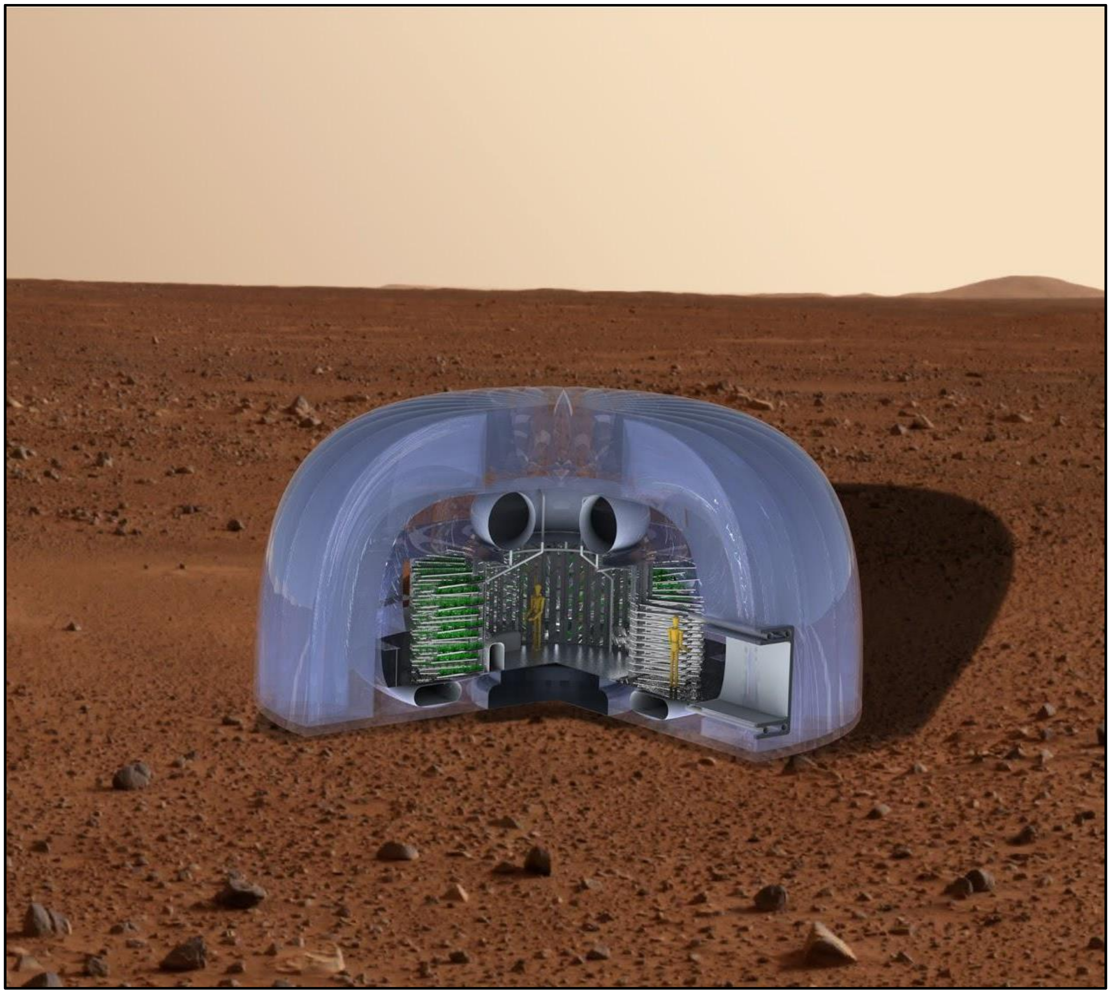
Dartmouth College, Thayer School of Engineering

Technical Paper - 2019 NASA BIG Idea Challenge



DEMETER Advanced Concept of Operations

Team
Zoe Ault Rivas, Alexa Escalona, Grace Genszler, Thomas L. Hodsden III, Morgan McGonagle,
David Dick, Peter Mahoney, Christopher Yu

Faculty Advisors
Benoit Cushman-Roisin, Laura Ray, John Collier, Lee Lynd

Table of Contents

1. Introduction

1.1. Introduction and Overview

Our greenhouse design concept, DEMETER, is a Deployable Enclosed Martian Environment for Technology, Eating, and Recreation. DEMETER incorporates ice shielding from the Mars Ice Home habitat design and will provide sufficient nutritious food for a four-person astronaut crew on a 600-sol surface mission to Mars. The design has been conducted in five primary phases: determining the nutritional need of the astronaut crew, selecting a plant-based diet to meet the nutritional need, sizing the greenhouse architecture to grow the plants, developing the necessary subsystems to support the growth of the plants, and iteration using the knowledge gained during the prototyping process. The design is an automated hydroponic growing system which utilizes a cylinder inside a torus. This cylinder stores the system that dispenses and recycles the water and nutrients. The greenhouse also provides a circular track for exercise and recreation.

1.2. Purpose, Scope, and Background

The primary purpose of the greenhouse is to feed the crew, but it will also support the effort to create a closed loop habitat by recycling biomass, energy, water, oxygen (O_2), and carbon dioxide (CO_2) with the Ice Home. With consideration for future missions, the targeted operating lifespan of DEMETER is 15 Earth years. This greenhouse will be part of the first effort to establish a human presence on Mars, which has only been visited by probes and rovers. Similar technologies used in this series of Martian missions will be tested in cislunar and lunar missions, providing opportunity for improvement and astronaut practice.

1.3. System Overview

The system includes the Martian Environment, the Ice Home, and DEMETER, as illustrated in Figure 1. Water and electricity are generated by the Ice Home, and the human crew provides CO_2 and liquid waste in the form of urine. DEMETER will provide food and O_2 to the Ice Home.

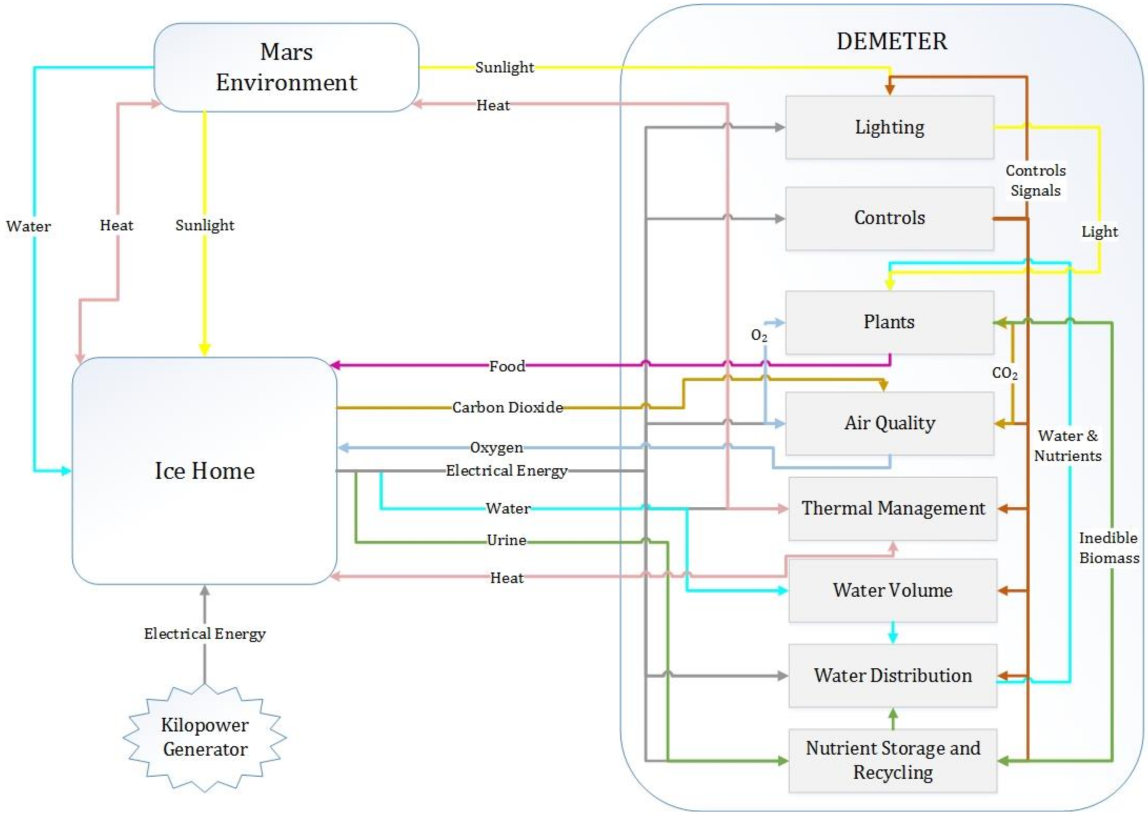


Figure 1: DEMETER system overview map. "Controls" here refers to the compilation of all sensors and actuators, as well as the computers and interface.

1.4. Needs, Goals, Objectives, and Requirements

1.4.1. NASA Need

In the interest of establishing a human presence in space, NASA seeks to send a human mission to Mars as early as 2030. In 2017, the Mars Ice Home feasibility study developed the Ice Home, an inflatable habitat structure designed to house an astronaut crew on Mars. The Ice Home makes use of *in situ* resource utilization to fill an inflatable structure with water for radiation shielding and CO_2 for insulation.

1.4.2. Technical Goal

For the 2019 NASA BIG Idea Challenge, our team presents a design for a greenhouse capable of producing sufficient food to support an astronaut crew living and working in the Ice Home.

1.4.3. Team Goal

Our goal was to fabricate a proof-of-concept experimental prototype in order to address design and operational challenges. We met this goal with three experimental prototypes and a gas composition model.

1.4.4. Objectives and Requirements

We determined the objectives and requirements for our greenhouse design from the 2019 BIG Idea Challenge Competition Basics and the NASA-facilitated Q&A session. The primary objective that guided our design process was to sustain a four-person crew for a 600-sol mission on Mars, optimized to support consecutive missions for 15 years.

2. System Description

2.1. System Context

DEMETER will be a Closed Ecological Life Support System unit of a Mars outpost. It will be directly connected to the Ice Home via airlock to support crew members with all necessary food, a means for daily engagement, and a space for recreation. DEMETER will draw its power and water through an interface with the Ice Home. In return, it will offer a means to support and balance Ice Home air composition.

2.2. Basic Assumptions

2.2.1. Inflatable Structure

The greenhouse structure will be inflatable in order to maximize space and reduce payload size. A toroidal shape, similar to the Ice Home, was chosen for the pressure vessel of our greenhouse for its complementary deployment methods and stable footprint [1].

2.2.2. Placement and Site Preparation

After landing, the packaged greenhouse will be robotically transported to the deployment site. This site will have been flattened and cleared of large debris (rocks larger than 4 cm) [1].

2.2.3. Ice Home Capabilities

The Ice Home will have the means to produce 1000 L of water every 10 sols and pump this water to the greenhouse via the interface. The Ice Home will have a pump that interfaces with the Martian atmosphere in order to provide initial inflation with CO_2 for the greenhouse. The Ice Home will transmit the necessary amount of electric power to the greenhouse via the interface power connection. This amount is assumed to be a fraction of the total Ice Home power supplied by 4 to 5 10kWe kilopower generators [2]. The pressure inside the Ice Home is assumed to be 101 kPa [1].

2.2.4. Resource Margins

A 30% resource margin for water, mass, and peak power consumption will be maintained. The greenhouse will help maintain many of the Ice Home systems, so we assume it is reasonable for DEMETER’s peak power demand to be no more than 20 kWe [1].

