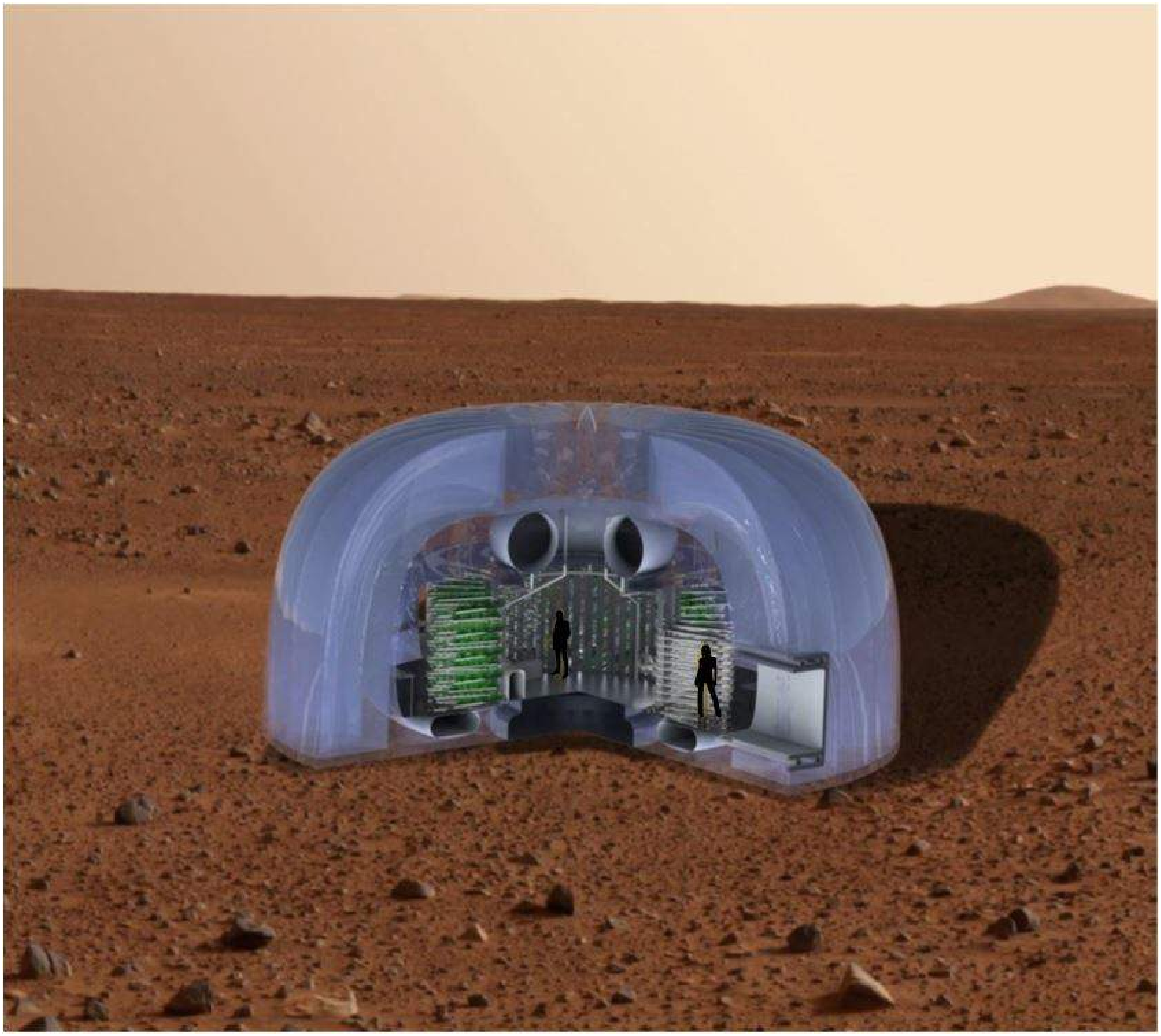
NASA: Game Changing Development Program
2019 Mars Ice Home Use Case



CYBELE Advanced Concept of Operations

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1. Introduction

1.1. Introduction and Overview

This greenhouse design concept, CYBELE, is a Crop Yielding, Bioregenerative Environment for Life-support and Exploration. CYBELE will incorporate ice shielding from the Mars Ice Home (MIH) habitat design and will produce enough food to meet the dietary requirements for a four-person astronaut crew on a 600-sol surface mission to Mars. This appendix is the summation of the final contestants' papers for the 2019 Breakthrough, Innovative, and Game-changing (BIG) Idea Challenge. The design features an automated hydroponic growing system which utilizes a cylinder inside a torus with a surrounding ice dome for radiation protection.

1.2. Purpose, Scope, and Background

The primary purpose of the greenhouse will be to feed the crew, but it will also support the operation of a closed loop habitat by recycling biomass, energy, water, oxygen (O_2), and carbon dioxide (CO_2) between the greenhouse and the MIH. With consideration for future missions, the targeted operating lifespan of CYBELE will be the same as the MIH, which is 15 Earth years. This greenhouse will be part of the first effort to establish a long duration human presence on Mars. The technologies that will be used in this series of Martian missions will be tested with cislunar and lunar missions, providing opportunity for improvement.

1.3. System Overview

The overall system will include the interactions and exchanges between the MIH and CYBELE, as well as inputs and outputs derived from the Mars environment as illustrated in Figure 1. Water and electricity will be generated by the MIH, and the human crew will provide CO_2 and waste, while CYBELE will provide food and O_2 to the MIH. In Figure 1, "Controls" refers to the compilation of all sensors and actuators, as well as the computers and interface. The nutrient storage and recycling will be an intensive process with several steps, which will be described later in Section 3.11 The goal of the nutrient subsystem will be to reduce maintenance as much as possible. Additionally, the system has a large-scale input at the beginning of every mission for consumables, which the crew will bring with them from Earth.

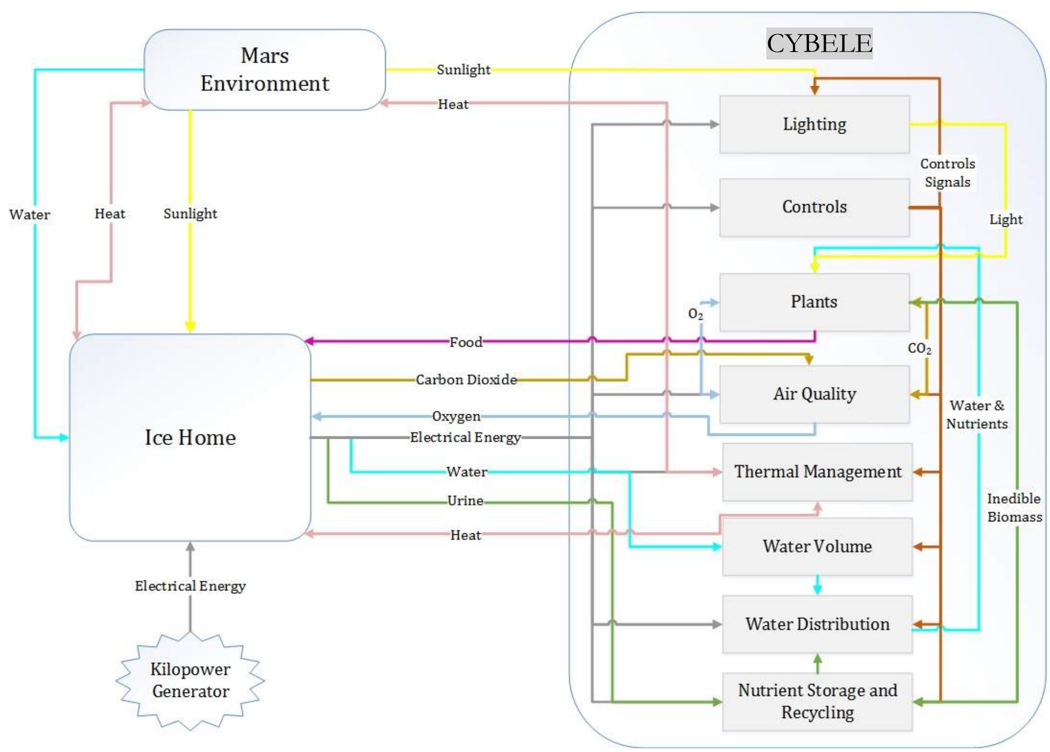

Figure 1: CYBELE system overview map.

1.4. Needs, Goals, Objectives, and Requirements

1.4.1. NASA Need

As part of NASA's Strategic Objective 2.2 of "Conduct[ing] Human Exploration in Deep Space, Including to the Surface of the Moon", NASA is working to send a human mission to Mars as early as 2030 [1]. In 2016, the "Preliminary Architectural Report Ice Home Work Session" feasibility study proposed the MIH, an inflatable habitat structure designed to house an astronaut crew on Mars [2]. The MIH will make use of *in situ* resource utilization, or ISRU, to fill an inflatable structure with water for radiation shielding and CO_2 for insulation.

Based on the high resource demand of the MIH mission architecture, the concept will be most feasible if it can support multiple "outpost mode" missions that would each last approximately 600 sols. For Mars missions of this duration, launching prepackaged food from Earth becomes quite costly. For this reason, NASA needs a system, such as CYBELE, for astronauts to grow food on Mars during their stay.

1.4.2. Objectives and Requirements

The objectives and requirements for CYBELE were governed by the NASA BIG Idea competition basics, which can be found at: http://bigidea.nianet.org/. The primary objective was to develop a system that will sustain a four-person crew for a 600-sol mission on Mars, optimized to support multiple missions for 15 years by developing a cost effective greenhouse for an early Martian outpost. This concept is shown in Figure 2 below.

Figure 2: Ice Home concept connected to a greenhouse.

2. System Description

2.1. System Context

CYBELE will be a controlled ecological life support system unit of a Mars outpost. In this context, the system will not be fully closed. The greenhouse will receive power from the generator, as well as regular mass inputs of water, CO_2 filtered from the Martian atmosphere, nutrient amendments, emergency rations, and seed stock [3]. The mass within the greenhouse will cycle to some extent, and processes to facilitate the mimicry of biogeological cycles will be incorporated. CYBELE will be directly connected to the MIH via airlock and will support crew members with all necessary food, a means for daily engagement, and a space for recreation. CYBELE will draw its power and water through the MIH interface and derive CO_2 from the Martian atmosphere for inflation and atmospheric control. This will allow CYBELE to support and balance the MIH air composition. Additionally, water collected from the Martian regolith through ISRU will be used for growth systems and radiation shielding.

2.2. Basic Assumptions

2.2.1. Inflatable Structure

The greenhouse structure will be inflatable to maximize deployed volume and reduce payload size. A toroidal shape, similar to the MIH, was chosen for the pressured habitation area of the greenhouse for its complementary deployment methods and stable footprint [4].

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) [4]. Based on Entry, Descent and Landing (EDL) constraints, the MIH will be expected to deploy in the +/- 30° latitude range [5].

2.2.3. MIH Capabilities

By accumulating water from an external ISRU water collection system in an overhead storage tank, the MIH will have the means to provide at least 1000 L of water every 10 sols to the greenhouse via the interface. The MIH will also have an air pump that compresses the thin Martian atmosphere in order to provide initial inflation with CO_2 for the greenhouse. CYBELE will have its own version of this inflation device, which will be used to pressurize the greenhouse initially. The MIH will relay the necessary amount of electric power obtained from external power systems to the greenhouse via the interface connection. This amount is assumed to be a fraction of the total MIH power, which is supplied by four to five 10 kWe "Kilopower" generators that are currently under development at NASA. [6]. The pressure inside the MIH is assumed to be 101 kPa [4].

2.2.4. Resource Margins

As CYBELE is currently in Phase A of development, a 30% resource margin for water, mass, and peak power consumption will be used. As the greenhouse will help maintain many of the MIH systems, it is reasonable for CYBELE's peak power demand to be no more than 20 kWe [4]. A 5% agricultural resource margin will be maintained for crop area, and an additional 5% of total calories will be designated for storage. The 30% resource margin was not maintained for crop area and food storage due to constraints on storage and nutrient recycling processes.

2.2.5. Food Production

The required calories for each crew member will be 3000 kcal/day. This caloric requirement is a conservative estimate in all but the most extreme case where the crew is comprised of four men. By sizing the system for this extreme case, CYBELE is able to feed any crew of four. Crews with smaller caloric needs have flexibility in their growing space and planting schedule.

2.2.6. Natural Lighting

While some light will pass through the water ice cells, CYBELE will not rely on natural light. This is due to the thick ice shielding and the large inconsistencies in weather such as long winter nights and dust storms which are characteristic of Mars [5].

2.2.7. Cosmic Ray Environment and Radiation Shielding

The greenhouse will employ the same radiation shielding strategy as the MIH, with CO_2 and water ice membranes built into the inflatable structure. The shielding thicknesses will be designed to reduce radiation exposure by > 50% [5]. The MIH design anticipated that this would be equivalent to a radiation dose of 70 mSv/year [5]. Over the course of a 600-day mission, the crew would receive approximately 115 mSv on the Martian surface. These levels are well below the Effective Dose Limit of 700 mSv for a 40-year-old non-smoking female and 880 mSv for a 40-year-old non-smoking male. This assumes a 3% value for the Risk of Exposure Induced Death (REID) [5, 7].

The units of radiation exposure dosage for humans are Sieverts, however, to measure radiation damage to other organisms, Grays are used. In the event of radiation shielding failure, the internal environment of CYBELE may be exposed to radiation levels of 0.213 mGy d^{-1} based on Curiosity MSL-RAD data in the Gale Crater [7]. These levels fall under the limits set by the United Nations Scientific Committee on the Effects of Atomic Radiation (10 mGy d^{-1}), International Atomic Radiation Energy Agency's threshold for radio-protection of plants (10 mGy d^{-1}), and the EU-funded ERICA project's screening value of 0.24 mGy

d^{-1} threshold dose rates for plants [8]. Even while taking into account the varying sensitivities between species, according to the International Commission on Radiological Protection, the dosage rate that might cause radiological damage for herbaceous plants is 1 – 10 mGy d^{-1}. This suggests that CYBELE can begin crop production at any stage of membrane filling, if the human crew take proper precautions for their own radiation intake [8]. This is because plants and humans have fundamentally different morphologies. For example, plants are already well-stocked with antioxidants to neutralize byproducts of photosynthesis, and many have multiple sets of chromosomes, or higher ploidy levels. This providing additional redundancy of genetic material [8]. With these considerations in mind, the radiation shielding on CYBELE will maintain safe radiation limits for the crops.

2.2.8. Human-System Standards

With any project following NASA mission architecture, CYBELE will meet or exceed NASA standards for its human-systems. Specifically, CYBELE is designed to accommodate a crew of a wide range of physical characteristics and capabilities as well as perceptive and cognitive abilities. In addition, the environments, functions, architecture, equipment, crew interfaces, operations, and maintenance of the habitat meet or exceed the requirements set by NASA. The following are specific requirements that were taken into account while designing CYBELE. However, this list is not exhaustive, and one should refer to NASA-STD-3001, Volume 2, Revision A for a complete listing of standards [9].

First, in terms of physical characteristics, CYBELE would be unable to support any crew members who had an allergy to the crops selected (Section 3.1), unless supplement intervention is possible. Next, as hydroponics stacks in CYBELE are up to 4 m in height, the personal lift will be sized to ensure the crew member of the smallest stature can still easily remove the uppermost tray from the tallest stack. Similarly, lifting a tray full of fully grown wheat, which is our heaviest crop, should be possible for someone with the lowest anticipated strength.

Regarding atmospheric conditions, a comprehensive atmospheric monitoring system will closely monitor the gas exchange between the crew and the crops to ensure that the atmospheric constituents of CYBELE remain within the required physiological ranges for both the crew and the crops. As CYBELE has many plants that are transpiring - relative humidity (RH) will also need to be closely controlled to ensure that CYBELE's relative humidity remains at 70 ± 5% (with the 75-85% range being acceptable if for less than 24 hours at a time). This range is within the ideal humidity range for most of CYBELE's crops while also remaining under the 75% RH limit in the NASA standard [9]. In addition to RH, atmospheric pressure, CO2 and O2 levels, and temperature will be adjusted and monitored by the crew. Finally, if levels of trace volatiles are detected beyond accepted limits, the crew will be alerted.

In terms of biological components, the amount of the fungal genus *Muscodor*, which will be exposed to the greenhouse atmosphere when being used for sanitization, shall never exceed fungal contamination limits [9]. For more information on *Muscodor* see Section 3.6. In addition, [9]. All crop, food, and nutrition standards were given special considerations, including food acceptability, microorganism level, and preparation standards (for food nutrition standards, see 3.1).

While most of the lighting in CYBELE will be focused on plant growth, there will also be lights designated for lighting walkways and crew performing tasks. The red-blue lighting color that crops prefer can be uncomfortable for human vision. Therefore to meet the NASA lighting color standards for vision, the CYBELE LED strips will have the option to add green lighting [9].

2.3. System Phases

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

The packaging of CYBELE will resemble that of the MIH. However, instead of tight ribs on the sides, all of the membrane layers 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 3.

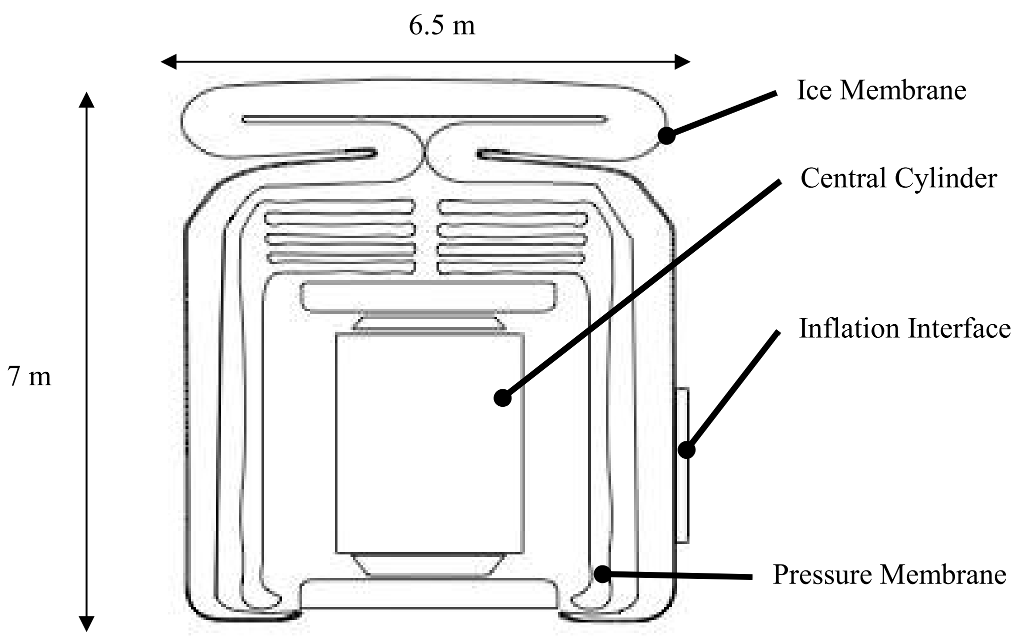

Figure 3: CYBELE packaged schematic.

The entry, descent, and landing (EDL) analysis was modeled using the Space Launch System (SLS) capabilities and parameters [4, 10]. In EDL simulations, it is assumed the package could withstand up to eight times the force of Earth's gravity [11, 12, 13]. This assumption is based on the capabilities of the materials used in CYBELE. 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 4. For the purposes of this simulation, propellant refers to the amount needed when using an unguided landing system plus a 30% margin. As the vehicle begins its descent into the Martian atmosphere, the entry mass will be comprised of all four components displayed in Figure 4, totaling 14,731 kg. When the package lands, the mass will be composed of the engines, 30% extra fuel, and the cargo.

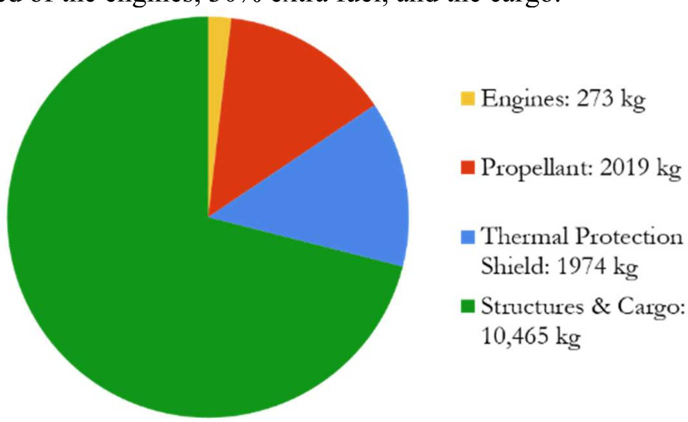

Figure 4: Mass budget for EDL analysis.

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 MIH. While still packaged, CYBELE will be placed within 1 m of the end of the MIH tunnel interface. The accordion soft goods tunnel, similar to the NASA Dual-Chamber Hybrid Inflatable Suitlock conceptual design will connect the greenhouse interface ring to the MIH, as illustrated in Figure 5 [18]. This feature will allow the greenhouse to be placed in its final position before deployment.

