Martian Agriculture and Plant Science Greenhouse (MAPS)

Technical Report for the NASA 2019 BIG Idea Challenge

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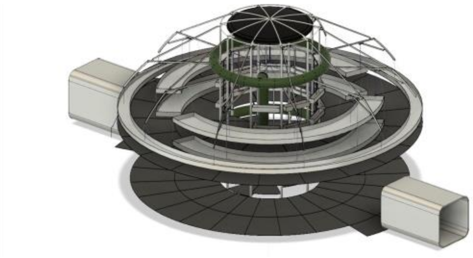

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1. Introduction and Purpose

In order to execute a successful mission to Mars, it is necessary to provide adequate sustenance for the crew that is renewable, sufficiently nourishing, and self-sustaining. The best way to achieve this is with a greenhouse. The Martian Agriculture and Plant Science (MAPS) greenhouse will be a two-story inflatable structure that builds upon time-tested farming techniques with a variety of sensors and automated systems. This will increase the overall reliability of the system and reduce the cost in crew time required to support proper plant growth. MAPS will provide a stable and nutritious, plant-based food supply that will enable a sustainable, long-term Human presence on Mars. It is engineered to endure the high-radiation, low-sunlight environment of Mars all while providing a safe and secure habitat for crew members to work.

MAPS is a necessary addition to the Mars Ice Home, a concept for a manned Martian habitat developed by NASA in 2017. It builds upon the assumptions and design choices made in the technical reports written on this concept to develop a greenhouse add-on that could be seamlessly integrated and provide an efficient and reliable source of food for crew.

Martian greenhouses have been a popular point of research and conceptual design for decades as establishing a working greenhouse on Mars requires overcoming numerous engineering challenges associated with working within its environment. Mars has a thin, poisonous, and often frigidly cold atmosphere, making it a challenging place to establish Earth-like environments to work and grow food.

2. Goals and Objectives

The objective of MAPS is to provide an efficient and reliable architecture for the growth of plants on Mars that can provide the nutrients to sustain a team of astronauts for the duration of a potential two-year research mission. Our primary goals in designing the various components of MAPS are as follows:

I. Select plants that will provide sufficient nutrients and a balanced diet that can be grown efficiently, rapidly, repeatedly, and reliably in our Martian greenhouse architecture.
II. Design plant growth systems that are power efficient, reliable, and robust while reducing overall complexity such that the components can be deployed remotely with minimal human setup.
III. Design greenhouse structures to minimize weight and overall complexity such that all essential structures can be deployed remotely and robotically. Ensure structures support weight and space needs of interior systems.

3. Design Overview

MAPS is designed as a complement to the 2017 NASA Ice Home concept and operates under the same environmental and technological assumptions outlined in the original Ice Home ConOps. We additionally co-opted many key design features of the Ice Home, particularly the inflatable dome structure with water ice radiation shielding and carbon dioxide insulation layers. This is primarily to reduce Non-Recoverable Engineering (NRE) as well as tooling and manufacturing costs.

Our systems are meant to integrate seamlessly with those of the Ice Home, meaning power generation and water extraction for our greenhouse is designed to come directly from pre-existing systems in place on Mars before deployment with only minimal supplement. The basic assumptions our design utilizes to make general calculations about our environment and needs on Mars are as follows:

I. Water will be extracted from Martian surface via In-Situ Resource Utilization (ISRU) technologies that will be deployed to support the Ice Home prior to greenhouse arrival. Water production rate of 0.25 m^3/day is assumed.
II. Power will come primarily from NASA's Kilopower nuclear reactors. These reactors will be deployed prior to greenhouse arrival and deployment to support the Ice Home. Power output of 40 kW is assumed per the EMC notes of the 2017 Ice Home report (10 kW per generator).
III. The environmental conditions of Mars around our greenhouse are around the Martian average in terms of temperature, soil composition, solar exposure, etc.

MAPS as a whole utilizes unique design features to achieve efficiency and reliability in every system. Some key features of our design are the utilization of soil growth over hydroponics, the use of grow-bags to create efficient and highly automated irrigation, and our attention to automated deployment of internal structures. These features and many more are outlined in our system descriptions section.

4. Structural Design

4.1 Overview

This section will propose a greenhouse structure that can reliably protect against external hazards while maintaining internal operations. Our design provides protection from radiation using the same method proposed by the Ice Home ConOps and will connect directly to the Ice Home through a passageway. All internal structures are designed to fold up for launch and to be deployed remotely. These key design choices will enable our greenhouse to operate in a similar manner to the Ice Home, simplifying deployment and overall design of the greenhouse structure.

4.2 Key Design Choices

1. Use of Ice Home's method of shielding and materials choices
    a. Water is a proven method of radiation shielding. Ice Home's use of shielding will provide sufficient radiation shielding for our plants and the crew members working in it.
    b. Due to similarities between the structural design of the Ice Home and the MAPS greenhouse, materials used will mirror those discussed in the Ice Home ConOps
2. Connection to the Ice Home
    a. The greenhouse will be attached to the Ice Home via an airlock. This allows for easy access between both structures so that the crew members can tend to the greenhouse without wearing a suit.
    b. Ventilation will also be installed to connect the two modules so that oxygen and carbon dioxide may circulate

4.3 Challenges and Solutions

The challenges presented by our design are as follows:

1. Pressure differential between internal pressure and external pressure
2. Maintaining insulation
3. Protecting plants against galactic cosmic rays (GCR’s)
4. Holding weight of increasing biomass inside the greenhouse

Since Mars's atmospheric pressure is only 0.6% of that of Earth, the greenhouse must be able to maintain strong structural integrity which can be achieved through strategic internal and external support. Furthermore, insulation and harmful GCR’s would threaten biomass inside if left unregulated. To address these challenges, the greenhouse will follow the Ice Home’s choice of materials and water-cell design.

Since biomass may grow to a noticeable weight, heavier plants will be grown on the first floor, and lighter ones grown on the second floor. All biomass, objects, and crew members operating on either floor must be withstood by the support structures described further in the following subsection.

4.4 The MAPS Greenhouse

To reduce development costs, MAPSs’ inflatable dome structure will be of similar material and composition as that of the Mars Ice Home, mostly clear teflon and tedlar. It will feature a 9 m external radius and a 7 m internal radius. This allows for 2 m of water ice radiation shielding necessary for the 58% reduction in effective radiation dose as outlined in the Ice Home ConOps document. The inflatable dome is essentially a pressure vessel and is the primary load-bearing component of the structure. A preliminary analysis of the average pressure on the dome resulting from the weight of the water-ice shield is around 67.3 kPa. Assuming 101.3 kPa internal pressure, the dome is more than capable of supporting the mass of the ice alone. An internal column consisting of ten upright aluminum 6061-T6 posts will add additional support to the top of the dome. All internal structures will be made of aluminum 6061-T6. This is a lightweight aluminum alloy with a long-proven heritage in aircraft and space vehicle structures. While the dome supports the external loads, the central column will support most of the internal structure including the second floor, upper canopy, and an irrigation water reservoir bladder. The structure has been designed to distribute loading on the central column supporting members as much as possible and assure a structure that is safe.

The first and second floor will consist of carbon fiber panels that will easily snap into place. A spiral stairwell will inhabit the inside of the central column to allow access to the second floor. A stairwell was selected over a ladder to ensure safety so that crewmembers are not operating on a ladder while carrying tools and produce. The upper canopy is designed to suspend planters for load distribution purposes. The second floor supports are made safer by only needing to support the weight of the crew. Planters on the lower floor are built directly into the bottom of the inflatable dome structure and require no further support.

An internal air lock will connect the Ice Home to the greenhouse. This will serve as the main access point for everyday use. Across from this entrance is a pressure door exiting directly to the Martian atmosphere. This is for safety in the event of evacuation as well as to allow Martian regolith to be transported into the greenhouse during deployment operations without risking contamination of the Ice Home. It is not necessary to introduce an external airlock as this operation will be performed in equilibrium with ambient Martian atmosphere.

4.5 Analysis of Support Structures

A safety factor of 1.5 was assumed after the support structure holding up the second floor and the canopy holding the planter bags on the second floor were analyzed for failure for their maximum loading scenarios.

For the second floor support structure, each segment may experience a maximum load of 372 N. This signifies a crew member falling to the floor with a fair amount of harvested produce in hand. Analysis of each member of the support structure show that the structure will safely withstand the load, reaching a maximum stress of 0.135 ksi.

Using simulation software, the canopy was analyzed with loads of 3144 N and 3503.4 N applied at two points, the end of the outermost member of the canopy and at a cable attachment point on the horizontal member, respectively. These loads were based on the planter bag and biomass weight each canopy segment needs to support. It was found that the topmost bracket connecting the member to the central column experienced rapid disassembly, and therefore will need to be redesigned.

Assuming that the top-most bracket is fixed, the analysis shows that the members do not experience deformation greater than 3 cm and a stress no greater than 16.67 ksi as shown in **Figure 1**. Accounting for safety factor, the adjusted maximum stress is 25 ksi. From Department of Defense materials handbook, the maximum tensile strength of Aluminum 6061-T6 is 35 ksi meaning the structure currently meets safety requirements. However, the brackets experienced a much greater stress at 37.7 ksi. To meet our safety factor requirement, the brackets will need to be redesigned.