2.2.5. Cosmic Ray Environment and Radiation Shielding

The greenhouse will employ the same radiation shielding strategy as the Ice Home, with CO_2 and water ice membranes built into the inflatable structure. The shielding thicknesses will be designed to reduce radiation exposure by 50% [3]. The amount of cosmic radiation experienced on Mars varies with location, so we assumed a landing site of ± 30^o latitude when considering cosmic radiation and climate conditions.

2.3. System Phases

2.3.1. Launch, Flight, Entry, Descent, and Landing

The packaging of DEMETER resembles that of the Ice Home. However, instead of tight ribs on the sides, the membrane will pack tightly on top of the cylinder, and all of the equipment and consumables will fit inside. The upper and lower structural support pieces will be collapsed into the cylinder and will extend vertically during deployment. A diagram of the packaging is shown in Figure 2.

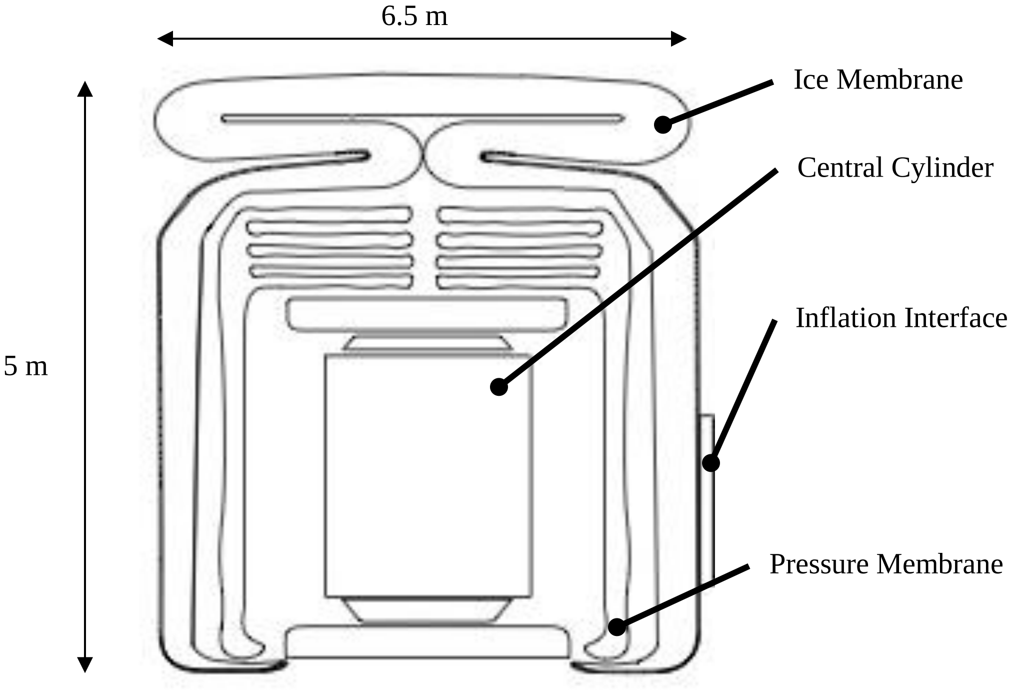


Figure 2: DEMETER packaged schematic.

The entry, descent, and landing (EDL) analysis was modeled using the Space Launch System (SLS) capabilities and parameters in a dynamics calculation spreadsheet created by aerospace engineer and advisor Max Fagin. In these simulations, we assumed our package could withstand up to eight times the force of Earth's gravity [4, 5, 6]. This assumption is based on the capabilities of the materials used in DEMETER. For example, containers that hold acid will use a Teflon-lined Kevlar capable of withstanding launch and operational conditions. A more detailed mass budget is shown in Figure 3. For the purposes of this simulation, propellant refers to the amount needed when using an unguided landing system plus a 30% margin.

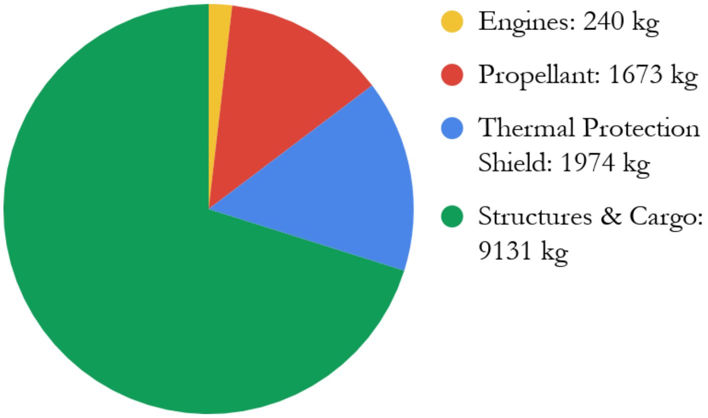


Figure 3: Mass budget for EDL analysis.

As the vehicle begins its descent into the Martian atmosphere, the entry mass is comprised of all four components displayed in Figure 3, totaling 13,018 kg. About five seconds before the spacecraft lands, at an altitude of 800 m, the Thermal Protection Shield is ejected and the engines begin to fire, using up the propellant. By the time the payload lands on the Martian surface, only the cargo and engines will remain, for a landing mass of 9371 kg.

2.3.2. Deployment

Deployment will begin with the robotic transport of the packaged greenhouse payload from the landing site to the deployment site, a pre-cleared site adjacent to the Ice Home. The packaged cylinder will be placed within 1 m of the end of the Ice Home tunnel interface. The telescoping tunnel will connect the greenhouse interface ring to the Ice Home, as illustrated in Figure 4. This feature will allow the greenhouse to be placed in its final position before deployment.

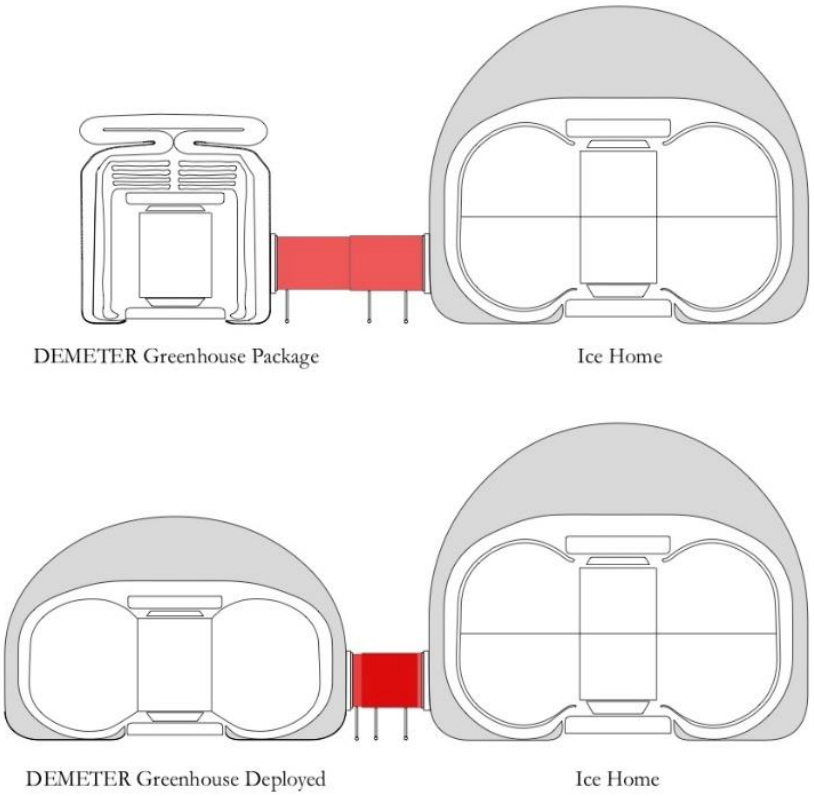


Figure 4: Initial and final stages of inflation. The telescoping tunnel is shown in red.

After telemetry, sensor data, and visual confirmation via cameras provide evidence of successful connection, the inflation of the greenhouse will begin. Through the interface, the air compressor inside the Ice Home will inflate the greenhouse to 101 kPa, equivalent to the Ice Home pressure. With 300 m^3 of working space and 407 m^3 of CO_2 membrane to inflate, initial inflation will occur over a 52 sol period, based on our calculations using a scaled scroll air compressor [7]. Throughout inflation, the telescoping Ice Home interface tunnel will passively contract in increments of 7 cm per sol. The greenhouse's 416 m^3 of ice shielding and 6500 L of working tank volume will take 4225 sols to fill at a pumping and production rate of 100 L per sol.

We constructed an inflatable prototype to demonstrate the packaging of the membranes and the inflation of the innermost membrane. This helped us understand the feasibility of the geometry and prompted us to change our design to package the membranes above the cylinder instead of on the sides. The inflatable membrane is modeled with a vinyl polymer and the inner cylinder is modeled with high density polyethylene. This is shown in Figure 5.

Figure 5: Inflation of the inflatable prototype.

To ensure successful deployment, strain sensors will monitor the greenhouse membranes, flow rate and pressure sensors will monitor the air and water lines, and cameras will provide visual confirmation of the deployed state throughout the entire deployment timeline. Automatic systems monitored by ground operators on Earth will halt or adjust deployment if necessary.

Another deployment prototype was created which addressed the deployment of the plant growing system. Specific aspects of the prototype require more information about our design. Therefore, information on this prototype can be found in Section 3.4: Structural Support System.

2.3.3. Deployed State, Outfitting, and Checkout

Before the crew arrives, DEMETER will be completely inflated and the ice shield will be partially filled. The percentage of the volume partially filled depends on the water extraction rate allowed for the greenhouse and the order of priority after the human habitation area. The 0.1 m^3 per sol water production rate results in a lengthy filling time, as mentioned previously, so the radiation shielding will not be completed upon the crew's arrival. However, if the greenhouse could get a higher rate after the priority areas are filled, this time could be reduced dramatically. In the case of an incomplete shield upon crew arrival, plants can still be grown safely [8]. Protective equipment, such as EVA suits, may be worn by astronauts while they work in the greenhouse for additional shielding.

At the time of crew arrival, the water reservoir will contain 6500 L, the greenhouse will be fully inflated to a diameter of 16.2 m, the plant growing tray structure and related systems will be in place, and the Ice Home interface airlock will be established and functional. DEMETER will share its atmosphere with the Ice Home, and the air composition will become human-compatible by the time the crew lands. Diagnostic tests will ensure proper functionality of all systems. The interior greenhouse temperature will be held just above 0°C until the crew arrives, when it will be heated to 20°C.

Once the crew has arrived, they will check and maintain all systems. They will then prepare the hydroponic solution and plant seeds for germination. Until a critical plant mass is reached, the greenhouse will be ineffective in balancing CO_2 levels with O_2, so additional O_2 will be necessary.

2.3.4. Operations and Maintenance

DEMETER, like the Ice Home, is designed to be a multifunctional Mars habitat component. Though its primary role is to produce food, it is also designed to serve as a space for recreation and a viable living area in the event of an emergency Ice Home failure.

Based on plant climate averages, the temperature of the system will be set to 20 ± 2°C and the humidity will be set to 70 ± 10 % [9, 10, 11, 12, 13, 14]. The lights, temperature, humidity, air composition (CO_2, O_2, and nitrogen levels), nutrient concentration, pH, flow rate, and reservoir water pumps will be regulated autonomously unless intervention is necessary. Humans will oversee and control waste and water transfer and monitor general plant health. We estimate that DEMETER will require up to 21 total person-hours of labor per week, divided amongst the four crew members. This is based on our experience with our hydroponic prototype (which we will discuss in section 3.5), visits to local greenhouses, and data from the Lunar Greenhouse project [15].