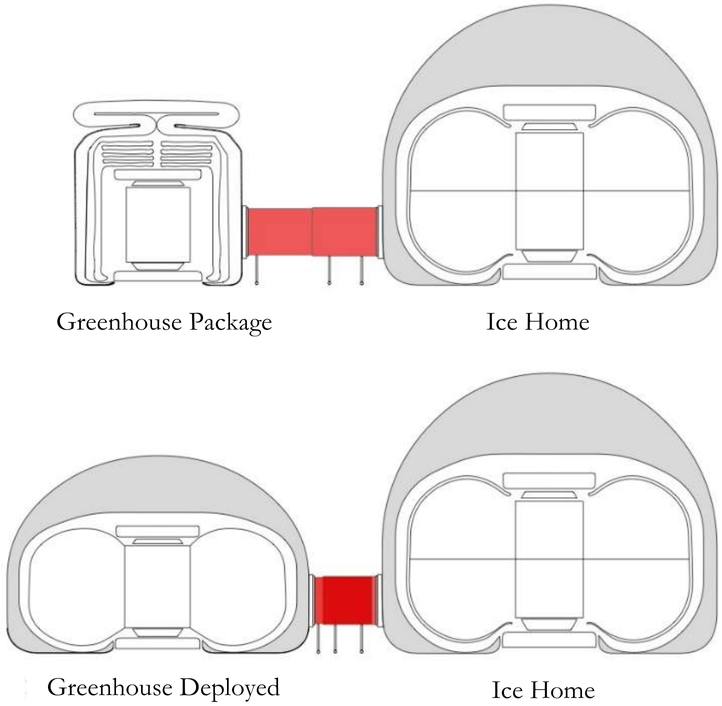

Figure 5: Initial and final stages of inflation. The accordion tunnel is shown in red.

After telemetry, sensor data, and visual confirmation via cameras provide evidence of successful connection, the inflation of the greenhouse will begin. Through an independent inflation system, an air compressor similar to that of the MIH will inflate the greenhouse to 101 kPa, equivalent to the MIH pressure. In addition, the water cells will be inflated to ~10 kPa to making water filling easier later on. This redundant inflation system will serve as a backup to the MIH's inflation system if the MIH inflation system were to fail, as gas can be exchanged between the greenhouse and MIH. There will be 500 m^3 of working space and 1600 m^3 for the entire structure. Therefore, if the entire structure is filled with CO_2 first, the initial inflation will occur over an 11 sol period, based on calculations using a scaled scroll air compressor [14]. Inflation will occur through the accordion soft goods tunnel, which is shown in detail in the Deployment Testing of an Expandable Lunar Habitat [15].

The Ice Home ConOps shows that a 50% reduction in GCR dose compared to no shielding will be achieved with 1.5 m thick ice, however, CYBELE will use 2 m thick water cells to account for the gaps in the ice shielding that the CO_2 cells create [5]. With the current design, approximately 490 m^3 of water will be needed for the shielding, and 16.3 m^3 will be needed for the hydroponic system. The current worst case autonomous water extraction rate is assumed to be 0.1 m^3/sol, based on the BIG Idea Challenge Basics and the Ice Home ConOps [4]. The best case for autonomous extraction is 0.25 m^3/sol, which is the assumed rate for the MIH water shielding set up. If the crew were to get there before the shielding was completed, the radiation they would be exposed to would be much greater, but human assistance could increase the extraction rate significantly. For this analysis, the increase would be by a factor of four. For the beginning of the first mission, the crew would limit their time in the greenhouse to basic operations, and recreation time would increase as the mission went on.

A total of 506.3 m^3 of water ice at the worst case fill rate would take 14 years, far too long to be a sustainable approach. Fortunately, this case is unlikely, because after the Ice Home finishes filling, all of the water extraction could be used for the greenhouse. Also, provided that the first crew can withstand more radiation for the beginning of the mission, they will be able to help fill the cells much more quickly. There are several scenarios for water extraction rates, which will now be outlined.

The greenhouse would likely get the worst case scenario extraction rate of 0.1 m^3/sol for at least the first two years, followed by an increased rate after the Ice Home has been shielded. If the greenhouse has the worst case rate for four years, then by the time the first crew gets to Mars (two launch opportunities later) the greenhouse will have been supplied 142 m^3 of water, requiring 364.3 m^3 more. At the extraction rate of 1 m^3/sol after crew arrival, this will take approximately 1.03 Earth years to fill. As the year progresses, the radiation shielding is continuously increasing. So long as the Ice Home provides a fully shielded area, this is a feasible option. Alternatively, the greenhouse could be crewed at the soonest launch opportunity (and therefore only filled autonomously for two years), in which case it would take 1.23 Earth years for the crew to finish the filling.

Instead of using the previously described systems, it is possible to specify the maximum time it can take to fill, and from there determine the required sizing of the system. For instance, if the greenhouse needed to be filled one launch opportunity after it lands (approximately two Earth years), then the required extraction rate is 0.7134 m^3/sol. If this target changed to two launch opportunities after the greenhouse lands, then that rate would be 0.357 m^3/sol.

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. Temperature sensors will keep the membranes and water within strict temperature ranges based on the requirements for both inflation and filling. Automatic systems monitored by ground operators on Earth will halt or adjust deployment if necessary.

The floors in the greenhouse will deploy automatically after inflation of the membranes. There are 32 floor panels on the outside of the cylinder, each 1.2 m long. Once the greenhouse is inflated, the floor will deploy. The panels are each three meters in length with curved top sections to fit the circular shapes of the torus. Each panel will have two folded triangular sections that will open out to complete the floor in between each of the sections. This design was modelled off of work done by Tom C. Jones from NASA LaRC and Scott Howe from JPL [16]. CYBELE will use more panels than their design to accommodate the plant holders, which are also outside of the cylinder.

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

2.3.3. Deployed State, Outfitting, and Checkout

Before the crew arrives, CYBELE 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 [17]. Protective equipment, such as ergonomic polyethylene radiation protection vests developed by StemRad, could be worn by astronauts while they work in the greenhouse for additional shielding [18]. Alternatively, consumables with high water content such as pre-packaged meals could be placed on top of the tray stacks to serve as an interim measure of protection against radiation.

At the time of crew arrival, the water reservoir will contain 16,300 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 MIH interface airlock will be established and functional. CYBELE will share its atmosphere with the MIH, 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. They will also need to attach some piping for the water transfer systems. Until a critical plant mass is reached on day 34 of plant growth, the greenhouse will be ineffective in balancing CO_2 levels with O_2, so additional O_2 will be necessary (for more information on greenhouse gas composition, see Section 3.7.1).

2.3.4. Operations and Maintenance

CYBELE, like the MIH, is designed to be a multifunctional component of a Martian outpost. Though its primary role will be 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 MIH failure. The greenhouse will include many subsystems necessary to function as a habitat, including a waste disposal system, kitchen, and emergency deployable sleeping quarters that are stowed during normal greenhouse operations. The MIH and the greenhouse are connected by an airlock which allows the two systems to operate independently.

Based on plant climate averages, the atmospheric temperature of the system will be set to 20 ± 2°C and the humidity will be set to 70 ± 5 % [19, 20, 21, 22, 23, 24]. 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. The crew will oversee and control waste and water transfer.

2.4. Greenhouse Entrances and Exits

The greenhouse will interface with the MIH with a 2 m x 2 m pressure door which will connect to an accordion soft goods tunnel extending from the MIH habitation zone. The greenhouse pressure door is based on the International Berthing Docking Mechanism (IBDM), which operates on the International Space Station. This mechanism will consist of two components, one active and one passive, and enables robust, pressurized mechanical connection as well as power, data, air, and water transfer [25]. The interface ring for the greenhouse will have similar embedded connections as the IBDM with an additional connection for human waste transfer. Mechanically, the greenhouse ring will be passive, with the locking components integrated into the interface on the MIH tunnel. To facilitate simple and quick initial connection of the structures before inflation, the resource connections on the greenhouse interface ring and complementary MIH 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. As mentioned in Section 2.3.2, the NASA Dual-Chamber Hybrid Inflatable Suitlock conceptual design has been chosen as an analog. It is expandable and provides both suitlock and traditional airlock capabilities [26]. This airlock tunnel will be portable and will attach to the greenhouse with a similar interface as the MIH. Air, power, and data connections will interface with the external airlock.

3. Plant Systems Design and Systems Integration

3.1. Crop Selection Based on Nutritional Requirements

The initial pool of candidate crops was selected from crop choices made by each of the five finalist teams. To narrow the options, criteria such as yield/area, growth time, nutrient and caloric density, palatability, harvest index, and horticultural growth requirements are considered. After rating each crop by these metrics, input from literature on potential crop selection is used for verification. Based on these factors, the final crop selection for CYBELE is potato, sweet potato, strawberry, tomato, pepper, broccoli raab, kale, wheat, chufa, soybean, and sunflower [27, 28, 29, 30, 31, 32, 33, 34].

Potatoes, sweet potatoes, and wheat fulfill the bulk of the calorie and carbohydrate requirements for the crew. Selection for these three is based largely off the edible biomass density (EBD) ($g\ m^{-2}\ sol^{-1}$), with secondary weight placed on caloric density, post-processing requirements, and dietary versatility. The protein and oil crops are soy, chufa, and sunflower, and they were chosen for their comparably high EBD, caloric and protein density, post-processing requirements, and their amino acid/fatty acid profiles. The fruit: strawberry, tomato, and pepper – are chosen for yield, vitamin/micronutrient profiles, and taste/dietary interest. Broccoli raab and kale are selected for similar reasoning. To ameliorate the potential for dietary fatigue, herbs will also be grown in addition to the crops listed here. They will be chosen by the crew based off their dietary and cultural preferences, and will be grown within the central cylinder of the greenhouse.

The USDA Food Database is the basis for the nutritional information of the crops [35]. To maintain some level of regularity across the different plants, the nutritional values used are for the raw crop, and have not been processed or cooked in any way. It is understood that the values will vary based on how the produce is prepared. There are many repetitions in the micronutrients to ensure there is nutrient redundancy in the crew's diet in case of any failure for a specific crop. Each of the dietary characteristics can be found in Table 1, which uses the USDA Food Database values mentioned previously [35].

Table 1: Dietary Characteristics of Selected Crops

Crop	Category	Vitamins	Minerals	Caloric Density (kcal/g)
Potato	Carbohydrate	B3	K	0.7
Sweet Potato	Carbohydrate	A, B5	Na	0.86
Wheat	Carbohydrate	B3, B5	P, Mg, Mn, Se	3.29
Soybean	Protein	B1, B2, B6, B7,	Ca, Fe, Mg, P, K, Zn, Mn, Cu	4.46
Chufa	Lipid/Protein	B7	P, K, Zn	4.09
Sunflower	Lipid/Protein	B1, B2, B3, B5, B6, B7, E	Fe, Mg, P, K, Zn, Cu, Se	5.84
Strawberry	Fruit	C	--	0.32
Tomato	Fruit	A, C	--	0.18
Dwarf Pepper	Fruit	A, C	--	0.26
Broccoli Raab	Vegetable	A, K	Ca	0.22
Kale	Vegetable	A, C, K	Ca	0.35

To substantiate the values for yields, crop life spans, and horticultural requirements, specific cultivars from literature were selected. The cultivars do not necessarily reflect overall crop averages, but care was used in choosing ones that fit the parameters of CYBELE. However, due to limited quantitative information in literature, cultivar selection was highly skewed towards those with available and specified data. See Section 7 for more details on future crop cultivar selection and biotechnology. The horticultural information is shown in Table 2, and all future information is relevant to the specific cultivars in this table.

Table 2: Horticultural Characteristics of Selected Crops

Crop	Cultivar	Yield (g/m^2)	Grow Time (sols)	EBD ($g/m^2/sol$)
Potato [36, 37, 38]	Denali	19700	132	149
Sweet Potato [39, 40]	Centennial	12272	95	129
Wheat [41, 42, 43]	Perigee	21911	80	20
Soybean [28, 44]	Hoyt-951	1876	90	6
Chufa [24, 45, 46]	Alboraia*	5581	80	28
Sunflower [47]	Aurora	2635	110	11
Strawberry [48, 49]	Seascape	13315	90	244
Tomato [50, 51]	Red Robin	1570	55	34
Pepper [52, 53, 54]	Dwarf**	2250	80	70
Broccoli Raab [55, 56, 57]	Happy Rich	539	55	48
Kale [58, 59]	Red Russian	1224	50	266
* The growth information for Chufa was found in Bios-3 research, which did not specify a cultivar. Alboraia has a few similar parameters [60]				
** Triton Peppers were used for growing parameters, but a different dwarf cultivar will be used on Mars.				

Using dietary standards established by NASA and the US Department of Health and Human Services, relative amounts of crops are portioned to meet the daily caloric and nutrient needs of the crew [9, 61, 62]. Assuming each member of the crew will eat a 3000-calorie diet, they will receive have 15-20% calories from protein, 20-35% from fat, and the remainder from carbohydrates [63]. The values for the general guidelines, along with the amount that the greenhouse will be producing are in Table 3. All of the cells shaded green fall within the dietary guidelines, those in yellow will be produced in excess, and those in red fall short. Concerning the yellow cells, the amount produced is above the recommended Upper Limits defined by the National Center for Biotechnology Information (NCBI). These values do not reflect the absolute upper limit at which they become toxic – rather, it means that taking any less than this will not cause issues for 95% of the population [64]. On the hand, the vegetarian nature of the diet will make it unlikely that sufficient levels of nutrients such as sodium, Vitamin B12, and Vitamin D will be achievable. To compensate, sodium will be brought with the astronauts as a seasoning and recovered from urine, the process for which will be further described in Section 3.11. Vitamin D will be provided through routine crew exposure to full spectrum lamps, and Vitamin B-12 will be brought as a supplement.

Table 3: Nutrients Produced and Dietary Guidelines per Crew Member

Nutrients	Per Person	Units	Guideline Min [9, 61, 62, 64]	Guideline Max [9, 61, 63, 64]
Calories	3000.3	kcal	3000	3150
Protein	128.5	g	112.5	157.5
Total Lipid	86.2	g	66.7	122.5
Saturated	11.1	g	0	24.5
Polyunsaturated Fat	32.6	g	12	17
Carbohydrate	489.5	g	487.5	354.4
Fiber	106.2	g	28	33.6
Ca	1302.1	mg	1000	2500
Fe	44.0	mg	10	45
Mg	1252.8	mg	350	350
P	2983.2	mg	1500	4000
K	9078.0	mg	3500	3500
Na	503.3	mg	1500	3500
Zn	24.5	mg	15	40
Mn	20.1	mg	2	11
Cu	5.4	mg	1.5	10
Se	244.7	μg	70	400
Vit C*	861.9	mg	100	2000
Vit B-1*	4.6	mg	1.5	1.5
Vit B-2	2.9	mg	2	2
Vit B-3	39.3	mg	16	35
Vit B-5	10.8	mg	5	5
Vit B-6	5.5	mg	2	100
Vit B-7	1294.1	μg	400	1000
Vit B-12	0	μg	2	2
Vit A	3809.5	μg	1000	10000
Vit E	46.3	mg	15	1000
Vit D	0	μg	10	100
Vit K	1097.7	μg	90	120
Red cells are less than the minimum.				
Green cells are in the correct range.				
Yellow cells are above the maximum.				
* Vitamins C and B-1 (Thiamine) are bolded above because they were of particular concern for nutrient degradation. Both of these are well above the acceptable lower limits.				

To supply the levels of nutrients listed above, the crew will need to consume certain amounts of each crop every day, as seen in Table 4. Altogether, each crew member is provided with 3000 calories, or 2583 g worth of food every sol. To mediate poor harvests or crop failures, an excess of 600 calories will be produced every sol. The top contributors to the calories consumed by the crew will be wheat, soybean, and sunflower. By mass, the top contributors are potatoes, strawberries, and sweet potatoes.

Table 4: Mass and Caloric Value of Crops Consumed by Individuals and Crew

Crop	Mass/Person (g/sol)	Calories/Person (kcal/sol)	Mass Produced/Crew (g/sol)	Calories/Crew (kcal/sol)
Potato **[36, 37, 38]**	516	361	2063	1444
Sweet Potato **[39, 40]**	398	342	1591	1368
Wheat **[41, 42, 43]**	264	867.5	1055	3470
Soybean **[28, 44]**	97	431.5	387	1726
Chufa **[24, 45, 46]**	96	392.5	384	1570
Sunflower **[47]**	72	421.75	289	1687
Strawberry **[48, 49]**	475	152	1900	608
Tomato **[50, 51]**	79	14.25	315	57
Pepper **[52, 53, 54]**	269	69.75	1075	279
Broccoli Raab **[55, 56, 57]**	107	23.5	428	94
Kale **[58, 59]**	212	74.25	848	297
Total	**2583 g**	**3,150 kcal**	**10,333 g**	**12,600 kcal**
Required	------	3,000 kcal	------	12,000 kcal

3.2. Increasing Efficiency of Space, Growth Time, and Harvest Cycles

Physical spacing will be one of the greatest constraints in crop production, and thus to best use the available space, crops will be grown vertically. This will be done with vertical stacking which optimizes for small plant heights and accessibility. Then, taking advantage of the smaller size of young plants, the crops will be placed in a germination area after seeding. Following this, they will be transferred to condensed nursery stacks until they reach a more mature size. The grasses, wheat and chufa, will only have their heights reduced for the nursery, not the area. Section 5 will go into further detail on how the young crops are monitored and which crew tasks are required for crop management. The total amount of crop growth area is 177.95 m^2, however, the 4 m of vertical space allow it to be condensed to around 34 m^2 of floor space. More details on the vertical stacking systems can be found in Section 3.4.1. The timing and space requirements for each crop is available in Table 5, and the total surface area sums to 177.95 m^2.

Table 5: Growth Time, Life Phases, and Space Requirements for each Crop

Crop	Growth Phases			Surface Area (m^2)	Mature Height (m)
	Germination (sols)	Nursery (sols)	Maturation (sols)		
Potato [36, 37, 38]	14	28	90	9.89	0.60
Sweet Potato [39, 40]	10	28	57	7.76	0.60
Wheat [41, 42, 43]	5	28	47	33.15	0.45
Soybean [28, 44]	5	24	61	45.96	0.45
Chufa [24, 45, 46]	10	28	42	7.52	0.60
Sunflower [47]	7	14	89	22.05	1.00
Strawberry [48, 49]	0	28	62	5.62	0.30
Tomato [50, 51]	7	24	24	4.23	0.25
Pepper [52, 53, 54]	8	24	48	9.71	0.25
Broccoli Raab [55, 56, 57]	5	24	26	4.43	0.30
Kale [58, 59]	4	24	22	1.47	0.65
Nursery	--	--	--	26.16	0.15

In addition to space efficiency, the crew time and harvested amounts need to be optimized. While crew time efficiency might be increased if, at one time, the crew harvests everything needed to meet their dietary needs until the next round of crops could be regenerated from seed, however, that is unrealistic when considering the constraints of shelf life, storage, and the capabilities of the waste management system. As a result, the total amount of the crop needed was split into cycles – staggered stages that would allow smaller and more frequent harvests. Of the 600 sols, crops will be harvested 506 times, which is equivalent to 239 harvest sols once the overlaps in crop harvest cycles are accounted for. Figure 6 illustrates the variances in life spans and how the generations of crops will progress throughout the 600 sol mission.