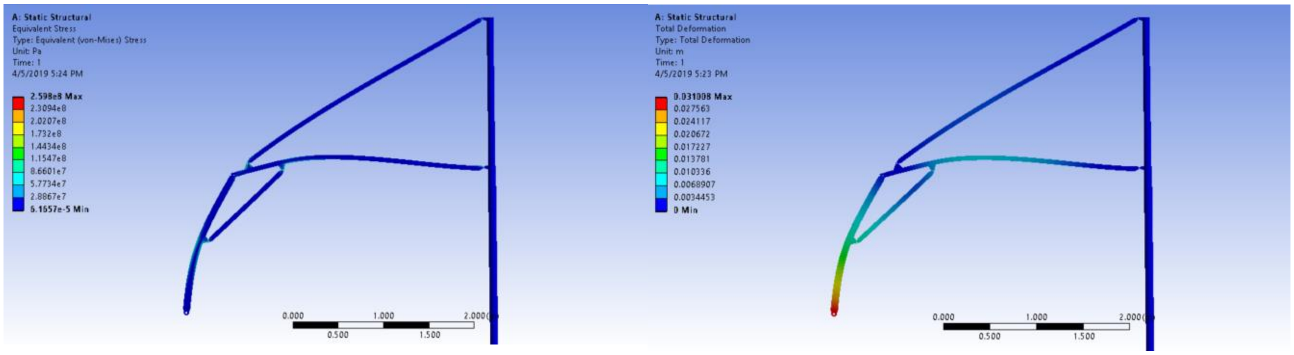

Figure 1: *Stress and deformation analysis of canopy structure. Measured in pa and m, respectively.*

5. Irrigation and Plant Growth Systems

5.1 Soil Growth versus Hydroponics

An important choice in the design of any sort of high-tech farming system is whether or not to grow plants via traditional methods like planting in soil or to implement a complicated hydroponics system instead. Despite some of the challenges associated with establishing a soil-based greenhouse on Mars, our team ultimately decided soil growth provided the most positive benefits of any growth method while maintaining relative safety and reliability.

The choice of utilizing soil-based growth over alternative methods like hydroponics was made with system reliability in mind as our primary design goal. Our analysis of mission-critical failure points in each system showed that the risks associated with either method were roughly equal in severity and likelihood overall, see **Table 1**. While hydroponics provides some increased efficiency and likely requires less setup than a soil growth method; the operation of a hydroponics system over a long period of time requires more upkeep to prevent critical failures. Such as, one of the many pipes or pumps breaking down and leading to incredibly rapid death of plants that lose their source of nutrients. Soil growth, on the other hand, is tried and true. Once soil planting is setup, it can be automated or done by hand depending on need, making it much less prone to failure in the case of a malfunction with the electronics. The risk with soil growth comes almost entirely from the upfront processing which requires intake from the Martian surface and removal of toxins among other things. While the risk factors overall seemed fairly close in severity between the two systems, we determined that soil growth would be a more reliable and adaptable platform for a long-term mission, as even in the case of major system failures growing could continue relatively unimpeded.

In addition to examining the risks and reliabilities of the different systems, we made sure to look at the additional benefits of each system, particularly in regard to their effect on crew members. In this area, soil growth has its most obvious advantages over hydroponics. Growing plants in a familiar and accessible way will provide the crew with a space they can put work in that requires real physical activity. It will also provide the crew a space to relax in that feels familiar and Earth-like. A study published in 2010 in the Journal of Health Psychology found that even just 30 minutes of gardening was an effective stress reliever with more lasting effects than reading, which is another common stress reliever. Hydroponics systems are less likely to invoke the same sort of relaxing and Earth-like feeling of soil-based gardening that will be extremely important on such a long and isolated mission.

Table 1: *Assessment of mission critical failure modes. Comparing hydroponics and traditional soil. Weight values are on a scale of 1 - 5, 5 being most severe.*

Hydroponics	**Weight Value**
Pump Failure	5
Energy Intensive	2
Nutrient Solubility	3.5
Root Growth Favoritism	1.5
Algae	3.5
Pathogens	3
Total:	**18.5**

Soil Growth	**Weight Value**
Pathogens	5
Weight	3.5
Front-end Labor Needs	2.7
Soil Conditioning	4
Total:	**15.2**

5.2 Modular Grow Bags

In order to achieve a high degree of system reliability while reducing complexity and weight, we developed a planter design that utilizes a mix of traditional soil growth, plant grow bags, and a network of sensors. Modular grow bags were identified early on as a way to minimize setup complexity and to reduce overall payload weight and volume. In culmination of all these design considerations, we developed the Martian Grow-bag for Integrated Control (MAGIC), our specialized grow bag in which plants will be grown and monitored.

MAGIC, like most conventional grow bags used in Earth gardens, is made of a fabric which allows each bag to be lightweight and foldable before deployment. Fabric grow bags have advantages over other planters especially when it comes to volume constraints because the porous nature of fabric allows the soil on the sides to dry out better and therefore prevents roots from growing in circles and becoming entangled. Our planter bags are designed with an additional external bladder to allow water moisture to move through the planter's fabric and then be recycled into the greater irrigation system. Additionally, our grow bags each feature a collection of sensors to keep track of soil pH, moisture, nutrients, and other pertinent information. This information is routed to a central computer that ensures the irrigation and lighting systems are properly tending to each plant's individual needs. An automated and fully integrated system like this reduces setup time and complexity and reduces time the crew needs to spend tending to individual plants, rather letting them focus on overall system upkeep.

The various structures in our greenhouse are meant to support a variety of plants of various sizes and weights. Importantly, the MAGIC grow bag system can easily be scaled to work for plants of various sizes and root depths.

5.3 Soil Processing

5.3.1 Martian Regolith Chemical Breakdown

There have been eight successful landers on Mars: Vikings 1 and 2, Pathfinder and Sojourner, Spirit, Opportunity, Phoenix, Insight, and Curiosity. Of these eight, four were mobile (with Pathfinder/Sojourner being partially mobile) and were able to explore a wide range of areas. Early analyses of Mars consisted mainly as Alpha Particle X-Ray Spectrometer (APXS) analyses, or similar simple chemical breakdowns of rocks and regolith. Viking 1, the first successful mission to Mars, landed in Chryse Planitia. It found the regolith to be made predominantly of Silicon Dioxide (SiO_2), with roughly 17% Iron Oxide, and the rest of various other mineral oxides, a view corroborated by its twin, Viking II in Utopia Planitia, and later Pathfinder, which also landed in Chryse Planitia, but farther Southeast, all of which measured for roughly the same elements, see **Table 2**. What all the landers don't seem to agree on is what type of Iron Oxide Mars is made of. With all but Viking listing their findings as Iron (II) Oxide but claiming that up to 50% of the amount listed could actually be Iron (III) Oxide. This is significant as it does affect the arability of the soil. Also significant, is the detection of elemental chlorine, later confirmed to be some form of perchlorate salt at levels of roughly 0.5%; levels toxic to humans.

Curiosity's Chemistry and Mineralogy X-Ray Diffraction (CheMin) system later found the mineral composition of the planet to be 40.8% Plagioclase Feldspar, 22.4% Forsteritic Olivine, 14.6% Augite, 13.8% Pigeonite, 2.1% Magnetite, 1.5% Anhydrite, 1.4% Quartz, 1.3% Sanidine, 1.1% Hematite, and 0.9% Ilmenite. Calcium Sulfate, Potassium Sulfate, Iron (III) Sulfate, Magnesium Sulfate, Magnesium Carbonate, Iron (II) Carbonate, Iron^{+3} ion, Calcium Perchlorate, and Magnesium Perchlorate levels were below the levels detectable by CheMin. Notably, Curiosity's Sample Analysis at Mars (SAM), found in the three areas it tested in the Bagnold Dune Field, an average of 236 ± 62 ppm NO_3 (0.026% weight). In addition, Clay minerals have been found to cover much of the surface and are visible in the lighter colored deposits.

Samples from the opposite sides of Mars were found to be remarkably similar, leading to the hypothesis that the extremely fine, inhospitable makeup of the regolith allowed it to be scattered across the planet as it lacked the water and organic matter to bind it together into aggregates. Thus, it can be assumed, that though each area of Mars may differ slightly in composition, differences in mineral breakdown are likely to be negligible regardless of what spot is eventually chosen for the MAPS mission. As such, mission location is not constrained by geology.

