NASA'S BIG IDEA CHALLENGE

Mars Greenhouse

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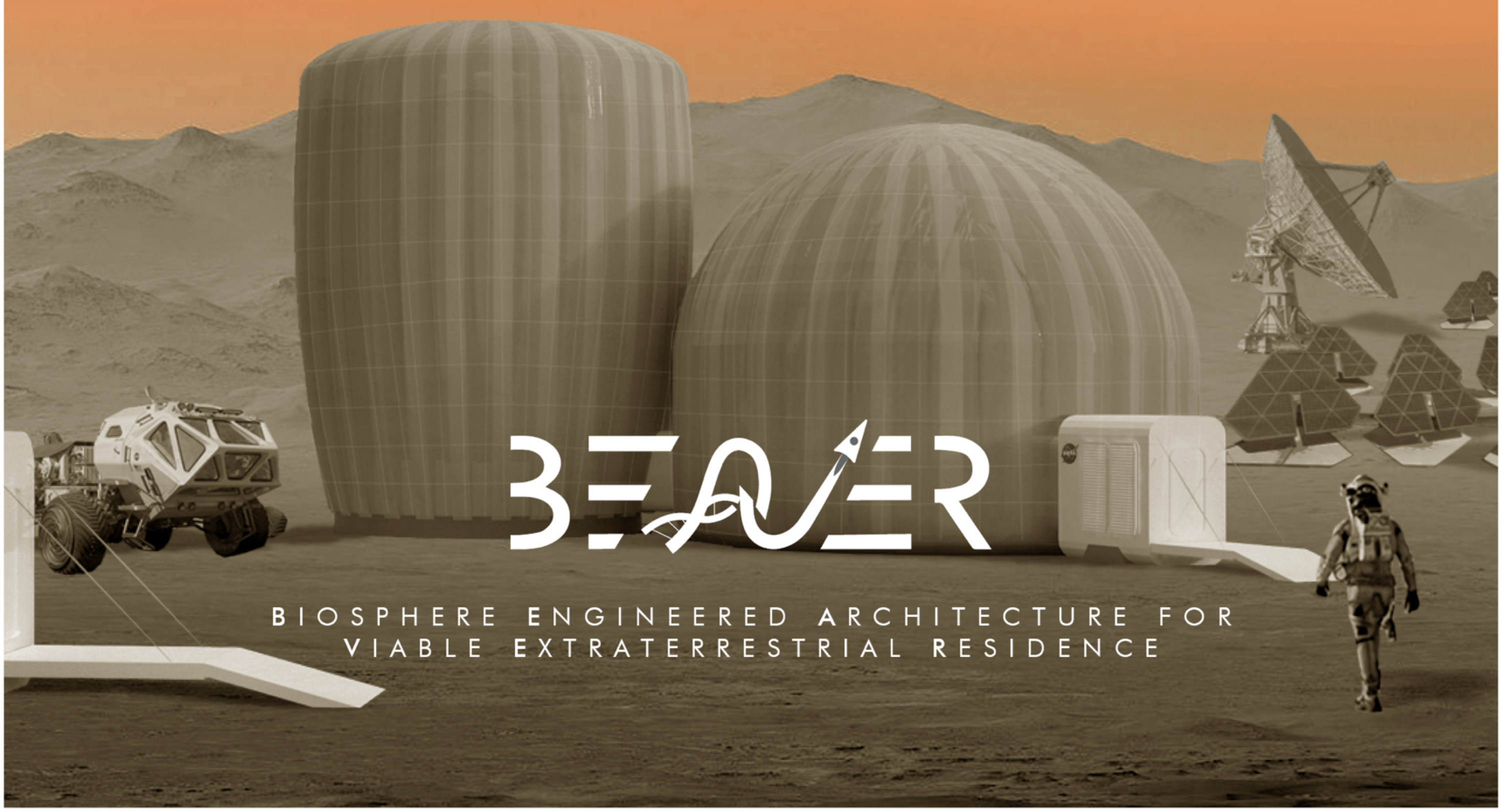


BEAVER

BIOSPHERE ENGINEERED ARCHITECTURE FOR VIABLE EXTRATERRESTRIAL RESIDENCE

Section 1: Introduction

Habitation of Mars, whether in an exploratory or permanent sense, requires a certain level of sustainability. Food is at the forefront of many of these discussions; a sustainable habitation on Mars should be able to produce its own food in order to reduce reliance on Earth supplies. Even for shorter-term exploratory missions, the potential for significant mass reduction during interplanetary flight may make it economically beneficial to grow food on Mars rather than to deliver it from Earth. For this reason, a Mars greenhouse is proposed to satisfy the nutritional requirements of a four-person human crew on an extended Mars mission. An additional benefit of the greenhouse is its potential to improve the mental health of the crew through interaction with greenery and nature.

The MIT team introduces the Biosphere Engineered Architecture for Viable Extraterrestrial Residence (BEAVER), a greenhouse designed to optimize growth space that will yield 100% of the nutritional and caloric requirements for a crew of four and provide a specialized area for mental health improvement. BEAVER has been designed to satisfy all constraints given by the BIG Idea Challenge's requirements but with additional constraints that the MIT team deemed important. These include optimization of the gas exchange system between the greenhouse and habitat, intelligent use of waste resources, flexible growth areas to accommodate a variety of crops, and a systems-wide focus on redundancy and risk reduction. The ecology decisions (Section 2), architecture (Section 3), and systems engineering (Section 4) for BEAVER will all be described in this report. These will be followed by a brief discussion of the prototyping effort (Section 5) and a conclusion (Section 6).

Section 2: Ecology

The success of BEAVER relies on building a near closed-loop ecosystem optimized for both sustainable healthy crop production and providing leisure to the crew. The Mars premise sets constraints and requirements on the greenhouse different from its Earth counterparts, which will be addressed in (Section 2.1). A comprehensive analysis of the crops (Section 2.2), the hydroponic growing systems (Section 2.3), processing of crops (Section 2.4), a model developed to predict greenhouse output and labor requirements (Section 2.5), a daily CONOPs (Section 2.6), and additional factors that are essential for mission success (Section 2.7) are also discussed.

2.1 Requirements Overview

The MIT team assessed traditional and artificial growing systems to sustain a crew of four, based on a 2,700 calorie per day nutrient-balanced diet, over the duration of 600 days. An adequate variety of plants to meet dietary needs, available options for growth medium, the reduced gravity on Mars, and the scope of the growing systems all contributed to the system design. As a result of careful tradespace analyses with these design drivers in mind, the team concluded that a closed-loop hydroponic system is the most effective solution for a Mars greenhouse.

Several options were considered for BEAVER's design regarding the growth medium for crops. Transporting soil from Earth was ruled out early in the design phase due to its high bulk density of $1.6 g/cm^3$ [1]. Martian regolith lacks organic matter, which contains necessary nutrients and the microbiota for plant growth. While one could "seed" the regolith with organic material transported from Earth or produced in the greenhouse, the presence of toxic perchlorates [2], the additional mass presented by the "seed" organic matter, and the labor associated with cleaning and seeding the regolith make in-situ utilization of Martian regolith as a growth material unfavorable during the initial phase of colonization. Finally, Earth-based experience has shown that soil-based agriculture is labor intensive, water intensive, and space inefficient. Several varieties of soil-less techniques were also considered: aquaponics, aeroponics, and hydroponics. Aquaponics is attractive as it presents an additional protein source. However, fish have been shown to react poorly to microgravity environments [3], and unless significant strides in cryogenics or other forms of preservation (perhaps biologically engineering fish eggs to enter cryptobiosis) throughout the transport process can be made, aquaponics is not practical. Aeroponics was also considered as it has been shown to be conducive to root crops such as potatoes [4]. However, hydroponics was ultimately chosen because it is a more established technology, resulting in lower mission risk.

The reduced gravity on Mars, which is approximately 0.38 times that of Earth's, was also a key design driver. Gravitropism is a fundamental process of plants that govern their metabolism and growth pattern. Fortunately, the limit of gravitropism in most plants is below 0.3g [5,6,7], meaning that gravitropic responses would still be present on Mars. However, secondary effects of reduced gravity such as fluid flow were still considered in BEAVER's design.