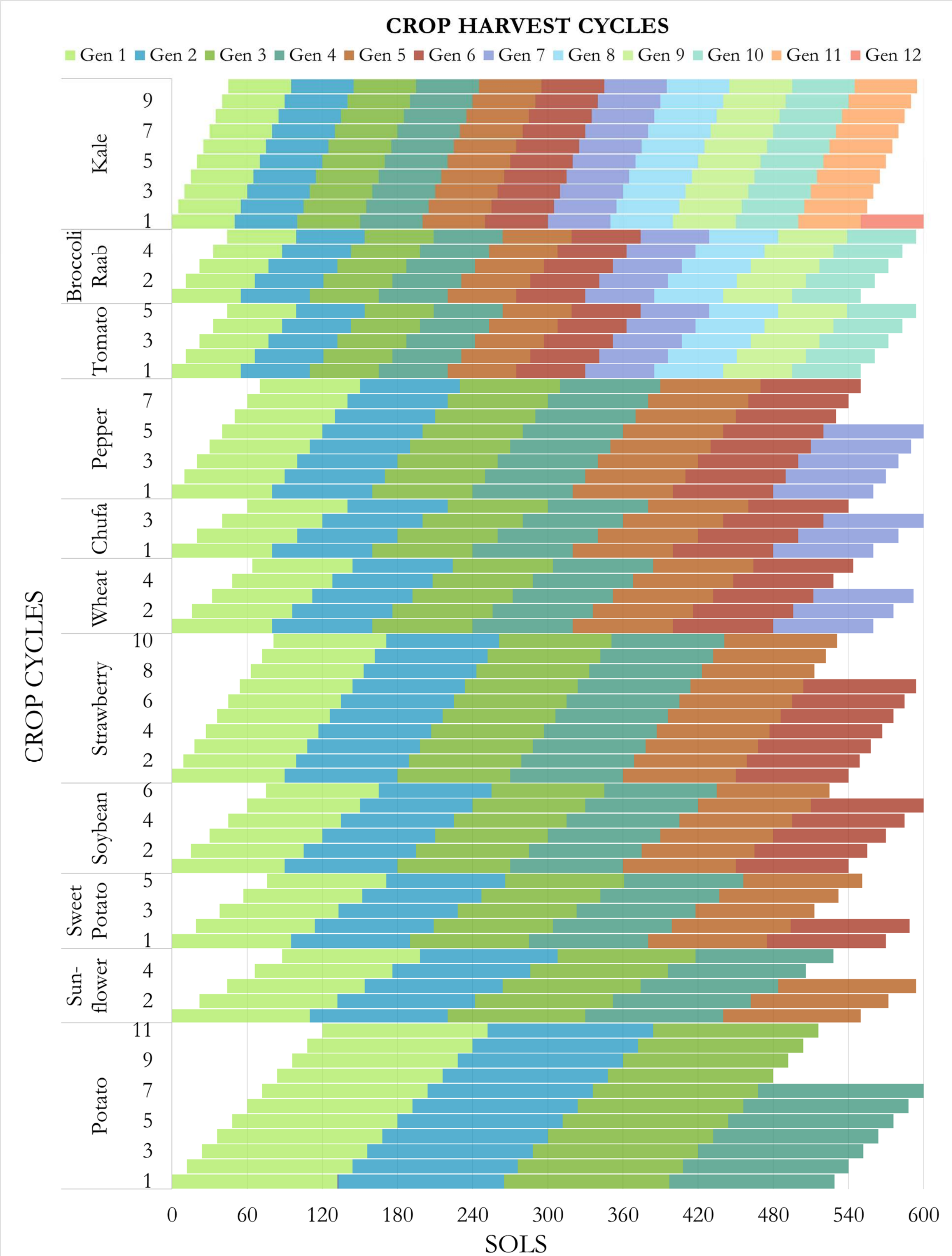

Figure 6: Crop cycles for each plant.

The time between harvests, as shown in Table 6, is largely influenced by the shelf life and post processing requirements. Crops which higher requirements for post-processing and long shelf life, such as wheat and sunflower, will be harvested less often compared to crops like strawberries and kale with limited processing needs and a short shelf life. Based on the desired time between harvests, the crop life spans are divided into staggered cycles, as shown in Figure 6. Every harvest cycle will yield enough food for the crew until the next harvest date, with the production buffer of 600 calories/sol worth of excess crops built into the system to mediate against poor yields. Harvesting more frequently will also reduce the strain on the waste management system, which is discussed further in Section 3.11.

Table 6: Crop Harvests and Harvest Amounts

Crop	Number of Cycles	Time between Harvests (sols)	Area Harvested (m^2)	Edible Yield / Harvest (kg)
Potato [36, 37, 38]	11	12	0.9	24.75
Sweet Potato [39, 40]	5	19	1.55	30.23
Wheat [41, 42, 43]	5	16	6.63	16.87
Soybean [28, 44]	6	15	7.66	5.81
Chufa [24, 45, 46]	4	20	1.88	7.68
Sunflower [47]	5	22	4.41	6.36
Strawberry [48, 49]	10	9	0.56	17.09
Tomato [50, 51]	5	11	0.85	3.47
Pepper [52, 53, 54]	8	10	1.21	10.75
Broccoli Raab [55, 56, 57]	5	11	0.89	4.71
Kale [58, 59]	10	5	0.15	4.24

3.3. Growth Media

CYBELE will primarily feature a Nutrient Film Technique (NFT) hydroponic system. Nutrients will be delivered through the water, and additional media will provide the plants with structure to support the plant weight and ensure upright growth. In addition, for germination and seed starting, media will need to be provided, as many plants cannot start directly in a hydroponic setting. The first growth cycles of crops will use condensed rock wool cubes as growth media, however as plants are harvested and the inedible biomass is processed, following generations would be grown in pelleted hydrochar. Details on how hydrochar is produced from inedible biomass are included in Section 3.11. The exact properties of the hydrochar will change based on the particular waste biomass used, however, it is projected that the mean bulk density will be around 0.128 g cm^{-3} , air filled porosity of about 28% and a water holding capacity of 54% [65]. The media will be held by reusable grated plastic hydroponic growing cups.

3.4. Structural Support System

3.4.1. Structural Design Overview

The overall structure of CYBELE closely resembles that of the MIH; this allows the two structures to be developed concurrently, reducing development costs and timelines. The toroidal layout was selected for its efficient volume, stable footprint, and ease of deployment. The size of the structure was scaled to the volumetric needs of the plant growth and was constrained by limits on the package size. CYBELE has the same dimensions as MIH except it is slightly shorter and has only one floor.

The plants are held in modular hydroponic growing trays, illustrated in Figure 7. These trays have a rectangular base with trapezoidal sides to allow for tight packing. They are arranged radially around the central cylinder. The amounts of each crop was optimized for the following conditions: each crop must be included; there cannot be more than three serving of any crop in one sol; and the area and volume had to be minimized. This achieved a balance of plants that provides a diverse and nutritious diet.

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 7.

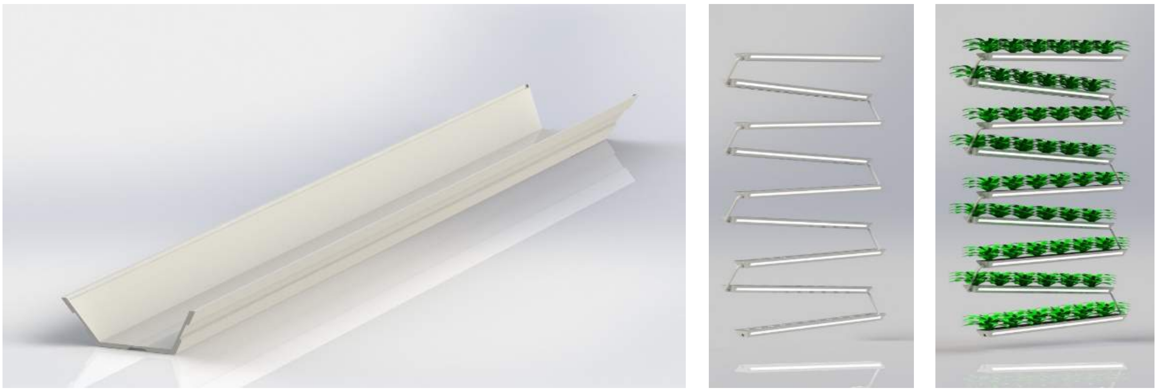

Figure 7: A single tray without end caps (left), a stack without plants (center), and with plants (right).

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 the 1.5 m trays are designed to have two tray covers, each 0.75 m long. The trays themselves will stay in place to minimize piping and water flow changes. The covers will be removed for all harvesting and maintenance. Additionally, 1.5 m was determined as a comfortable width for the circular track around the growing space. The central cylinder will have a height of 4 m, which will necessitate a lift to access the tallest plants. Since two crew members will work together, two access carts will be sent, one for inside the cylinder and one for outside, which fit into the walls on the outside of the running track.

Figure 8 shows the top-down view of the working space in the greenhouse with a few major dimensions and a breakdown of the plants by stack. The working area has a diameter of 12 m, the same as the MIH. The nursery is further broken down by tray, which can be found in Table 7. Not shown in this diagram is the small shelf outside the circular track where the torus blows out. This provides a place to rest any plant trays or other equipment instead of walking back into the cylinder if that is preferable. Along the membrane walls are gutters to collect any condensation on the wall, which will feed into the clean water tank below the cylinder.

Table 7: Nursery Tray Breakdown

Nurseries	Tray Breakdown
Nursery 1	1 Sweet Potato
	11 Chufa
	18 Wheat
Nursery 2	2 Potato + Kale + Broccoli
	1 Sunflower + Pepper + Tomato + Strawberry
	3 Soybean
	24 Wheat

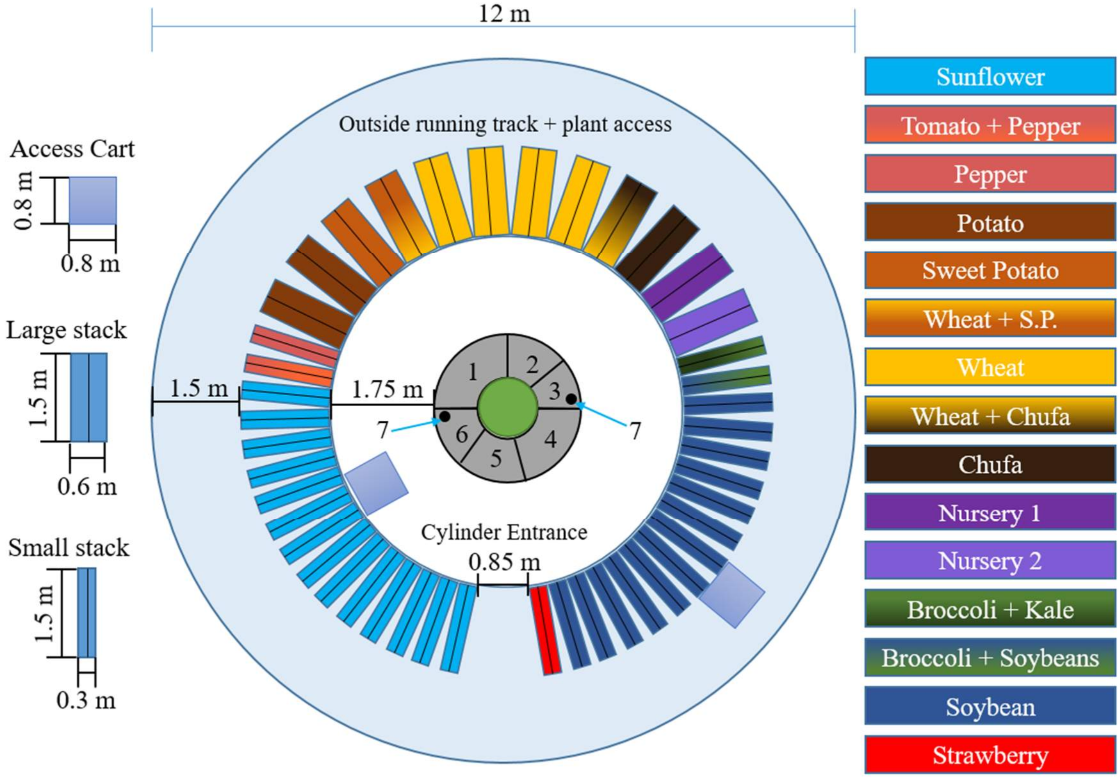

Figure 8: Top-down view of CYBELE with plant breakdown.

The grey area is a work table with storage provided below. The numbers in the center grey area designate the portion of storage area as described in Table 8. This area also functions as a compact kitchen. The oven "section" encompasses one cooking oven and one desiccant oven. Above these ovens are two induction burners inset in the table top. A cover slides over the stove top to automatically turn off both burners when not cooking. Underneath the ovens and sink area, there will be a cooking set with pots, pans, bowls, knives, an immersion blender, cutlery and cutting boards. There will also be a monitor and computer displaying the conditions of the greenhouse set above the freezer. Several foldable chairs will slide under the table top work space.

Table 8: Storage Breakdown for Grey Area

Grey Area Storage
1. Ovens (Cooking and desiccant)
2. Harvest Equipment and 3D Printer
3. Sink
4. Freezer and Fridge
5. Mill + Thresher
6. Germination Station
7. Points about which tables can pivot, includes water and electrical piping

The green area in the center has two layers of herbs on the surface, each 0.79 m^2 area from a 1 m diameter circle. This specific section is Ebb and Flow hydroponics. Below this herb section is storage for room temperature food. Surplus crops can be vacuumed sealed before placement in this storage to save space and preserve the food. The gray area is composed of two halves surrounding the green herb section. These two halves can swing outwards, allowing access to the center and the ability to work on both sides of the table. The way the tables swing out from the compact position is demonstrated in Figure 9.

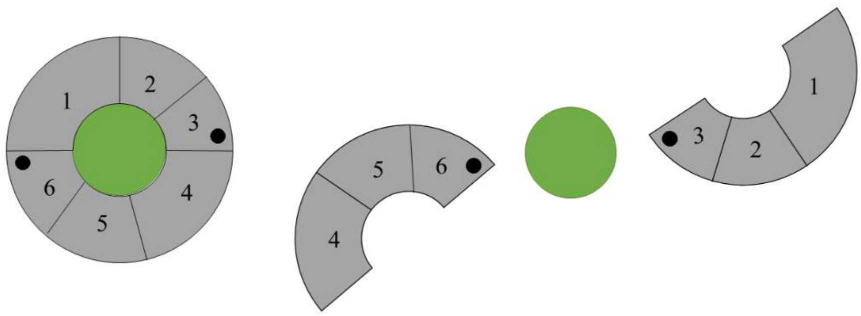

Figure 9: Middle work area configurations.

The top-most volume of the cylinder, above the central table, will hold the heating, ventilation, and air conditioning (HVAC) systems, including the air handler, humidity control, and a fan. In total the machines and materials will take up a 3.5 m diameter circle and come down 1.07 m. More on these systems can be found in Section 3.7.

The clean water and nutrient solution, as well as the nutrient cycling and microbiome processing, is placed below the floor of the central cylinder inside the bottom piece which will extend out during deployment. More details on these processes are provided in Section 3.11.

3.4.2. Stack Deployment Prototype

To better understand the deployment of the hydroponic growing system, a subscale prototype was developed, shown in Figure 10. It features hinges that allow the trays to fold upward during packaging and unfold to a predetermined angle. Custom hinges stop the trays at the correct angle, and 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. A cylindrical glide track was replaced by 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 4 m tall, the bottom-most 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 can 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 10: 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 [30, 66]

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.

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 approximately 6 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. The longest continuous distance that the water is expected to travel throughout the NFT stack is 46.5 m, therefore the stacks will be equipped with input sites to maintain healthy dissolved oxygen levels of 7 mg/ L within the nutrient solutions if necessary [67]. These systems are demonstrated in Figure 11.

At the beginning of a mission, each plant will be fed a Hoagland solution composed of the ideal amounts of nitrogen, potassium, phosphorus, and other elements essential for plant growth [68, 69, 70]. As the mission continues, more of the nutrients will be recovered from the humans and inedible biomass, and this process is described thoroughly in Section 3.11.

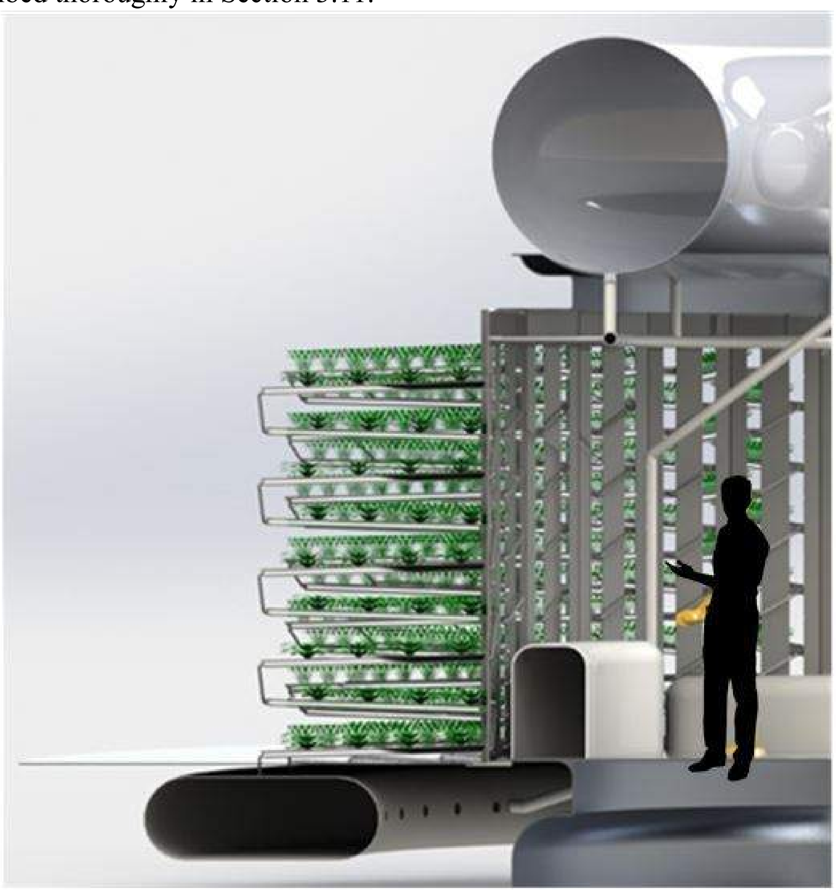

Figure 11: Section view showing water and nutrient delivery system with blue lines representing water flow.

Given that most of the research has been done for systems on Earth, the equations in Table 9 were used to convert Earth parameters to parameters usable on Mars. The variables remain the same except for those which depend on gravitational acceleration.

Standard NFT conventions indicate a flow rate of 1 L/min is suitable for each of the plant varieties [71]. To determine the 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°. These angles were related to Mars, using the equations in Table 9 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°. Empirical data will need to be collected to determine the effects of root build up on the water flow rate through the system.

Table 9: Parameter Conversions from Earth to Mars

Variable	Earth	Mars
NFT System Angle ($\boldsymbol{\theta}$)	θ_e	$\theta_m = \mathrm{asin}\left(\left(\frac{g_e}{g_m}\right) * \sin(\theta_e)\right)$
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}	$Q_{Mars} = Q_{Earth} * \frac{g_e}{g_m}$

The trays 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 non-disruptive pump maintenance. The total volume of water that passes through the system in one sol will be 64,988 L. The plants are divided into four sections, where each section has its own set of tanks which does not mix with any other tanks. The reservoir above the cylinder is divided into four smaller tanks, one for each crop division, as well as another small one that has clean water for the sink. The bottom reservoir is likewise divided into four tanks, and each tank requires its own pump to return the water above. The reservoirs each hold over 19,200 L.

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 three times per sol, while smaller reservoirs require more continuous pumping. Large water tanks can decrease the risk of nutrient over-saturation or dilution for hydroponic systems. Salt levels can build up in the nutrient solution to levels which are deadly for plants, and having a larger water volume ensures that this will not happen quickly. Each tank is refilled four times every sol for about 12 minutes each time, operating at 250 W. The pumping is done consecutively, rather than at the same time, to lower peak demand. The pump used to estimate the power, mass, flow rate, fill time and volume for each tank was the DAYTON 120/240VAC Open Dripproof Centrifugal Pump [72].

3.6. Sanitation

There are several risks related to the plant microbiome responses on Mars. Imbalances could lead to the prevalence of opportunistic plant and human pathogens, so sanitation practices will limit microbial growth on seeds and stored produce [33]. Therefore, the nutrient solution will be cleaned periodically with UV treatment as a preventive measure to avoid potential algae and bacteria growth or plant disease. While UV light is effective on broad smooth surfaces, its efficacy decreases when used on the often highly textured surfaces of leaves, fruit and seeds. On the International Space Station, citric acid wipes are used, a process that both is time intensive and requires complete physical contact to be effective. Avoiding the inefficiencies associated with UV and citric acid wipes, bioregenerative and broadly effective - species from the fungal genus *Muscodor,* will be used within CYBELE for sanitation of crop propagules and stored produce. First discovered in the 1990's, *Muscodor spp.* are sterile endophytic fungi that produce volatile organic chemicals (VOCs) with broad spectrum antimicrobial properties [73, 74]. Of the multiple species within the genus, most of the available literature concentrates on the first discovered - *M. albus.*

M. albus produces 28 volatile organic compounds (VOCs) that synergistically work as a powerful yet selective mycofumigation biocontrol measure [73, 75]. Composed of short-chain alcohols, organic acids, esters, ketones, and multiple aromatic hydrocarbons, the VOCs are produced at low concentrations of 150 PPB. They effectively kill or inhibit a selective but wide range of potential human and plant pathogens [76, 77]. The use of *M. albus* has been USDA and EPA approved for use on all food crops and seeds/propagules, and in these EPA tests, no toxic, infective, or pathogenic effects were observed in mammals [78]. Similar to *M. albus,* the species *M. crispans* was recommended for use by Dr. Gary Strobel, the scientist who discovered the genus, along with many of the species and their properties [79].

The VOCs produced by *M. crispans* are all found on the FDA Generally Recognized as Safe (GRAS) list, yet has been found to have sanitizing properties equivalent to those of bleach [75]. Strobel claims that a diluted solution containing the VOCs from the fungi is safe enough to use as mouthwash [79]. Both of these species could be viable options for use in CYBELE.