2.4. Interface between Greenhouse and Ice Home

The greenhouse will interface with the Ice Home with a 2 m x 2 m pressure door which will connect to a telescoping tunnel extending from the Ice Home habitation zone. The greenhouse pressure door is based on the International Berthing Docking Mechanism (IBDM), which operates on the International Space Station. This mechanism consists of two components, one active and one passive, and enables robust, pressurized mechanical connection as well as power, data, air, and water transfer [16]. The interface ring for the greenhouse will have similar embedded connections as the IBDM with an additional connection for urine transfer. Mechanically, the greenhouse ring will be the passive component, with the locking components integrated into the interface on the Ice Home tunnel. To facilitate simple and quick initial connection of the structures before inflation, the resource connections on the greenhouse interface ring and complementary Ice Home attachments will be attached via quick connect/disconnect fittings.

In addition to this interface, a secondary exit and entrance to the greenhouse will be available via an external airlock, located on the opposite side of the torus. We have chosen the NASA Dual-Chamber Hybrid Inflatable Suitlock conceptual design as an analog, which is expandable and provides both suitlock and traditional airlock capabilities [17]. This airlock tunnel will be portable and will attach to the greenhouse with a similar interface as the Ice Home interface. Air, power, and data connections will interface with the external airlock.

3. Plant Systems Design and Systems Integration

3.1. Crop and Growth System

3.1.1. Crop Selection Based on Nutritional Requirements

Plant selection was dictated primarily by the dietary needs of the crew. This selection was optimized to include the most nutritionally-dense plants with the shortest growing time, highest edible biomass density (EBD), and highest harvest index. We assumed each member of the crew will eat a 3000-calorie diet with 60% of calories from carbohydrates, 15-20% from protein, and 20-25% from fat [18].

In total, 90 species of vegetables, grains, fruits, herbs, nuts, and seeds were compared based on the specified criteria. The ideal growth environment for each plant was considered, and priority was given to plants that have been suggested for use in closed ecological systems such as Bios-3 [14, 19]. Our final plant selection includes kale, soybeans, sweet potatoes, potatoes, strawberries, broccoli, wheat, and chufa. The relative amounts of these plants were optimized to create a diet that meets the daily proximate and caloric requirements of the crew. This diet dictated the required growing area for each plant and the required size of the greenhouse. The nutritional content for a daily diet is shown in Table 1.

During preliminary analysis, we also identified daily requirements for thirty vitamins and minerals, but consultation with a nutritionist encouraged us to introduce a multivitamin to support these additional dietary needs. To supplement our plant selection and multivitamin, we compiled a list of optional herbs and spices that the crew can grow to personalize their diets. This list includes garlic, basil, tarragon, mint, rosemary, thyme, oregano, nasturtium, onion, flax seed, chia seed, sunflower seeds, and sesame seeds.

Table 1: Nutrition Content of Each Plant

Plant	Amount (g/sol)	Energy (cal/sol)	Protein (g/sol)	Fat (g/sol)	Carbohydrate (g/sol)
Kale [20]	2200	770	64	33	97
Soybeans [21]	330	1472	117	70	99
Sweet Potato [22]	1824	1568	29	1	367
Potato [23]	630	485	13	1	110
Strawberries [24]	110	35	1	0	8
Broccoli [25]	390	133	11	1	26
Wheat [26]	1175	3982	161	29	835
Chufa [14]	876	4158	70	197	526
Total	**7535**	**12,603**	**466**	**332**	**2068**
Required (Crew)	------	12,000	450	267	1800

3.2. Growth Time, Harvest Cycles, and Efficiencies

After finalizing our plant selection, we developed suggestions for optimal cultivars based on growth time, harvest time, and yield. We also devised an optimal surface area distribution for plant growth, as shown in Table 2.

Table 2: Key Parameters for Selected Crops

	Cultivar	Growth Time (sol)	Yield (g/plant)	Surface Area (m^2)	Vertical Space (m)	Volume (m^3)	EBD (g/m^2)
Kale [27, 28, 29]	Premier	120	800	4.6	0.42	1.9	49,600
Soybean [30]	Wheeler's 891	94	33	11.6	0.42	4.9	2050
Sweet Potato [31]	Ti-155	130	1790	8.1	0.6	4.9	28,640
Potato [32, 33]	Denali	114	3990	8.1	0.6	4.9	9980
Strawberry [34, 35, 36]	Strawberry Festival	120	100	2.3	0.42	1	1110
Broccoli [37, 38]	Imperial	90	650	1.9	0.6	1.2	4060
Wheat [26, 33]	Perigee	80	--	35.1	0.42	14.7	1740
Chufa [14, 39]	Alboraia	80	--	20.3	0.6	12.2	2250

3.3. Growth Media

We researched and compared soil, aeroponic, and hydroponic growth mediums for the greenhouse. Much of this work included visits to local greenhouses and consultations with experts and professionals. After comparing each system's design parameters, the most important being safety, reliability, and energy usage minimization, we chose the Nutrient Film Technique (NFT) hydroponic system. Hydroponic systems have the advantage of greater yield than soil; for example, strawberries have a smaller growing area, lower water usage, and 17% increase in yield when grown hydroponically versus grown in soil [36].

3.4. Structural Support System

3.4.1. Structural Design Overview

The overall structure of DEMETER closely resembles that of the Ice Home; this allows the two structures to be developed concurrently, reducing development costs and timelines. After an independent analysis of shapes including cylinder, torus, and dome, we selected the toroidal layout for its efficient volume, stable footprint, and ease of deployment. The size of the structure was scaled according to the volumetric needs of the plant growth, and was constrained by limits on the package size.

We designed modular hydroponic growing trays and calculated the yield of a growing tray for each plant variety. These trays have a rectangular base with trapezoidal sides to allow for tight packing. They are arranged radially around the central cylinder. We used an optimization algorithm to meet the caloric and proximate needs of the crew while minimizing the growing area and keeping at least one stack of each plant variety. This achieved a balance of plants that provides a diverse and nutritious diet. These trays are illustrated in Figure 6.

This hydroponic system was designed with deployment and harvesting in mind. The top covers of the hydroponic growing trays can be removed for plant harvest and tray storage, and a tower of hydroponic growing trays - from now on referred to as a "stack" - can compress together. This allows the trays to fold tightly against the central cylinder during transport. The stacks are shown in Figure 6.

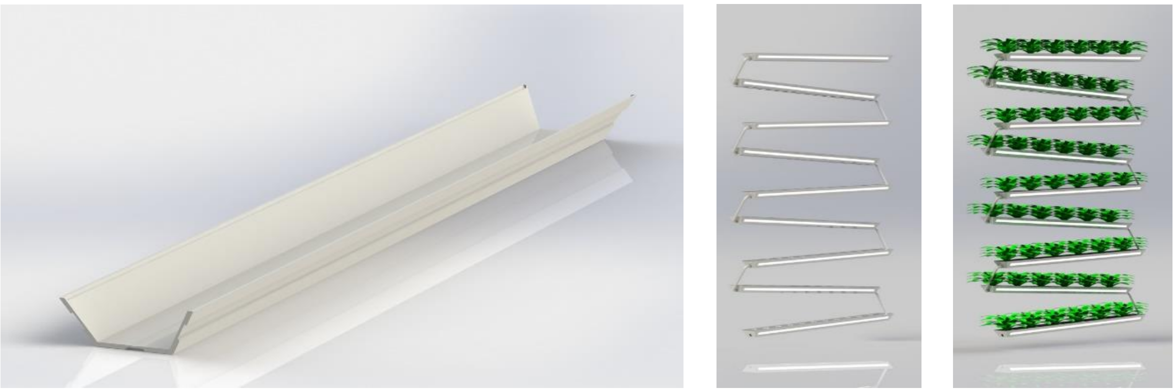


Figure 6: A single tray without end caps (left), a stack without plants (center), and with plants (right).

Early on in our design process, we wanted to ensure that the dimensions of the trays were realistic and comfortable for astronaut operation. To help us visualize the space, we made a full scale chalk outline of the circular growing area and took note of the vertical height of the inner cylinder. This exercise, and several trips to local greenhouses, helped us determine the appropriate dimensions and spacing of the trays that human crew members will interact with. We found that humans can comfortably work with a removable tray cover that is 0.75 m long. The crew will need to remove the tray covers and transport them as part of harvesting activities, so we designed the 1.5 m trays to have two tray covers, each 0.75 m long. We also determined that 1.5 m is a comfortable width for the circular track around the growing space.

The central cylinder will also house storage for surplus harvested crops, including a freezer for the kale, broccoli and strawberries. The other crops can use non-refrigerated containers. Additionally, a small stack will hold the herbs and edible flowers previously mentioned, as well as a few extra trays for the nursery.

In our initial proposal, our design featured an inner cylinder height of 2.5 m. During our feedback call with the BIG Idea Challenge judges, we were encouraged to revisit the vertical space requirements of our chosen plant varieties. After further research and discussion, we increased our cylinder height to 3 m to give the plants more vertical space. The spacing between trays is now equal to the vertical space requirement of each plant variety, given in Table 2 in Section 3.2. The nursery trays require less vertical space, with 0.15 m of spacing between each tray. Figure 7 shows the greenhouse with updated overall dimensions.

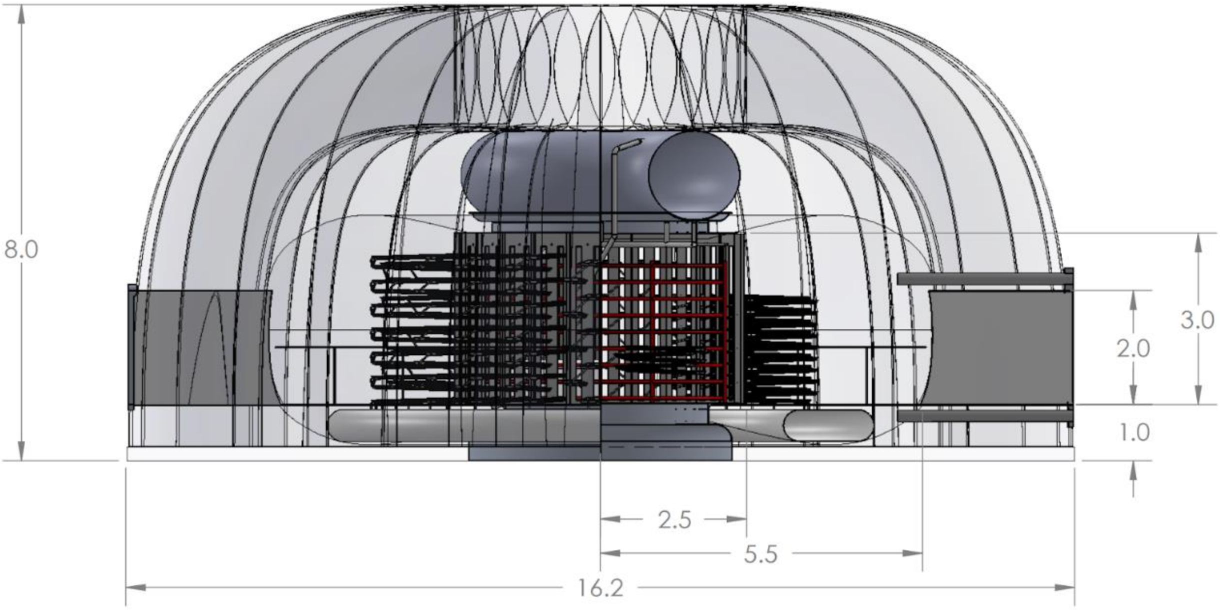


Figure 7: Major dimensions of DEMETER in meters.