Table 2: *Percent weight of various compounds detected by landers and rovers Viking 1, Viking 2, Pathfinder, Spirit, and Opportunity*

Chemical	Viking 1 *(Chryse Planitia)*	Viking 2 *(Utopia Planitia)*	Pathfinder *(Chryse Planitia)*	Spirit *(Gusev Crater)*	Opportunity *(Endeavour Crater)*
SiO_2	44%	43%	48.48%	45.8%	45.93%
FeO; Fe_2O_3	17.5%	17.3%	16.03%	15.8%	18.17%
Al_2O_3	7.3%	7%	8.5%	10%	9.22%
MgO	6%	6%	7.67%	9.3%	7.39%
CaO	5.7%	5.7%	6.45%	6.1%	7.03%
SO_3	6.7%	7.9%	5.47%	5.82%	6.1%
TiO_2	0.62%	0.54%	1.17%	0.81%	0.99%
Na_2O	-	-	2.28%	3.3%	2.19%
Cl	0.8%	0.4%	0.62%	0.53%	0.7%
K_2O	< 0.5%	< 0.5%	0.32%	0.41%	0.5%
P_2O_5	-	-	-	0.85%	0.88%
Cr_2O_3	-	-	-	0.35%	0.39%
MnO	-	-	-	0.31%	0.38%
Ni	-	-	-	0.045%	0.043%
Zn	-	-	-	0.03%	0.033%
Br	-	-	-	0.004%	0.0062%

5.3.2 Hazards

The most notable regolith hazard on Mars is its perchlorate content. Mars contains between 0.4% and 0.8% perchlorate, though the exact number has been difficult to pinpoint since such measurements can fall below the sensitivity limits of certain measurement processes such as CheMin. Even 0.5% perchlorate impairs the thyroid and acts as an effective bactericide, so great care will have to go into removal of the chemical. The regolith's particle size can also act as an inhalation hazard. Regolith dust particles range between 1-15 µm and can cause lung damage if inhaled, much like hazards posed by volcanic eruptions or the massive fires that have been blanketing California.

Additionally, the Planetary Protection Policy in accordance with the 1967 Outer Space Treaty states that "States Parties to the Treaty shall pursue studies of outer space, …, and conduct exploration of them so as to avoid their harmful contamination ["forward contamination"] and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter ["back contamination"] and, where necessary, shall adopt appropriate measures for this purpose" (NASA Policy Instruction). At this time, it is unknown what possible life may exist on the red planet, and as such possible exposure to the crew could be deadly. Care must be taken to avoid all possible contamination, both with the crew as well as anything that may return to Earth. With the long trip back to Earth serving as quarantine (the policy for the Apollo missions requiring a quarantine of 21 days), the main concern is to avoid unknown bio-contamination with the crew rather than with the Earth as a whole, as NASA and other Earth agencies will be given plenty of warning if contamination with the crew has occurred, and will be able to isolate humans on Earth from any Martian organism. In addition, care must be taken to avoid introducing any Earth organism to a possible Martian biosphere. However, there are many research benefits for using soil. If soil on Earth were to be contaminated by Martian regolith, research on Mars could be beneficial.

5.3.3 Decontamination

Basic safeguards can be put in place to avoid any chance of contamination. Regolith must remain isolated from crew and interior areas of MAPS until it has been sufficiently treated as to remove perchlorates and render any potential Martian microorganisms inactive. Therefore, decontamination must occur in the pressure chamber. Care must be taken to ensure that all possible chemical toxins and microbial contents of the regolith is eliminated before introduction to the crew. In the pressure chamber, every person and object must be flushed with compressed CO_2 to remove fine regolith particles after every entry and exit throughout the regolith processing phase.

Several means of regolith bio-decontamination were considered including Iodine treatment, Gamma irradiation, electron beam emitters, boiling, chloroform (or other chemical) fumigation, autoclaving, dry heat, microwaves, solarization, or the utilization of the already present perchlorate. Most methods were rejected due to its intensive energy draw, some not being possible in the Martian environment (such as solarization), or having a potentially harmful chemical byproduct.

Eventually, the choice came down to gamma irradiation and electron beam emitters. Both are decontamination methods that kill microorganisms without changing the chemical makeup of the soil. They may also both be potentially used to irradiate the entire dome when necessary. Gamma irradiation relies on a radioactive isotope so it will require no additional form of energy supply. It is also well established in industry and safe practices have long been known and utilized. However, shielding the emitter adds a great deal of strain to the mass budget. It also poses potential safety risks in regards to long term storage and disposal of radioactive material.

A study by A. D. McLaren et. al. showed that sterilization of soils with an electron beam is possible given a sufficient radiation dose. The study showed a dose of 4 Mrep is enough to deactivate microbial life within a soil sample. 4 Mrep corresponds to 37.2 kilojoules of energy per kilogram of material. Assume a beam width of 1 cm and a sample size that is 2 cm thick and 30 cm wide. Given a regolith density of 1,665 kg/m^3, the sample will have a mass of 0.1 kg. For a one second exposure, a 3.72 kW electron beam emitter will be required to be confident that the sample has been properly sterilized. Commercially available electron beam emitters used in sterilization of food products, medication, and medical supplies are typically available in the 8 - 20 kW maximum power range. This places the required electron beam emitter well within current technology.

It is proposed that a crew member collect virgin Martian regolith, sift out rocks and larger particles, and pour the sifted regolith into a hopper. The hopper will be designed such that it will allow a 1 cm thick layer of regolith to be deposited on a 30 cm wide conveyor belt. Immediately after leaving the hopper, an electron beam will continuously scan the sample as it passes beneath the beam emitter such that each 30

cm^2 top surface area is exposed for at least one second. Shortly after, as the sterilized regolith reaches the end of the conveyor belt, it will fall down a chute into the wash bin where perchlorates will be leached from the regolith. Assuming an 840 kg batch size, this process should take 140 minutes per batch.

After biological decontamination, the soil moves on to have the chemical toxins removed. As perchlorates are a water-soluble salt, all regolith to be used must first be flushed with water to remove the toxin. A specific decontamination system will be designed for use in the pressure chamber. Using solubility data for Potassium Perchlorate, the least soluble of the perchlorate salts, we have determined that at 25° C one liter of water can dissolve 2.8 kg of regolith. With 47,994 kg of total soil, 17,140 Liters of water will be needed, though this number is reduced to 300 L by processing the regolith in batches of 840 kg and recycling the water. This process is expected to take 20 minutes per batch.

Once the regolith is saturated, a water release valve will be opened, and the perchlorate-contaminated water will be allowed to drain through a porous bottom into a specific water chamber. After the soil has been removed by the astronauts and placed inside the greenhouse, the next step is to depressurize the pressure chamber using a vacuum pump, causing water vaporization. The evaporated water will be pumped into an inflatable container for the water and carbon dioxide mixture. At 25 degrees, the pressure would need to be below 1 kPa, or roughly 7.5 torr, for water to become gaseous. Since this is a closed system, no water will be lost, but rather collected for re-use, as outlined in **Figure 2**. The solid byproducts of evaporation will be sealed off for removal. This process is also expected to take 20 minutes per batch.

It was considered to use activated carbon for the removal of dissolved perchlorates from the wash water. This technique, however, would require either a large mass of activated carbon to be brought along or the activated carbon to be purged of contaminants in order to be reused. Purging of activated carbon typically embodies a large industrial process and is not realistic for this purpose.

Solid perchlorate is extremely explosive and is often used as an ingredient in rocket fuel. They are very unstable and when detonated have very exothermic reactions. Thus, once collected, it must be carefully disposed of far from the habitation area. As perchlorate comprises of around 0.5% weight of regolith with batches of 840 kg of regolith, 4.5 kg of perchlorate will be produced per batch.

In addition, wetting the regolith will help bind the particles together, as will the addition of organic matter. Once the regolith is soil, not dust, it should no longer pose an inhalation hazard. The entire process of regolith preparation is expected to take 180 minutes per batch. Because continuous crewmember attention is not required during electron beam sterilization, it is possible to run three batches per sol while the crew completes other unrelated tasks. 57 batches are required to prepare the total volume of regolith needed for the green house. At three batches per sol it would take 19 sols to complete this step in MAPS deployment operations.

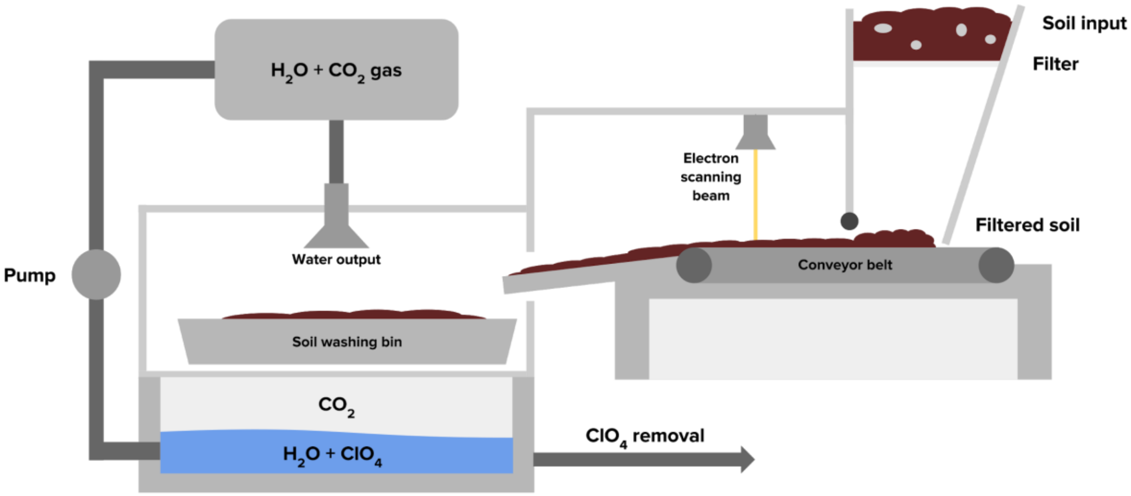

***Figure 2**: Biological and chemical decontamination process*

<u>5.3.4 Mineral Nutrition</u>

Besides treatment, regolith must be collected such that mineral ratios are viable to plant life. The three basic soil mineral types are classified by particle size- sand, silt, and clay. Sand ranges from 50-2000 µm, silt from 2-50 µm, and clay with a particle size of less than 2 µm. These soil particles are then combined into different ratios. The final soil mixture must consist of around 45% sand, 25% water, 25% air, and 5% organic matter. The rover Opportunity found samples of Eolian sand to be 50-125 µm with a 20 µm layer dust and grains sized at 1-3 µm. Further deposits of extra fine clay minerals have been identified in bedrock all over Mars.