The unique combination of VOCs has a complex mode of action with multiple targeted pathways, allow the various *Muscodor spp.* to be broadly effective against gram-negative bacteria like *Escherichia coli*, gram-positive bacteria like *Staphylococcus aureus*, other fungi like *Aspergillus fumigatus*, nematodes, and arthropods [76, 80]. Microbial levels can be reduced across the entire surface area without impacting the organoleptic quality of produce, and using *Muscodor* requires minimal crew time. Lacking reproductive structures, the fungus reproduces via vegetative growth, and, if supplied with carbon and nitrogen rich moist media such as sterile grain, populations of the fungus can be grown and harvested as needed [80, 81].

Muscodor is inoculated onto wheat grain by incubating it in a sealed container with a sterilized grain wheat [81]. After two to three weeks, the inoculated grain can be used immediately or desiccated for long-term storage [82, 83]. To revitalize desiccated grain, one study placed the grain in tea bags, soaked them in water for 4 hours, and placed them near seeds and propagules [84]. For seed sterilization, other studies have mixed the inoculated grain into growth media, along with the seeds, or within close proximity to seedlings [83]. Once the produce is harvested, *Muscodor* will be used to reduce levels of microbial presence within storage. This will not only decrease the possibility of food-borne illnesses, but will also extend the shelf life of produce by reducing populations of microbes linked to rot and decay. As the VOCs require at least 24 hours to reach full potency and then remain effective for up to three days, 'tea bags' of the fungus could be alternated and exchanged with each harvest [76]. The grain itself acts as a limiting factor to the life duration of *Muscodor*; once the nutrients are depleted, the mycelia die and VOC production is halted. This characteristic prevents *Muscodor* itself from becoming problematic [80, 84]. It is expected that within the closed storage environment that even relatively small amounts of the VOCs will be potent enough to maintain reduced levels of microbial contaminants.

For transport, the *Muscodor* mycelia can be grown on sterile paper strips, desiccated, and either stored at -20 ^{o}C for over a year or stored on potato dextrose plugs in sterile distilled water at 4^{o}C for over 4 years, or storing desiccated and inoculated wheat at -70°C [73, 74, 81]. Then, once within CYBELE, *Muscodor* will be produced and held in the same section of the center table as the germination station.

3.7. Environmental Requirements

Root temperature and pH are some of the most important environmental requirements for plants, detailed in Table 10 [20, 21, 22, 23, 24, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103]. The overall humidity should be 60-80% for healthy plant transpiration, and the ambient temperature of the greenhouse should stay within 18-22 °C [85].

Table 10: Hydroponic Specifications for Each Tank

	Tank 1	Tank 2	Tank 3	Tank 4
Root Temperature (°C)	15.6-18.3	15.6-18.3	22.2-26.7	22.2-26.7
pH	6.5	6.5	6	6

To keep the CO_2 at 800-1200 PPM, the Martian atmosphere will be brought into the greenhouse using the same intake and filtration method used to originally inflate the greenhouse. Any excess O_2 can be can separated from the air to then be used for fuel production.

For humidity control, greenhouse air cannot be ventilated outside and mixed due to planetary protection regulations and the incompatible Martian atmosphere. Traditional large-scale dehumidifiers would take a large portion of the available power, so humidity will be controlled using hydrogels [86]. The hydrogels take approximately one hour to absorb water vapor from air, and they take one half hour to desorb. Three sets of hydrogels will be in use at any given point in time. An oven at the top of the cylinder will desorb one third of all the hydrogels while the other two thirds are absorbing next to the oven. After half an hour passes, they will switch positions by turning as a ring, shown in Figure 12. This is done through a motorized circular track which is attached to the ceiling. The hydrogels absorb water at ambient temperature until they reach 160% mass, then desorb water at 50ºC. In total, to absorb the 900 L of water from the greenhouse atmosphere each day, 94 kg of hydrogels will need to be sent, and 1 kWe is used continuously to heat them. Piping, large enough to handle the 0.609 L/min of water that the hydrogels will be desorbing, will go from the hydrogel oven, down through the middle herb growth area, to the clean water tank below the cylinder floor. Placed inside this ring is the air handler and one of the fans.

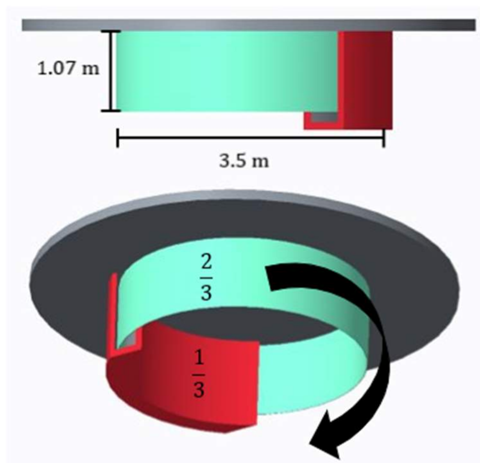

Figure 12: A schematic of how the hydrogels move. The red shows the oven, the blue is the hydrogels, and the grey is the cylinder ceiling. One third of all hydrogels are in the oven at a time.

To dehumidify all of the air in the greenhouse continuously, there will also be air circulation in the form of fans. These fans will also remove transpired water from leaf surfaces to encourage continued evapotranspiration. The fans have to circulate the working air volume of 500 m^3, at least once an hour for full contact with the hydrogels and crops. This requires three fans placed tangentially around the torus, as well as one inside of the central cylinder to push the air toward the hydrogels, each able to move at least 125 m^3/hr.

3.7.1. Gas Composition Model

A gas composition model of the greenhouse ambient air is required to analyze how the crops and crew will affect the closed system. First, each crop was individually analyzed for the amount of CO_2 consumed and therefore their O_2 produced, with an assumed photosynthetic quotient of 1.0. This took into consideration each crop's photosynthetic rates, areas of growth, photoperiods, day period PAR, and respiration during the night period. Based on this analysis, when all crop sections are in use, after the ramp up period, the greenhouse will produce 5767 g (180.23 mol) of O_2 a day [87, 88, 89, 90, 91, 92]. This O_2 is used by three different sources. First, each crew member requires 830 g (25.94 mol) of O_2 a day to produce 1000 g (22.72 mol) of CO_2 a day [93]. Second, the two greenhouse aerobic bioreactors use a total of 1000 g (31.25 mol) of O_2 a day. This leaves 1447 g (45.22 mol) of O_2 a day remaining to be separated from the air via cryogenic cooling, which will require 9.04 W continuously [94]. This separated O_2 can then be used to produce rocket fuel or stored for future missions' ramp up periods. However, for the first mission, extra O_2 will either need to be brought along or produced through alternatives means until day 34, when the crops are producing enough O_2 for crew respiration and bioreactor usage [95].

The control system for the greenhouse gas composition was then modeled with several simplifications using the STELLA software program. This STELLA system map for the carbon budget of the smaller model is shown in Figure 13. The model shows that crew respiration does not produce enough CO_2 for crop photosynthesis, so CO_2 will need to be extracted from the Martian atmosphere through the inflation system to compensate for this.

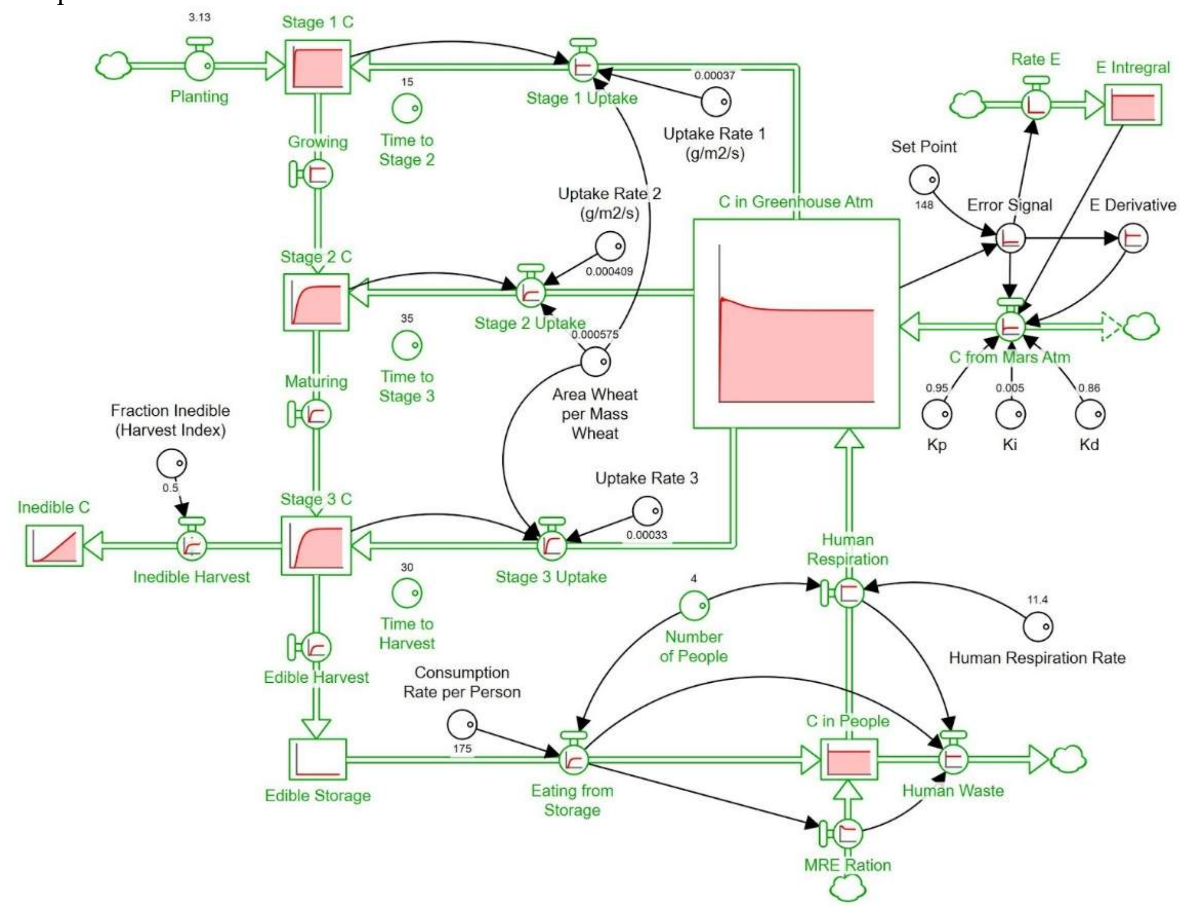

Figure 13: System map of carbon budget for CYBELE. The black lines indicate connections or dependencies, the green arrows indicate rates of change, the boxes or stocks represent carbon accumulations, and the red graphs display the carbon levels in each stock over time.

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 is for a smaller growth model and will require additional validation with experimental studies, it provides a first-order understanding of the interaction of the systems in CYBELE.

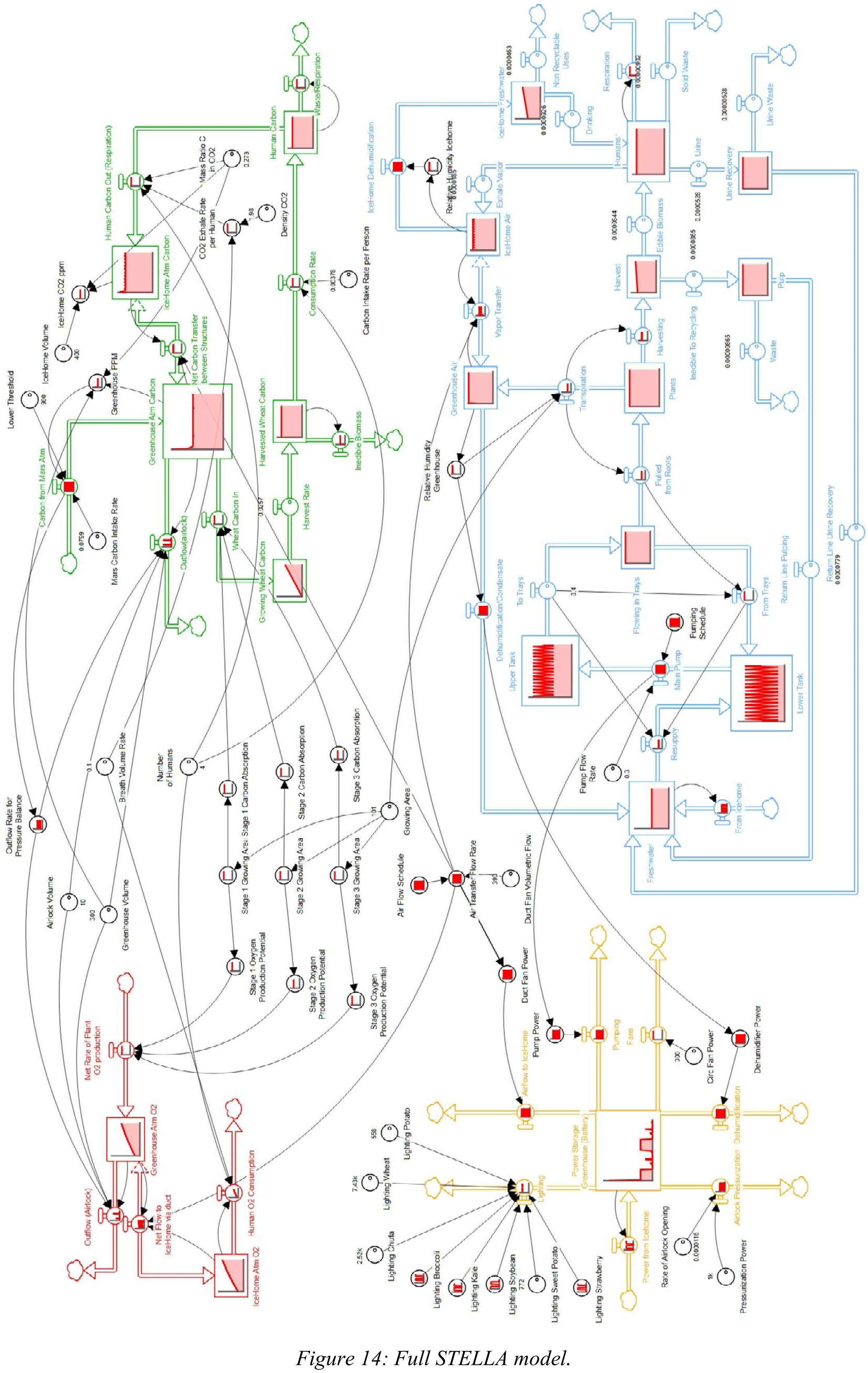

Figure 14: Full STELLA model.

3.8. Lighting System

Given low insolation levels and the potential for dust storms, artificial lighting is required. Like the other automated aspects of the design, the lighting timer can be manually overridden. To decrease energy usage, if the PAR sensors receive more than the necessary amount of light due to natural lighting, the LEDs will dim in response. A first-order analysis suggests alternate PCB designs can vary the intensity of the LEDs along a strip 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, the most conservative option was considered with the lights following a schedule that only considers artificial lighting at maximum intensity, found in Table 11.

Table 11: Lighting Schedule for One Sol (Yellow Indicates Lights on for That Plant)

Crop (PAR)	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)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■								
Tomato (300)	■	■	■	■	■	■	■	■									■	■	■	■	■	■	■	■
Broccoli (400)													■	■	■	■	■	■	■	■	■	■	■	■
Potato (244)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Swe. Potato (360)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Strawberry (500)	■	■	■	■	■	■	■	■	■	■	■	■												
Chufa (391)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Pepper (316)									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Sunflower 1 (1000)									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Sunflower 2 (1000)	■	■	■	■	■	■	■	■									■	■	■	■	■	■	■	■
Sunflower 3 (1000)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■								
Soybeans 1 (815)	■	■	■	■	■	■	■	■	■	■	■	■												
Soybeans 2 (815)													■	■	■	■	■	■	■	■	■	■	■	■
Wheat (666)	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

CYBELE 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 [96]. The topmost trays receive lighting from LEDs mounted to the underside of a tray which does not hold any plants. This allows for customizable PAR settings for peak yield. In addition, green LEDs on the strips can light up while crew members occupy the greenhouse to provide white light. Though this consumes more power, this also increases the crew's comfort. If the crew stays in the greenhouse for longer periods than allotted, especially during peak demand, the lights will go back to red/blue wavelengths only. The trays are made of highly reflective material to maximize photosynthetic photon flux density. Partitions, such as curtains, can be used to accommodate each plant's photoperiods and minimize unused light.

To estimate the power requirement for lighting all of the crops, power consumption and PAR output was consulted from 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 [97]. Scaling this power consumption to the area, lighting schedule, and PAR requirements yields a peak power consumption of 22.4 kW for lighting.

These calculations are based on the 2014 efficiency of the Apache LED system. A U.S. Department of Energy report from 2016 estimates that LED efficacy (lumens/watt) will increase by a factor of 2.5 by 2030, which could reduce the hourly lighting power demand to a peak of 11.6 kW [98]. This 2.5 factor increase of the lighting system efficacy is the culmination of the increase of efficiencies of several components, which includes LEDs, drivers, etc. Factoring in a 30% resource safety margin results in a 15.1 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 as well as the greenhouse fans will provide convective heat transfer away from the lights to cool the system. There will be triplicates of LED strips under each tray, and power will be supplied to only 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, a central computer will regulate variables such as nutrient level, pH, and lighting. In addition to sensors, CYBELE will have software which utilizes proximal hyperspectral cameras and machine learning to monitor plant health by taking images that quantify light within a 400-1930 nm range. These cameras will utilize a broadband flash that will allow it to observe the crops in this wavelength range. This allows for documentation of pathogen infection, nutrient content, abiotic stress, heat stress, biotic stress, plant biomass, yield of the crops, and growth media properties. To track the progression of the plants, large sets of samples for each species will be collected and the software, potentially State Vector Machines (SVMs) or Artificial Neural Networks (ANNs), will optimize based on color density [99]. Currently, there are databases such as PlantVillage with a total of 54,306 images including healthy and diseased plants that can be used to train the software to recognize plant types and diseases [100]. In addition to readily available datasets, it is recommended that the software be trained on data from analogs such as KSC and EDEN ISS to reduce bias and include hydroponic-specific scenarios.

The software detects disease symptoms and harvest readiness by analyzing pictures taken periodically by cameras on individual stacks. A notification will be sent to the crew to take the necessary steps if anything is detected. The pictures of the crops will also be sent back to Earth periodically to be reviewed by plant health experts for additional analysis. There will be one camera per stack which can move up and down the stack support beam (T-slot bar) with a linear actuator.

Additionally, the crew would benefit from an automated task list linked to the AI software that will keep track of all necessary crop care tasks required per day. This will relieve the crew from the time consuming task of continuously observing the plants and reduce the human subjectivity in the process. The AI system could also assist with crop scheduling based on crop yield, and be equipped with fault detection and mitigation on a local scale, should the crew be unavailable.

The trays are manually cleaned after they are emptied with each harvest. After harvesting, the inedible biomass will be combined with the human waste and go through a treatment process described in Section 3.11.

3.10. Pollination

All of the seeds will be brought from Earth. This was decided with consideration of some of the challenges involved in continuing generations – particularly genetic variability and transgenerational epigenetic mutations. Vegetative crops (potato, sweet potato, broccoli raab, and chufa) will all be harvested prior to seed/fruit set, so no pollination steps are required [101]. Wheat, soybean, tomato, and pepper are all seed/fruit crops which are self-pollinating and would not require any additional crew time, providing that there is sufficient ventilation [102, 103, 104, 105]. Sunflower and strawberry, while able to self-pollinate, would likely require additional pollination efforts to improve seed/fruit set [101, 106, 107]. The crew could abstain from pollinating these crops during the first cycle of sunflower and strawberry growth to determine if intervention is required. If manual pollination is necessary, crew members will use an electric pollinator, which is similar to an electric toothbrush, to pollinate the crops after they begin to flower [107].

3.11. Waste Processing

A bioregenerative life support system recovers resources from waste products. The combined MIH and CYBELE systems will produce three major streams of waste: liquid human waste, solid human waste, and solid inedible biomass. In addition to this, there will be greywater from hygiene processes and circulated nutrient solution from the hydroponics system. The waste management mechanism is shown in Figure 15.