In order to ensure a sufficient variety and quantity of crops, the team created an Excel-based model to evaluate the scope of a growing system that can maintain a 2,700 calorie balanced diet. The sizing was done on a select group of crop archetypes that represents the complete spectrum of possible crops (See Section 2.2). The crops within these archetypes used for sizing were peanuts, potatoes, wheat, oats, rapeseed (also known as canola), tomatoes, beans, and lettuce. The model uses known growing parameters of crops (volumetric requirements, growing duration, yields, etc.) to estimate the spatial volume needed to meet the overall growing requirements. The principal output of the model is that to meet all of the following needs, about 560 m^3 of growing space is required:

Calories: 2,700 / day [8]	Carbohydrates: 500 g / day	Protein: 80 g / day	Oils/Fats: 140 g / day

These trade studies led the team to proceed with a closed-loop hydroponic system as the basis of BEAVER's food production system. A hydroponic system gives the user flexibility to adjust more growth parameters than a traditional soil-based system to suit the optimal growing conditions of each crop. The closed-loop setup allows for greater water efficiency and recovery, meaning that there will be less of a burden on the already limited water supply to the Mars Ice Home. Of course, the closed-loop setup also means that one needs to filter and re-adjust the composition in the recycled nutrient solution to prevent the spread of pathogens and potentially allelopathic or toxic compounds. In addition, the added complexity of the hydroponic system means that there is more room for failure, especially in the event of a power outage if the hydroponic system in question relies on automation for processes such as circulation and aeration. In the coming sections, the detailed crop selection and system designs of this architecture will be further discussed.

2.2 The Crops

The team undertook a detailed and ongoing study of the most suitable crops and quantities to meet astronaut and mission requirements. The resulting crop selection and subsequent growing conditions have defined the systems engineering requirements of the BEAVER. The crop selection can meet caloric and nutritional needs of the crew while maintaining dietary variety for the crew.

2.2.1 Crop Selection

System design was undertaken based on eight example crops found in four crop archetypes, which were selected to be representative of 'types' of crops with similar growing needs. This was done to reduce the use-considerations to a manageable level. The use of archetypes also emphasizes the fact that different crops serving the same function in the diet are needed in the case that one crop type fails due to unforeseen circumstances. The crops selected as the representative crops are as follows:

Root-producing Crops: Potatoes and peanuts were chosen to represent rooting crops. The hydroponic root growing system is challenging because consideration needs to be given to the space and structure of the rooting zone. However, potatoes are an important source of non-cereal based carbohydrates, as well as nutrients and vitamins. They are also a high-yielding crop, whilst peanuts are an important source of oil and protein.

Field-like Crops: Wheat, oats, and rapeseed were chosen to represent grass-like crops, which are important crops in producing large volumes of carbohydrates and energy. Popular crops like wheat are useful, as many commercial breeding cycles have developed high yielding genetics, reaching up to 15 T/hectare. Rapeseed is important for oil.

Climbing Crops: Tomatoes and beans were chosen to represent climbing crops. This archetype of crops is already commercially grown hydroponically on Earth, so methods are at a high Technology Readiness Level (TRL). It will be a high-yielding method to produce fruits and vegetables. The main challenge was providing appropriate climbing space for the crops to flourish. This is addressed in the architecture section of this report with an innovative column design.

Leafy greens: Lettuce was used to represent this group of crops. It is also commercially grown hydroponically on Earth, so methods are at a high TRL. It will be a high-yielding source of vitamins, minerals, and fiber.

2.2.2 Nutrient Requirements

The macro and micronutrients required by plants on Earth must be transported from Earth or made in-situ. Calculations below show the approximate mass requirements of chemical nutrients needed by the plant archetypes:

Table 1: Nutrient requirements of plants

Plant Nutrient Requirements		**Nitrogen**	**Phosphate**	**Potassium**	**Other micronutrients**	**Total**
		N	P_2O_5	K_2O		
Type of Fertilizer	Traditional Fertilizers (~50% content)	180 kg	70 kg	150 kg	~50 kg	450 kg
	Raw Chemicals (100% content)	90 kg	35 kg	75 kg	~25 kg	225 kg

A crop-nutrient usage model was built based on nutrients depleted from the soil during growing, with appropriate assumptions made where data not available [9].

The annual mass of nutrients needed by the plants to sustain four astronauts is roughly 225 kg, assuming the chemicals can be used in raw form. Even assuming that fertilizer needs a 1:1 carrier:nutrient relationship (as with traditional farm fertilizers) the system still needs just 450 kg per year. Because this mass is relatively small, it does not make sense to produce in-situ. The crops grown may need other treatments and growing chemicals, such as inoculants, growth hormones or growth regulators; however, it is assumed that these are low enough volume that they can be brought onboard and applied through the water delivery system or foliar spray as appropriate.

2.2.3 Pollination

Some of the crops grown in the greenhouse require no pollination intervention. These are either robust self-pollinators (i.e. peanuts), or require no pollination (i.e. potatoes). For the remaining crops, a range of interventions is planned. In the case of cereal crops, which benefit from a gentle wind at the time of pollination, artificial air flow will be generated. In the case of crops normally pollinated by insects, such as tomatoes, astronauts will artificially pollinate. This procedure is utilized widely among plant breeders and is viable in the BEAVER system.

2.2.4 Harvest Cycles

Some crops have a single harvest event, reaching maturity between 90 and 150 days. Other crops, such as tomatoes, will continue to yield fruit (and so need to be harvested) over a several month cycle. This will require careful crop planning so that the system can generate a balanced diet every day of operation while minimizing food storage requirements. The design of this system, with small modularized growing trays, will facilitate this. Fortunately, most commercial crops have different maturity traits (length of growing cycle). This means that a portfolio of crops and varieties taken to Mars can be designed with similar maturities in order to facilitate synchronized, continuous cropping cycles in the BEAVER system.

2.3 Hydroponic Growing Systems

With the plant archetypes selected, the next step was to design a closed-loop system capable of supporting the various growth requirements of the plants. After a careful tradespace analysis, nutrient film technique (NFT) was chosen for the hydroponics system due to its water efficiency and simplicity. NFT involves a continuous thin film of nutrient solution sent through a watertight gulley containing plant roots. All archetypal crops have been shown to grow in NFT systems [10, 11, 12].

2.3.1 Nutrient Solution System

Nutrient solution maintenance and delivery are paramount for a successful hydroponics system. Nutrient solutions can also harbor and spread disease throughout the system, with potentially catastrophic outcomes. The nutrient solutions will be primarily delivered to the roots of the plants, avoiding wetting the leaves as part of the disease control strategy. Calculations show that the growth system will conservatively need 4.6 m^3 of water per day [13], the vast majority of which will be recovered and recycled. The water system also needs to have the following properties and functions:

Nutrient Delivery: The nutrient delivery system is incorporated into the water system and is described in more detail in Section 4. The nutrient solution will meet the crops' requirements for macro and micronutrients and will be delivered on a scheduled basis (in the form of dissolved salts) to the roots. The system is also be capable of delivering nutrients on an immediate basis in reaction to plant response caused by nutrient deficiencies. Furthermore, there is the capability of foliar delivery of nutrients, delivered by spray nozzles in the growing area.

Plant Protection: The water delivery system is able to deliver crop protection chemicals when required to the roots of the plants. Specifically, these will include systemic insecticides or fungicides in emergency or preventative situations. There is also the option for foliar delivery as required.

pH and Electrical Conductivity: Hydroponic systems for most crops maintain a pH of 5.5-7, which is the target range for each crop in BEAVER. The salts ratio will be such to maintain an electrical conductivity of 1.5-3.5 mS/cm, as dictated by similar research. Both the pH and EC can be controlled with buffering products [14].

Oxygenation: The system will be aerated such that the roots do not experience anoxic conditions. Given that the employed nutrient film technique already allows roots to access air, the nutrient solution used in the system will not require further oxygenation.

Recirculation and filtration: The closed-loop hydroponics system requires a nutrient solution to be recirculated. Prior to recirculation, the nutrient solution will be directed to a computer-managed dosing injector that will re-balance the pH, EC, and fertigate the system with the appropriate nutrients using the prepared concentrated stock [15]. A passive filtration system consisting of a fine mesh or sand will be used to filter out any particulates such as root pieces before the nutrient solution is sterilized for recirculation. UV sterilization has been shown to be an economical and effective method of eliminating pathogens from the recirculating nutrient solution [16] and will be employed. Finally, a reverse osmosis, deionization (RODI) system will be implemented on a periodic basis to prevent the build-up of minerals and allelopathic compounds.