In the MAPS greenhouse, thirteen different types of plants will be grown, all requiring a mixture of loam, sandy loam, or sandy soil. Loam soil means that the soil contains less than 52% sand, between 28-50% silt, and 7-27% clay. Sandy loam soil contains around 60% sand, 30% clay, and 10% silt. Sandy soil contains even more sand. The quinoa, cabbage, and potatoes can grow in sandy loam soil, while peanuts grow best in sandy soil. The spinach, soybeans, kale, sweet potatoes, beets, carrots, broccoli, garlic, brussel sprouts, and red bell peppers grow best in loamy, well-drained soil. Additionally, the soil must be tilled to promote granular, porous soil that allows for adequate water flow so that the soil does not become too saturated.

Plants require a number of micro and macro-nutrients to grow. To analyze the nutrient requirements for MAPS, the assumption was made that the nutrient needs of potatoes generally reflected the nutrient requirements of the entire greenhouse, and for simplicity analysis will be based on that data. Based on our assumptions, the plants will need 0.012 percent weight Nitrogen, 0.004% Phosphorus, 0.0192% Potassium, 0.0012% Sulfur, 0.0025% Calcium, 0.002% Magnesium, 5.5×10^{-6} % Zinc, 0.000045% Manganese, 0.00009% Iron, 4.5×10^{-6} % Copper, 0.000009% Boron, 0.0005% Chloride, and 2.5×10^{-7} % Molybdenum, and 2.5×10^{-7} % Nickel. The Martian regolith contains 0.026% NO_3 (Nitrogen), 0.84% P_2O_5 (Phosphorus), 0.36% K_2O (Potassium), 6.47% SO_3 (Sulfur), 5.99% CaO (Calcium), 7.24% MgO (Magnesium), 0.03% Zinc, 0, 0.31% MnO (Manganese), 16.67% Iron Oxide, hematite, olivine, feldspar, etc, 0.59% Chlorine, and 0.044% Nickel. The only minerals not already existing in the respective quantities but is required are 0.22 kg Copper, 0.43 kg Boron, and 0.012 kg Molybdenum.

Most plants need to be kept around a pH of 6, though the specifics of the dome are somewhat broader (*Table 3).* To maintain pH levels between 5.2 and 7.5, calcium carbonate or another basic mineral will likely be added to the soil, the addition of organic matter should also help this process.

Table 3: *pH requirements for plants in the MAPS greenhouse*

Plant Name	*pH*	*Plant Name*	*pH*
Quinoa	6.0 - 7.5	Beet	6.2 - 7.0
Potato	5.2 - 6.0	Carrot	5.8 - 6.5
Spinach	6.5 - 7.0	Broccoli	6.0 - 7.0
Soybean	6.3 - 6.5	Garlic	6.0 - 7.5
Kale	5.5 - 6.5	Brussel Sprout	6.5 - 7.0
Sweet Potato	5.8 - 6.2	Red Bell Pepper	6.0 - 6.5
Peanut	5.9 – 7.0		

Much of Mars' crust is made up of various forms of iron oxide. This addition will cause problems in several ways. If the soil is allowed to become too acidic, the iron will become more readily available in the form used by photosynthesis and may become toxic as levels increase. Moreover, as iron oxide has a high isoelectric point, it is a high absorber of phosphorus. We will likely have a phosphorus deficiency problem throughout the stay on Mars. The formation of iron oxides also lowers the pH of soil. It is unknown what form of iron oxide exists on Mars; the early Viking reports say iron (III) oxide is predominant, while the rest claim it to be iron (II) oxide. Though noting that there could be anywhere from 10-50% iron (III) oxide of the amount reported. If the regolith is made predominantly of iron (II) oxide, it will oxidize to iron (III) oxide upon exposure to oxygen; a process which will harm plants and lower pH levels. If the pH drops this will release the aluminum from the average 8.2% aluminum oxide content in the regolith, potentially harming the plants. Care must be taken to keep the pH levels of the soil around a pH of 6 (though the needs vary for the different plants) in order to mitigate the potentially harmful effects of the high iron content of the Martian regolith.

5.3.5 Earthworms and Bacteria

In order to meet the nutritional needs of the various plants, supplemental nitrogen will be required. As a result, we will be bringing *Lumbricus terrestris*, or earthworm to Mars to promote root growth and the breakdown of decaying plant matter into fertilizer. In addition, Rhizobium microbes will be introduced to the soil. Rhizobium microbes take in carbohydrates from the roots of plants and releases ammonium into the soil and into the environment in order to promote nitrate retention.

Using earthworms is an alternative means of automating the plant growth system. Worms help facilitate the tilling of soil, composting of organic materials, and fertilization. The fertilizer provided by the worm castings will help facilitate the growth of bacteria and fungi in the soil. These three components are necessary for plant growth and limit the amount of human labor needed throughout the harvest cycle.

The ideal type of earthworm to use is the *Eisenia fetida*, commonly known as the *red wiggler*. This hardy breed has a fast reproductive cycle which allows the earthworms to adapt to the unfamiliar Martian environment faster. The adult worms lay between 2-3 cocoons on average per week. Each cocoon averages around 3 hatchlings. It takes 11 weeks for a hatchling to mature as well as 3 months to reach reproductive maturity. Therefore, a single worm has the ability to create 9 hatchlings per week ("Worm Reproduction and Development). Although they are living in simulated terrestrial soil, they will still need time to adapt to the slight changes in the environment and are better suited to do so given its fast reproductive cycle.

The soil must be prepped for the worms as well as the plants. This requires the pH of the soil to be between 6 and 7. The pH must be tested once a week in order to ensure the health of the worms. If the soil is too acidic, it can be treated with calcium carbonate ($CaCO_3$). Rather than bringing along many kilograms of $CaCO_3$, it can be easily synthesized from calcium oxide (readily available in Martian regolith, see Table 2), water, and carbon dioxide. It is also necessary that the soil in which the worms live in is high in mycelium in order to encourage eating and the production of castings that enriches the soil with nutrients. It is also helpful to have a high carbon to nitrogen ratio to support growth. Red wigglers do not tolerate bright lights, and therefore will dig up to 10 inches below the soil to find suitable darkness and moisture. Their burrowing will further aerate the soil and create better aggregate structure. *E. fetida* are very heat tolerant as well; the plant beds can reach up to 95 °F without stressing the worms.

Earthworms provide many advantages once they are within the greenhouse and in prepped soil but may be difficult to transport to Mars. Although red wigglers are of a hardy variety, there is not much research to support their ability to travel alone for months on end. However, according to a study published in Comparative Biochemistry and Physiology, earthworms have adapted to hibernate and survive through harsh winters. In order to fend off the cold, they burrow into deeper soil regions and become inactive in soil temperatures between 28.4^{o}F and 32^{o}F. They form a mucus-like outer shell in order to prevent the fatal freezing of their bodily fluids. During these freezing temperatures, worms will also lay collections of eggs, known as cocoons, closer to the surface of soil. This means that the cocoons themselves are much more tolerant to cold and are more likely to survive being shipped refrigerated. Survival rates are higher for cocoons than for hatched earthworms, therefore refrigerating and shipping cocoons will be more effective.

In order to encourage the growth of the worms, near the end of the trip to Mars the cocoons will be warmed and induced to hatch in a moist environment. This will allow them to live in terrestrial soil with bacteria, reproduce, and eat before arriving. The chances of survival are slimmer if the worms remain frozen for the entire trip to Mars, hence thawing them partway through and allowing them to live in a more natural state before their arrival will increase their vitality.

In addition to earthworms, to further improve nitrogen yields, the rhizobium species *Bradyrhizobium japonicum.* Bacteria of the genus Rhizobium form a symbiotic relationship with legume species, forming nitrogen fixing nodules on the plant's roots and using molybdenum and the enzyme nitrogenase to produce usable nitrogen whilst feeding off of the plant's organic matter. This process can increase nitrogen yields by up to 0.03 kilograms per meter squared of soil.

Rhizobium inoculants come readily available in the form of a white powder, which should be mixed with a ratio of 4.06 g inoculant per kilogram of soybean seeds. The inoculate should first be mixed with a liquid mixture of 10-20% sugar in water to ensure proper binding to seeds, and the seeds should be dried prior to planting. The amount of time allowed between mixing and planting varies based slightly depending on the supplier but tends to be between 8-24 hours. Like with the earthworms, the trip to Mars poses some risk to the health of the Rhizobium inoculants. The bacteria should be refrigerated, but not frozen, and have a shelf-life of approximately fifteen months, so the soybean seeds should be inoculated and planted soon following the setup of the greenhouse.