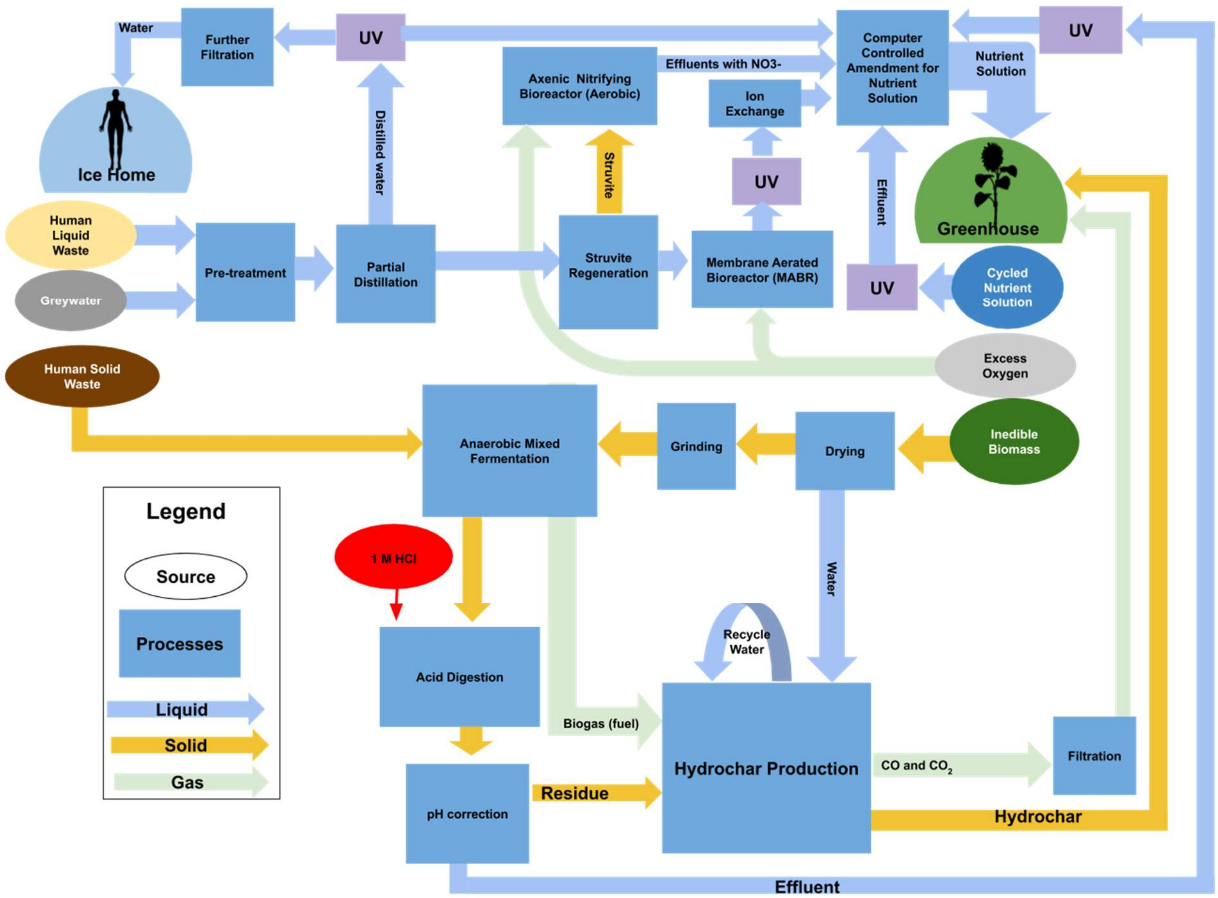

Figure 15: Waste management process overview.

Without any nutrient recycling, 830 kg of salts would need to be sent every mission, maintaining the 30% resource margin. With recycling, the machinery to cycle the nutrients would add 279 kg, as well as 71 kg of acid to leach the pulp, and the nutrient salts are 123 kg. In either case, 273 kg of acid for the nutrient solution will need to be sent. The comparison can be seen in Figure 16 below, with recycling and without, for three missions.

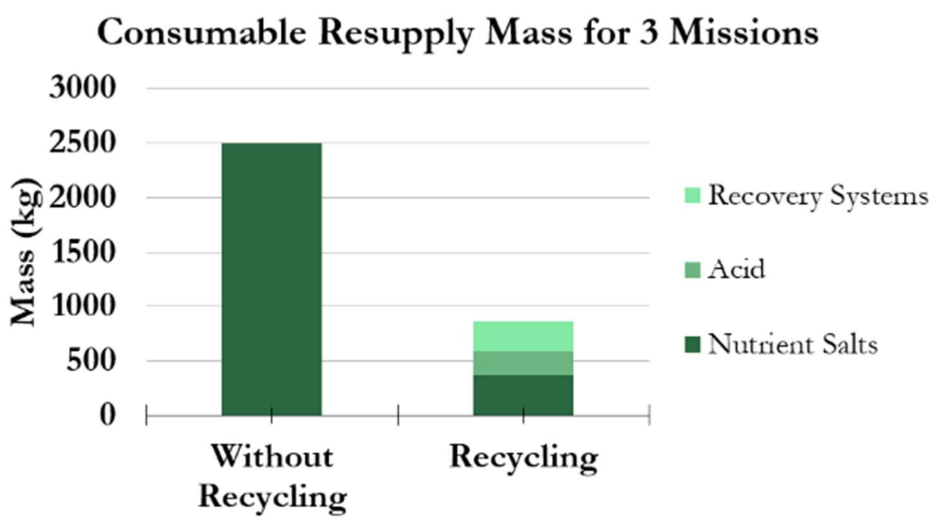

Figure 16: Comparison of mass for recycling nutrients.

3.11.1. Human Liquid Waste and Greywater

Human liquid waste requires its own nutrient recovery process. The assumed rate of urine production is 1.42 L d^{-1}, with a total nitrogen content of 11g d^{-1}.For a four-person crew, this translates to 44g N d^{-1}, with the majority of this being in the form of urea (NH_2CONH_2) [108].

Urea hydrolyzes into ammonia (NH_3) and ammonium (NH_4^+) depending on the pH and temperature [109]. While plants can use nitrogen in this form, it is inefficient and can be phytotoxic in high levels even while correcting for pH [110].

In the interest of efficiency and safety, CYBELE uses a membrane-aerated bioreactor (MABR) to further process ammonium into nitrate (NO_3^-), in addition to breaking down Dissolved Organic Carbon (DOC) that often contributes to biofouling of downstream processes. MABR systems have been extensively studied for application in human space exploration. A full-scale model, the Counter-diffusion Membrane Aerated Nitrifying Denitrifying Reactor (CoMANDR) at the Texas Tech University has shown the ability of such systems to process both urine and hygiene waste [111].

Being an aerated system, MABR consumes a significant amount of oxygen. According to Terada et al. (2003), ammonia oxidizing bacteria (AOB) in MABR can consume 921 g O_2 / day. In addition to nitrification, MABR can simultaneously denitrify, producing N_2 gas which can help maintain the pressure of CYBELE [112]. The nitrification to denitrification ratio can be adjusted with pH and oxygen concentration. It is unlikely that the denitrified nitrogen will be fixed back into the nutrient solution by the soybean crops, whose symbiotic root nodulation infected with *Bradyrhizobium japonicum* will be inhibited by the NO_3^- already present in the hydroponic system [110].

There are several challenges that need to be addressed before these systems can be applied in CYBELE. It is possible that particular processes such as nitrification will require inoculation with ammonia-oxidizing bacteria (AOB such as *Nitrosomonas*) and nitrite-oxidizing bacteria (NOB such as *Nitrobacter*), which are slow-growing and require a ramp up period after dormancy [112]. This bioreactor could be established on board the transit vehicle prior to crew arrival. However the mass, volume, and retention time associated with such a bioreactor will need to be addressed. In addition, CoMANDR has shown nitrification percentages greater than 60%, and primarily produced nitrites (NO_2^-) as opposed to NO_3^-. It is not unreasonable, however, for the nitrification efficiency and the NO_3^- production rate of MABRs to improve, potentially through synthetic biology methods of incorporating complete ammonia oxidation (comammox) [109]. Comammox bacteria are capable of converting NH_4^+ into NO_3^- without an intermediary organism, and could potentially decrease the level of denitrification that leads to nitrogen loss.

Alternatively, if MABR systems do not reach the appropriate Technology Readiness Level (TRL) for CYBELE, the liquid waste management system could incorporate the novel ammonia regenerative system from the Kennedy Space Center. This system uses Magnesium Phosphate dibasic trihydrate ($MgHPO_4$), which precipitates struvite from ammonia under standard temperature and pressure [113]:

$$MgHPO_4 \cdot 3\,H_2O\,(s) + NH_3\,(1) + 3\,H_2O\,(l) \longrightarrow MgNH_4\,PO_4 \cdot 6\,H_2O\,(s)$$

The process is regenerative in that the above reaction can be reversed to reclaim the ammonia and the substrate at elevated temperatures:

$$MgNH_4\,PO_4 \cdot 6\,H_2O\,(s) \longrightarrow MgHPO_4 \cdot 3\,H_2O\,(s) + NH_3\,(g) + 3\,H_2O\,(g)$$

Once separated from the liquid waste stream, the recovered NH_3 can be turned into NH_4^+ by adjusting the temperature and pH, and then into NO_3^- via a compact axenic nitrification bioreactor. Given the highly compact and regenerative nature of the system, the struvite regenerator could be activated onboard the transit vehicle to begin nutrient recovery prior to CYBELE activation.

A significant challenge associated with urine processing for hydroponics is the elevated salt level. According to Subbarao et al, Na^+ concentrations of 100 mM are sufficient to kill most plants [114]. The starting point of a typical Hoagland solution has 1.2 ppm of Na^+, which is approximately 0.052 mM. Throughout the 600-day duration of the mission, the crew of four is assumed to produce 400 mmol day^{-1} of

Na^+ [108]. As the nutrient solution volume is 16,300 L in CYBELE, this means that by the end of the mission, the sodium concentration will increase by approximately 15 mM. As most of the crops in CYBELE are not specifically salt-resistant, even concentrations of 25-50 mM can inhibit growth [115]. To minimize risk, the crew should have a combination of a low-sodium diet and periodic usage of electro dialysis (ED) or ion exchange to separate out Na^+ from the rest of the salts [116]. Another technology to consider is a combination of an Electro Deionization (EDI) process with an aluminum-based tribocharger to separate out specific ions from dry brine based on their triboelectric properties [117]. This option is still in conceptual phase and would need to be developed further for implementation.

The liquid waste processing system is shown in Figure 17. Liquid waste in the form of urine and greywater is first collected in a pre-treatment tank, which allows for urea to hydrolyze into ammonia. The effluent is then sent to a distillation tank, where a significant portion of the water is collected and polished for use in the hydroponics system and MIH. The remaining effluent could either be sent through a struvite regeneration system to recover ammonia, from which it will be fed to an axenic bioreactor of nitrifying organisms, or fed directly into the MABR system. After being processed with an ion-exchange membrane, the effluent will be sanitized with UV and corrected with a computer-controlled nutrient solution injector into the hydroponics system.

Other liquid human waste in the form of greywater can be simultaneously processed in the above system. Based on the NASA SPP 30262 Space Station ECLSS Architectural Control Document, there will be 26 L / person of liquid waste in addition to the urine, in the form of flush water, hygiene, laundry/dish water, and latent water in the system [118]. This will mean that including urine and greywater, the liquid waste processing system will be processing on average 110 L d^{-1} of liquid waste from the MIH. The entire estimated volume of the liquid waste processing system is approximately 1.5 m^3, and is expected to be stowed beneath the floor in the MIH as it also contains the human waste collection system for the mission. The crew maintenance required for the system is expected to be minimal, primarily comprising of routine checks on the influent/effluent tanks and sensors.

In terms of power consumption, the CYBELE MABR will use approximately 1 W continuously, given that the industry standard is 0.267 kW/m^3 for MABRs [119]. Based on verification with Lunar Palace – 1, a closed environment human habitation experiment in China that employed membrane bioreactors and a low pressure distillation system, the power consumption of the human liquid waste management system is expected to be less than 500 W, with the majority of the demand coming from the low pressure distillation system [120]. Further calculations will be required to determine the power consumption of the ammonia regeneration system.

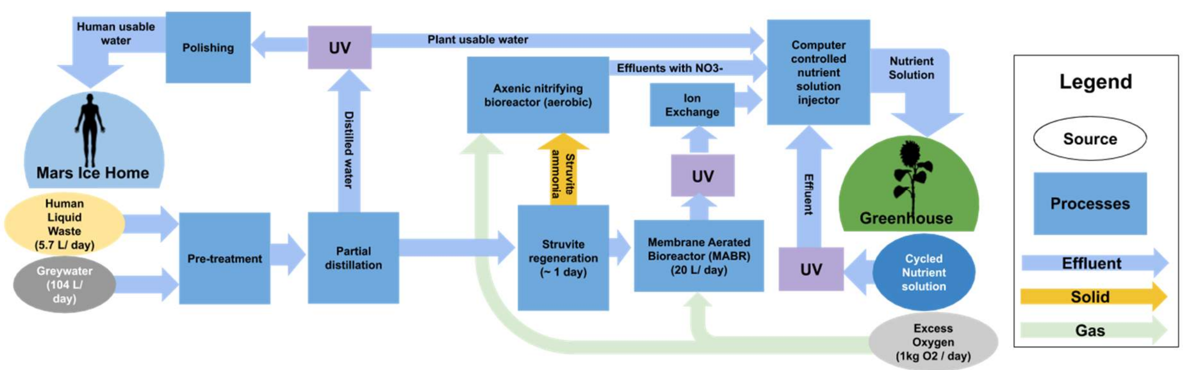

Figure 17: Urine waste processing system diagram.

3.11.2. Human Solid Waste

CYBELE also recovers nutrients from human feces. Given the high-calorie and high fiber diet used in this system, the rate of production of feces is assumed to be 0.375 kg d^{-1} wet mass, with a crew of four producing 1.5 kg d^{-1} [108]. Human solid waste will be processed alongside the inedible biomass from the greenhouse in an anaerobic mixed fermentation chamber. The main purpose of the fermentation process is to break down soluble organics, commonly measured through total organic carbon (TOC). Based on experiments conducted at KSC, a retention time of 3 days will be suitable to reach a TOC level plateau of 50 ppm [121].

As for the volume of the mixed fermentation tank, it is assumed that CYBELE produces approximately 1.2 kg of inedible biomass a day (dry mass) with the crew producing 0.174 kg of human solid waste (dry mass). Given the dilute nature of the fermentation reactor, it is estimated that the fermentation chamber will need to be at least 0.17 m^3 to hold the three-day batch. After the fermentation process, human feces will be processed in the same manner as inedible biomass, which is described in Section 3.11.3.

3.11.3. Inedible Crop Biomass

Utilizing crop harvest indices, expected edible yield, and crop cycling, it is anticipated that CYBELE's crop growth system will produce 3.7 metric tons of inedible vegetative biomass over the course of a 600-day mission. Left unmanaged, valuable nutrients and cellulose compounds would be lost to the system. This would make it necessary to bring all the biological inputs, primarily fertilizer and plant media, along with each mission. To reduce the amount of inputs the crew will need to bring, the priorities of CYBELE's inedible biomass waste management system revolve around the recovery of plant nutrients and plant growth media, in addition to reducing the volume and the mass of the waste produced.

The crop scheduling and waste management system has been designed to mediate the extent of fluctuations in plant biomass produced. Of the 600-day mission, crops will be harvested 239 days throughout, with peak harvest days yielding up to 50 kg of fresh inedible biomass, while others produce less than 5 kg, as shown in Figure 18. These fluctuations average to a rate of 6.22 kg of inedible vegetable biomass per day. To accommodate the inclusion of food waste and human solid waste, a system was designed to process up to 8 kg of fresh mass/ hydrated solid waste per day. Of the vegetable waste being processed, an assumption was made that approximately 80% of the mass would be composed of water.

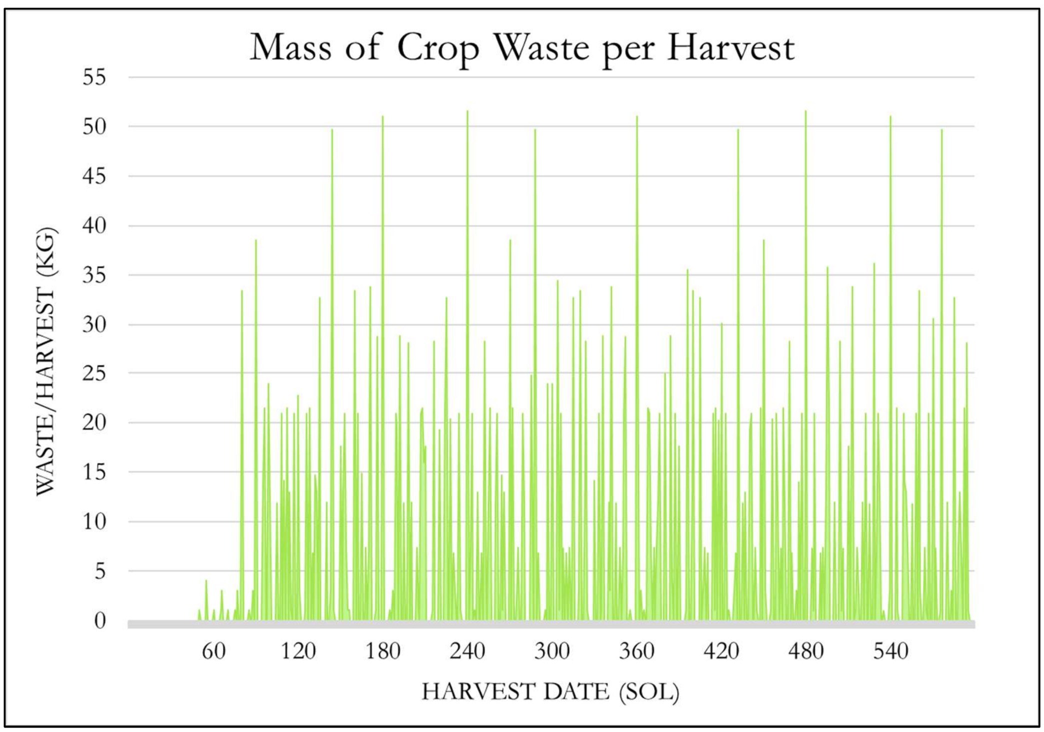

Figure 18: Inedible biomass production per harvest over the 600 sol mission.

Table 12 shows the main parameters which led to the inedible biomass production graphic. The total waste dry mass is 20% of the total waste fresh mass.

Table 12: Crop Waste Management Parameters

Crops	Time between Harvest (sols)	Harvest Index (edible/total)	Waste/Harvest (kg)	Waste/Sol (kg/sol)	Total Waste (kg FM)	Total Waste (kg DM)
Potato **[122, 123]**	12	0.77	7.39	0.49	295.73	59.15
Sweet Potato **[122]**	19	0.7	12.96	0.58	349.8	69.9
Wheat **[122, 123]**	20	0.44	21.47	1.18	708.66	141.7
Soybean **[122, 124]**	18	0.35	10.78	0.63	377.42	75.4
Chufa **[125, 123]**	16	0.6	5.12	0.23	138.17	27.6
Sunflower **[124]**	22	0.6	4.24	0.16	97.46	19.4
Strawberry **[126]**	9	0.45	20.89	1.98	1190.67	238.13
Tomato **[68, 123, 127]**	11	0.65	1.87	0.16	93.29	18.6
Pepper **[127]***	10	0.65	5.79	0.51	306.79	61.36
Broccoli Raab **[126]**	11	0.8	1.18	0.10	58.85	11.77
Kale **[126]**	5	0.8	1.06	0.20	117.35	23.4
Total	**--**	**--**	**--**	**6.22**	**3734.23**	**746.85**
*Made the assumption that Pepper HI would be similar to Tomato						

CYBELE features a waste management system integrating mechanical degradation, anaerobic fermentation, acid digestion, and hydrothermal carbonization, as shown in Figure 19.

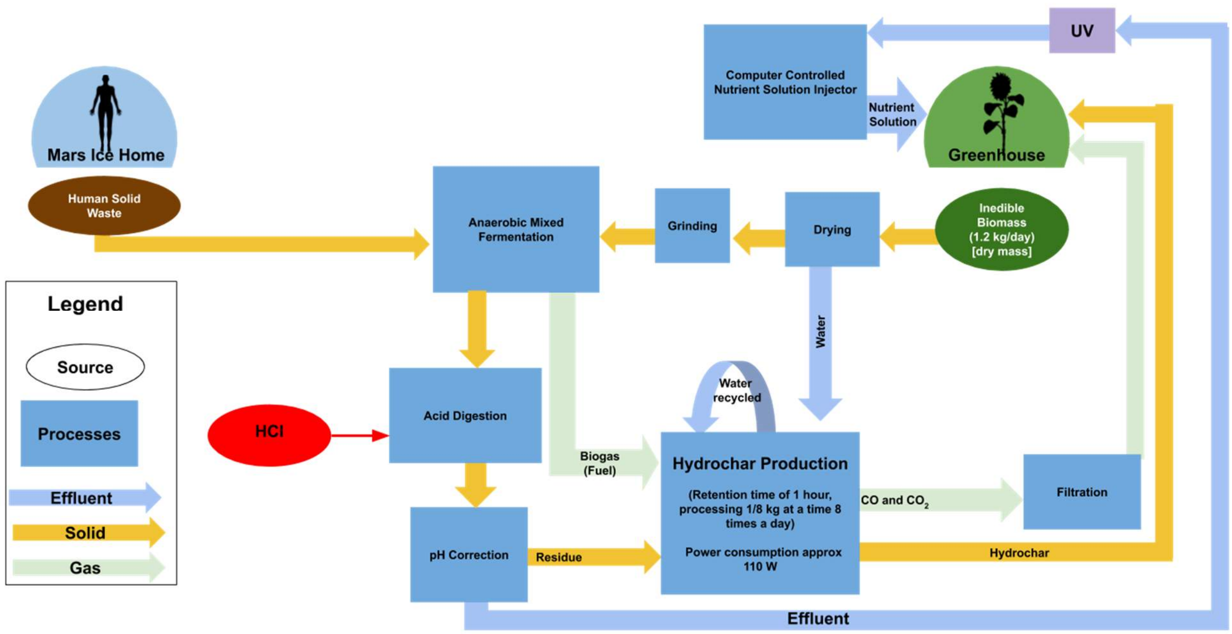

Figure 19: Human solid waste and inedible biomass processing system diagram.