2.3.2 Lighting System

BEAVER's lighting system is designed to take advantage of the natural light that reaches the interior of the greenhouse on Mars. However, assuming a 10% transparency of the ice walls, only 5.4 W/ft^2 of power is received from natural lighting. This means that the majority of lighting will be provided by a full-range, color-tunable LED system that replicates the color rendering index (CRI) of natural light. It has been shown that an optimized blend of blue and red wavelengths enhances crop yields by greater than 10%, and these will be employed by utilizing the spectrum shown in Figure 1, taken from studies on Earth [17]. In addition, LEDs are fully controllable, enabling the optimization of yields, crop quality, and growing times.

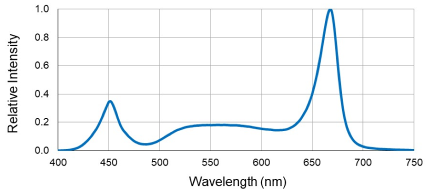


Figure 1: Lighting spectrum for BEAVER

Oftentimes in contained farms powered by LEDs, lights will be heavily skewed towards purple wavelengths, which can cause headaches in humans and is unpleasant to view. One of the main benefits of this lighting spectrum, apart from increased crop yield, is that it appears to the human eye to be normal light, allowing humans to work comfortably. The exact spectrum will be tuned to the specific plant that each LED strip is illuminating and that plant's current stage in its growth cycle in order to maximize yields. The lights will be mounted on the underside of the spirals (directly above the plants) and will be operated for approximately 18 hours per day. The remaining 6.6 hours will be devoted to a respiration period for the plants.

Commercial indoor growing practices recommend 32 W/ft^2 for high-light crops (such as tomatoes) and 16 W/ft^2 for low-light vegetative crops (such as lettuce) [18]. Therefore, it is clear that the artificial LED lighting will provide most of the growing light, while the 5.4 W/ft^2 of available natural lighting will be a small, but useful, supplement.

2.4 Crops Before and After Growth

2.4.1 Pre-Processing of Crops

Seeds will be packaged in tray-sized, serialized packs, and kept in a cool, dry place throughout the duration of the journey to Mars. A specially designed Seedling Zone in the center of the spiral will be used for germination and early care processes. The zone will provide the precise conditions needed for seeding, while allowing easy access during this high-care time. The Seedling Zone will have the following features:

- Germination that will take place in inorganic growth media using commercially available rockwool [19].
- Starter media will be immersed in an appropriate, diluted nutrient solution.
- An enclosed, locally-controllable grow tray structure for control of humidity, soil moisture, temperature, and light.

Transplanting of the mature seedlings into their permanent growing tray will happen after 2-4 weeks, depending upon the crop. This labor intensive task is critical for plant health and so will be done manually by the astronauts.

2.4.2 Post-Processing of Crops

The treatment of plants at the harvesting stage falls into two broad categories: crops that are ready to eat (tomatoes, lettuce, potatoes), and crops that require substantive post-processing (wheat, oats, beans, rapeseed, peanuts). The astronauts will psychologically benefit from harvesting the ready-to-eat crops manually. Potatoes should be stored in a cool, dark area with high humidity.

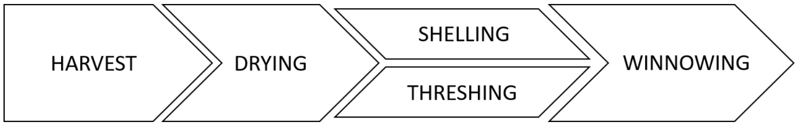


Figure 2: Process flow diagram for plant post-processing

Those crops that require substantive post-processing will share stages of processing as well as equipment. **Harvesting** and processing of these crops will be automated where feasible. Immediately post-harvest, these crops must be dried for 14-21 days. After **Drying**, crops are either shelled (beans, rapeseed, peanuts) or threshed (wheat, oats). Although this can be done by hand, commercial machines for both **Shelling** and **Threshing** exist on a table-top scale and will be employed. Much of the excess plant material (stalks and pods) is removed during the shelling and threshing stage, but additional small material, referred to as chaff, remains behind. The crops must be **Winnowed** to remove this material, which is a process that requires air flow.

The path of an individual crop diverges here. Beans will be ready for use at this point or may be dried for long-term storage. Wheat will be milled into flour in a commercially available grain mill. Rapeseed will be pressed into oil on a separate expeller machine, while peanuts can be kept whole or ground into a paste on the expeller. Oats can be rolled at this point on a third machine. These processes can, and should, be automated. Once harvested, a set quantity of the produce will be set aside for immediate consumption, while excess will be packaged using freeze drying and vacuum packaging methods to extend the shelf-life while preserving the nutritional value.

2.4.3 Post-Processing of Growing Trays

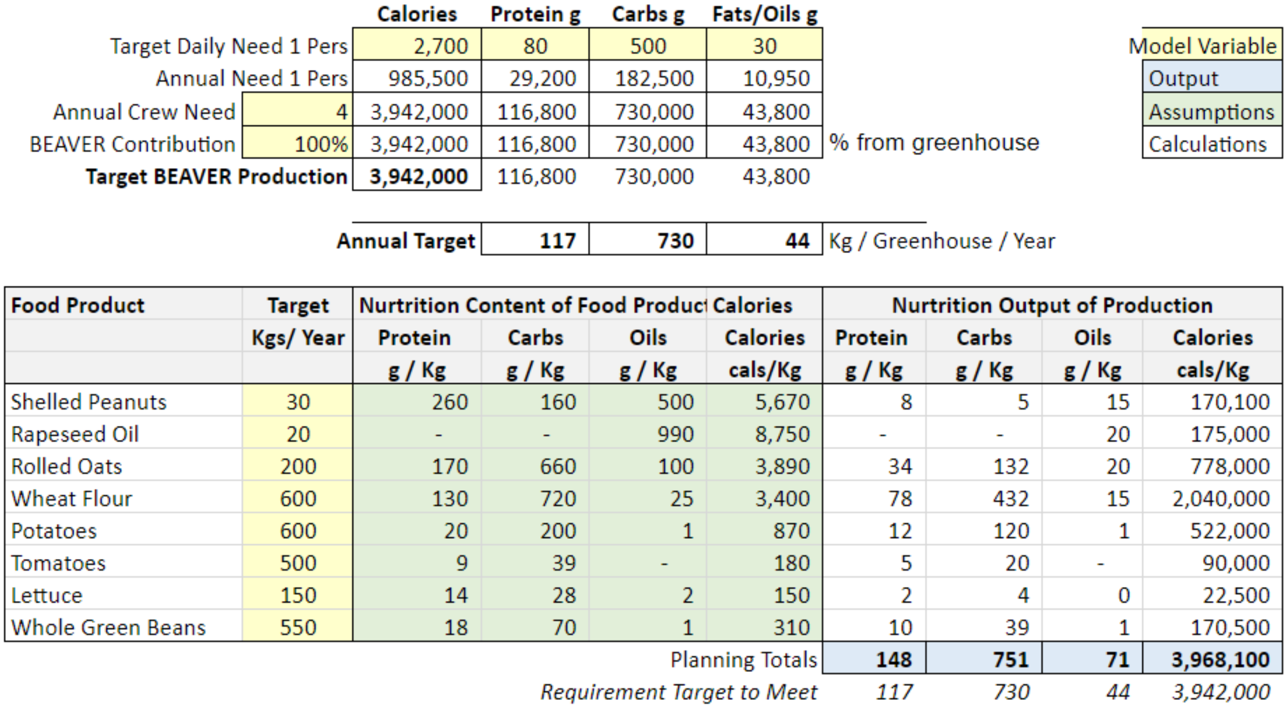
After each growing cycle, trays and rockwool starter blocks will be washed and sterilized using hot water and UV. The trays are non-porous and designed with flush finish and minimal surface area to facilitate cleaning. The purpose of cleaning is to ensure that existing plant matter, biofilm, or mineral buildup do not pass between growing cycles. The UV sterilization will minimize the spread of disease [20]. After sterilization, rockwool cubes are reused to germinate new seedlings, while rotating use through crop types to reduce the likelihood of disease spread [21].

2.5 Model Simulation of Greenhouse

2.5.1 Motivation and Approach for the Model

A computational model of BEAVER operations was built to understand system sizing and feasibility. The first stage calculated nutrition requirements: the nutritional balance between protein, carbs, oils, and calories.