3.4.2. Stack Deployment Prototype

To better understand the deployment of the hydroponic growing system, we developed several iterations of a subscale prototype. The first version of this prototype was made entirely with plywood and featured a cylindrical glide track. Based on how this prototype worked, insight from CAD modeling, and consultation with Dartmouth's resident machine shop experts, we made many changes for the second iteration, shown in Figure 8. This new version featured hinges that allow the trays to fold upward during packaging and unfold to a predetermined angle. We designed custom hinges that stop the trays at the correct angle. Sliders allow the trays to translate vertically into their final positions. This vertical motion is accomplished with a system of pulleys and cables that pull the sliders along a glide track. The prototyping process informed the decision to use a glide track and the decision to change the design of the trays to include a more flexible end cap. We switched from a cylindrical glide track to a T-slot bar system with a slider to reduce friction.

To minimize bending and stress in the long trays, cables will also support the far ends of the top trays. Because the trays are only 1.5 m long and the cylinder is 3 m tall, the bottommost trays do not need to move - they can be packaged in their final position and remain there. Therefore, only the top half of the stack needs to be translated vertically. This translation will be achieved by the lowering of a counter-weight from a high location. This will raise the trays to their final positions, and the lower trays will be pulled up by tension in the cables connected to the trays above them.

Figure 8: Deployment prototype in three configurations: packaged (left), partially deployed (center), and fully deployed (right). The top shows the CAD model, the bottom shows the physical version [40].

These prototypes are ⅙ scale except for some pieces which were made larger for ease of manufacturing. Specifically, the hinges and sliding mechanism are oversized for the ⅙ scale; in the full-scale design, they can be much smaller compared to the tray size. Additionally, the prototype stack contains only five trays, while the number of trays in a full-size stack ranges from nine to thirteen.

3.5. Water and Nutrient Delivery System

The NFT hydroponic system delivers nutrients to the plants via a thin film of water that flows at a constant rate over the tips of the plant roots. This is accomplished with a system of growing trays connected to a reservoir filled with a water-nutrient solution. The trays are angled to ensure steady, gravity-driven flow over the plant roots. Once the water has flowed through the system, it is collected in a reservoir at the bottom of the greenhouse. After the bottom reservoir is filled, water will be pumped 5 m upward back into the upper reservoir. The water in the bottom reservoir will be aerated, enriched with nutrients, and sanitized prior to pumping to the top reservoir. These systems are demonstrated in Figure 9.

The plants we selected for the greenhouse all grow well in a hydroponic system when supplied with a Hoagland nutrient solution, which is composed of the ideal amounts of nitrogen, potassium, phosphorus, and other elements essential for plant growth [30, 38, 41]. This allowed us to more fully integrate the nutrient delivery and water delivery systems without concern for specialized solutions for each plant variety. Two tanks are required, one with a water temperature between 15.6 - 18.3°C for strawberries, kale, soybean, potato, and broccoli, and another tank with a water temperature between 21.1 - 23.9°C for sweet potato, wheat, and chufa [10, 42, 43]. The electrical conductivity (EC) of the warm tank should be 1.25 dS/m and the EC of the cold tank should be 2.1 dS/m [44, 45, 46, 47, 48, 49, 50]. In order to maintain a healthy EC, the water-nutrient solution can be periodically directed through salt filters to remove excess salts. These excess salts will be stored until the end of the mission, when they can be returned to earth in the return vehicle.

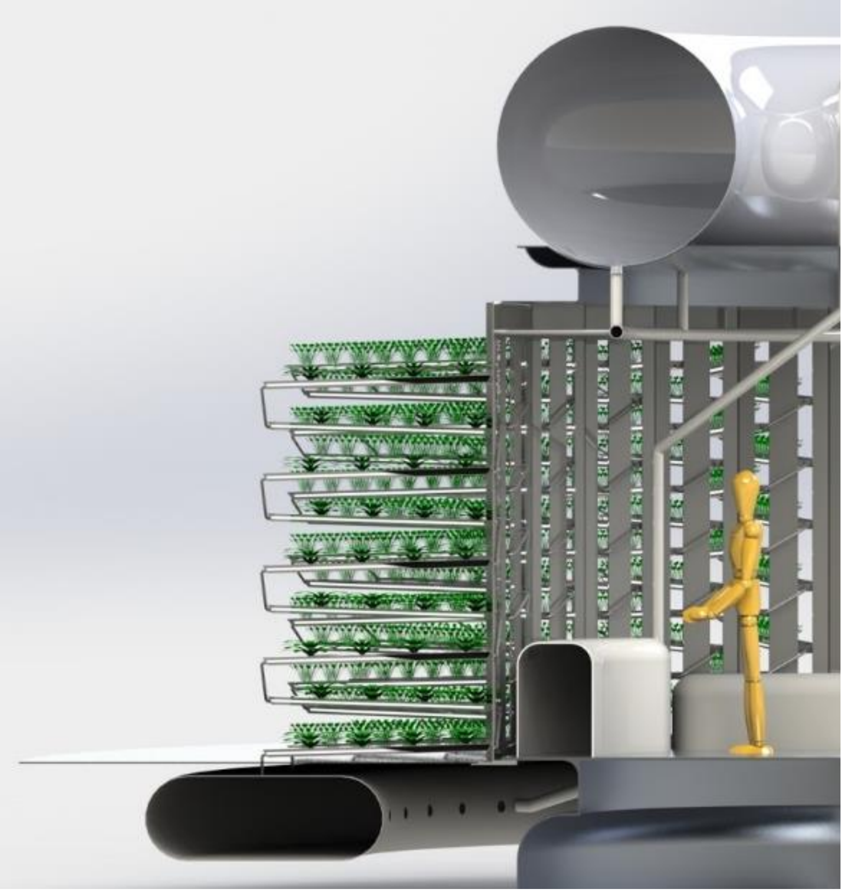


Figure 9: Section view showing water and nutrient delivery system [51].

Given that most of the research has been done for systems on Earth, we used the equations in Table 3 to convert Earth parameters to parameters usable on Mars. The variables remain the same except for those which depend on gravitational acceleration.

Table 3: Parameter Conversions from Earth to Mars

Variable	Earth	Mars
NFT System Angle ($\boldsymbol{\theta}$)	θ_e	$\theta_m = \text{asin}\left(\left(\frac{g_e}{g_m}\right) * \sin(\theta_e)\right)$
Pump Power ($\boldsymbol{P}$)	$P_{pump\ earth}$	$P_{pump\ Mars} = P_{pump\ Earth}$
Gravity ($\boldsymbol{g}$)	g_e	$g_m = 0.378 g_e$
Height of Cylinder ($\boldsymbol{h}$)	h_e	$h_m = h_e$
Density ($\boldsymbol{\rho}$)	$\rho_{water\ Earth}$	$\rho_{water\ Mars} = \rho_{water\ Earth}$
Viscosity ($\boldsymbol{\mu}$)	$\mu_{water\ Earth}$	$\mu_{water\ Mars} = \mu_{water\ Earth}$
Flow Rate ($\boldsymbol{Q}$)	Q_{Earth}	$Q_{Mars} = Q_{Earth} * \frac{g_e}{g_m}$

Standard NFT conventions indicate a flow rate of 1 L/min is suitable for each of our plant varieties [52]. To determine our final tray dimensions and angles, a simulation was created using an array of tray widths and a uniform flow scenario. For the plants with smaller trays, this led to an Earth angle of 0.88°. Wheat, chufa, potatoes and sweet potatoes have a larger tray, and the angle for those trays is 0.64°. We then related these angles to Mars, using the equations in Table 3 in order to achieve the same flow rate. All of the small trays require an angle of 2.31°, while the larger ones require an angle of 1.69°.

The stacks are connected so that the water-nutrient solution can flow through multiple trays as it moves from the top reservoir, through the plant roots, and into the bottom reservoir. This design allows for non-continuous pumping, which reduces energy costs and allows for nondisruptive pump maintenance. The total volume of water that passes through the system in one sol will be 35,448 L. Each reservoir is divided into a cold tank and a warm tank, and the total working volume is split between the two tanks, with roughly three-quarters of the volume circulating between the cold tanks and a quarter of the volume circulating between the warm tanks. The reservoirs each have a very large capacity of 19,200 L.

In the feedback call with the BIG Idea Challenge judges, we were encouraged to reconsider the necessity of filling such a large reservoir for daily operation. After research and consideration, we have chosen to maintain the large reservoir size, but only partially fill it during normal operation. One of the motivations for designing such a large reservoir was to allow pumping to be done in bulk. In the event of a pump failure, a larger reservoir allows the water to be pumped manually by an astronaut only twice per sol, while smaller reservoirs require more continuous pumping. Additionally, large water tanks can decrease the risk of nutrient over-saturation or dilution for hydroponic systems. The cold tank will be filled to 3138 L and the warm tank to 1292 L. We decided that pumping should take no more than 12 hours per sol, and from this decision we found new pumps more suitable to the adjusted volumes and pumping frequencies. We have chosen to implement two Alpine EcoSphere PUR4100 pumps, which each allow for a maximum flow rate of about 28 L/min [53]. With the adjusted water volume, these pumps now refill the tanks eight times per sol. The schedule for pumping is shown in Figure 10.

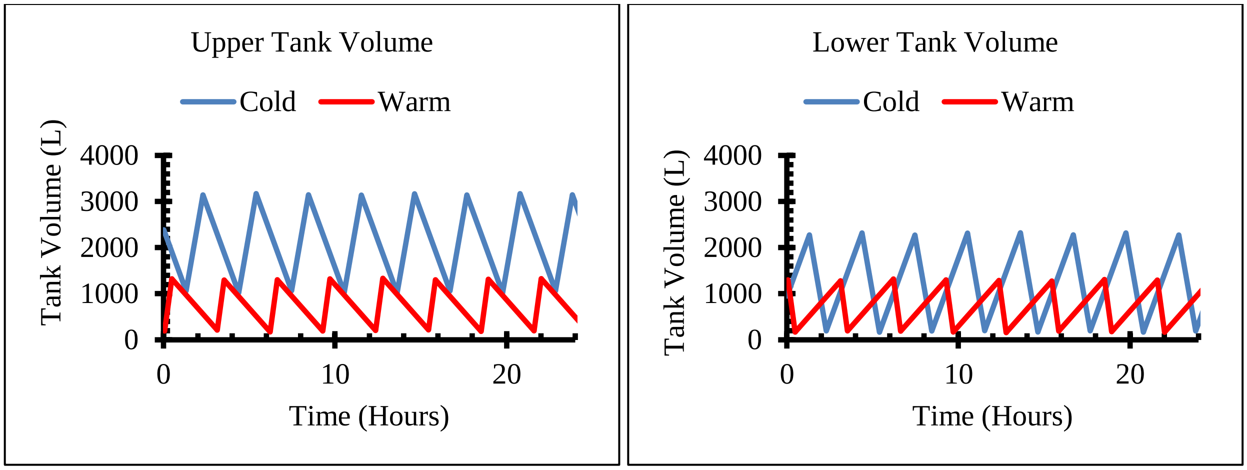


Figure 10: Pumping schedule and tank volumes for a typical sol.

3.5.1. Hydroponic Prototype

In order to study the operational ease of the system, we fabricated an NFT hydroponic prototype geometrically similar to our design. The prototype frame and trays were constructed out of PVC piping. The trays are approximately 1 m long (⅔ scale) due to space limitations. A ten-gallon, light-proof plastic storage container held the NFT aerator, pump, and General Hydroponics FloraSeries nutrient solution. From the storage container, the nutrient solution is pumped to the top tray, where it flows downwards through the other trays before returning to the storage container. Red and blue LED light strips were adhered to the bottom of each tray, illuminating the tray below. A fan provides circulation, and the system is covered by a reflective and insulative sheet.