Utilizing a process similar to the one described by Lunn et al., after the biomass is harvested, it is oven dried (losing 80% mass), and then milled to a particle size of ~2mm [121]. This mechanical breakdown facilitates thorough homogenization of the vegetable biomass, prior to integration of human solid waste. Once integrated, the amalgamation of plant dry mass and human solid waste is diluted to 50 g DM/L, creating a waste slurry that is fed to an anaerobic fermentation bioreactor. After 24 hours within the bioreactor, around 75% water soluble organics (measured as Total organic carbon) are broken down and digested [121]. At this point, the TOC levels in the slurry would no longer possess phytotoxic characteristics [128]. As a byproduct to this microbial digestion, methane is produced with potential synthetic biology applications. The high microbial communities contained by human feces work to resupply the bioreactor with a mixed community of heterotrophic anaerobes.

After the bioreactor, the slurry is treated with 0.1 M HCl acid digestion for 10 minutes [121]. While other studies have utilized water as a leaching tool, Lunn et al. found that acid was effective at leaching higher levels of nutrients with higher time efficiency than the values achieved through strict water leaching treatments [129, 121]. Utilizing both the numbers that Lunn achieved, along with values achieved through other experimentation done by Bugbee in 2003 and Garland in 1993, assumptions were made concerning the levels of nutrients that could be retrieved via the acid digestion as shown in Table 13 [130, 129, 121].

At this point in processing and the nutrients are leached from the slurry, around 60% of the original dry mass would remain (~440 kg), primarily composed of recalcitrant structural molecules such as cellulose, hemicellulose, and lignin [131]. While there are other potential synthetic biology options to be explored, at this point in time CYBELE will primarily use residual biomass as plant growth media. The direct use of the plant residue from the anaerobic fermentation and acid leaching process has been avoided due to lack of literature on its application in hydroponics Instead, the remaining biomass is funneled into a hydrochar production system.

Table 13: Elementary Recovery from Inedible Biomass

Nutrient	Average Dry Mass [132] (g/kg Plant DM)	Fraction Recovered	Recovered from Dry Mass (kg / kg DM over mission)
N	10.0 - 45.0	0.7 [130]	11.745
P	1.0 - 8.0	0.88 [121]	5.041
K	5.0 - 60.0	0.98 [121]	14.013
Ca	2.0 - 35.0	0.97 [121]	9.801
Mg	1.0 - 8.0	0.98 [121]	6.244
S	0.5 - 10.0	0.80 [121]	4.687
Mn	0.015 - 0.8	0.97 [121]	0.078
B	0.005 - 0.075	0.60 [130]	0.007
Zn	0.015 - 0.1	0.81 [121]	0.017
Cu	0.004 - 0.030	0.85 [121]	0.005
Mo	0.0001 - 0.005	0.50 [129]	0.0002
Fe	0.1	0.50 [121]	0.027

To create hydrochar, raw biomass is subjected to hydrothermal carbonization (HTC) - a thermochemical conversion process that involves high temperatures and pressures in a deoxygenated environment [133]. The bulk of the hydrochar produced would be utilized as seedling and hydroponic growth media, and if excess is produced, there could be potential application for use in air or water filtration [65, 134, 135].

To produce hydrochar, the residue would be first be fed into a mixer and water would be added until the slurry reached a dry biomass to water ratio of 0.19 [133]. Next, the slurry would be preheated before being pumped into the hydrothermal carbonization reactor. Within the reactor, the mixture would be subjected to 220°C and 10 bar of pressure within an airtight container for 1 hour, wherein the biomass undergoes dehydration, decarboxylation, and decarbonylation reactions [133]. After depressurization, the biochar solids are separated out and the water is recycled. From there the biochar can be milled to the desired size and then utilized as a plant growth media. To spread out the energy costs of utilizing this process, the reactor will be downsized and the operation broken into eight steps spread throughout the day. One day's worth of fresh inedible biomass, 6.22 kg, could be used to produce 0.6 kg of hydrochar.

3.12. Nutrient Management

To maintain and promote crop growth, it is essential that the plants have access to the necessary fertilizer requirements. Failure to provide each nutrient in the correct proportions could result in decelerated growth, decreased yield, and even death of the plant. While the focus of nutrient management in the hydroponics system would be preventing deficiency, the nutrient levels in the hydroponic solution also must be monitored for surplus and potentially toxic levels of nutrients [130, 136]. Bugbee advised using a stronger solution to initiate growth within the system, and then, according to the plant life cycles, use a more dilute solution to refill the system during the later vegetative and reproductive stages [130]. While it would be ideal to be able to supply the plants with the varied levels of fertilizer as their specific life cycles change, each tank of hydroponic solution supports continuous cycles of growth. To balance out the higher fertilizer input needs of the younger plants with those in later growth stages, a refill of a more concentrated solution (50% Hoagland's) every time a new tray of plants is added to the tank (lining up with the harvest cycles) [70, 136]. The vegetative refills used on non-harvest days are more plant specific – using mass balance calculations of the percent of nutrients contained in the dry mass of each crop. Then, utilizing the percent of nutrients that could be recovered from the inedible biomass, estimates could be made as to how much of the raw element would need to be brought. The final masses of the fertilizer would eventually increase however, as they would be transported as salts. These are shown in Table 14.

Table 14: Fertilizer Requirements after Recovery

Nutrient	Nutrients Required (kg)	% Recovery	Nutrients Recovered (kg)	Fertilizer Required (kg)
N	57.476	0.65	37.359	20.116
P	24.994	0.88	21.995	2.999
K	58.130	0.98	56.967	1.163
Ca	52.997	0.97	51.408	1590
Mg	27.479	0.98	26.929	0.550
S	24.081	0.8	19.265	4.816
Mn	0.482	0.97	0.467	0.014
B	0.062	0.6	0.037	0.025
Zn	0.098	0.81	0.080	0.019
Cu	0.024	0.85	0.020	0.004
Mo	0.003	0.5	0.001	0.001
Fe	0.204	0.5	0.102	0.102

3.13. Post Processing

Some crops, such as kale and strawberry, are ready to eat and require minimal processing. Other crops require some time and equipment to make them into ingredients for the crew's meals. The post processing steps for each crop is shown in Table 15. Post processing steps involving starter cultures and fermentation will likely need to be validated for feasibility and safety on a Mars mission.

Table 15: Post Processing for Each Crop

Crop	Post processing
Potato Sweet Potato Strawberry Tomato Pepper Broccoli Raab Kale	Minimal processing apart from cleaning.
Wheat	After manual removal from stalk, wheat heads are processed with a small thresher to remove wheat berries from the heads. The resulting berries can either be eaten or pounded into flour with a hand mill. Depending on availability of baker's yeast (*Saccharomyces cerevisiae*), the flour could be used to make tortillas or a variety of bread products. Wheat gluten could also be processed into seitan, which can be substituted for meat in various recipes.
Soybean	Young green pods can be eaten as edamame. Mature yellow pods can be separated from the beans with a thresher. Soybean can be processed into soy milk, tofu, tempeh, miso, and soy sauce. Tofu requires a mineral coagulant (in the form of nigari or gypsum), while tempeh, miso and soy sauce will require a starter culture (tempeh requires *Rhizopus oligosporus,* while miso and soy require *Aspergillus oryzae* or *Aspergillus sojae*). While tempeh fermentation would take on the order of several days, miso and soy sauce will take several months of fermentation, making it less likely for application.
Chufa	Tubers are removed from the roots and cleaned. They can be eaten raw or dried and converted to flour using a mill. Tubers can also be pressed into oil. Chufa can be incorporated into drinks (horchata) and used for baking.
Sunflower	Sunflower heads can be harvested by hand and left to dry. The seeds, once separated from the heads, can be milled to dehull them or pressed into oil using an oil press

4. Design Trades

4.1. Operational Life

CYBELE is designed for a 15 Earth-year operational life, including the approximate two to four year autonomous inflation, water filling, and setup prior to astronaut arrival. By utilizing nutrient recycling technologies and *in situ* resources, CYBELE will be capable of feeding the crew with minimal resupply. An initial consumable mass of 501 kg of nutrients salts, acid and seeds is needed for the first crewed mission. For all following missions, this will be the only resupply necessary [121].

4.2. Applicable Martian Latitudes

The MIH ConOps delineates feasible landing latitudes of 30° above and below the equator [5]. CYBELE will be adjoined to the MIH 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 MIH, 101 kPa. The internal temperature will be 20 ± 2°C. This is the temperature best suited for growing the crops and is also only a small variance from the 22.2°C MIH habitat.

4.4. Membrane Structure of the Water Ice Cells

CYBELE will adopt the MIH 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 at least 2 m thick to reduce the radiation exposure by more than 50% when filled [5]. The ice cells get thicker near the top to increase shielding in the direction of highest radiation exposure, and the middle area of the top is a solid block instead of cells. Insulating CO_2 cells will fill the gaps between the ice cells, as shown in Figure 20. 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.

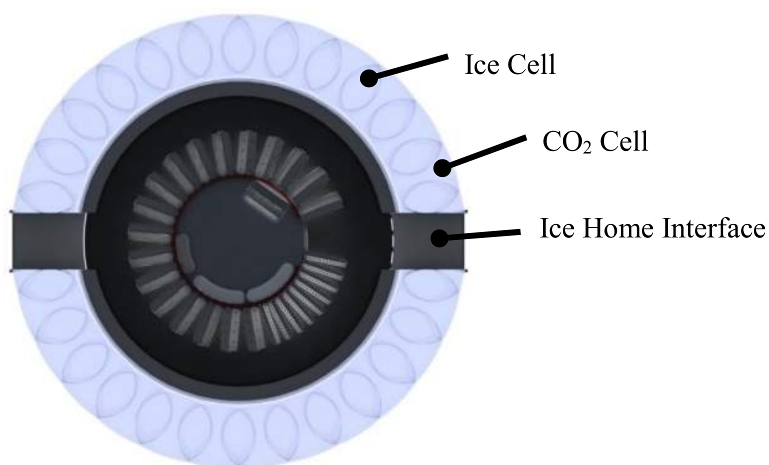

Figure 20: Top view of CYBELE showing membrane structure and overall layout.

4.5. Materials and Fabrication

The greenhouse integrates many of the same materials as the MIH. Multiple materials with various properties will be layered to ensure the structure is able to withstand the environmental conditions of Mars. Because of the high pressure, the materials must also have low creep properties. Nomex, a material with flame resistant, puncture proof, and acoustic absorption properties will be used for the inside scuff layer [137]. The next few layers, the inner bladders, will be created from high density polyethylene which is a sealable, durable and flexible material. Vectran, with a 2840 MPa tensile strength and good resistance to flex cracking and abrasion resistance, will be used for the structure restraint layer [137]. The water, ice, and CO_2 bladders will be clear Tedlar, which has UV resistance, acid resistance, and tolerance to cold temperatures while still being able to transmit light [5]. To protect from the Martian dust storms, a layer of ceramic fabric such as Nextel will be used [137]. The outer-most cover will be beta cloth, a well-known material used extensively in various space missions, known to protect against atomic oxygen damage.

The center cylinder will be aluminum, along with parts of the airlock interface tunnel between the greenhouse and MIH. These pieces are similar to the MIH's concept, so development will be cost-effective. Carbon fiber will be used for top and the bottom structures. It is a strong, durable material that is lighter than aluminum. The trays, lids, and irrigation pipes will be custom-made from HDPE and simple to manufacture. HDPE piping can be used for water and waste transfer. Teflon-lined Kevlar tanks will store acid for pH regulation.

4.6. Sensors

To maintain air quality, sensors around the greenhouse will monitor temperature, humidity, O_2 level, CO_2 level, and VOC level. To maintain an optimal environment for plants, sensors will monitor the temperature, pH, EC, dissolved 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. Additionally, a small hyperspectral camera will be mounted to the two T-slot bars of each individual stack to take pictures of individual tray of plants, which will be analyzed by the AI software. A simple bracket with two attachment sections to the T-slot bars and an angled middle section will hold the camera such that each photo will capture the entire tray. Once a sol, a linear actuator attached to the bracket will move the camera up and down the entire stack to take pictures of every tray. At each tray, a picture with front focus and another picture with back focus will be taken to ensure all of the crops can be seen clearly. Each sensor and camera 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 16.

Table 16: Sensors and Actuators

Category	Purpose	Sensors	Actuators
Thermal	Air temperature	Thermometer	Air handler
Air Quality	Humidity control	Hygrometer	Hydrogels, mister, air exchanger, fans
	Gas composition control	VOC, CO_2 and O_2 sensors	Fans, air exchanger, alarm
Hydroponic Maintenance	Water temperature	Thermometers	Heater coils
	Nutrient control	Nutrient sensors	Valve[1] to dispense, stirrer, computer display
	pH control	pH sensor	Acid dispenser, stirrer, computer display
	EC control	EC sensor	Computer (display/alert)
	Dissolved O_2 control	DO probe[2]	Aerator[3], stirrer
	Volume management	Volume sensor	Pump[4]
	Water sterilization	Timer for UV	UV lights[5], switch
	Nutrient recycling	Nutrient sensors	Computer display, pulper
	Plant health control	Hyperspectral Camera	Linear actuator, broadband flash
	Flowrate management	Flowrate meters[6]	Open/close valve
Structural Support	Membrane pressure	Strain gauge	Computer display/alert
	Membrane temperature	Thermocouple	Computer display/alert
Interface	Interface management	Computer commands	Open/close valve

[1]Nominal Plastic Solenoid Valve - 12V - 1/2" **[138]**

[2]Grove-Gas Sensor **[139]**

[3]EcoPlus® Eco Air Pumps **[140]**

[4]Dayton 120/240VAC Open Dripproof Centrifugal Pump **[72]**

[5]Lifegard® Aquatics Aquastep Pro UV Sterilizer **[141]**

[6]OMEGA™ FTB600B Series **[142]**

5. Day in the Life

Including cooking, which is estimated to take 2 hours per sol, the crew will spend an average 3.9 hours working on tasks associated with the greenhouse. There will be variabilities based on whether the crew is harvesting on that particular sol—these numbers are estimates based on the 600-sol mission period. There will also be flexibility to rearrange tasks and differ them to a later time, should one task take up more time than expected.

Astronauts will require a minimum of 2.5 hours of exercise per sol every 6 out of 7 sols [143]. While this number might be reduced for planetary missions, astronauts can use the greenhouse as an exercise track for dynamic warm-ups, walks and short jogs while breathing fresh oxygen. The central cylinder is both a storage and working space as well as a space for social activity and leisure. Table 17 shows the crew tasks associated with the crop lifecycle, structure, and waste management system.

Table 17: Crew Tasks within CYBELE

Task categories	Task	Crew Time / Sol (min)
Crop Lifecycle: Frequent	Seeding [144]	1
	Maintenance (pruning, visual checks)	15
	Harvesting	30
	Post-Processing [145]	6
	Cooking	120
Crop Lifecycle: Infrequent	Pollination	3
	Disease response	10
	Maintaining *Muscodor*	3
Structure	Tray cleaning after harvest	16.5
	Check sensors, nutrient levels	10
	Incidental repairs, cleaning, maintenance	30
Waste Management	Check sensors	5
	Incidental repairs, cleaning, maintenance	1
Total of Frequent Tasks		234.5

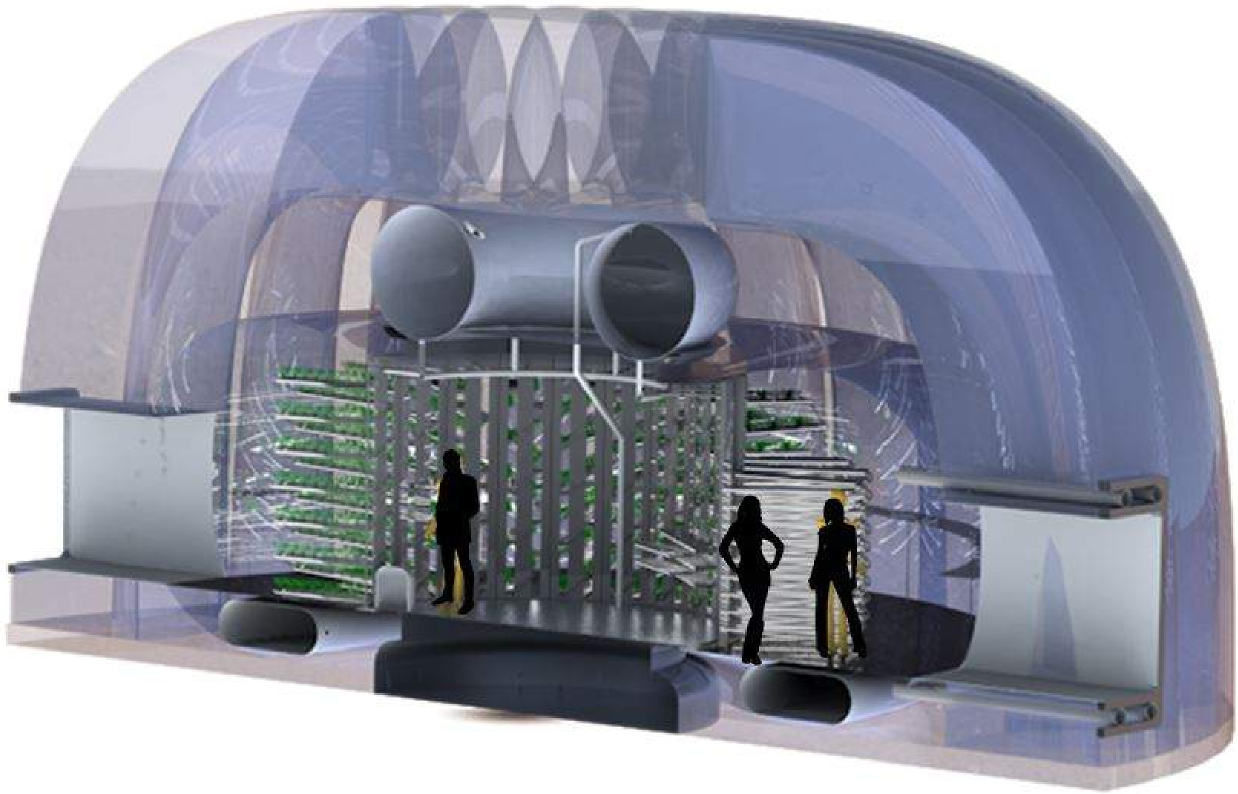

Figure 21: Two crew members maintaining the plants in CYBELE.

Figure 21 shows two crew members maintaining the plants inside the greenhouse in a cross section view. Two portable access carts will allow the crew members to easily reach the highest trays in the stacks for harvesting and maintenance. These can be housed inside the central work area and into the outer wall 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.

There are several power consumers throughout the day, some continuous and some on a schedule. More on these actions can be found in Section 6.1.

6. Mission Resources

6.1. Energy Schedule

A power demand schedule, shown in Figure 22, shows that the peak power demand of the greenhouse is approximately 17.3 kW if it were to launch with technology that will be available by 2030 while maintaining the 30% resource margin [98]. This total power was broken down into the lighting and non-lighting components to show that the lighting is by far the biggest consumer. If the efficacy of LEDs is better than anticipated in the future, the total power demand would decrease by a large factor.