Table 2: Nutritional requirement calculations (top) and food production with BEAVER crop archetypes (bottom)



		Calories	Protein g	Carbs g	Fats/Oils g	
Target Daily Need 1 Pers		2,700	80	500	30	
Annual Need 1 Pers		985,500	29,200	182,500	10,950	
Annual Crew Need	4	3,942,000	116,800	730,000	43,800	
BEAVER Contribution	100%	3,942,000	116,800	730,000	43,800	% from greenhouse
Target BEAVER Production		**3,942,000**	116,800	730,000	43,800	
		Annual Target	**117**	**730**	**44**	Kg / Greenhouse / Year

Model Variable
Output
Assumptions
Calculations

Food Product	**Target**	**Nurtrition Content of Food Produc**			**Calories**	**Nurtrition Output of Production**			
	Kgs/ Year	**Protein**	**Carbs**	**Oils**	**Calories**	**Protein**	**Carbs**	**Oils**	**Calories**
		g / Kg	**g / Kg**	**g / Kg**	**cals/Kg**	**g / Kg**	**g / Kg**	**g / Kg**	**cals/Kg**
Shelled Peanuts	30	260	160	500	5,670	8	5	15	170,100
Rapeseed Oil	20	-	-	990	8,750	-	-	20	175,000
Rolled Oats	200	170	660	100	3,890	34	132	20	778,000
Wheat Flour	600	130	720	25	3,400	78	432	15	2,040,000
Potatoes	600	20	200	1	870	12	120	1	522,000
Tomatoes	500	9	39	-	180	5	20	-	90,000
Lettuce	150	14	28	2	150	2	4	0	22,500
Whole Green Beans	550	18	70	1	310	10	39	1	170,500
					Planning Totals	**148**	**751**	**71**	**3,968,100**
					Requirement Target to Meet	*117*	*730*	*44*	*3,942,000*

Next, a simulation model of BEAVER was built using Python to understand the time series performance of the system. The model helped the team quantify (a) the growing space needed and (b) the labor hours, while helping the team to (c) understand the rhythm of operational life of the crew and (d) optimize yield and work hours. The major inputs and outputs of this model are shown in the following table:

Table 3: Major inputs and outputs of the BEAVER Python simulation

Model Inputs	**Model Outputs**
- Crop tasks required by day, with task lengths - Crop inputs required by day (water, nutrition) - Crop harvest expected by growing cycle - Crop sizing by day	- Crop tray locations and stage of growth by day - Work profiles in man-hours over 600 days - An operational Daily Task List for astronauts - Harvest expectations by day in kg for each crop

2.5.2 Results of the Model

From the target BEAVER production, the team estimated how many of each crop would need to be harvested to meet 100% of the nutritional requirements of a four-person, 2,700 calorie per day diet. A balance between the number of harvest cycles ensures astronauts readily acquire fresh produce without being overwhelmed by gardening labor or storage requirements. Based on the date that crops are planted, a 600-day schedule of all tasks required to be completed is generated by the model. The simulation optimizes this schedule by shifting the seeding times so that the astronauts are not overwhelmed with tasks on certain dates. Additionally, it minimizes the growing space required for optimal output. The model shows that a 2-week seeding interval for stockable produce (wheat, oats, peanuts, rapeseed, and potatoes) and a 3-day seeding interval for perishable produce (tomato, lettuce, beans) is the most optimal setup to satisfy space, labor, and produce freshness requirements. The simulation suggests that to meet the mission requirement, 360 m2 of growing space and an average of 2.5 man-hours per day are required.

Table 4: Key outputs from the Python simulation of BEAVER.

Key Model Outputs			
Growing Space Required	360 m^2	Average daily harvest	20 kg / day (edible)
Average Man-hours	2.5 man-hours/day	Max man-hours	3.5 man-hours/day

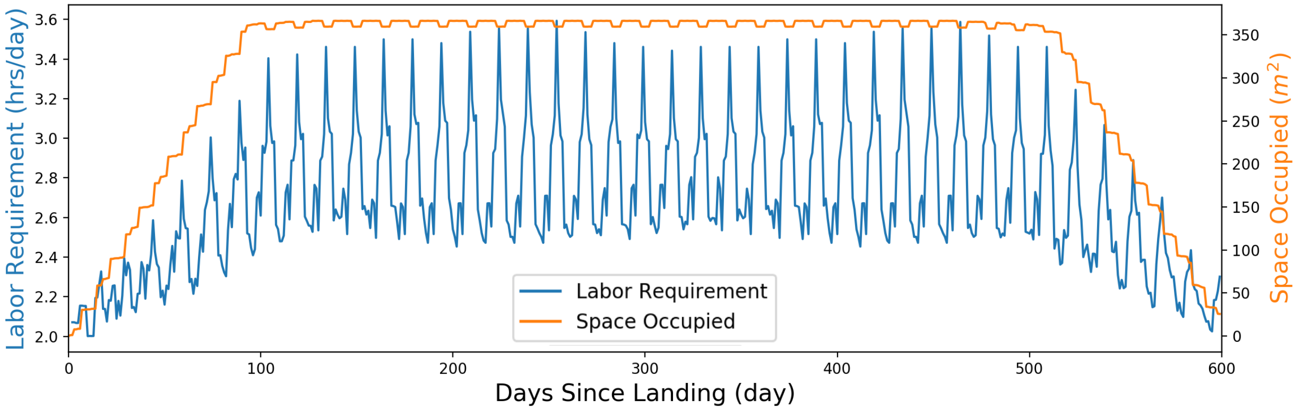
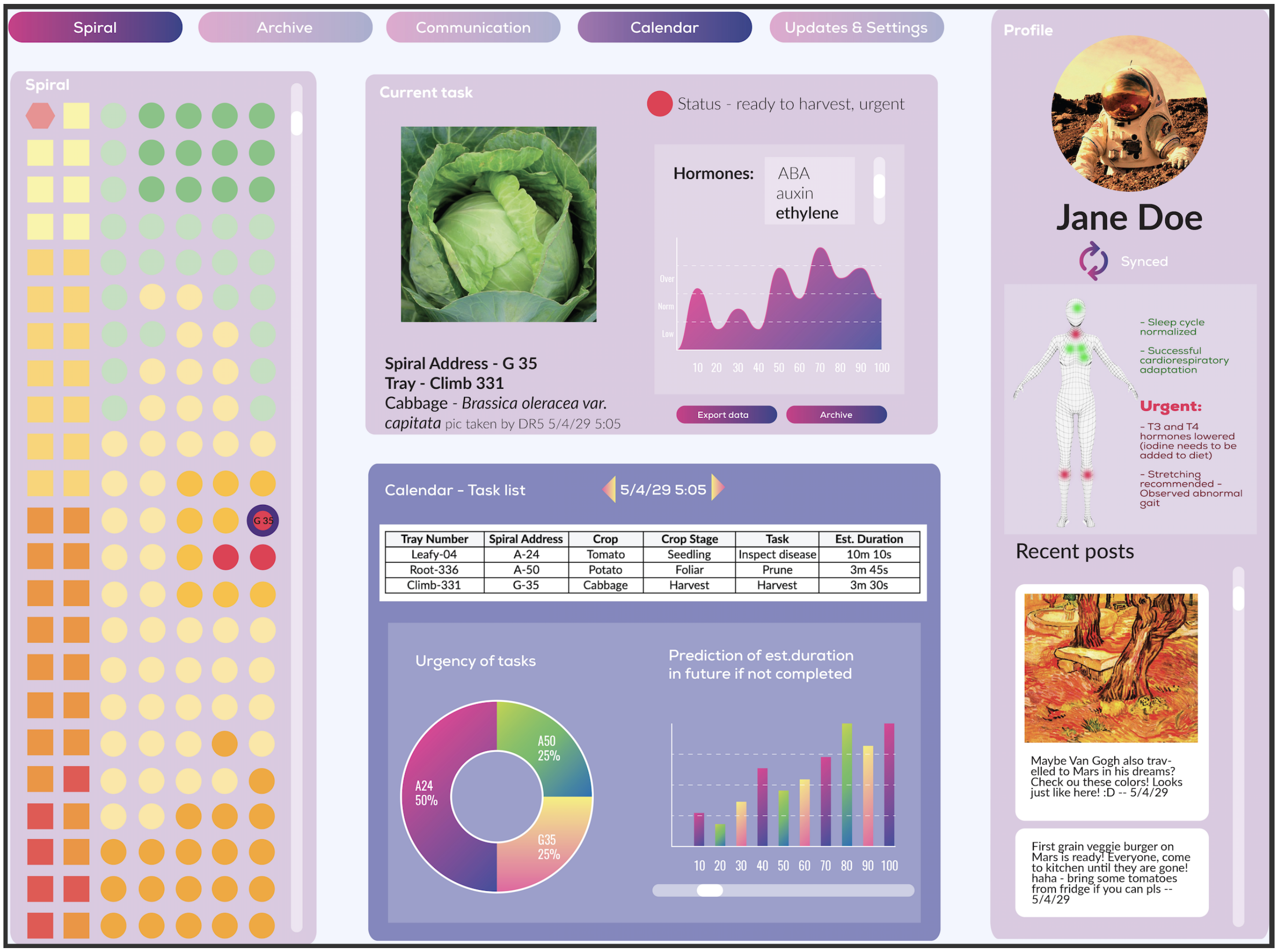


Figure 3: Simulated labor requirement per day (blue) and estimated growing space required (orange) over a 600-day mission. The labor requirement per day includes the estimated time for pre/post processing of crops and seed/produce, the time to perform various tasks on all crops (seeding, pruning, harvesting, etc.), and the overhead time between each task. The peak in labor requirements and the dip in space occupied correspond to harvesting of wheat and oats.