5.4 Irrigation Systems

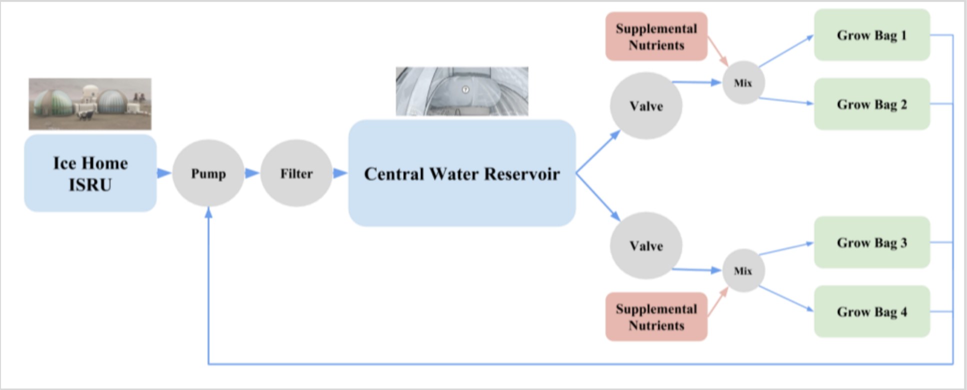

***Figure 3**: Irrigation system diagram*

Our greenhouse irrigation system was designed to maximize efficiency as well as minimize risk of system failure. Opting for soil growth meant our irrigation system would not have to provide a nearly constant flow of water as it would in a hydroponic system. This means less stress on each component of the system and less power consumption from pumps. Additionally, soil growth allows water and nutrients to be saturated into the soil, meaning that if the overall irrigation system were to fail or need repair, the plants could stay alive long enough for the crew to do repairs or switch to a manual watering method. In a hydroponics system, failure of the irrigation system could cause plants to dry out and die in a very short timeframe.

Our greenhouse is designed to carefully attend to the needs of plants on an individual level through an automated system of valves. Once the greenhouse is established on the surface of Mars, water will be diverted from the Ice Home's ISRU to the greenhouse for the purpose of filling an inflatable reservoir bladder placed above the central support column of the greenhouse. This reservoir serves to provide an upfront supply of water up to 4 cubic meters that will then become the basis of our semi-closed water system. During regular operations, our greenhouse computer system will actuate valves that will water plants as per their needs with water from the reservoir. Before the water reaches the plants, it can be passed through a mechanism to add additional nutrients that satisfy the needs of the specific plants the water is serving. Excess water will eventually pass through the fabric layer of our planter bags and move into the outer bladder where it will collect and eventually drain into a larger collection tube placed around the edge of the greenhouse. On one side of this ring is the single pump in our system. The pump will periodically pull water towards it, through a filter, and back to the reservoir. This process is visualized in **Figure 3**. This system ensures as much water as possible is recycled, reducing overall water consumption.

5.5 Lighting Systems

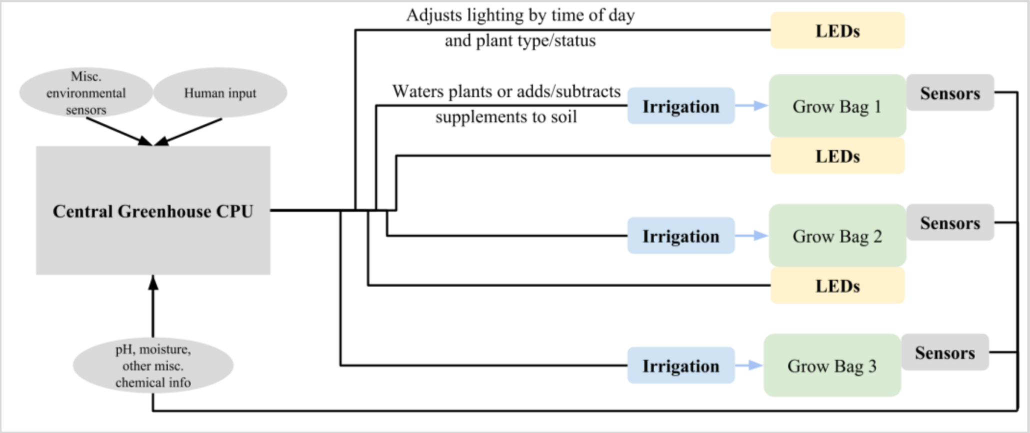

Figure 4*: Electronic control system for plant systems*

As with other aspects of our plant growth systems, our lighting system is designed to be efficient and cater to the needs of our plants on a very individualized level. While our greenhouse will receive some daily natural sunlight, Martian sunlight is only about 43% as bright as sunlight on Earth. Natural light will be diffused further as it passes through the water ice shield. The lack of consistent lighting means artificial lighting supplementation is necessary. Our system utilizes LEDs, which efficiently and reliably provide light across a large spectrum. Strips of LEDs can be easily integrated into our grow bags such that when the grow bags are placed in vertical racks, each plant bag is lit by LEDs integrated into the bottom of the bag above it. Each LED strip works as part of the greater network of electronic systems in each bag so that each strip can be customized to deliver exactly the right spectra of light for each plant to thrive, and each grow bag will be provided a photoresistor to ensure that the LEDs are functioning properly. Additionally, the lights can be turned on and off in a sequence to simulate light moving across the sky, combating favoritism in foliage that often occurs with stationary indoor plant lighting.

5.6 Biomass Resource Recovery

Biomass, including vegetable waste and plant trimmings from the green house, will need to be disposed of in a beneficial and sustainable manner. This waste constitutes significant nutrient and chemical energy content that can be recovered and utilized by well-developed processes. Electricity generation via combustion of biomass material has been practiced for some time with technologies developing quickly in light of recent global efforts to implement renewable resource energy production. As such, we propose a Controlled Combustion Steam Turbine Unit (CCSTU) that could be used to boil water and recover electrical energy in order to offset the power needs of the greenhouse. This sort of technology is developed well enough that a CCSTU could be flight certified with relative ease. Placing the CCSTU outside the greenhouse environment would allow a degree of isolation and safety, should a failure occur. It is also proposed that heated saturated liquid exiting the turbine could be pumped through a heat exchanger to offset heating loads within the habitat.

The combustion process would produce nutrient rich residual ashes. A study by the Energy Research Centre of The Netherlands presented at the 2005 European Biomass Conference, shows that biomass ashes can contain potassium, phosphorous, calcium, magnesium, and sulfur in varying amounts depending on the type, source, and quality of the biomass. This study concludes that reintroduction of ashes directly to the soil from which the biomass was harvested is the “most ecological and sustainable way to utilize the ashes" (Pels et al.). It is proposed that residual ashes from the combustion process be reintroduced to the soil beds within the greenhouse. This would complete the nutrient cycle and reduce the mass requirements of additional nutrients that would need to be brought from Earth. In addition, the CCSTU could potentially be used to dispose human byproducts produced by the crew members occupying the Ice Home.

6. Plant Selection and Nutrition

Due to the conditions of Mars and the thin Martian atmosphere's lack of ozone, our plants may have the potential to endure high levels of solar ultraviolet radiation. While ionizing radiation can stimulate plant growth at certain stages of development and may promote earlier flowering, the threat of adverse effects are worth accounting for. Such beneficial results can be attributed to the effects of irradiation on auxin balance. Per NASA's Education - SEEDS experiment, it was found that after seeds had been exposed to time on ISS more porous nutritional and epidermal layers were found than those of the ground-based control seeds. It's hypothesized that this allowed nutrients to disperse through the seeds more quickly, which explains the faster germination and growth rates observed in the space-exposed seeds.

As a precaution, our design accounts for adverse levels of UV radiation. Our plants will hold radio resistance; a property which makes organisms capable of coping with intense levels of ionizing radiation. This characteristic will exist through the use of the bacterium, *Deinococcus radiodurans,* one of the most radioresistant organisms known. We will bring cultures of the bacterium, upon arrival, cultures will be rehydrated or diluted using the appropriate medium. This will then be worked into the water and taken up by the plants. The optimal pH and temperature for *D. radiodurans* growth in is 7.0 and 37°C, respectively. *Deinococcus radiodurans* is a bacterium used for mechanisms of extreme radiation resistance and for bioremediation of environmental radioactive waste sites. *D. radiodurans* is resistant not only to ionizing radiation but also to UV, desiccation, and oxidizing and electrophilic agents. This organism can grow continuously under 60 Gy/hr, and has the ability to reduce contaminant metals and radionuclides including Cr, Tc, and U to less soluble species. *Deinococci* are extremely resistant to the severe DNA damage caused by irradiation and oxidizing agents. In the study, Redesigning Living Organisms to Survive on Mars, led by Amy M. Grunden and Wendy F. Boss, it was reported that following exposure to a dose of 10 kGy, *D. radiodurans* can mend over 100 double strand breaks without lethality, mutagenesis or rearrangement. As study results have shown, pre-exposure to either small doses of ionizing radiation or non-ionizing radiation may induce resistance against subsequent exposure to high doses of ionizing radiation in plants, therefore seeds created by the first generation of plants, will be more radioresistant than their plant parents.