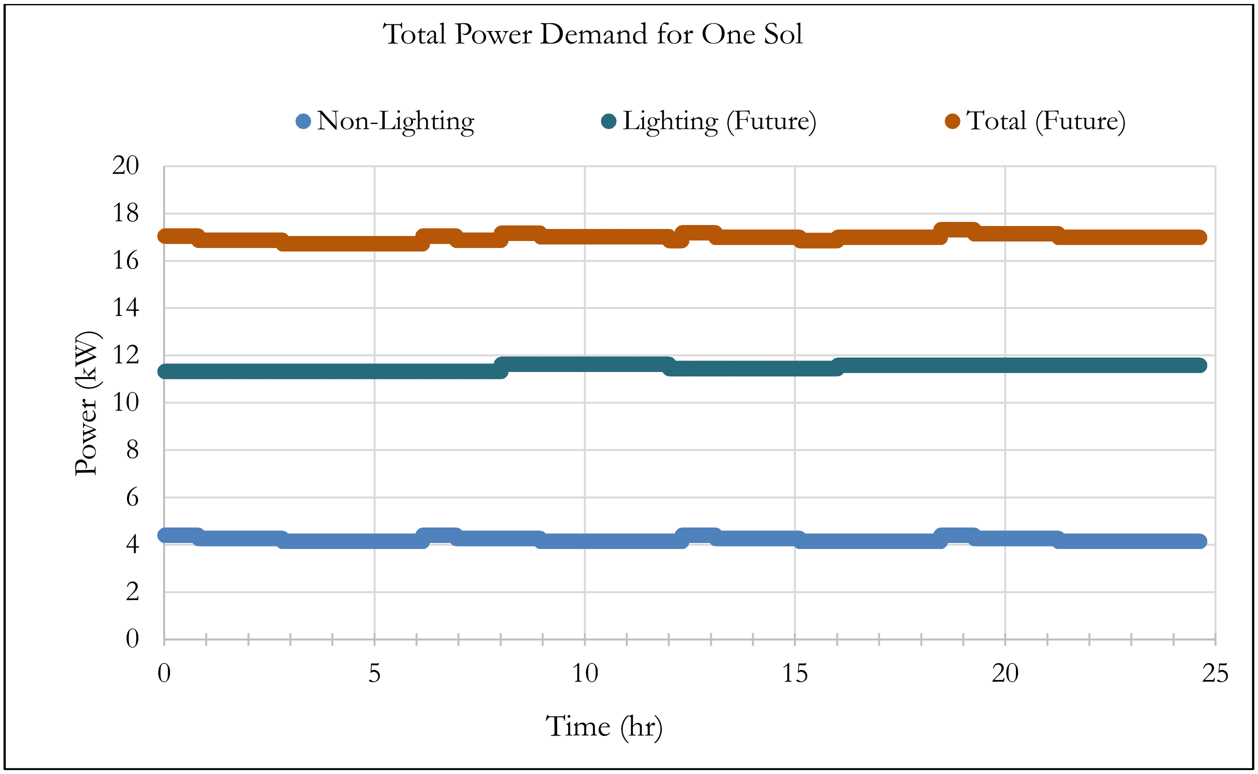

Figure 22: Total hourly power consumption of CYBELE with projected LED efficacy and 30% margin.

The non-lighting power demand can further be broken down to give an exact schedule of actuators. Figure 23 shows the power demand and length of time for each operation. The values in the graph represent the sum of the power required for pumping, the biological subsystems, humidity control, and the other sensors and actuators listed in Table 16, Section 4.6.

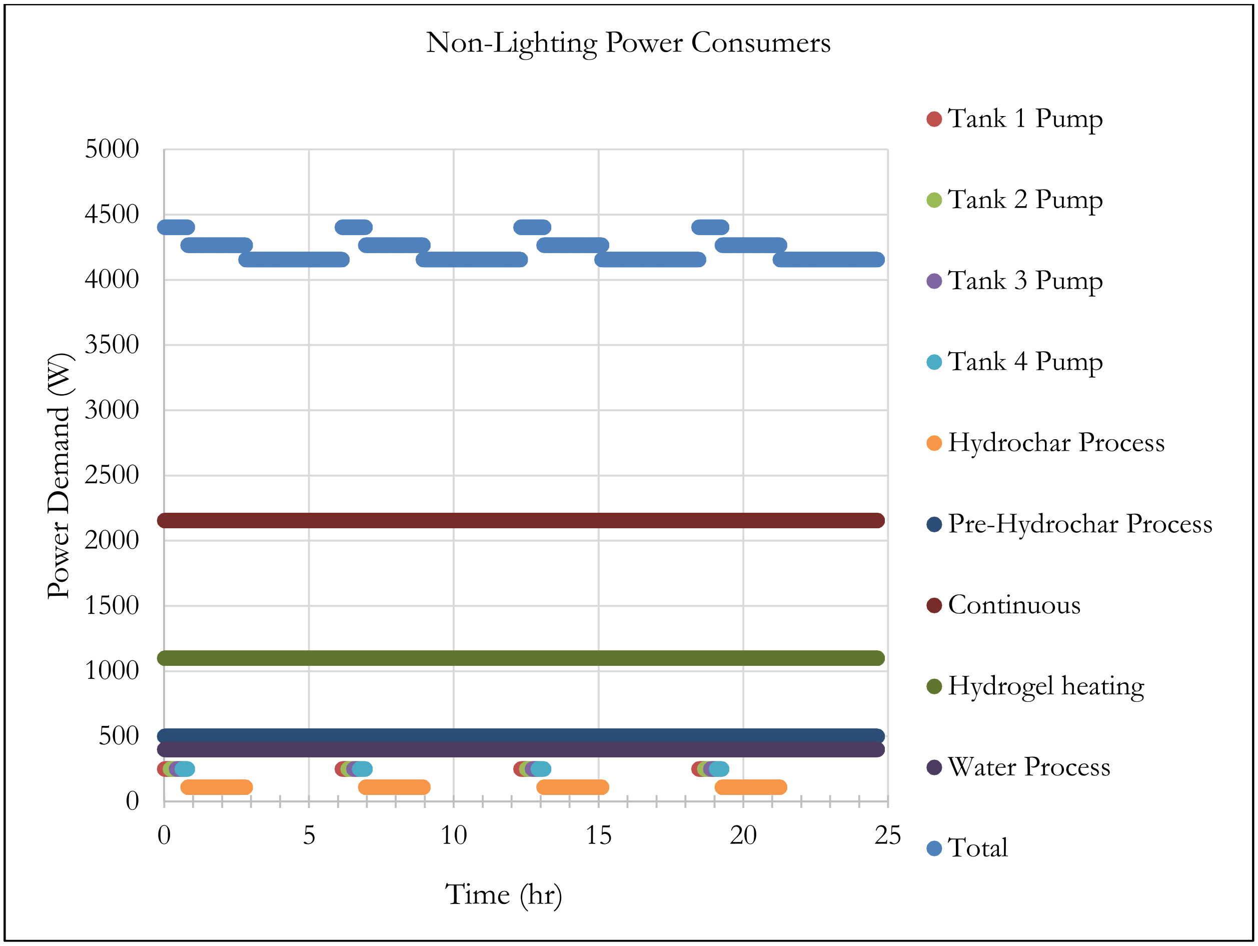

Figure 23: Non-lighting power consumption of CYBELE for one sol.

6.2. Mass Estimate

The total mass of the greenhouse with all consumables is 10,465 kg. This is broken down into the mass of the structural elements, at 9963 kg and the mass of consumables, contributing 501 kg [121]. A full list of the components and their masses is available in Table 18.

Table 18: Mass Estimates for the Components of CYBELE

Structural Elements	Estimated Mass (kg)	Consumables	Estimated Mass (kg)
CAD Model*	7818.46	Acid for pH	273.00
Stacks	1411.42	Nutrients	122.73
Actuators Total	692.55	Acid for Recycling	70.72
Cups	25.50	Seeds	25.00
Sensors Total	15.63	Growth Media	9.50
Total Mass: 10464.51 kg			
*Includes cylinder, pipes, flooring, interface rings, membranes, tables, acid tanks, nutrient tanks			

6.3. Economic Analysis

The following first-order economic analysis compared the mass required for CYBELE with the mass required to bring prepackaged food. If fresh food is not grown, it is assumed that each crew member would need 1.8 kg/sol for a 600 sol missions [146]. To minimize risk, each greenhouse mission will still have enough calorie-dense rations to stay above starvation limit. This assumes 0.325 kg of prepackaged food per sol, totaling to 780 kg over a 600 sol mission for the crew [147]. The full mass of the CYBELE payload is

10,465 kg, which will need to be launched with the SLS Block 2, which has a $500,000,000 launch cost for 45,000 kg [148].Therefore, given the large excess of mass, the greenhouse could be sent with other large payloads. For following missions, the consumable mass required for each mission cycle is approximately 491 kg, along with 1500 kg for ramp-up period and surplus food, and this can be launched with the Falcon 9 at $50,000,000 for 4020 kg [149]. There would be an excess of 2150 kg, which could be used for other supplies. The prepackaged food is 4320 kg for every mission, which would be launched with the Delta IV Heavy at $350,000,000 for 8000 kg. This would have a larger excess of mass, 3680 kg could be used for other equipment. Although CYBELE has a larger initial mass, the long-term cost analysis shows economic benefits to having a Martian greenhouse.

After two missions, a mission architecture that includes CYBELE would be more cost effective than prepackaged food according to launch costs. However, this graph does not reflect the extra equipment which could be sent with either option. The prepackaged food launch vehicle would be capable of carrying a much larger payload than just the food itself. Figure 24 shows the total mass and cost of each scenario over a 15-year operation period.

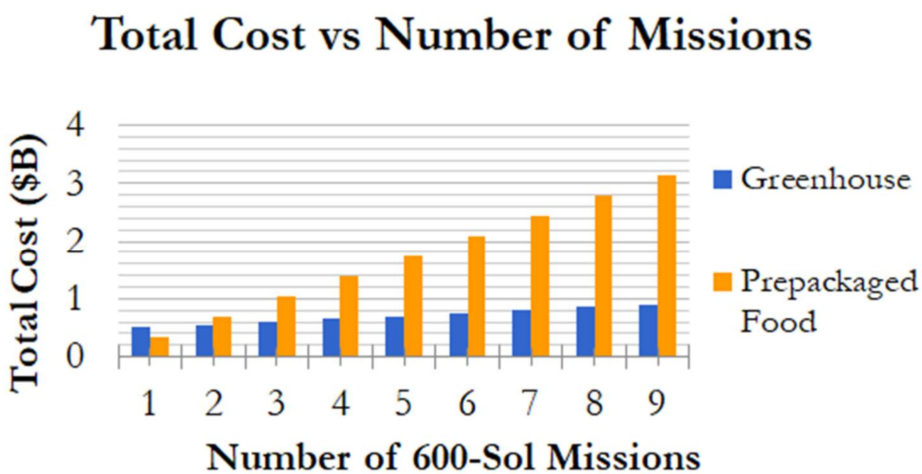

Figure 24: Economic comparison of three scenarios: send prepackaged food with the astronauts; send CYBELE and run missions continuously; send CYBELE and run missions non-continuously.

The lessons learned in growing crops on Mars will have a far reaching impact on the ability of humans to expand and explore locations throughout the solar system. This benefit, though difficult to quantify at this time, will prove invaluable for future missions.

6.4. Psychology Benefits

In addition to providing necessary nutrients, the greenhouse will provide psychological benefits as well to the crew. The brighter colors of plants add visual enhancements to the normally white and beige environments of space craft and habitats [150]. Seeing, smelling and tasting fresh fruits and vegetables provide a link to planet Earth and home for the astronauts. This connection is crucial during long duration missions where isolation can take a toll on the mental health of crew members. 85% of crew members who have lived in Neumayer Station, Antarctica over the winter have indicated that fresh crops would improve their overall well-being [151]. Flowers have also been shown to increase positive moods and elicit Duchenne (true) smiles from both men and women [152]. Multiple plants in CYBELE will flower and contribute to increasing the mood of the crew.

Allowing astronauts to cook and create various dishes with fresh food in the included kitchen area is another beneficial component of the greenhouse. Astronauts have always cared about the food they have been provided in previous space missions and have always provided input in the food selections [153]**.** Dr. Fred Davis, AgriLife Research Faculty Fellow at the Texas A&M University, has mentioned that biting into food with a skin membrane and eating non-dry foods can also provide innumerous psychological effects [154]**.** Along with being able to cook and create dishes, the kitchen is a place to interact and socialize with other crew members through communal meals [155].

Cosmonauts and astronauts have also been known to enjoy taking care of plants. Valentin Lebedev, a cosmonaut on Salyut 6 has said "It is amazingly pleasant onboard to look after plants and to look after plants and to observe them… they are simply essential to men in space" [155]**.**

7. Risk and Mitigation

To account for the possibility of full system failure, it is recommended that the first mission is supplied with enough prepackaged food to last the duration of the mission. For all following missions, the crew should take enough prepackaged food to stay above starvation level. If the entire system fails, the crew can subsist on a lower calorie diet for the rest of the mission. If the preceding crew built up a large amount of food storage, then less prepackaged food needs to be brought in the future. Regular inspections will be required throughout the mission, as shown in Figure 25.

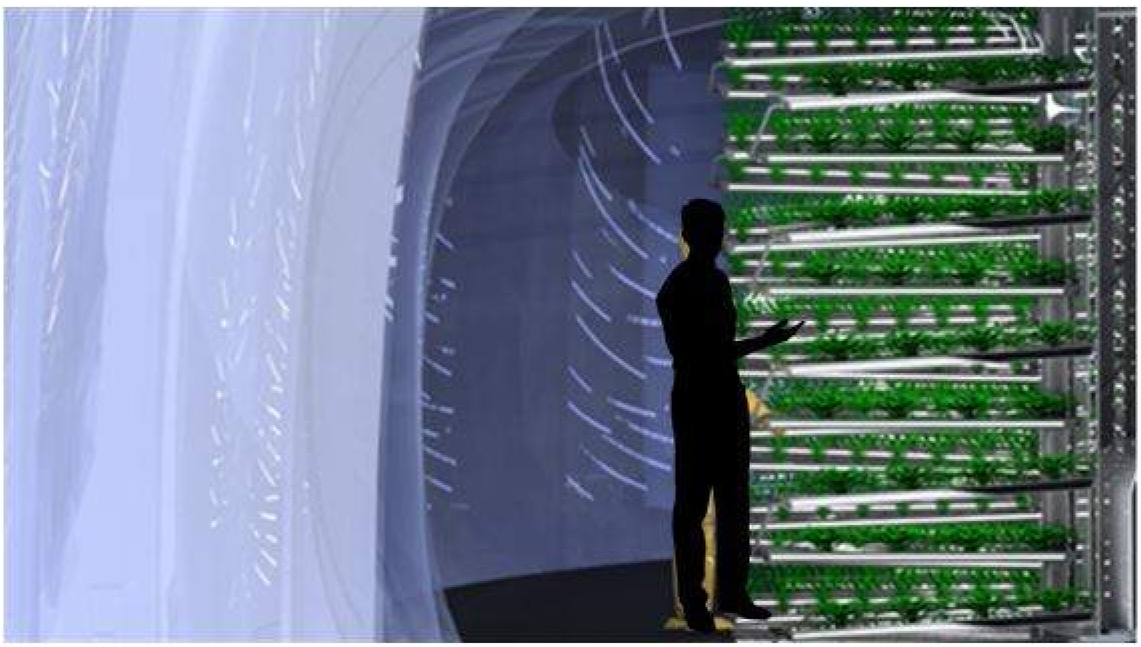

Figure 25: A crew member preforming a scheduled inspection of the system components.

Table 19 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. Figure 26 is a risk matrix which contains all of the risks before the control methods. The risk matrix in Figure 27 contains all of the risks after taking into account all the mitigation strategies, and because of these strategies, the consequences and likelihood of each of the risks are lower than when they started initially. The risk matrices were created using the Development of Risk Assessment Matrix for NASA Engineering and Safety Center paper as reference for the format, likelihood and consequence numbers [156].

Table 19: Failure Modes and Controls

Subsystem	Failure Mode	Cause	Control Method
Fluid Network	1. Power loss	Power failure; short-circuit in network; valve failure	Redundant network logic; manual option
	2. Broken pumps	Mech. failure; damage; clog	Spares; design for 3D printing; manual pumps
	3. Residue builds	Saturated/stagnant solution	High pressure flushing; frequent inspection
	4. Floods	Pump/sensor failure; leakage	Waterproofing; surplus space in both reservoirs
	5. Clogs	Decomposed matter in solution; pump failure	Access to pipes and valves; plungers; high pressure flushing
Membrane	6. Depressurized	Puncture/abrasion, damaged inflation component (back flow)	Triplicated sensors (each cell); cell layout prevents severe failure; pressure door to MIH
	7. Incomplete inflation	Stays folded; inflation line failed	Careful design; testing
	8. Misshapen	Fatigue; stress	Testing
Interface	9. Complete disconnection	Mech. failure of attachment ring	Test max strain on ring; auto shutoff if disconnected
	10. Sever connection line	Failure of connector, piping or ducting; strain on harness	Strain relief in harnesses; proper size of tubing, wires, ducts; secure connectors; auto shutoff
Thermal System	11. Power loss	Power failed, failure in heat exchangers	Design to retain heat, require minimum heating
Plant Life	12. Wilt or discoloration	Environmental issues stress the plants	Visual inspections; hyperspectral cameras; modify environmental conditions
	13. Fruit/ flower drop	Internal or environmental stress, poor pollination	Increase ventilation; check sensors and modify environmental conditions
	14. Bolting	High ethylene levels, crowding	Increase ventilation; reduce plant density
	15. Root rot	Decomposed matter; slow flow/flood; algae	Flush and scrub trays; reduce plant density; hyperspectral cameras; prune roots
	16. Nutrient deficiencies	Fe: pH high; Mg: high K; Ca: high humidity; nutrient/pH fluctuate	Hyperspectral cameras for early detection; monitor pH along fluid path; check nutrient levels; modify environmental conditions; buffer solutions
	17. Disease	Pathogen; susceptible plants; spread across stacks	Disease resistant cultivars; remove tissue; isolate; positive biological agents; seed/media sanitize; UV sterilization; hyperspectral cameras
	18. Decreased germination	Seed storage technology fails	Extra seeds in separate storage technology; test on Earth; adjust germination; protect from radiation
	19. Radiation	GCRs; Solar Particle Events	New seeds every cycle; measure radiation levels
All Systems	20. Sensor failure	Cable/connectors break; un-calibrated	Spare sensors; recalibrate frequently; visual inspections; alert crew
	21. Cold store failure	Loss of power; broken piping	Secondary storage in Martian environment; other preservatives; dissimilar cooling technologies
	22. Gas imbalance	Climate systems fail	Design to be self-sufficient
Post Process	23. Mill/thresher fail	Clog; damaged parts	Design to be 3D printed; spares; manually remove organic matter
Waste System	24. Overflow	Too much waste; clog	Access to pipes/valves; plungers; waste stored in MIH waste collection system
AI system	25. AI system fail	Power failed; short-circuit; software bug	Visual inspections; pictures sent to Earth for review by plan experts
	26. Camera break	Damaged part	Spares; visual inspections
Lighting	27. Broken LEDs	Burn out; ballasts break	LEDs in parallel; spares; triple LEDs for each tray

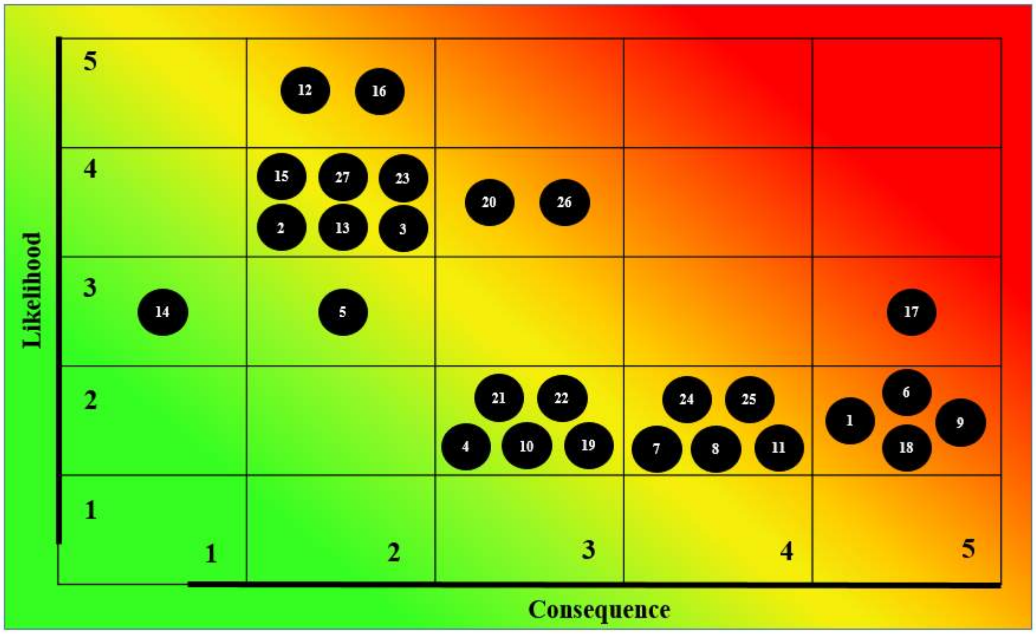

Figure 26: Risk matrix showing risks without control or mitigation strategies. Specific risks in Table 19.