2.6 A Day in the Life of an Astronaut

Day-to-day operations and maintenance of the greenhouse will be kept to a minimum once the greenhouse is operational. The BEAVER **Operational Management System** produces a **Daily Task List** for the astronauts based on the following input parameters: (a) the system's knowledge of each tray's location, crop, and stage of growth, (b) input from the sensor network informing the state of each tray, and (c) how much time the astronauts are able to dedicate to crop management on this specific day. The manual tasks are those that cannot initially be completed by robots, or are planned as psychologically beneficial tasks for the astronauts; while some harvest tasks can be completed robotically, they are considered emotionally fulfilling and are therefore suggested to be completed by humans. BEAVER tasks are planned on a day-to-day basis, but flexibility is included to allow tasks to be completed within a +/-3 day tolerance without impact. The model shows that BEAVER tasks require a total of 2-4 labor hours each day. The **Daily Task List** is a tray-by-tray list of tasks that are ordered by Spiral Address, starting from the top of the growth spiral and working downwards. A snapshot of the **Daily Task List** is shown below, with details of task times and locations on the spiral shown. The user interface pictured also displays the implications of not completing the tasks, gives access to technology to capture the visual and biochemical states of plants, gives information about the astronaut's health, and provides communication tools amongst the crew and with Earth.



Status - ready to harvest, urgent

Spiral Address - G 35
Tray - Climb 331
Cabbage - *Brassica oleracea var. capitata* pic taken by DR5 5/4/29 5:05

Tray Number	Spiral Address	Crop	Crop Stage	Task	Est. Duration
Leafy-04	A-24	Tomato	Seedling	Inspect disease	10m 10s
Root-336	A-50	Potato	Foliar	Prune	3m 45s
Climb-331	G-35	Cabbage	Harvest	Harvest	3m 30s

- Sleep cycle normalized
- Successful cardiorespiratory adaptation

Urgent:

- T3 and T4 hormones lowered (iodine needs to be added to diet)
- Stretching recommended - Observed abnormal gait

Maybe Van Gogh also travelled to Mars in his dreams? Check ou these colors! Looks just like here! :D -- 5/4/29

First grain veggie burger on Mars is ready! Everyone, come to kitchen until they are gone! haha - bring some tomatoes from fridge if you can pls -- 5/4/29

Figure 4: User interface including Daily Task List that BEAVER astronauts will use to efficiently complete tasks

Maintenance will be another labor requirement of astronauts. General maintenance on the pumps and electronics cabinets will be conducted as necessary in accordance with a preventative maintenance schedule. When maintenance is conducted, the secondary system will be placed online first to ensure continued operation.

2.7 Additional Factors

The environment in which the crops grow is just as important as the crop selection and the hydroponic systems. There are various factors and considerations that are essential for maintaining healthy plant growth, including atmosphere control, trace gas regulation, temperature regulation, biomass, and disease control.

2.7.1 Atmosphere Control and Trace Gas Regulation

The BEAVER system is designed around the importance of atmospheric control in an enclosed ecosystem, which can affect plant growth [22] and survival of astronauts. CO_2 will be collected from the Ice Home and exchanged with O_2 from the greenhouse, as described in Section 4. Additional trace gases emitted by both plants and crew will be closely monitored and removed if they exceed a predetermined safety threshold.

While trace gases released by humans and plants on Earth are recycled through atmospheric chemistry and/or photochemistry, the accumulation in an enclosed ecosystem could quickly lead to an overdose that can be harmful to both plants and humans. For example, high levels of ethylene can lead to plant reproduction issues like seed abortion [23]. For completeness, the typical composition of human breath (besides N_2, CO_2, O_2, Ar and water vapor) is 1 ppm of ammonia, and less than 1 ppm of acetone, methanol, ethanol and other volatile organic compounds [24]. Plants, on the other hand, emit trace amount of methane, ethylene, N_2O, NH_3, isoprene and sulfur compounds [25, 26]. Therefore, the enclosed ecosystem of the Ice Home and greenhouse will require the delicate monitoring of its atmospheric composition and methods to absorb or flush harmful trace gases. BEAVER will be equipped with tools such as ethylene scrubbers to oxidize ethylene into CO_2 and water, which will be fed back into the system. BEAVER will also be equipped with volatile organic compound (VOC) scrubbers such as potassium permanganate.

2.7.2 Temperature Regulation

Each crop will have an optimal growing temperature and possibly even an optimal temperature throughout its growing cycle. These values, along with other relevant temperatures, are consolidated below.

Table 5: Temperature range for optimal crop growth [27]

	Temperature			
Crop	**Minimum Growing**	**Minimum Germination**	**Optimal**	**Maximum**
Peanuts	13 °C	18 °C	30 °C	-
Rapeseed	3 °C	6 °C	20 – 25 °C	35 °C
Oats	1 – 2 °C	12 °C	20 – 25 °C	24 °C
Wheat	1 – 2 °C	4 °C	20 – 25 °C	35 °C
Potatoes	7 °C	4 °C	16 – 21 °C	27 °C
Tomatoes	12 °C	18 – 29 °C	21 – 27 °C	32 – 35 °C
Lettuce	10 °C	21 °C	16 – 18 °C	27 – 29 °C
Beans	13 °C	13 °C	18 – 29 °C	32 °C

As shown, the germination temperatures for crops vary widely. These will be controlled in specialized compartments within the system's germination chamber. Once out of the germination stage, the plants will be loaded into the spiral. The optimal growing temperatures for most crops are roughly the greenhouse ambient temperature (22 °C). While some crops benefit from temperatures different than the ambient - peanuts thrive in warmer temperatures and lettuce requires cooler temperatures - all can still grow at 22 °C. Therefore, in an effort to keep the BEAVER design as simple as possible, a uniform temperature will be used throughout.

2.7.3 Repurposing Biological Waste

Human Waste

To recover nutrients used in growing crops, the current design captures urine as a feedstock for the plant water system. As the median urine generation is 1.42 L/person/day, a crew of 4 would produce approximately 6 L of urine daily, which represents 41.22 g of carbon and 48.72 g of nitrogen by dry mass [28]. The NPK ratio of urine is 18:2:5, with the P and K nutrients being directly plant-available [29]. The main form of N is in urea, but ammonia and creatinine are also contained in urine [30].

It has been shown that utilizing urea as the sole source of nitrogen is unsuitable for plant cultivation, leading to nutritional deficiencies [31]. However, the ability to use urea as a nitrogen source has been shown to increase with plant maturity in soybeans, suggesting that urea could be used as a supplement for older plants in the greenhouse. The addition of enzymes such as urease that break down urine into ammonia may assist with plant absorption of nutrients in a hydroponics system [32].

Other trace elements such as phosphorus are also expected to be recovered, and the nutrient feed system will monitor and correct any discrepancies.

Plant Waste

The growing systems will generate additional biomass. This will be disposed of or recycled in a closed-loop system to increase system efficiency and mitigate the risk of forward contamination. This addresses planetary protection requirements while recovering as many nutrients as possible from this bio-residue (together with human waste). This will require sophisticated nutrient recovery techniques. However, the immediate problem is to dispose of the residue with a method that (a) is protected from the Martian environment (b) protects the growing system from pathogens created by rotting plants and (c) takes up minimal space. The residual biomass is estimated at:

Table 6: Annual biomass generation of BEAVER's eight food archetypes

Food Archetype	Additional Biomass / Year	Types of Biomass Generated
Peanuts	371 kg	Shell husks, roots, leaves stems
Rapeseed	371 kg	Roots, stems, leaves, oil cake
Oats Grains	607 kg	Roots stems, leaves, husks
Wheat Grain	929 kg	Roots stems, leaves, husks
Potatoes	325 kg	Roots, stems, leaves
Tomatoes	500 kg	Roots, stems, leaves, rotten fruit
Lettuce	30 kg	Roots, excess leaves, damaged heads
Beans	660 kg	Roots, stems, leaves
Total Additional Biomass	**3,793 kg**	**Per Year**

The immediate problem is isolating the excess material while it naturally decomposes. The team proposes an Isolated Composting Bin (ICB) located outside of the main habitation structures. The crew will periodically package bio-waste in vacuum sealed bags, carry it through the habitat and out of the airlock, and dispose of it in the ICB. This allows an easy way to remove the excess biomass each day that is compliant with planetary protection requirements, which recognize that the risk of forward contamination cannot be fully eliminated for human missions but must nevertheless be mitigated using available technologies [33]. It also provides a store of packaged compost material that can later have its nutrients chemically extracted if desired.