Initially, six strawberry starter plants were placed in a single tray. These plants struggled in part due to algae growth caused by light leakage into the root chamber. Additionally, when we measured the photosynthetically active radiation (PAR) of the LED strips that we ordered, we found they did not provide the intensity that our design intended. After replacing all but one of the strawberry plants, we augmented the strip lighting with LED bulbs to provide a PAR level of 300. Opaque tape was also applied to any gaps in the assembly to reduce light exposure on the roots. This setup has been successful, with steady vegetative growth since the modification, shown in Figure 11. The prototype verified the Earth ground testability of our design, as we were able to use the angle conversions we calculated to build the proper tray angles.

In a test of the durability of our system, the plants went without nutrients and water during a 30-hour period following a power outage at our facility. Once the nutrient solution flow was restored, the plants were able to fully recover, demonstrating the resilience of our hydroponic system.

Figure 11: The hydroponic growing prototype a few days after planting (left), and with fruit-bearing strawberries (right).

3.6. Microbiome Description

The plants will be fed a careful balance of nutrients, so microbes won't be necessary to fix nitrogen or perform other functions for the plants. The nutrient solution will be cleaned periodically with UV treatment as a preventive measure to avoid potential algae and bacteria growth or plant disease. These choices were based on general hydroponic practices found in literature review as well as interviews with professors at Dartmouth College [54].

3.7. Environmental Requirements

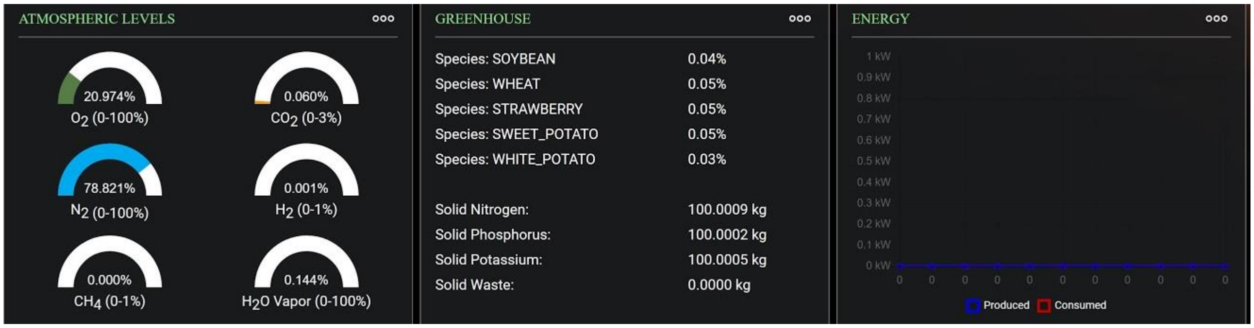
Root temperature, nutrient solution pH, and lighting cycles are the most important environmental requirements for plants, detailed in Table 4. We found the overall humidity should be 60-80% for healthy plant transpiration and the ambient temperature of the greenhouse should stay within 18-22 °C [55].

Table 4: Hydroponic Specifications for Selected Crops

	Kale [10, 44, 56]	Soybean [45, 57, 58]	Sweet Potato [10, 46, 59]	Potato [10, 46, 47]	Strawberry [12, 48]	Broccoli [10, 28, 46]	Wheat [13, 49, 60]	Chufa [14, 50, 61]
Root Temp (°C)	15.6-18.3	17.8-26.7	21.1-29.4	15.6-18.3	7.8-18.3	15.6-18.3	15-30	22.2-27.8
Photoperiod (h)	16	12	24	24	12	16	24	12
pH	6-7.5	5.2-7	4-6	4.5-7	5.5-6.5	6.5	6-6.5	6.3-7

3.7.1. Gas Composition Model

To better understand the feasibility and behavior of our system, we decided to use a computational model. We partnered with SIMOC, a Scalable, Interactive Model of an Off-world Community. SIMOC is a high-fidelity agent-based model (ABM) capable of simulating closed-loop systems like that of the Ice Home and DEMETER. ABMs comprise programmable entities meant to interact and exchange different currencies in a given environment. In this case currencies are solids like edible biomass, liquids like water, gases like CO_2, and energy. The simulation can be viewed through the live action feed, an example of which is shown in Figure 12. The non-linear biomass production feature in SIMOC has been verified against data from various experimental studies on our plant varieties, including data from the Lunar Greenhouse [13, 62, 63, 64, 65, 66, 67, 68]. While the input parameters do not perfectly match the parameters of our system, the model can be adjusted to more accurately model DEMETER.



Species: SOYBEAN	0.04%
Species: WHEAT	0.05%
Species: STRAWBERRY	0.05%
Species: SWEET_POTATO	0.05%
Species: WHITE_POTATO	0.03%
Solid Nitrogen:	100.0009 kg
Solid Phosphorus:	100.0002 kg
Solid Potassium:	100.0005 kg
Solid Waste:	0.0000 kg

Figure 12: An example of a SIMOC simulation live action feed.

At the present time, SIMOC is incapable of performing high-fidelity analyses of gas exchange in a closed system. We developed our own computational model in STELLA to understand the carbon, oxygen and water exchange in the greenhouse. This enabled us to model the conditions of DEMETER, especially the ramp-up period of the crop growth from day 0 of the mission to day 100. During this period, our model revealed that CO_2 in the greenhouse is initially too high for healthy human activity, so supplemental O_2 will be necessary until the greenhouse reaches steady-state production. Once steady-state has been reached, the system will trend toward higher O_2 levels, and supplemental CO_2 from the Martian atmosphere will be required. The STELLA system map for the carbon budget is shown in Figure 13.

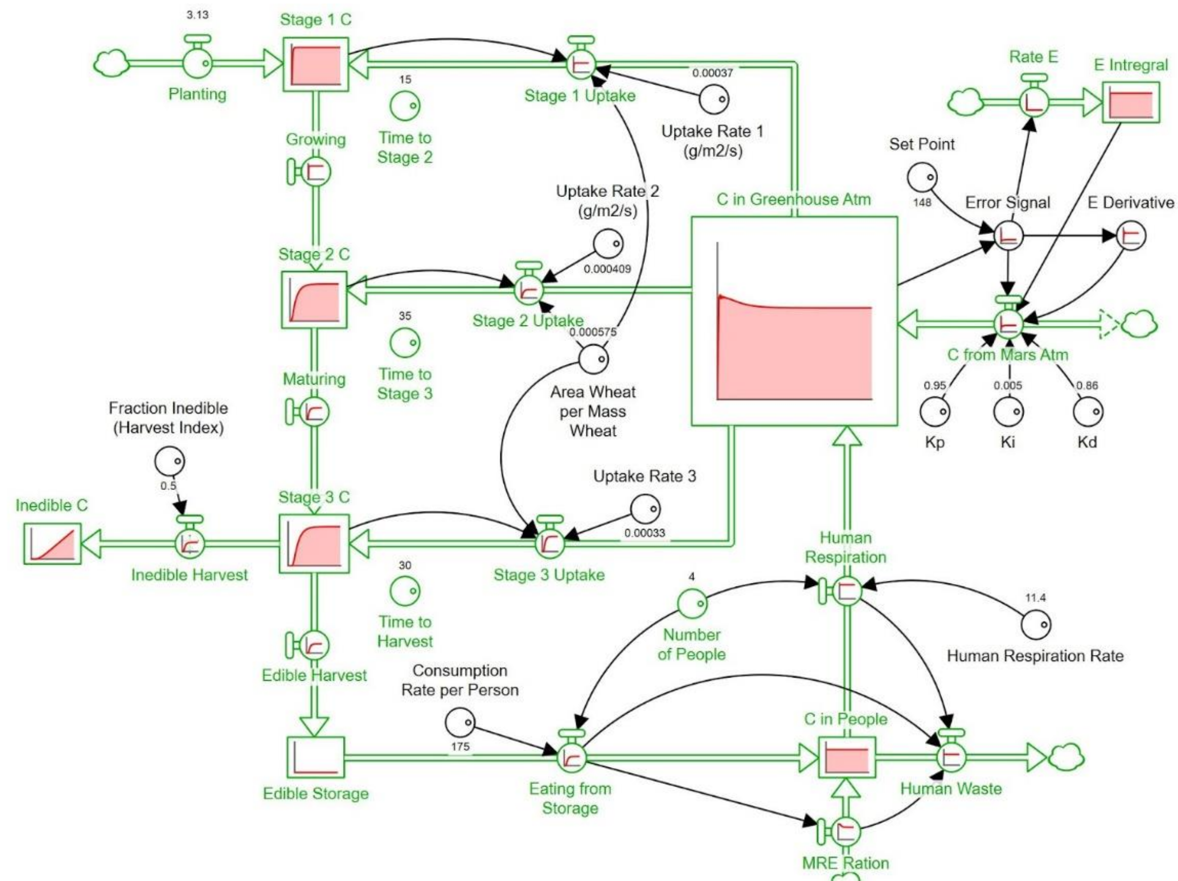


Figure 13: System map of carbon budget for DEMETER. The black lines indicate connections or dependencies, the green arrows indicate rates of change, the boxes or stocks represent carbon accumulations, and the red graphs display the carbon levels in each stock over time.

The gas composition model also provides insight into the balance of humidity and transpiration in the greenhouse, providing critical values for dehumidification, air transfer between the greenhouse and Ice Home structures, and required water supply. For example, in order to maintain a relative humidity of 80% within the greenhouse, a dehumidification rate of 0.44 liters per minute is required. The schedule for air transfer between structures is critical for various aspects of the systems design, including humidity and air composition. Using STELLA, we determined that one hour of isolation for every three hours of transfer suited the humidity and air composition cycling.

Figure 14 shows the relationships between sub-models and the organization of the full model. The carbon cycle is represented in green, the oxygen cycle in red, the water cycle in blue, and energy allocation in yellow. In this fully integrated STELLA model, inputs are connected across models. While this model will require additional validation with experimental studies, it provides a first-order understanding of the interaction of the systems in DEMETER.