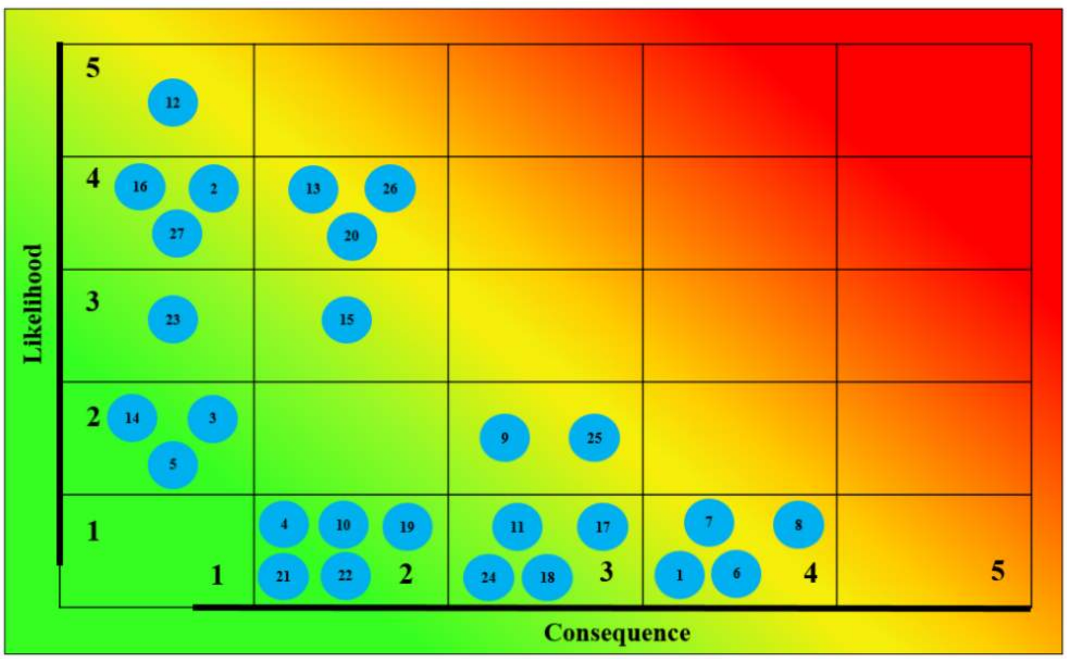

Figure 27: Risk matrix showing risks with control and mitigation strategies. Specific risks in Table 19.

8. Future Work

8.1. Verification

To progressively increase the TRL of the systems within the greenhouse and verify the greenhouse itself, many verification tests will be conducted leading up to the MIH mission launch. These tests will reduce the risks of each system and assess the effectiveness of the mitigation strategies.

First, the yield of the selected crops using the selected NFT system will be tested in EDEN ISS or a similar Antarctic greenhouse analog. This test will show if the observed yield is similar to the models. It will also document the frequency of “fluid network” and “plant life” failure modes, which will allow us to calculate the crew time needed for maintenance, plant monitoring and upkeep. These crop growth tests should have a similar timespan to the MIH missions and should be repeated until the "mean time between failures" of each part in the crop growth system is found with statistically significant confidence.

Second, the associated diet of the crops should be empirically investigated by a closely monitored crew in Johnson Space Center's Human Exploration Research Analog (HERA), Hawai'i Space Exploration Analog and Simulation (HI-SEAS), or a similar Martian analog. This test will collect "hard" data such as adequate astronaut nutrient consumption, as well as "soft" data such as the astronauts' thoughts on food palatability, variety and any missing flavors. The emotional response of the astronauts to these same foods over a long period of time should be recorded. These analog environments will be testbeds for determining how to initially outfit the greenhouse. With a full scale greenhouse demonstration system, the simulated crop startup and production modes will improve the design to optimize efficiency.

Third, more tests are needed to find the level of light and radiation which will penetrate through ice at various thicknesses in low pressure. This is both to see how thick the ice shielding should be, as well as how much beneficial UV gets to the astronauts. This will also help determine whether the astronauts will receive sufficient levels to make the Vitamin D.

Finally, structural tests will need to be continued to verify that the structural integrity of the MIH will remain adequate throughout the extreme Martian temperature swings. These tests range from small scale testing of individual ice cells to complete system testing of a full-scale, fully functional MIH prototype. Most of these tests can be done at NASA Langley Research Center to keep testing in a centralized location. However, the MIH can also be tested at the McMurdo Station in Antarctica similar to the inflatable habitat tested by ILC Dover, NASA, and the NSF that started in January 2008 [157]. This testing will be especially beneficial in verifying deployment in very cold temperatures which includes the filling of the water ice cells over an extended period. Specifics for each test are documented in Table 20.

Table 20: Verification Testing

Test	Description	Location	Success Criteria
Crop Yield	Find g/m^2 yield of each crop, compare to theoretical	EDEN ISS	Know g/m^2 range for each crop, adjust growth area
NFT system	Document mean time between failures of parts. Find methods to reduce risk	EDEN ISS	Know amount of spares and average maintenance time, develop techniques to reduce maintenance time
Nutrient Uptake	Documenting food consumption and nutrient deficiencies	HERA or HI-SEAS	Know nutrient gaps in diet and adjust required diet, if necessary
Diet Palatability	Document reactions and thoughts on the same diet over long periods	HERA or HI-SEAS	Confirmation that astronauts find the diet satisfactory
Radiation	Document the effectiveness of water ice as radiation protection at different thicknesses and times	TBD	Continued improvement of radiation models, risks, and shielding strategies
Structural Analysis (with a 4.0 prototype test factor)			
Creep	Document dimensional changes in MIH over lifetime	NASA LaRC	Keep dimensional changes within specifications with 4.0 FOS
Fatigue	Document formation of cracks	NASA LaRC	Avoid crack initiation with 4.0 FOS
Impact	Document impact strength of material	NASA LaRC	Keep impact strength within specifications with 4.0 FOS
Shear	Document shear strength of materials in structure	NASA LaRC	Ensure materials can withstand the max shear stress with 4.0 FOS
Thermal Shock	Document crack initiation and dimensional changes during temperature swings	NASA LaRC	Avoid crack initiation and keep dimensional changes within specifications with a 4.0 FOS
Wear	Document material losses between ice cells when subject to Martian conditions	NASA LaRC	Keep material losses within specifications with a 4.0 FOS

Based on the provided economic analysis, continuous missions are recommended, which would minimize the need for the ramping periods of plant growing. Additionally, increasing the number of missions would further the cost offset from sending pre-packaged food. Like the MIH, CYBELE will benefit from larger power and water extraction systems [5]. Given the energy findings, increased LED efficiencies with respect to plant use will further optimize the power usage of CYBELE. A more detailed analysis to optimize LED intensity along the trays would also be of benefit.

The crops selected for CYBELE could be incorporated into the existing breeding program of NASA and other space agencies to maximize their edible biomass density through genetic modification and/or selective breeding. This could potentially decrease the system requirements by a significant margin. Beyond yield and general environmental resilience, traits such as dwarfism, compact size, and day neutrality would be valuable across all of the crops that were selected [27, 158, 159].

It is also possible that gene editing technology could be utilized to increase the phytoremediation capabilities of the crops – to increase their ability to filter the air and water within the greenhouse [160]. If significantly developed, the crops could potentially have a more direct role in grey/waste water management [160]. It could also be eventually possible to produce transient expression of pharmaceutical products in plant tissue that would simply need to be eaten to deliver the dosage [161, 162].

8.2. Alternatives

In addition to the technology that will already be integrated into the CYBELE, there are additional innovative designs and technologies for an alternate Martian greenhouse from the 2019 BIG Idea Challenge finalists. Though most of these options currently have low TRL or other disadvantages, with future technology these options could become achievable improvements.

Other inflatable greenhouse geometries such as a cylinder would maximize volume and surface area. A helical track system for hydroponics would be another method to optimize space vertically. Refer to the Biosphere Engineered Architecture for Viable Extraterrestrial Residence (BEAVER) paper for further details [32].

Mobile plant racks would be another style for a hydroponics system. The racks would fit concentrically around edge of the inflatable structure and can be maneuvered on a circular track. The racks would automatically detach and reattach to the water valves that connect to the greenhouse water supply. Each of the racks can also be closed off to other racks. To read more about the racks, look into the GAIA - Greenhouse Attachment for the MIH Architecture paper [163].

The current system will send vitamin B12 supplements, however, there is potential for the vitamin to be produced via synthetic biology. There are multiple organisms that naturally produce the molecule through either aerobic or anaerobic fermentation, including *Pseudomonas denitrificans* and *Propionbacterium shermanii* [164]. It is also possible that the genes necessary to produce B12 could be inserted into an organism that researchers are more familiar with, such as *Escherichia coli* [164]. This would be an effective means to produce the necessary quantities as needed, utilizing relatively simple organic molecules as inputs, qualities that have great potential in long duration space travel [164, 165]. Another possibility would be to use the Black Soldier Fly (*Hermetia illucens)* for both its value as a dietary component (providing a source of B12, and dietary protein and fats) and its extraordinary ability to convert inedible waste into edible biomass. The insect has a 44 day lifespan, has "self-harvesting" capabilities, and would require minimal crew interaction. Larvae would be collected autonomously before entering the pupae stage, and could be ground into flour and utilized as a component of the astronaut diet. Beyond this, they would be a source of scientific study to see multiple lifespans in an organism over the course of a mission. To read more about the black soldier flies, look into the GAIA - Greenhouse Attachment for the MIH Architecture paper [163].

Himawari, a fiber optic system that collects and funnels sunlight into the greenhouse, could be a possible addition to LED lighting to reduce power usage. Integrated Multi-Trophic Aquaponics (IMTA) would be another possibility for growing various species of plants, fish, and mussels in one ecological system. Spirulina, a genus of algae, could be grown in photobioreactors in the greenhouse to provide a nutritional supplement. For further information, refer to the SIRONA - Sustainable Integration of Regenerative Outer-space Nature & Agriculture paper [34].

A soil-based greenhouse is another possibility for crop growth on Mars, which may be less prone to failure than an aquaponics or hydroponics system. To remove all biological and chemical contaminants including perchlorates, the electron beam scanner and a wash would be used on collected Martian regolith. The plants will be grown individually in modular grow bags on decontaminated regolith. Refer to Martian Agricultural and Plant Sciences (MAPS) paper for a detailed explanation on the process [31].

In addition to implementing an AI system, automated farming with robots is another future technology that is being developed. Iron Ox is currently a company that has developed an automated hydroponics system that uses two custom robots [166]. One of the robots known as Angus can lift hydroponics trays and move them to any location in the greenhouse [166]. The other robot is an arm with stereo cameras on the wrists which can lift plants located in pods and identify disease with the AI system connected to the robot [167, 168]. The stereo cameras can simulate human binocular vision. CYBELE is designed to work with the robots' capabilities. The trays and cups in CYBELE will be customized for robots to lift easily.

Bioregenerative life support systems are continuously developing, with new possibilities yet to be discovered. By combining these innovative technologies and methods with efficient resource and space use, CYBELE is an effective addition to the MIH mission architecture. CYBELE will provide food, to support the first humans who will venture forth from this planet to Mars, the next giant leap for humankind.

9. Subscale Model Prototype

A prototype of the full model was 3D printed, shown in Figure 28.

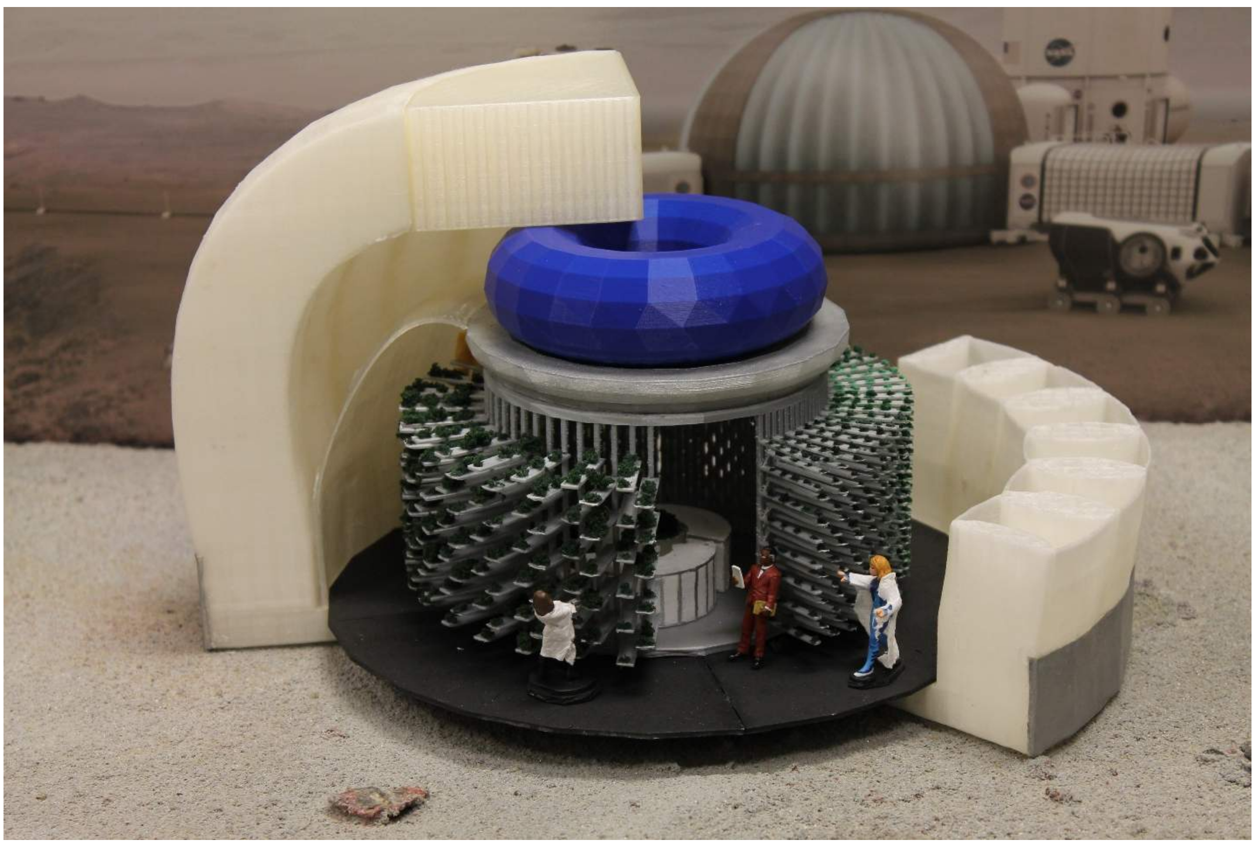

Figure 28: Subscale prototype of CYBELE.

To demonstrate the membranes, two pieces were created to show different section views. These are shown in Figure 29.

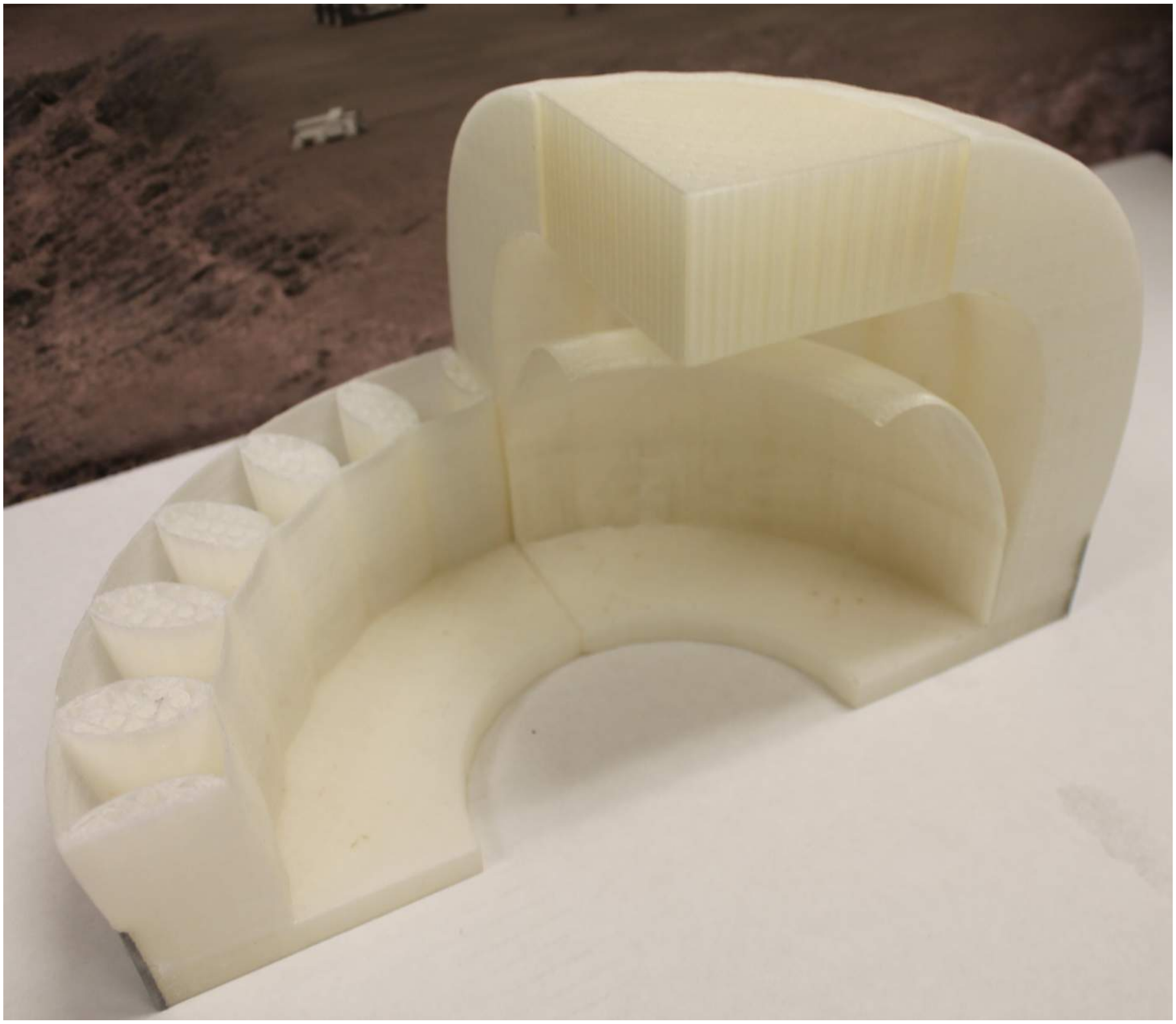

Figure 29: Membrane cross-sections.

10. Acknowledgments

We would like to thank many people for the incredible help and advice they have given us over the course of developing CYBELE, shown in Figure 30. The BIG Idea Challenge judges, Molly Anderson, Dan Barta, Christina Ciardullo, Kevin Kempton, Bob Moses, Ray Wheeler, and Melodie Yashar, as well as program staff Shelley Spears, Stacy Dees, and Victoria O'Leary gave helpful feedback and made the challenge possible.

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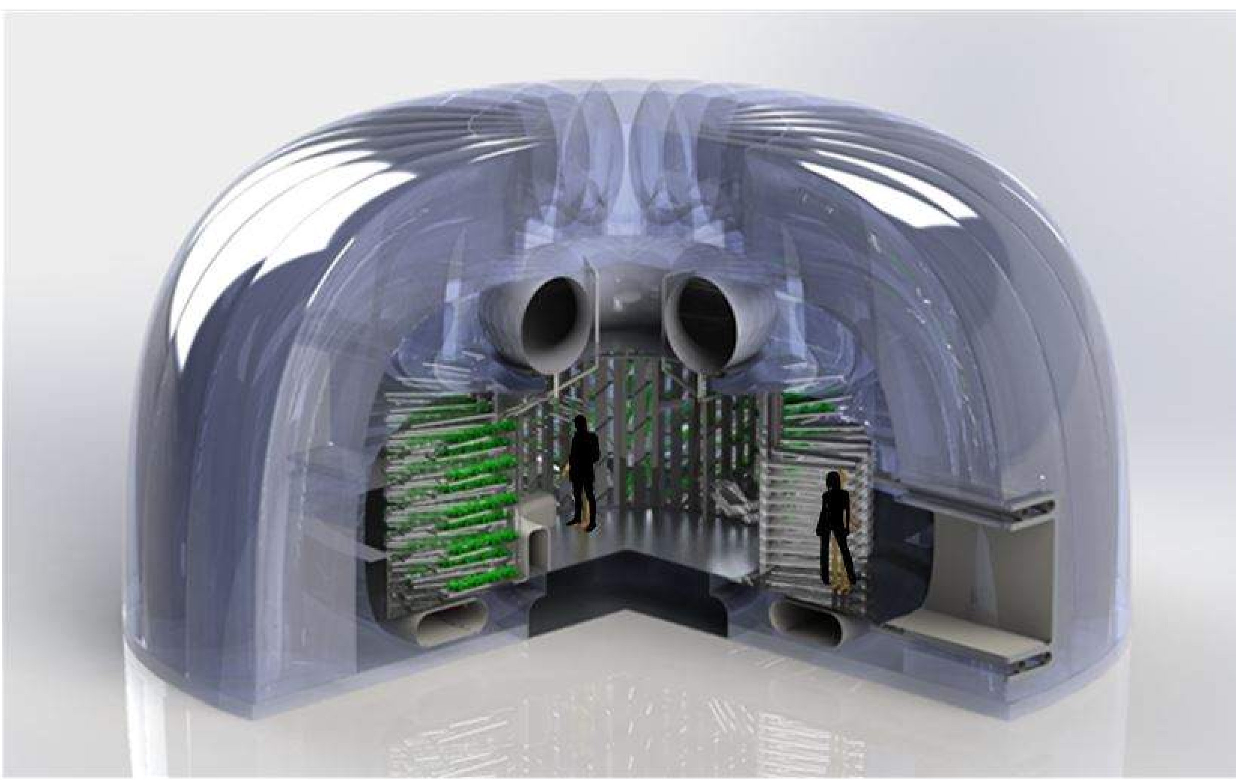

Figure 30: CYBELE, three-quarter cross-section.

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