As shown in Table 6, BEAVER generates about 4 MT of plant residues each year. From experience on Earth, this is likely to be equivalent to a volumetric 100 m^3 per year. However, natural decomposition and staggered harvest cycles lead the team to conclude that the ICB capacity will need to be no more than 20 m^3 during the first several years, especially if used in conjunction with a basic biomass shredder.

2.7.4 Disease Control

A disease or pest outbreak can have catastrophic consequences and is an unacceptable risk for a Mars greenhouse. The BEAVER system is designed to minimize, and mitigate, the risks based on the principle that prevention is better than curing. This approach assumes best efforts to maintain a pathogen- and pest-free environment, but there is always a possibility that plants could suffer from any or all of the same pests or stresses that occur on Earth.

Preparation – Pre-Mission: Pre-mission preparation will begin over a decade before launch with selective breeding to develop disease-resistant lines. Once genetics have been fixed, the lines will undergo several generations of isolated breeding (but without preventative fungicides) to identify and select out any genetically carried parasites and diseases. Mission seeds will undergo irradiation [34] in order to neutralize any parasites or pathogens in the seeds.

Prevention – Growing Operations: During the mission, the hardware and process will be designed with disease prevention in mind. For example, the spiral has a flush-surface design to enable easy cleaning and limit hidden places where insects or pathogens could live. Trays are designed to be easily disassembled and sterilized between batches. The plants will be grown in optimum growing conditions, thus minimizing stress and so helping their resistance to disease. Drainage water will be sterilized before being reused. Astronauts will remove dead or decaying leaves from plants as part of a daily routine. These old leaves, together with end-of-life plants will be removed from the system quickly and efficiently. When possible without the risk of wider effects, biological controls can be used. For example, these could be in the form of *Pseudomonas* or *Bacillus* additives applied to the growth medium that break down mucilage and hinder the growth of the notorious *Pythium* parasite [35].

Monitoring – Automation and Sensors: Sensors and prediction algorithms will provide a full-time plant monitoring and prediction coverage network in all growing areas. The enclosed, controlled environment provides good conditions for making use of computer vision and artificial intelligence-enabled systems.

Sensors: Fixed location multispectral sensors focused on each tray location, atmosphere and water sampling, and harvest metrics will provide a continuous stream of plant performance data.

Crop monitoring: Learning algorithms will have been trained on pre-mission Earth-based trials and will be able to infer issues with plant health using non-visual methods of disease detection. These include routine testing using the ELISA method or vegetation indices [36] coupled with computer vision.

Treatment: The system will be equipped with a range of crop protection chemicals and other treatments or nutrients for use in response to emergency cases. On first signs of disease or fungus, the infected plants will be removed and all susceptible plants will be treated with a general purpose preventative chemical (chlorothalonil) [37]. If the outbreak spreads, a stronger chemical will be used as appropriate. If insects appear, a strong insecticide program will immediately be deployed on the entire growing area. As there are no beneficial insects or other ecosystems to worry about, it would be possible to use stronger insecticides than those used on Earth. If just one crop is susceptible, then that crop could be removed from the growing cycle, and quarantined from the system for several cycles in order to break the pest's lifecycle. If nutrient deficiency becomes a problem, the necessary nutrients will be identified in conjunction with Earth-based experts and supplemented as necessary. Finally, if the plants experience abiotic stress, the conditions causing the stress (temperature, light, neighboring plants, etc.) will be identified in conjunction with Earth-based experts and changed as necessary.

2.7.5 Plant Genetics

Plant Breeding: Pre-mission preparation will commence years before launch in a pre-mission breeding program, with the aim of achieving several unrelated varieties for each crop to provide risk-management through diversification. Parent material will be sourced from diverse sources on Earth, but from greenhouse varieties where these lines already exist. The breeding program will make use of all available genetic engineering methods and be based on the following principles:

- High yielding, but with a preference for yield stability over absolute yield
- Resistance to fungus and disease (which the team has assessed as the biggest danger)
- Uniform harvest timing where required
- Performance under hydroponic conditions

The above traits can be selected for, at the expense of the following, which can be relaxed:

- Insect and pest resistance; strong chemicals can be used in the Mars greenhouse if needed
- Resilience against environmental growing stresses; assumes controlled, stress-free conditions
- Fruit uniformity, color or other important commercial traits used on Earth

Post Breeding Operations: The focus for post-breeding will be on genetic stability and parasitic cleanliness. Seed treatment will include fungicide and insecticide, and seed batches will be direct siblings with common parents for traceability. In addition, the seeds will be packaged directly on serialized paper sheets that can form the seedling growing media on a just-add-water basis. This will facilitate full life traceability down to seed level and thus greater control in the BEAVER system.

Ongoing Line Development: Trait selection for low gravity conditions of Mars is impossible on Earth and there will not be time or capacity to undertake breeding activities on Mars. However, in order to develop a genetic pool that is optimal for Mars, the BEAVER design includes sending a serialized seed bank, with variability at batch level, while maintaining genetic twins on Earth. Then, the growth and harvest performance of each seed batch on Mars will be assessed automatically using sensors, which will, in turn, inform a parallel Earth-based selection and breeding program to develop the next generation of Mars optimal varieties.

Section 3: Architecture

3.1 Why a Cylinder?

When addressing space architecture, vertical loads become minor constraints compared to internal pressure loads, especially when an inflatable structure is used. Several different inflatable shapes allow structural optimization for pressure forces: the sphere, the torus, and the cylinder, but only the latter provides volume and surface optimization with vertical walls. This led to the use of a modified cylinder for BEAVER, with a reduction of the module diameter at its foot in order to further decrease horizontal loads at its ground support. Cylinders also open the possibility of 3D printing the module should an inflatable solution appear unfit in future studies.

3.2 Structure

The structure is primarily a cylindrical core and two circular series of aluminum columns. The inflatable layers are attached to a top and a bottom aluminum plate. Two helical elements revolve around the module: an inner track for growing plants; and an outer ramp for crewmembers to move vertically within the greenhouse.

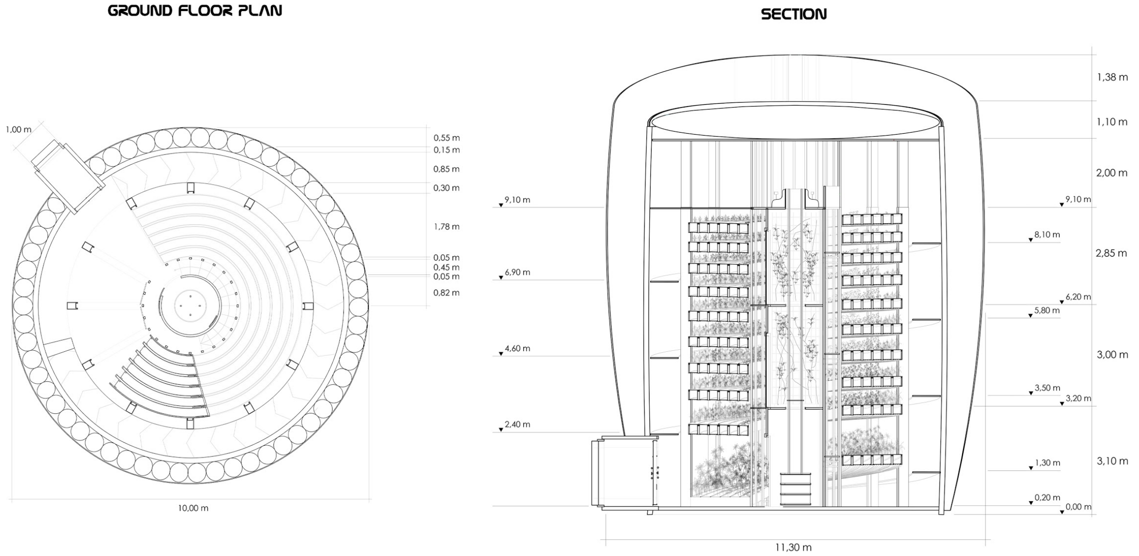


Figure 5: CAD of the ground floor plan and section view of the BEAVER architecture with key dimensions

Finite Element Analysis was performed to evaluate the structural performance of the outer shell and the inner structure of the greenhouse. The overall algorithm was parametrically scripted in Grasshopper and Karamba to allow for quick optimization feedback. The final geometry configuration was then updated and analyzed using this custom FEA script.

