	0.5	-
Iron [Fe]	15.2	11.2	13.6	12.7 +/- 2.0
Nickel [Ni]	-	-	0.1	-
Not Directly Detected*	-	-	-	50.1 +/- 4.3
Sum	100	100	100	49.9

* Includes H_2O, NaO, CO_2, NO_x, and trace amounts of Rb, Sr, Y and Zr

Fig. 1 Composition of Martian Regolith

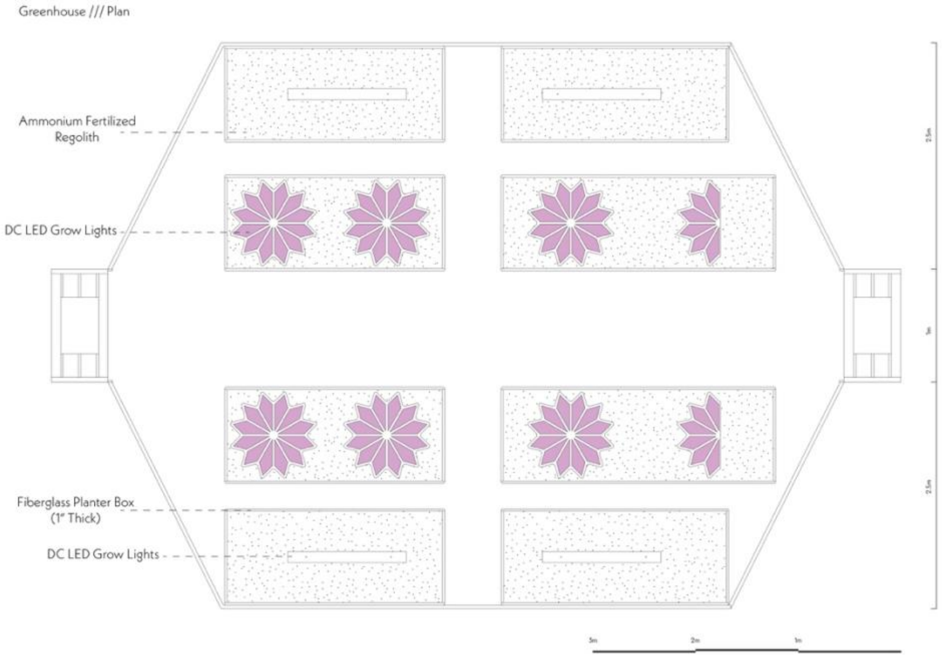

Fig. 2 Prefabricated Greenhouse Plan

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