Deinococcus radiodurans will travel in cultures and will be stored in a stowed refrigerator on board the mission to Mars.

In order to achieve a sustainable long-term presence on Mars, nutrition is of the utmost importance. Studies have shown, when individuals lack proper calorie and nutrient intake their mental and physical performance suffers. For these reasons, we have chosen to plant *Chenopodium quinoa* (quinoa), *Solanum tuberosum* (potato), *Spinacia oleracea* (spinach), *Arachis hypogaea* (peanuts), *Glycine max* (soybean), *Brassica oleracea var. sabellica* (kale), *Ipomoea batatas* (sweet potato), *Beta vulgari*s (beetroot), *Daucus carota var. sativus* (carrot), *Brassica oleracea* Italica Group (broccoli), *Allium sativum* (garlic), *Brassica oleracea* Gemmifera Group (brussel sprouts), *Capsicum annuum* (bell pepper).

Based on a 2000 daily calorie intake for adults, we found *Chenopodium quinoa* (quinoa) to be an essential crop. We will focus specifically on Red and Black cultivars because of their betacyanin concentration, which consists mainly of the pigments betanin and isobetanin. Darker quinoa seeds have higher phenolic concentration and antioxidant activity.

Solanum tuberosum (potato) are high in carbohydrates and contain a moderate amount of calories as well as healthy amounts of fiber, vitamins and minerals. The healthiest potato varieties are those with darker-colored flesh, which is why we chose cultivars 'Yukon Gold', 'All Red' and 'Kennebec'. The pigments in these potatoes provide flavonoids and carotenoids that promote good health. Potatoes thrive best when planted alongside crops from the Brassicaceae family, therefore this crop will be planted alongside broccoli and brussel sprouts.

Spinacia oleracea (spinach) is high in vitamins and minerals. The amounts of calcium, vitamin-A, vitamin-C, fiber, and folic acid help to strengthen bones, fight against injury, and protect against colon and breast cancer. For an elongated and staggered growing season we have chosen cultivars 'Bordeaux' for its rapid growth and significantly early harvest and 'Space' for its slow smooth leaf spinach to follow close behind. Best planted with the Brassicaceae family, this crop will grow alongside kale.

Arachis hypogaea (peanuts), are best grown after root crops such as carrots and potatoes. This superfood holds noteworthy nutrient levels including protein, dietary fiber, Phosphorus and potassium. Peanuts also provide significant amounts of Vitamin E, Vitamin B3, Folate, Pantothenic Acid, and 22711 mg of Omega-6 fatty acids.

Glycine max (soybean) is among the best source of plant based protein. High in glycinin and conglycinin Soybeans are rich in fat, with the predominant fat type being linoleic acid. Soybeans are high in iron, vitamin-B6, potassium, and magnesium.

Brassica oleracea var. Sabellica (kale) has the ability to outlast most crops. This superfood contains high levels of vitamin-A, vitamin K, vitamin-C, and significant amounts of potassium, Omega-3, and vitamin-B6. We have chosen the cultivar 'Wintebor' for its ability to regrow after the initial harvest and for its adaptability to tight growing spaces.

Ipomoea batatas (sweet potato) has great values of vitamin-A,pantothenic acid, in addition to significant amounts of vitamin-B1, vitamin-B2, vitamin B-6, fiber and potassium. The cultivar 'Vardaman', is a compact bush variety that takes up less space than most others and generally out-yields other varieties. Grown alongside 'Vardaman' will be, 'Beauregard', for its production of large, dense and smooth textured burgundy roots and orange center.

*Beta vulgari*s (beetroot), is among the richest source of phytonutrients of all vegetables. Best grown alongside broccoli and brussel sprouts, beetroot can yield large crops in the smallest of spaces. The varieties chosen are 'Detroit Dark Red' for its sweet taste that has little to no soil-like hints. In addition, this variety contains one of the highest concentrations of the red pigment betalain. Grown alongside it will be 'Red Ace', a similar variety which is just as tasty but even easier to grow. This variety is even more disease-resistant and quicker growing, producing great leaves similar to chard.

The color of *Daucus carota var. sativus* (carrots), is determined by two groups of pigments: carotenoids, which produce red, yellow, and orange hues; and anthocyanins, which develop the color purple. Carotenoids and anthocyanins are phytonutrients, which act as antioxidants that counter free radicals in the human body helping to protect against cancer and cardiovascular disease. Orange carrots contain alpha- and beta-carotene; these pigments are converted into vitamin A which helps bolster the immune system and supports healthy vision. For this reason, we have chosen two orange cultivars: (1)'Royal Chantenay', and (2)'Danvers'. We have chosen the yellow variety 'Jaune De Doub' since yellow carrots contain lutein a carotenoid pigment that prevents against macular degeneration, an eye disease, and 'Cosmic Purple' because purple carrots contain anthocyanins which help prevent cancer, heart disease, and stroke.

Brassica oleracea Italica Group (broccoli), is a member of the cabbage family whose large flowering head contains large amounts of sulforaphane, a compound that can prevent some types of cancer, antioxidants that protect the body from diseases, and plenty of Vitamin A, B, and C, plus potassium, phosphorus, calcium, and iron. We chose the varieties 'Dicicco' and 'Green Goliath' for their medium to extra-large heads that mature in a non-uniform fashion, making harvesting a staggered process that lasts over a longer period. Cultivars 'Calabrese' and 'Belstar' were chosen for their prolific production of side shoots once the initial crown is harvested. ‘Nutribud’ is a cultivar high in glutamine, a protein building block known to be a healing nutrient. As a result we have chosen to plant ‘Small Miracle’ and ‘Munchkin’.

Allium sativum (garlic) is a crop high in manganese, vitamin-B6, vitamin-B1, and calcium. These minerals and nutrients work together to reduce cholesterol and blood pressure. Allicin in garlic contains antibacterial and antiviral properties. The antioxidant properties of this crop reduces the risk of brain cell death, preventing potential issues such as Alzheimer and dementia. In addition, this crop helps to rid the body of toxins, improving liver function.

Brassica oleracea Gemmifera Group (brussel sprouts) will continue producing past most vegetable crops. This crops thick stems are heavy bud producers allowing for a plentiful growing season. Brussel sprouts are high in vitamin-C, and vitamin-K. High levels of antioxidants in Brussels sprouts could help protect against certain types of cancer. A study by TNO Nutrition and Food Research Institute, Zeist, The Netherlands found that when participants ate about 2 cups (300 grams) of Brussels sprouts daily, damage to their cells from oxidative stress decreased by 28%.

Capsicum annuum (bell peppers) is a bountiful crop, that once harvested will continue to produce new fruits. Rich in vitamin-A , vitamin-C, and omega-3 fatty acids; this plant won’t fail to provide nutrients along with taste. The cultivar ‘Ace’ was chosen for its low maintenance and bountiful harvest that provides early crops of large fruits. Accompanying ‘Ace’, ‘Gourmet’ was selected for its ability to keep and adapt well to varied growing conditions. The last cultivar is ‘Jingle Bells’ for its plentiful harvest and compactness, making it well adapted to tight spaces.

Fungi are potent degraders of chemical pollutants and extremely tolerant to potential toxicity. For this reason, mushrooms will grow symbiotically with our plants to help build nutrient rich soil and provide for the red wigglers. The root structure of mushrooms, known as Mycelium, functions as a mycofiltration system. Mycelium is a dense tangle of threads that can both physically trap runoff material and bind chemicals out of water onto the charged sites of its surface. In addition, adding mycelium spawn to the planters will improve aeration, water retention, and carbon sequestration. In order for mushrooms to decay organic matter, its root system will create a connective network of living tissue that brings more structure to soil by increasing the development of humus and large soil aggregates. In turn, allowing for plants to have more access to nutrients and water. These techniques are applicable to any type of soil, from sandy loam to clay, as long as fungi cultures and compostable waste is available to add. Excess biomass, including vegetable waste and plant trimmings will serve to feed the fungi.

Since the Martian soil will be relatively new and unproductive, fungi will be tilled into the soil so that it will inoculate and aerate at a deeper depth. Top dressing is recommended for soils that are relatively healthy, with a developed layer of humus and organic matter.

The process to create a mushroom garden is to either start from spawn, stem butts, or through fungi cultures. We will carry fungi cultures to Mars through spore prints. Reports have shown that spore prints can last 2 to 5 years, though due to this long dormancy they may have trouble germinating. If this problem is prevalent, in order to counter attack it spore prints can be rehydrated in sterile water for 24 hours. Once the mushrooms are planted and fully mature, crew members will select the most productive stem butts, and harvest them for the purpose of transplanting them back into the planters for future generations.

The most common and simple method to store the spore prints is to put the print in a ziplock bag, sealed and let it sit in the fridge. It can be simply kept in a file folder or any location that is clean, dry, and average temperature. The best way to make spore prints last is to store them on glass slides in a cool dark place.