The analysis of the outer shell shows that the outer structure is subject to mainly tensile stresses due to the interior and exterior pressure difference of almost 1 atm. The ice and reduced gravity load do not fully counterbalance the internal pressurization. However, the maximum displacement of the structure is 5 cm and, therefore, acceptable.

In addition, the internal spiral and core system were analyzed, taking into account the reduced gravity on Mars, the water of the hydroponic system, and the crops' load at different growth stages. The results for the inner structures show a combination of compressive and tensional forces due mainly to the spiral geometry. The algorithm returned a maximum displacement of 0.219 cm on top of the cantilevered runway, which was acceptable.

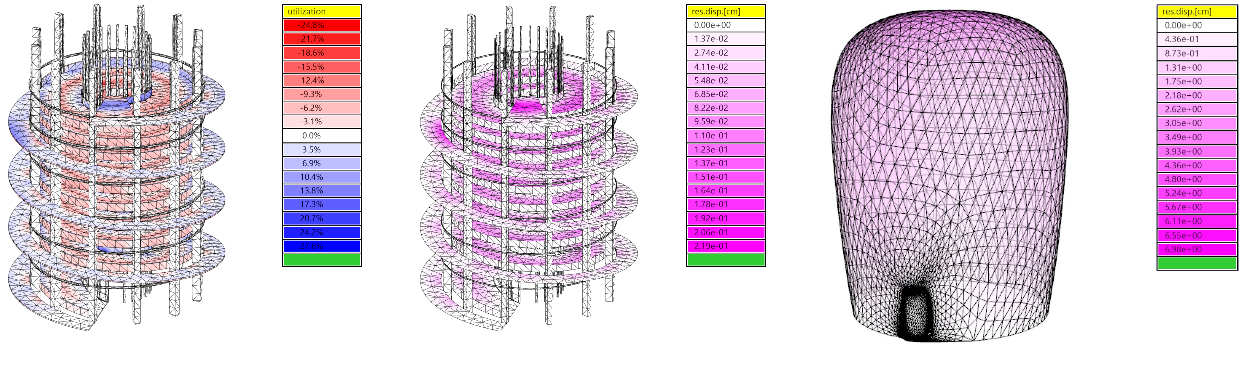


Figure 6: FEA analysis of BEAVER CAD showing minimal levels of displacement

3.3 Internal Space

The internal space complements the structural need of a cylindrical shape; the space is organized vertically in two main floors, which are connected by the helical track and the spiral ramp. The ground floor is dedicated to the harvest and germination of plants, including a work space and areas for control and storage. The top floor is reserved for a functional lounge area, combining additional space for plant growth with psychologically beneficial features such as a water fountain and lounge furniture.

The existing architecture is sized to provide 100% of the food requirements of a crew of four. This includes 103% of the carbohydrates, 126% of the protein, 161% of the oils and fats, and 101% of the calories based on a 2,700 calorie/day diet.

3.3.1 Helixes

The inner helical track optimizes productivity with a conveyor belt: crewmembers use trays to plant crops at the top of the module, and the trays slowly move down the track to the bottom via gravity and rollers, reaching the ground floor when plants are ready for harvesting. In order to optimize this solution, the distance between successive rounds of the spiral trays decreases with height: at the top of the greenhouse when the plants are young and short, the spirals are close together vertically, while at the bottom when the plants are mature and tall, the spirals are farther apart. This also leaves space for crewmembers to pass beneath the tracks and use the area at the bottom of the module. Five constraints were used to define the final shape of the track: maximum pitch (at the end of the first revolution), pitch at the end of the second revolution, minimum pitch (at the end of the last revolution), total height, and total number of revolutions. These constraints were translated into points and interpolated by a helix parameterized in cylindrical coordinates. This vertical transport design is one of the main innovations of the BEAVER system; it optimizes the use of vertical space while minimizing the number of moving parts and the human labor required to operate it.

The outer helical ramp can be used for maintenance of the growing system and as a running track for the crewmembers. It is inflated out of BEAVER's shielding layers and attached to the outer row of columns. The ramp has a constant pitch between its revolutions and serves as the primary connecting element between the bottom and the top floors of the module. A short bridge connects the ramp with the human factors area at the top of BEAVER next to the start of the helical growing track.


Figure 7: Bottom floor and harvesting area of BEAVER

3.3.2 Core

The core is the heart of the structural and functional system of BEAVER. At the ground floor, it hosts a germination darkroom for seedlings, with two additional rooms for growing vine-like plants placed at mezzanine levels between the top and the bottom of the module. Plants such as tomatoes and beans grow well on the sides of walls, so the core is a perfect fit for them. The remaining space contains ventilation, electrical and water systems, two platforms, LED lights, hydroponics for the crops and a small lift for transporting trays from the germination room to the top end of the helical track. A spiral staircase revolves around the core, providing an additional connection between the ground and top floors, granting access to the growing rooms and allowing maintenance of the innermost portion of the helical track.

3.3.3 Human Factors

Together with structural and functional needs, human needs are a key consideration in this design. The close proximity of greenery, arranged in a spectacular spiral organization, has crucial benefits for the crew's psychological health. Moreover, the design reserves space for working and leisure on both the top and bottom floors of the greenhouse.

The space beneath the bottom revolution of the spiral contains two desks and two closets and is equipped with freezers, for the storage of crops, seeds, and tools. Desks can be expanded both in height and in surface, growing to more than twice their regular size for working needs. Screens showing information on the module's conditions are integrated into the furniture. Chairs can slide on radial tracks, also used in BEAVER's deployment, and can be converted into small step-ladders for crop maintenance. Space can, therefore, be adapted to crewmembers' needs, providing important psychological benefits.

The top of the module is conceived as a quiet space for relaxation and intimacy of crewmembers. Above the inner core, an inflatable sofa, with embedded digital screens, is arranged around the core shape, allowing room for resting. Behind it, a few vases can contain decorative or edible plants. Water pours from the water reservoir on top of the greenhouse into a fountain, before continuing on to its other purpose of irrigating the hydroponics below, introducing a natural sound inside the otherwise artificial environment of the module.

Figure 8: Human factors area, top floor

In addition to the greenhouse, BEAVER proposes the addition of herb gardens in the Ice Home itself, just outside the crew's quarters. Each astronaut will have his or her own private herb garden that is viewable from the bedroom in the main Ice Home habitat and is the responsibility of that astronaut. The purpose of this addition is threefold: to give the astronauts a relaxing view of a garden when they wake up or are spending time in their quarters; to provide herbs for cooking; and to give the astronauts something alive of their own that requires their attention and care. There is therapeutic value in horticulture and gardening that would benefit the astronauts [39]. Humans are innately attracted to other living organisms, including plants [40], and many studies have shown positive effects of gardening on mental health [41]. Therefore, apart from the obvious benefit of producing herbs to enhance the meals the astronauts will eat, the herb gardens provide significant benefits to the astronauts' well-being.

3.4 Packaging and Deployment

BEAVER fits easily inside a 6.7 m diameter x 9.3 m height rocket fairing via simple compression. Several of its major structural components use innovative folding and collapsing methods to fit the cylindrical shape of a fairing while maximizing available greenhouse space when unfurled on Mars. The compression and expansion of the module are accomplished through radial and vertical movement, exploiting the cylindrical layout of the structure.

3.4.1 Compression

The module is packed in a 6.7 m diameter x 9.0 m height cylindrical volume to fit the rocket fairing space. The top portions of the inner core and of the columns are compressed, and the outer row of columns is slid towards the center of the module, leaving space for the folding of the shield layers. The outer spiral is deflated and folded together with the shield. The inner helix is compressed vertically and horizontally.