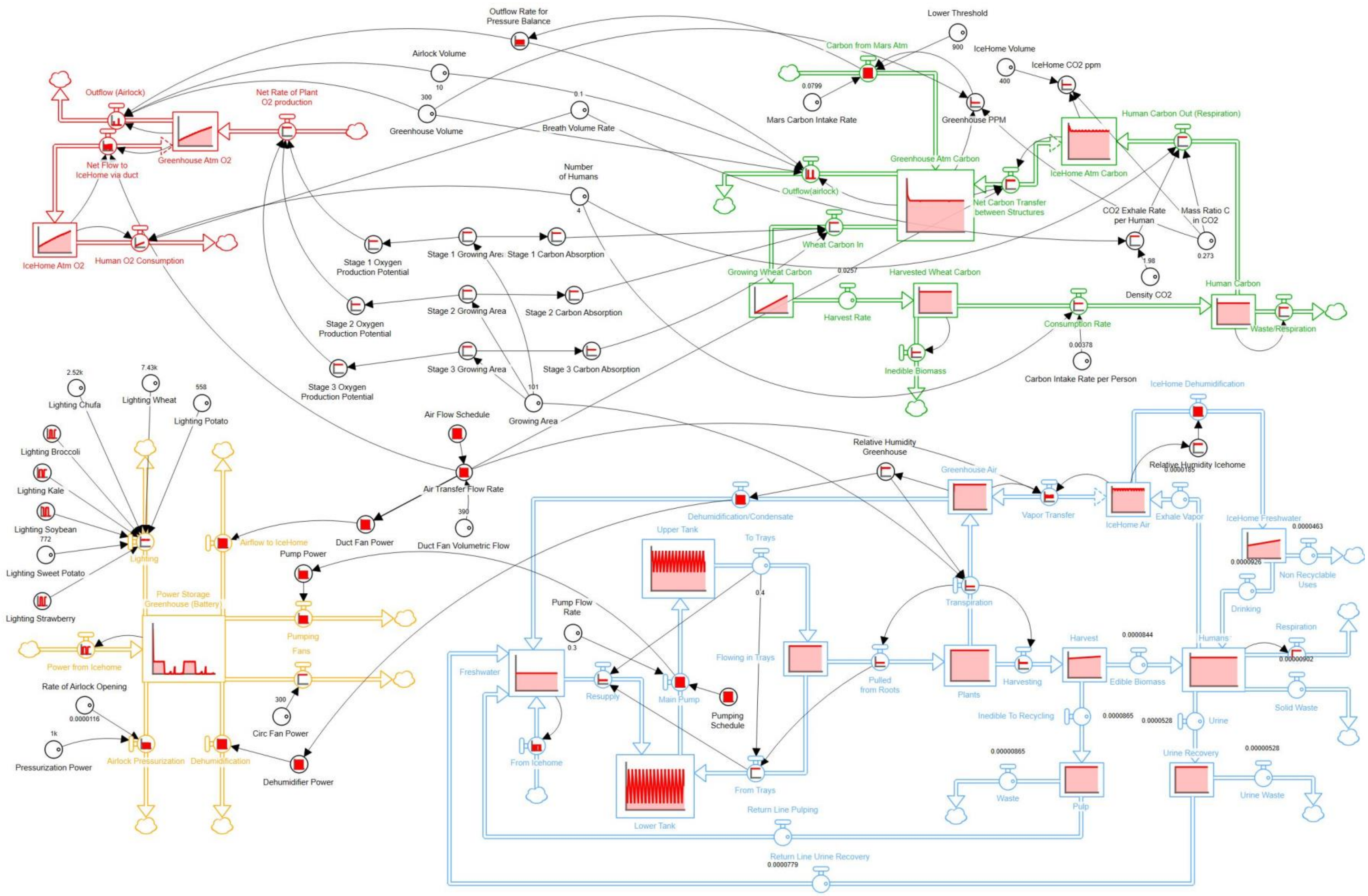


Figure 14: Full STELLA model.

3.8. Lighting System

Given low insolation levels and the potential for dust storms, artificial lighting is required. Like the other automated aspects of our design, the lighting timer can be manually overridden. To decrease energy usage, we give the astronauts the option of turning the lights off on particularly sunny days. A first-order analysis suggests the intensity of the LEDs along a strip can vary as a function of distance from the inner cylinder, where the trays experience maximum light closest to the cylinder. Therefore LEDs could be dimmed toward that end of the tray. However, we considered the most conservative option with the lights following a schedule that only considers artificial lighting at maximum intensity, found in Table 5.

Table 5: Lighting Schedule for One Sol (Orange Indicates Lights on for That Plant)

Plant Type	Hour																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Kale – 300 PAR									🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Soybeans – 815 PAR	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧												
Sweet Potato – 360 PAR	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Potato – 244 PAR	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Strawberry – 500 PAR													🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Broccoli – 400 PAR													🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Wheat – 666 PAR	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Chufa – 391 PAR	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

DEMETER utilizes red and blue LED light strips (90% 660 nm red and 10% 470 nm blue) attached along the undersides of each tray as the primary lighting source [69]. The topmost trays will receive lighting from LEDs mounted to the underside of a tray which does not hold any plants. This will allow for customizable PAR settings for peak yield. In addition, white light will provide lighting while crew members occupy the greenhouse. Trays will be made of highly reflective material to maximize photosynthetic photon flux density. Partitions, such as curtains, could be used to accommodate each plant's photoperiods.

The Big Idea Challenge judges encouraged our team to revisit our lighting energy calculations, as they seemed too low for our growing area. We performed new calculations using power consumption and PAR output from the datasheets for the Apache Tech AT200 Red/White LED system. With an input power of 230 W, the Apache AT200 produces an average PAR of 861 over a 0.84 m^2 area [70]. Scaling this power consumption to our area, lighting schedule, and PAR requirements yields a peak power consumption of 14.3 kW for lighting.

These calculations are based on the 2014 efficiency of the Apache LED system. The U.S. Energy Information Administration estimates LED efficiency to increase by a factor of 1.6 by 2030, which will reduce the hourly lighting power demand to a peak of 8.9 kW [71]. Factoring in a 30% resource safety margin results in an 11.6 kW peak power demand for the LED lighting system.

The primary concern of using LEDs is their lifetime, as excessive heat can cause damage to the hardware. The water on the opposite side of the trays will provide convective heat transfer away from the lights to cool the system. We also recommend having triple the amount of individual LEDs per strip than is necessary, and only supplying power to a third of them. Then, if an individual LED fails, the other LEDs on the strip can be turned on, eliminating the need to replace the entire strip.

3.9. Maintenance, Automation, and Growth Cycle Control

Unless manual adjustment is required, sensors and actuators controlled by a computer in the greenhouse will regulate variables such as nutrient level, pH, and lighting. The trays will be cleaned after they are emptied with each harvest. After harvesting, the inedible biomass will be collected, pulped, and leached of nutrients. Urine from the Ice Home will be transferred to the greenhouse regularly where it will be treated to recover phosphates and other nutrients. The nutrients from both recovery processes will be integrated back into the nutrient supply. Consultation with hydroponics experts encouraged us to use the remaining plant fibers to make a growing substrate material, which will be used in the plant cups to help support the root structure.

To optimize growing space and food production, we developed a schedule of nursery and regular tray durations for each plant. The nursery section allows for crops to begin growing in a smaller volume with an expedited growing process. For example, kale will spend 24 sols in the nursery before being moved into regular trays. Then it will grow for 96 sols, with harvesting occurring over the last 10 sols. Schedules for the other crops follow this format, shown in Table 6.

Table 6: Nursery and Tray Growth Times for Each Plant Variety

	Kale	Soybean	Sweet Potato	Potato	Strawberry	Broccoli	Wheat	Chufa
Time in Nursery (sols)	24	24	24	24	0	30	28	28
Time in Trays (sols)	96	66	106	90	120	60	52	52

4. Design Trades

4.1. Operational Life

DEMETER is designed for a 15 Earth-year operational life, excluding autonomous inflation and setup prior to astronaut arrival. By utilizing nutrient recycling technologies and *in situ* resources, DEMETER will be capable of feeding the crew with minimal resupply. An initial consumable mass of 695 kg of nutrient salts, 190 kg of acid, and 26 kg of seeds is needed for the first crewed mission. For all following missions, a resupply of approximately 347 kg of nutrient salts, 190 kg acid, and 26 kg of seeds will be required [72]. The mass of the nutrient salt resupply could be reduced with improved nutrient recycling procedures.

4.2. Applicable Martian Latitudes

The Ice Home ConOps delineates feasible landing latitudes of 30° above and below the equator [3]. DEMETER will be adjoined to the Ice Home and will be able to withstand the conditions at any latitude.

4.3. Crew Operational Environment: Internal Pressure and Temperature

To maximize human comfort and to reduce airlock requirements, the internal pressure of the greenhouse will be the same as the Ice Home, 101 kPa. The internal temperature will be 20 ± 2°C.

4.4. Membrane Structure of the Water Ice Cells

DEMETER will adopt the Ice Home radiation shielding concept scaled to fit the dimensions of the greenhouse. The shielding will consist of 28 vertically-arranged water ice cells with internal pressure of 20.68 kPa, each 2 m thick to reduce the radiation exposure by more than 50% [3]. Insulating CO_2 cells will fill the gaps between the ice cells, as shown in Figure 15. The translucency of the ice cells is not essential to the function of the greenhouse, and natural light will be a supplement to the artificial lighting.

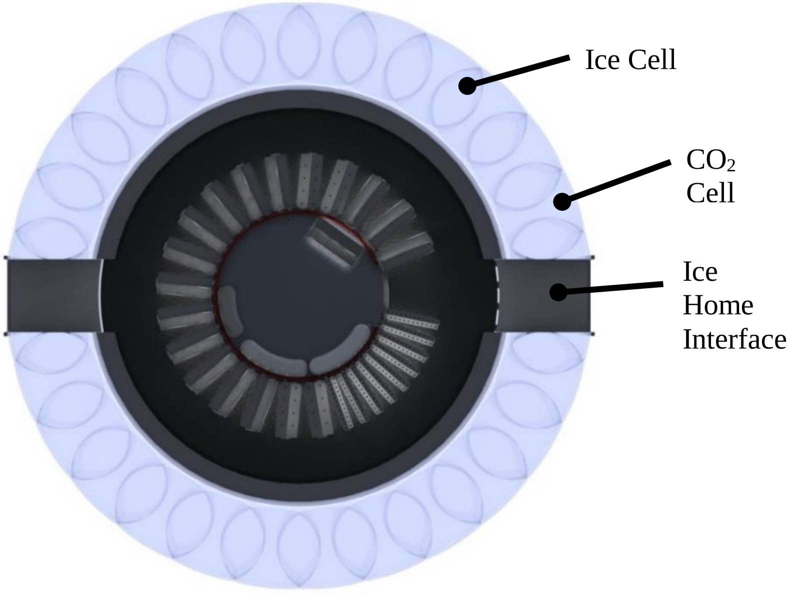


Figure 15: Top view of DEMETER showing membrane structure and overall layout.

4.5. Materials and Fabrication

The membrane material is Mylar. The top and bottom structural support pieces are aluminum, along with parts of the airlock interface tunnel between the greenhouse and Ice Home. These pieces are similar to the Ice Home's concept, so development will be cost-effective. The cylinder, trays, and lids will be custom-made from high density polyethylene and simple to manufacture. The irrigation piping is polyvinyl chloride (PVC), with rubber piping between trays. Teflon tanks will store acid for pH regulation.

4.6. Environmental Considerations

In the Martian region where the greenhouse will be deployed, surface temperatures range from -120°C to 30°C [73]. Initial thermal analyses for both ideal and extreme temperature showed that the heat loads from LED lighting, pumps, and other electronic equipment, with the thermal mass of the water tanks, balance with the heat loss through the greenhouse membrane to different steady state values. Minimal heating and cooling will be required to maintain an ideal temperature range of 18-22°C and dehumidification will be necessary to maintain a relative humidity range of 60-80%. The greenhouse environmental control system will include a central air handler to heat, cool, and remove moisture from the air, as well as a passive humidity control system to collect excess water vapor as it condenses on the cooler inner membrane. Because humidity will likely need the most regulation, we have several low-energy solutions to maintain it. One option would be to use the cold Martian atmosphere as a heat sink, which can then be used to condense water out of the air through specific sized tubing. We also recommend looking into hydrogels as a method for dehumidifying. They could be kept in an air-tight container until dehumidification is needed, and then opened to the greenhouse atmosphere. Recovering clean water requires relatively little energy, and certain hydrogels can be used for cooling and energy production under the right circumstances [74]. From our estimates, the energy associated with recovering the water from the hydrogels is approximately 0.4 kW on average [75].

Continuous air transfer between the Ice Home and greenhouse via the Ice Home interface will help maintain the O_2 and CO_2 balance. The optimal greenhouse CO_2 concentration is 1000 PPM [76]. We found that the large amount of crops will take in more CO_2 than the four-person crew produces, necessitating a supplementary CO_2 source for the greenhouse. This CO_2 can be sourced from the Martian atmosphere.

4.7. Sensors

To maintain air quality, sensors around the greenhouse will monitor temperature, humidity, O_2 level, CO_2 level, and volatile organic compounds (VOC) level. To maintain an optimal environment for plants, sensors will monitor the temperature, pH, EC, O_2 level, and nutrient levels in the hydroponic solution. Flow rate meters for each stack and volume sensors for each tank will monitor the total balance of water in the system. To maintain the structure, sensors will monitor the pressure and temperature of the water ice and CO_2 membranes. Each sensor will be connected to the computer located inside the inner cylinder of the greenhouse, which will control actuators based on sensor input and serve as an interface for the crew. A full list of sensors and actuators can be found in Table 7.