7. Environmental Control and Life Support System (ECLSS)

Our Environmental Control and Life Support System (ECLSS) is modeled after that of the International Space Station (ISS). The ISS ECLSS is a proven model for providing comprehensive closed-system environmental control for up to seven crew members over long duration stays. However, the unique environment of the Martian atmosphere provides resources that can be utilized in making our greenhouse particularly efficient and better suited for growth. Additionally, the needs of plants vary from the needs of humans when it comes to an optimal atmospheric makeup and given the limited time the crew will be spending in this environment, it is therefore best to adjust the environmental conditions to favor plant growth over human comfort. To increase yield, a higher saturation of CO_2 than found in average air on Earth would be beneficial. According to a report by Oklahoma State University, plants with a C_3 photosynthetic pathway, which is what the majority of our selected plants have, experience anywhere from 40-100% increase in yield when grown in CO_2 levels in the 800-1000 ppm range, with a maximum growth rate increase of just over 200% occurring around 1100 ppm. Research however does suggest that increased CO_2 exposure can reduce the nutrient content of plants. This can be partially alleviated with careful adjustment of the nutrient contents of soil, which our irrigation system is designed to do. Our system is highly controlled and adjustable, so CO_2 and nutrients can be adjusted at any time if needed, but a normal operating condition of 1000 ppm of CO_2 is suggested to increase plant yield and growth rates while keeping saturation on the lower end for safety.

The ISS ECLSS system uses a four-bed CO_2 scrubbing system, which is equipped to handle people living there full-time. The greenhouse is not meant to be regularly inhabited by humans, and they will only spend a small amount of time tending to and harvesting plants. Plants also grow more efficiently in a CO_2-rich environment, thus, a two-bed system can be used in the greenhouse. This smaller two-bed system will less likely require repairs and it will use less energy. One bed is for CO_2 scrubbing, while the other is used for humidity removal. We want to have a healthy level of humidity in the greenhouse, or else the high humidity will cause the plants to become prone to fungal diseases. The CO_2 bed required is a regenerative Zeolite 5A molecular sieve bed. The CO_2 scrubbing beds will be active at night and kept inactive during the day in order to save energy. All CO_2 brought in will be used by the plants. There will also be a system for scrubbing oxygen from the environment in order to save it and store it for the nighttime.

For C_3 plants, we are assuming a daytime gross photosynthetic rate of 23 μmol of CO_2 per square meter per second and a total planting surface area of 107 m^3. We also are assuming an ideal 1:1 photosynthetic ratio for CO_2 input to O_2 output. CO_2 from the Martian atmosphere will be scrubbed and used within the greenhouse to support the plant growth.

The schedule for crew members tending to the greenhouse is as follows: They will spend no time in the greenhouse at night (i.e. 12 hours with no human inhalation or exhalation per day), with an upper limit of 4 crew members spending 12 hours per day inside and a lower limit of 4 crew members spending 1 hour per day inside. Crew members are unlikely to spend an entire 12 hours in the greenhouse, but the upper limit provides us with an absolute maximum value in the event they must spend extended time inside. The single hour per day lower limit refers to the minimum time needed to harvest.

When assuming these factors, there is an excess of O_2 within the greenhouse during the daytime, **Figure 5**. This excess O_2 will be scrubbed from the atmosphere and stored for the latter half of the day, when the photosynthetic process reverses and becomes cellular respiration and requires the plants to take in oxygen. The rate of cellular respiration is then 10 μmol of O_2 per square meter per second at night (**Figure 6**), resulting in excess CO_2 to be scrubbed and released back into the Martian atmosphere. Although the majority of excess O_2 from the daytime cycle will be used in the nighttime cycle, there will still be excess oxygen that can then be vented into the atmosphere or depending on the engineering of the Ice Home, can be vented into the living spaces.

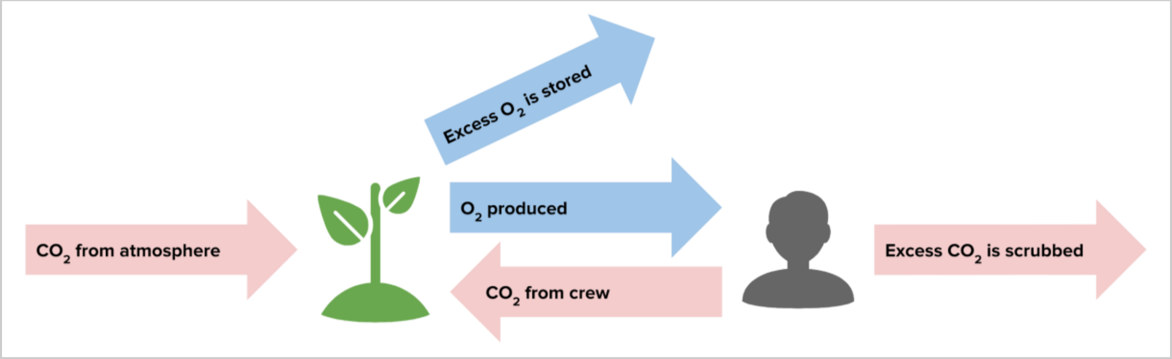

Figure 5: *The exchange of oxygen and carbon dioxide during the daytime*

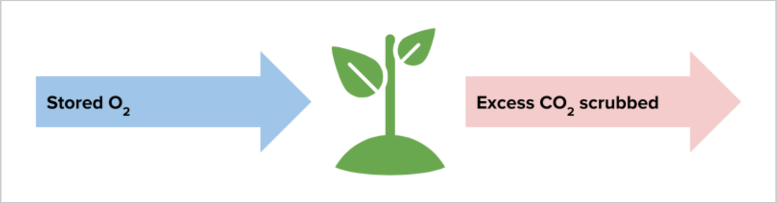

Figure 6*: The exchange of oxygen and carbon dioxide during the nighttime; no human interaction*

Our greenhouse will operate at around 80 ºF (~27 ºC) to significantly increase photosynthesis rates in the CO_2-rich air to about 33 µmol of CO_2 per square meter per second. This means nighttime heating will take more power than in the Ice Home per unit volume. The use of artificial lighting during the day will provide for most of daytime heating requirements. Assuming an average of -81 ºF (-63 ºC) on the Martian surface, the total energy required to heat our greenhouse to normal operating conditions will be around 9.8 kW. This heating load was calculated by doing a heat transfer analysis to determine heat losses through our dome walls to the outside environment. After this initial heating, energies required for maintaining this temperature will drop significantly due to the insulation being provided by the walls of the greenhouse structure as well as increased presence of CO_2.

Cooling will be passive, as the Martian atmosphere is extremely cold and capable of absorbing any excess heat in our environment. An additional benefit to our collection of water into an overhead reservoir is that it makes sprinkler systems a viable option for fire suppression. If fire is detected in our greenhouse, sprinklers can pull water directly from the reservoir.

8. Power Systems

As the majority of the power load comes from the lighting system, power consumption by the MAPS greenhouse can vary widely depending on time of day, time of year, and weather conditions. The maximum power load will occur during full supplemental lighting conditions, providing full Earth sunlight intensity to all plants. Current high performance LED lighting systems operate at around 120 lumens per watt. Assuming minimal advances is LED technology as well as 9.82 kW of peak heating, the theoretical maximum power consumption is 97.58 kW. Assuming zero light supplementation and minimal heating and ventilation, the theoretical minimum power consumption is 3.05 kW. It is unlikely that either the minimum or maximum power usage will ever be achieved as our growing system does not call for all lights to be on or off at any given time, but rather supplemental lighting is actively optimized by the Central Greenhouse CPU unit to balance natural light entering the environment through the semi-translucent water ice walls with the specific needs of each plant type. It is likely that an average sustained power load will be around 40 kW for about eight hours a day. This number coincides with NASA's initial estimate for the needs of a preliminary Human outpost. It is reasonable to assume that a sustainable, continuous, cycled-crew presence would necessitate a food production operation on the scale of the proposed MAPS greenhouse. The fact of the matter is that growing ample food in a low-to-no natural light situation is going to be an energy intensive endeavor.

During deployment, the maximum power load will be around 4 kW, just above the theoretical minimum power consumption during normal MAPS operation. This will occur during regolith bio-decontamination and represents the power of the electron beam emitter as well as a ½ HP electric motor driving the conveyor belt.

9. MAPS Concept of Operations

9.1 Launch

The internal structure of MAPS has been designed such that the central column telescopically contracts to a structural height of just 4 m. All other internal supporting members will fold in on themselves creating a cylindrical space with a radius of 6 m. **Figure 7** shows a diagram of structure in the stowed configuration. Accounting for the additional bulk of the inflatable dome which will be folded in a similar way as the Ice Home. The total stowed dimensions are predicted to be 6.7 m in diameter and just under 7 m in height. This puts the stowed height slightly lower than the Ice Home. The total landed mass is estimated to be 16,020 kg leaving a 1,980 kg margin. All other non-structural components, such as the carbon fiber panels, irrigation system, planter bags, etc. can be stowed within the volume of the central column. The choice of aluminum 6061 alloy for most of the structural components comes partly from its widespread use in aerospace, giving high proven confidence the structure will be able to withstand launch and entry loading. NASA's Space Launch System (SLS) Block 2 Cargo rocket currently in development would be an ideal candidate for launching our greenhouse given its 10 meter fairing and Mars transfer capabilities. SpaceX's Falcon Heavy and BFR rockets, currently in development, are other potential candidates for launch.