Table 7: Sensors and Actuators

Category	Purpose	Sensors	Actuators
Thermal	Air temperature	Thermometer	Air handler
Air Quality	Humidity control	Hygrometer	Dehumidifier, mister, air exchanger, fans
	Gas composition maintenance	VOC, CO$_2$ and O$_2$ sensors	Fans, air exchanger, alarm
Hydroponic Maintenance	Water temperature	Thermometers	Heater coils
	Nutrient management	Nutrient sensors	Valve[1] to dispense, stirrer, computer display
	pH management	pH sensor	Acid dispenser, stirrer, computer display
	EC management	EC sensor	Computer display/alert
	O$_2$ management	O$_2$ meter[2]	Aerator[3], stirrer
	Volume management	Volume sensor	Pump[4]
	Water sterilization	Timer for UV	UV lights[5], switch
	Nutrient recycling	Nutrient sensor for leached waste	Computer display, pulper
	Flowrate management	Flowrate meters[6]	Open/close valve
Structural Support	Membrane pressure	Strain gauge	Computer display/alert
	Membrane temperature	Thermocouple	Computer display/alert
Ice Home Interface	Interface management	Computer commands	Open/close valve

[1] Nominal Plastic Solenoid Valve - 12V - 1/2" [77]

[2] Grove-Gas Sensor [78]

[3] EcoPlus® Eco Air Pumps [79]

[4] Alpine Eco-Sphere PUR4100 [46]

[5] Lifegard® Aquatics Aquastep Pro UV Sterilizer [80]

[6] OMEGA™ FTB600B Series [81]

5. Day in the Life

Astronauts require a minimum of 2 hours of exercise per day. In order to fulfill this requirement, they can use the greenhouse as an exercise track and jog around the plants while breathing refreshing oxygen. The central cylinder duals as a storage space for acid and nutrient tanks, food storage, and a space for social activity and leisure. Table 8 describes a general day in which the astronauts are harvesting every sol.

Table 8: Schedule for a Sol

Time	Event	Time	Event
01:00-01:30	Nutrient Replenishment, UV On	**13:00-14:00**	Lunch***
01:30-01:55	Warm Water Pump On	**13:00-13:30**	Nutrient Replenishment, UV On
02:00-03:00	Cold Water Pump On	**13:30-13:55**	Warm Water Pump On
04:00-04:30	Nutrient Replenishment, UV On	**14:00-15:00**	Cold Water Pump On
04:30-04:55	Warm Water Pump On	**16:00-16:30**	Nutrient Replenishment, UV On
05:00-06:00	Cold Water Pump On	**16:30-16:55**	Warm Water Pump On
05:00-05:30	Two People, Harvest for the Day	**17:00-18:00**	Cold Water Pump On
06:00-07:00	Cooking*	**18:00-19:00**	Cooking
07:00-08:00	Breakfast	**19:00-20:00**	Dinner
07:00-07:30	Nutrient Replenishment, UV On	**19:00-19:30**	Nutrient Replenishment, UV On
07:30-07:55	Warm Water Pump On	**19:30-19:55**	Warm Water Pump On
08:00-09:00	Cold Water Pump On	**20:00-21:00**	Cold Water Pump On
08:00-09:00	Two People, All Plant Maintenance**	**22:00-22:30**	Nutrient Replenishment, UV On
10:00-10:30	Nutrient Replenishment, UV On	**22:30-22:55**	Warm Water Pump On
10:30-10:55	Warm Water Pump On	**23:00-24:00**	Cold Water Pump On
11:00-12:00	Cold Water Pump On	**24:00-24:10**	Warm Water Pump On
12:00-13:00	Cooking	**24:10-24:30**	Cold Water Pump On

* The one hour specified is reserved for any high-energy cooking such as stove-top or oven cooking. Energy-efficient slow-cookers require power for long periods so we have not budgeted for them.

**For instance, to replace and clean trays, visually inspect plants, germinate seeds.

***We recommend not cooking during peak power demand. Currently, that is from 09:00-12:00.

Figure 16 shows two crew members maintaining the plants inside the greenhouse in a cross section view. A portable step-stool will allow the crew members to easily reach the highest trays in the stacks for harvesting and maintenance. This can be housed inside the cylinder when not in use. A table surrounds the perimeter of the track, recessed into the empty space created by the curvature of the torus. This can be used to put the plants on while harvesting and cleaning trays.

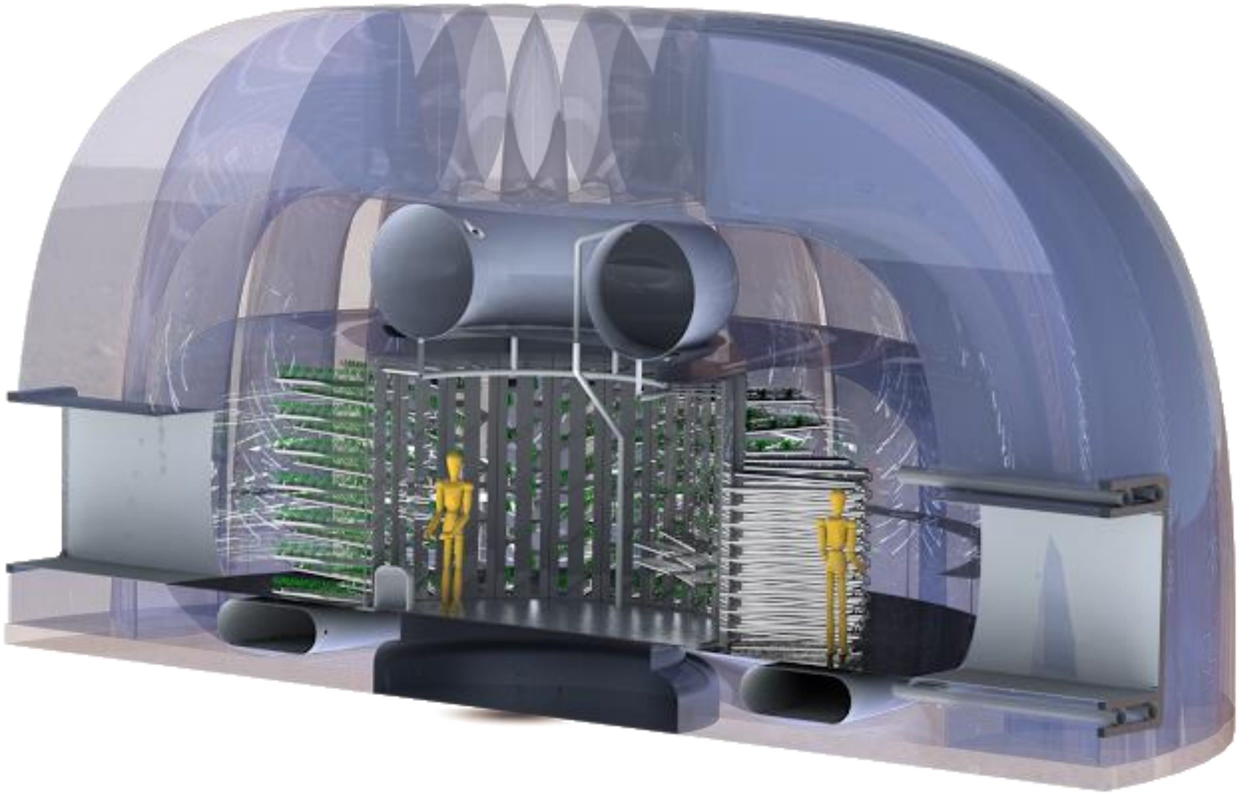


Figure 16: Two crew members maintaining the plants in DEMETER [51].

6. Technical Resource Estimates

6.1. Energy Schedule

We developed a power demand schedule, graphed in Figure 17, which shows that the peak power demand of the greenhouse is approximately 20.5 kW if we were to launch with today's technologies, maintaining the 30% resource margin. However, based on the projected increase in efficiency of LEDs and other technologies, our calculations show that the peak demand will be approximately 13.5 kW, with an average demand just under 13.3 kW [82]. The values in the graph represent the sum of the power required for lighting, pumping, the freezer, and the sensors and actuators listed in Table 7, Section 4.7.

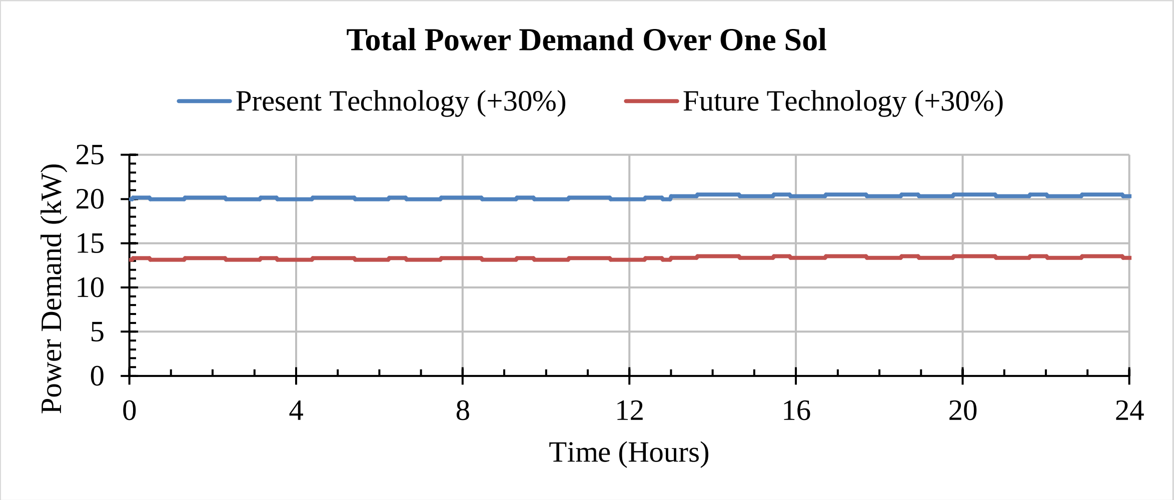


Figure 17: The total hourly power consumption of DEMETER with present-day LED efficiencies and projected LED efficiencies. Each line incorporates a 30% margin.

6.2. Mass Estimate

The total mass of the greenhouse after landing is 9131 kg. The mass of the structural elements is 7954 kg. The nutrient salts and acid contribute 876 kg [72]. A full list of the components and their masses is available in Table 9.

Table 9: Mass Estimates for the Components of DEMETER

Other Equipment and Consumables	Estimated Mass (kg)
Computer	20.0
Cups	0.1
Nutrients	694.0
Acid for pH	182.0
Acid for Recycling	6.0
Seeds	25.5
Containers	2.0
Freezer	30.0
CAD Model*	7954.0
Sensors Total	7.6
Actuators Total	209.4
Total Mass	**9130.6**
*Includes cylinder, trays, pipes, flooring, interface rings, membranes, tables, acid tanks, nutrient tanks	

6.3. Economic Analysis

We performed a first-order analysis comparing the mass required for DEMETER with the mass required to bring prepackaged food. If fresh food is not grown, each crew member would need 1.8 kg of prepackaged food per sol, totaling to 4320 kg over a 600 sol mission [83]. The mass of the DEMETER payload is 9131 kg and the consumable mass required for each mission cycle is approximately 1000 kg. Although DEMETER has a larger initial mass, the long-term cost analysis shows economic benefits to having a Martian greenhouse.

After four noncontinuous missions, the difference between the masses of the prepackaged option and DEMETER is approximately 4429 kg, in favor of DEMETER. However, if missions were made continuous, the DEMETER option becomes advantageous at the third mission mark. Here, we make the distinction that noncontinuous missions have an initial 100-sol startup period while crops are still in their growth stages and cannot be harvested, so prepackaged food will be necessary. If missions are continuous, crops grown by the previous mission can be used to support the next mission, and not as much prepackaged food is needed. In either case, this mass difference only increases with each additional mission. Mass savings result in cost savings, as each kilogram of mass costs approximately $81,400 [84, 85]. Figure 18 shows the total mass and cost of each scenario over a 15-year operation period.

There are also psychological benefits associated with having fresh food and a space to relax in filled with plants. The crew would gain additional psychological benefits from tending plants and cooking fresh meals together.

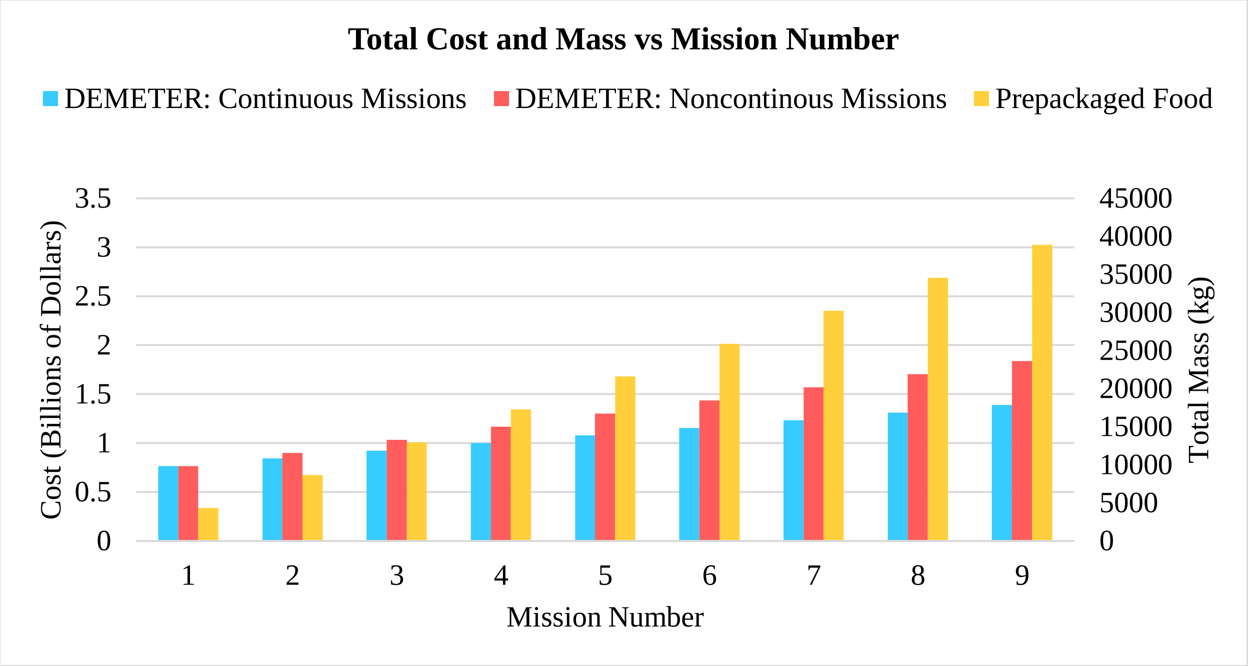


Figure 18: Economic comparison of three scenarios: send prepackaged food with the astronauts, send DEMETER and run missions continuously, and send DEMETER and run missions noncontinuously.

7. Failure Modes Summary

Taking into consideration the possibility of full system failure, we recommend sending additional prepackaged food on the first mission. If the entire system does fail, the crew can subsist on a lower calorie diet for the rest of the mission. From then on, the first mission's level of success can inform the number of prepackaged meals needed for future missions. Regular inspections will be required throughout the mission, as shown in Figure 19.

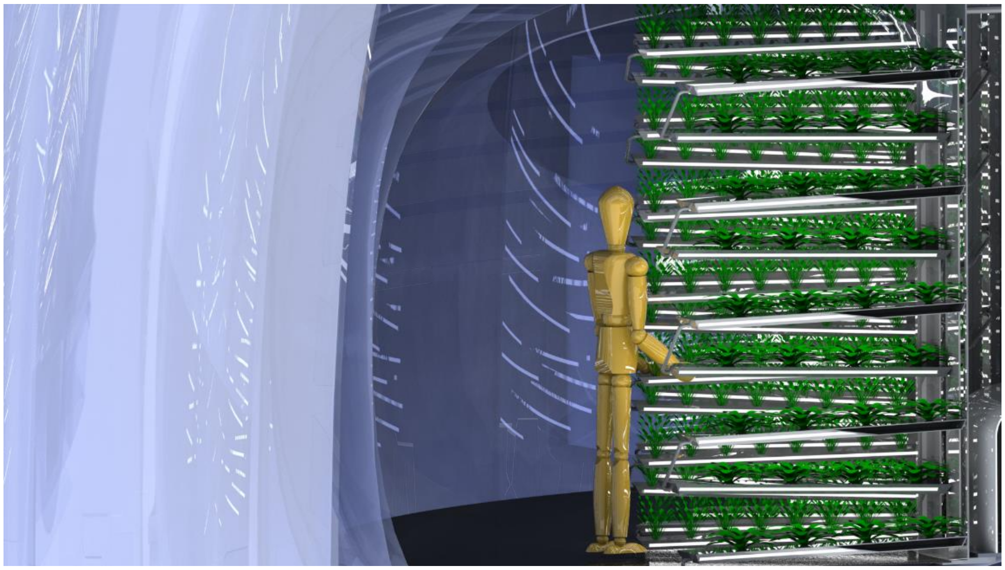


Figure 19: A crew member preforming a scheduled inspection of the system components [51].

Table 10 contains a summary of all the failure modes referenced throughout this paper, as well as some additional considerations. The control method gives preventative measures to avoid the failures, as well as plans of action in case failure does occur.

Table 10: Failure Modes Summary

Subsystem	Failure Mode	Cause	Control Method
Fluid Network	Loss of power	Power supply failure; short-circuit in network; valve failure	Redundant network logic; hand-controlled valves and pumps
	Residue build-up prevents actuation	Saturated nutrient solution, stagnant fluid, air intake	Regular flushes, scheduled visual inspection of components
Membranes	Depressurization	Puncture or abrasion on membrane, damaged inflation component allowing back flow	Triplicated pressure sensors in each cell, control inflation components, cell layout to prevent severe failure
	Incomplete inflation	Section fails to unfold, inflation line failure	Careful design, testing
	Misshapen	Fatigue, stress	Testing
Interface	Complete disconnection	Mechanical failure of attachment ring	Test for max strain on ring, auto shutoff when disconnection detected
	Severing of connection line(s)	Failure of connector, failure of piping or ducting, strain on electrical harness	Strain relief in harnesses, proper size of tubing, wires, ducts, secure connectors, auto shutoff
Thermal Control System	Power loss to thermal control system	Disconnection of power lines, failure within heat exchangers	Design system to retain heat, require minimal heating to mitigate effect of thermal control system failure
Plant Life	Wilt or discoloration	Environmental issues stressing the plants	Examination of the root system, use UVs to sterilize solution
	Fruit and flower drop	Internal plant stress, environmental issues	Lower plant density, more CO_2, and cultivars less prone to drop
	Root suffocation	Nutrient solution flood, decomposed organic matter in solution, slow flow rates, algae	Scheduled visual inspection, flush and scrub trays, sensor control, lower plant density
	Nutrient deficiencies	Fe: pH running high; Mg: high K uptake; Ca: high humidity	Check pH and add acid/base solution, check nutrient solution levels, regulate humidity
	Gas imbalance	Failure of climate control systems	Design system to be self-sufficient, minimize adjustments

8. Recommendations for Future Work

Based on the provided economic analysis, we recommend continuous missions, which would minimize the need for the ramping periods of plant growing. Additionally, we suggest maximizing the number of missions total for the same purpose. Like the Ice Home we recommend sending larger power and water recovery systems [3].

Give the energy findings, we highly suggest putting more resources towards increasing LED efficiencies, especially optimized for plant wavelengths. Though NASA and other agencies have been working on this for many years, we also suggest taking the cultivars we have specified and maximizing their edible biomass density through genetic modification and/or selective breeding, as this could potentially decrease system requirements by a significant margin. A more detailed analysis to optimize LED intensity along the trays would also be of benefit.

9. Acknowledgments

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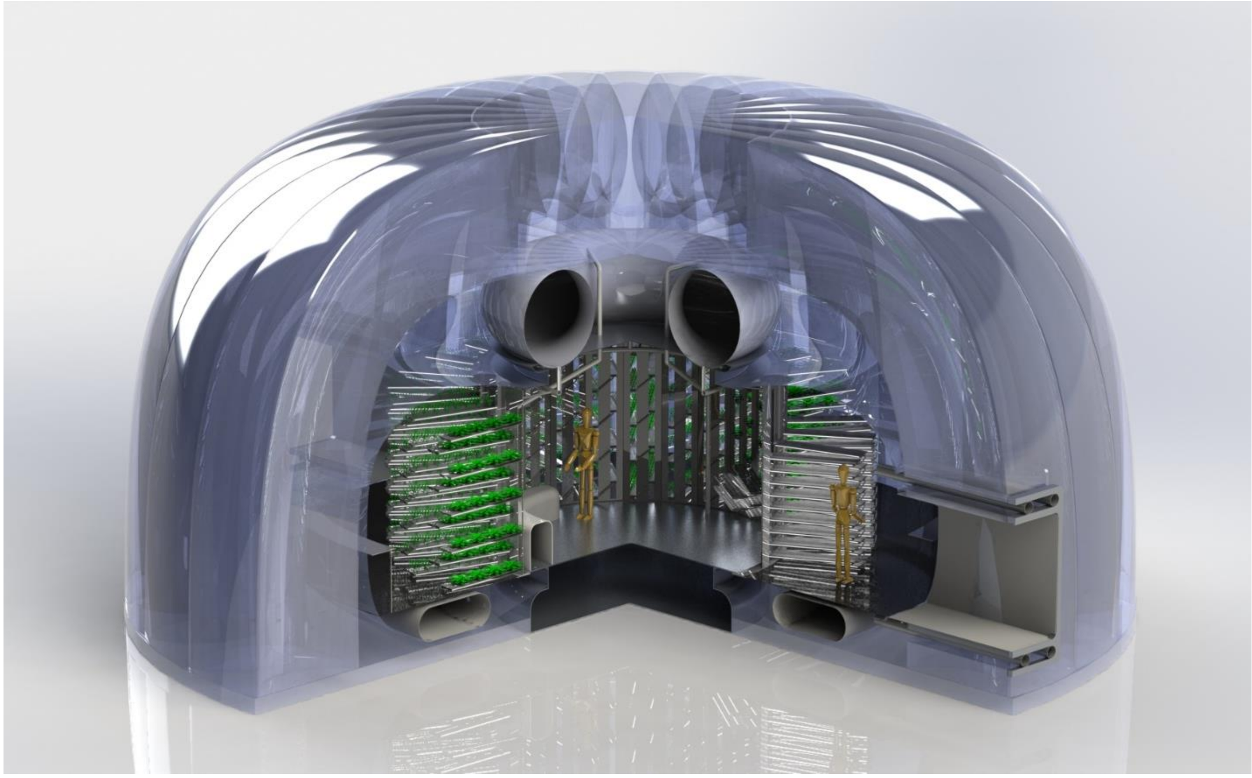

Figure 20: DEMETER, three-quarter cross-section [51].

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