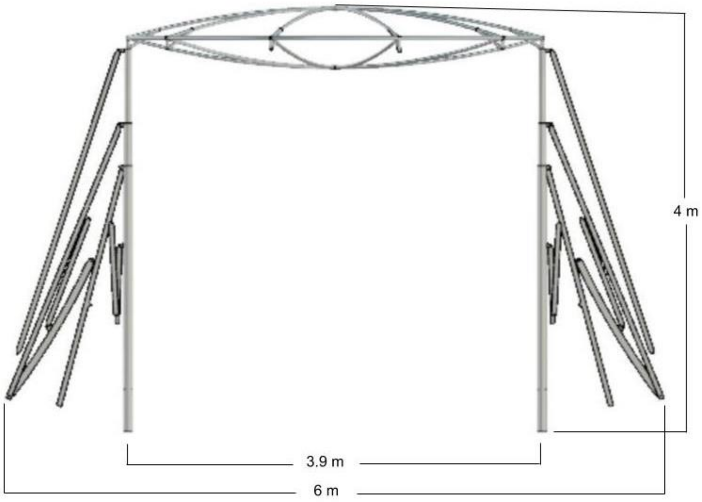

Figure 7 *Dimensions of structure in the stowed configuration.*

<u>9.2 Deployment</u>

MAPS will be robotically transported to its deployment site and connected to the Ice Home habitat. CO_2 will be pumped into the insulation layer of the dome walls at a rate balanced with the addition of air into the internal volume of the greenhouse. As the greenhouse is inflated and the internal volume increased, the top of the of the dome will steadily rise, pulling with it a structure attached to a central support column. The column will rise telescopically in three sections, each section locking into place as it reaches its final height. The rising of the column will unfurl the 2nd floor support structure as well as the canopy structure much like an umbrella. This is demonstrated in **Figure 8**. These structures will lock in place upon full extension. At this point, the internal support structure is completely erected by the simple act of inflating the dome.

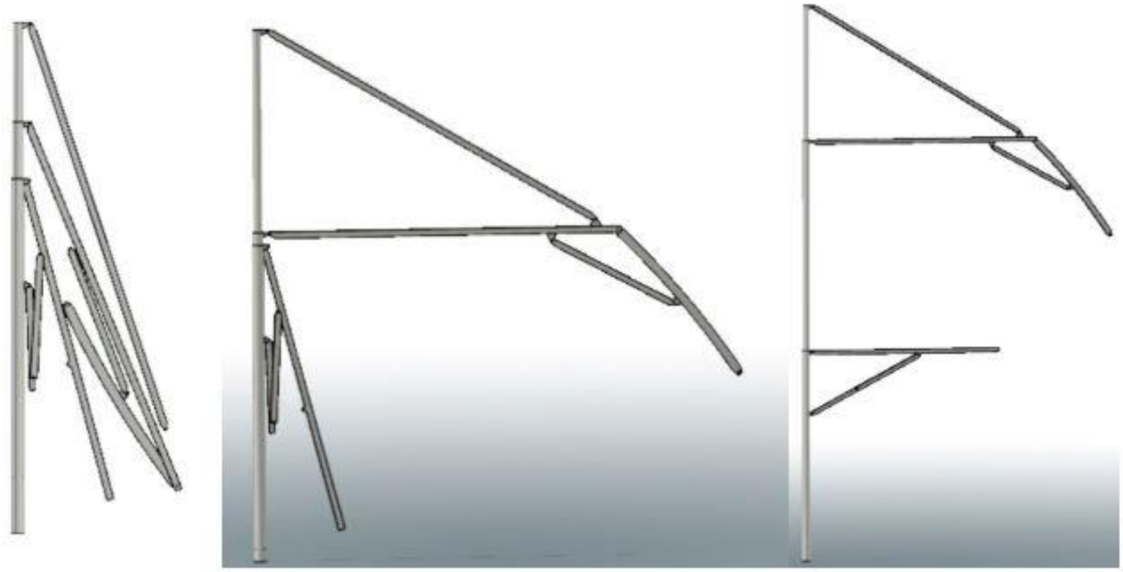

Figure 8: *From left to right- represents the three stages in which the greenhouse will inflate.*

Upon arrival of the crew, the carbon fiber panels that make up the lower floor will need to be snapped into place. The central column has brackets onto which the stair panels will connect. Upon reaching the top stairs, a crew member will begin snapping the panels for the upper floor into place. A flexible perforated canvas tubing will act as a ventilation duct. A crewmember will connect this to the heating and ventilation unit and run it through the 2nd-floor support structure and the canopy structure.

Flexible wireframe planters will be strung up by cables attached to the canopy and MAGIC planter bags placed accordingly into them. Most of the main irrigation lines and hardware will be attached to the canopy structure during flight. Once the canopy is unfurled, the crew will merely need to run the final section of drip tubing before filling the MAGIC bags with regolith. The procedure for transferring untreated regolith into the habitat will require the pressure door to the Ice Home to be sealed and the internal pressure of the greenhouse equalized with Martian atmosphere. While the water ice shielding will not have accumulated at this point, the pressure of the CO_2 insulation layer as well as the central core structure will be sufficient to support the weight of the dome material while internal pressure is released. Having the greenhouse now isolated from Ice Home, untreated regolith will be transferred through the rear pressure door and into the MAGIC bags without chance of contaminating Ice Home with perchlorates and other volatiles.

Following the treatment of the regolith as described above which is automated by our smart irrigation system, the greenhouse is effectively ready for operation. Because the dome is essentially a pressure vessel and the water ice shielding is not structural, completion of the ice shield is not necessary to begin plant growth.

9.3 Sustained Food Production

After initial set up, steady state greenhouse operation will require minimal man-hours as all irrigation, lighting, and environmental control will be highly automated by our smart plant growth system. Occasional crew time will be required for pruning and removal of dead vegetation. Harvest is not automated in our system and will need to be performed by crew members. Harvest constitutes the largest investment of crew time. As the crew members begin to plant the seeds, each spot will have 3 seeds as shown in **Figure 9**. This constitutes for extra resources in the case of failure. When one seed grows successfully the remaining 2 seeds will be thinned out. Initiating this reconfiguration system will ensure a continuous growth and harvest cycle.

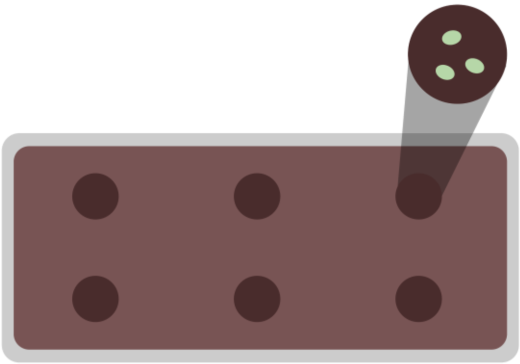

Figure 9: 3 seeds per hole ensures extra resources

In order to sustain our crew members beyond the first harvest, we have considered a variety crop and seed storage methods. Some crops will rely on seed storage, while others will do best by keeping bulbs or trimming. Regardless of the method used, the drying process and storage environment of all crops is crucial to the success of the next harvest.

Some seeds do not fare as well in storage. Crops in the Apiaceae or Umbelliferae family such as carrots, tend to be short lived. For these crops, freezer storage is best method as seeds from these plants will quickly lose their ability to germinate and grow at room temperature.

The Amaryllidaceae family, which onions belong to are best stored in sets. While growing from seed is possible, using the bulb of the onion will significant cut down the growing time. First, dry onion sets under light in a row with their tops partially covering the bulbs skin until the outer layer is papery and the roots are dry. Remove roots, depending on how crew members would like to organize their storage area, they can either braid bulb tops together or remove tops by cutting 1 inch from the bulb. If crew members choose to cut tops, they should leave an inch of the stem. Bulbs need to be stored properly in a cool, dry place, with adequate air circulation. If braided, they can hang in a storage area, if tops are cut, they should be placed in a mesh bag.

9.4 End of Life Procedure

Per the rules of the Planetary Protection act, and also as responsible scientists and explorers, we must protect any possible Martian ecosystem from contamination with Earth pathogens. As such, when the time comes for the decommissioning of the MAPS greenhouse it must be stripped of all life and its environmental footprint reduced as much as possible. All vegetable matter should be incinerated in the CCSTU system described above. Vegetable matter could also be rendered inactive by decompression and freezing. All soil should then be run through the electron beam sterilization procedure. Commercial electron beam emitters are small enough such that they could be fitted to a bi-axis gimbaling platform. In this way, the entirety of the interior of the dome could be irradiated from different positions in order to assure sterilization.

The dome should be left in decompressed state and open to the environment to avoid future explosive structural failure that might cause materials to be scattered. Samples of the material layers from around the dome should be taken back to Earth as a valuable material exposure study. Heavy equipment and floor panels should be stowed in the central column to protect them in the event that a future mission to the region could utilize those material resources.

10. Conclusion

The Mars Agricultural and Plant Sciences (MAPS) greenhouse is a smart habitat utilizing existing high-TRL technologies to provide a cost-effective and sustainable Marsboreal greenhouse solution. MAPS has been engineered for simplicity and reliability. Simple soil and drip irrigation farming techniques produce the majority of the food in the United States. The addition of some intelligent automation will enable these practices to provide sustenance for the explorers as they work to expand our horizons and ensure continued American leadership in space exploration for generations to come.

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Appendix

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