3.4.2 Expansion

After landing on Mars, robots will move the packaged greenhouse next to the Mars Ice Home. The top portions of the inner core and of the columns will be activated and expanded via a standard telescoping mechanism. The outer shielding layers and helical ramp will then be inflated with air. The outermost circle of columns will be pulled outwards to its original position, while also decompressing the inner helix. The ice shield will then be robotically attached to the water tank to begin filling. Once the structure is in place, the helical track will be lifted into position with a controlled and remote activation of the gas springs. In the unlikely event that this system fails, hinges supporting the spirals can be manually opened and fixed by unscrewing the gas springs and opening a kickstand. One of the advantages of BEAVER's design is that it does not require the use of any customized robotics and can be set up prior to the crew arriving on Mars.

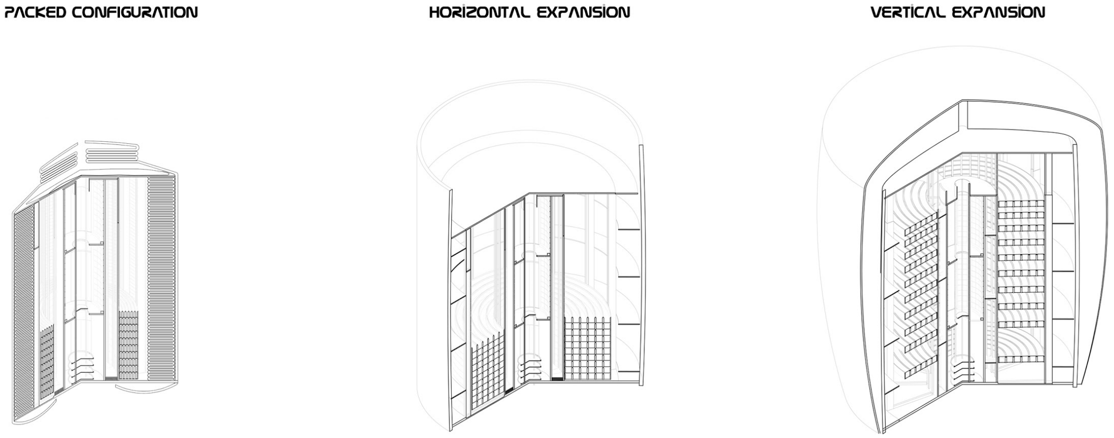


Figure 9: CAD demonstrating the compressed greenhouse (left) and expansion mechanisms (center and right)

3.4.3 Focus: Helical Track Decompression

The horizontal compression and expansion of the helical track are obtained through a double telescoping structure. In the packed position, one structure is completely hidden inside the other, while during the decompression, the internal structure simply slides out of the external one. The length of the internal structure increases from the innermost to the outermost portion of the track. When the track starts to slide and unpack, its diameter increases from 4.1 to 6.2 m while keeping the same circular shape.

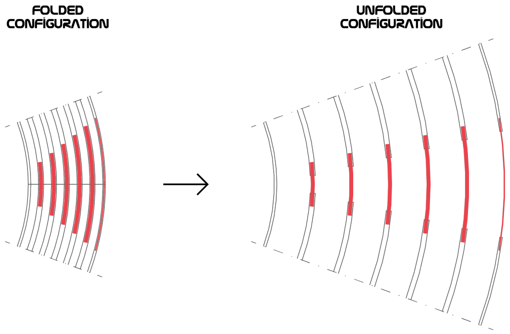


Figure 10: Telescoping track expansion

3.4.4 Additional Setup

Once autonomously deployed and expanded, the system will require a few more preliminary steps before it is fully functional. These steps are best accomplished by the crew rather than using expensive machinery to automate the process, as they are relatively simple and straightforward. Once BEAVER has been completely deployed, the crew will move the hydroponic trays and tubing into place and set up the LED lights to begin seeding. Crewmembers will also assemble the furniture for the working area at ground floor and the relaxation space on the top floor. Lastly, atmospheric control will need a human set up to complete BEAVER's deployment.

One of the strengths of BEAVER is the extent to which it minimizes the need for human setup; it is able to completely expand and begin filling its shielding with water without any human intervention or presence. The only activities required of humans are the aesthetics and growth area setup that would be too costly and impractical to have automated.

3.5 Materials

BEAVER is designed with a similar outer structure and integrates many of the same systems and materials as those in the Mars Ice Home. The outer covering will be made with Beta cloth, with the optional addition of Chromel-R for abrasion resistance [42]. The ice, insulation, and water bags will all be made with Mylar, which has high strength and is impermeable to both gases and liquids. The interior structural layer will be made with Teflon, chosen for its strength and low creep value, and the structure's inner bladders are to be made with HDPE, which is puncture resistant and flexible at a wide range of temperatures.

In selecting the materials for the interior of BEAVER, the team took into account each material's versatility, durability, strength to weight ratio, cost, and precedent in space use. With this in mind, the interior of BEAVER will be made with a combination of plastics such as polypropylene, polyethylene, polycarbonate, and ABS [43, 44]. In particular, the spiral structures used to support the plant systems in the greenhouse will be made with carbon fiber, chosen for its strength and low weight [45].

Table 7: Greenhouse building materials

Greenhouse Part	**Material**
Vertical support beams	Aluminum
Structural columns and core	Carbon Fiber
Spiral	Carbon Fiber with aluminum structural reinforcement
Trays	Plastic (Polyethylene)
Inner Stairs	Carbon Fiber with aluminum structural reinforcement
Other inflatables	Kevlar, reinforced with RFP (Reinforced Fiber Polymer)
Water tank at top	Kevlar, reinforced with RFP (Reinforced Fiber Polymer)
Germination cabinets	Aluminum
Water Tubing	Reinforced Tygon

3.6 Tray Design and Movement

Six of the eight archetypes of plants will be grown in the main spiral of the greenhouse, described in detail in Section 3. The other two archetypes will be grown in the central column of the greenhouse in order to provide their required amount of vertical growing space. Each of the six spiral archetypes will have a dedicated track in the spiral that they flow down during their growing lifecycle. The plants will begin as a germinated seedling at the top of the spiral, flow down their respective tracks during their lifetime, and be harvested at the bottom. In order to facilitate their movement down the spiral, polyethylene trays will hold the plants.

Each tray is made of durable polyethylene plastic and holds several plants in place. In this way, it is lightweight and easy for the astronauts to manually remove from the spiral if necessary. The tray is supported by rollers that connect to the track and allow the trays to slide down the spiral under the force of gravity. The trays are a maximum of 30 cm to support traditional hydroponics and provide room for stem and root growth.

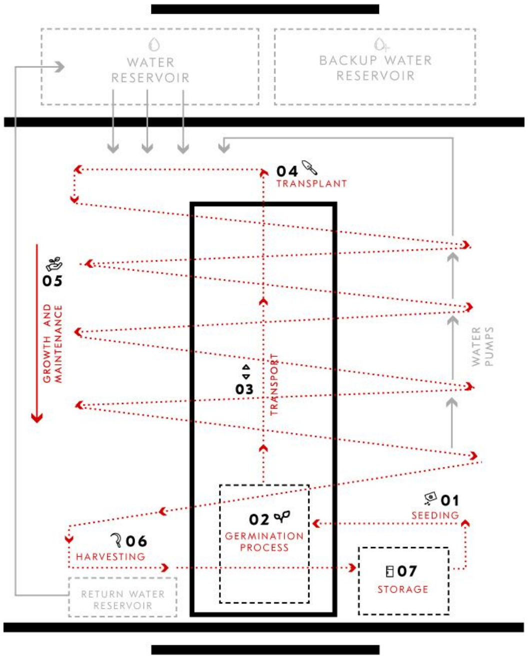


Figure 11: Water movement in BEAVER spiral

Trays in the greenhouse follow a repeating life cycle: they begin at the top of the spiral, gradually slide down under the force of gravity as the plants they are holding mature, are removed at the bottom when the plants are ready for harvesting, pass into a cleaning and reseeding chamber, spend some time in a germination cabinet, and complete their cycle by being sent up to the top of the greenhouse on a vertical lift with fresh plants.

Beginning at the top of the spiral, a tray is manually placed in its appropriate track. The track is chosen based on the large number stamped on the tray that corresponds to the type of plant it holds in order to reduce confusion for astronauts since it may be difficult to tell which type of plant the tray holds when the plants are small seedlings. For example, trays with a "1" stamped on them hold lettuce-like plants and are slid into the innermost spiral track.

The trays move down the spiral under the force of gravity and require no moving parts. This is one of the innovations of the spiral design; it uses gravity to remove the need for any mechanical means of moving trays as the plants grow. The trays are constrained laterally by the sides of the track in which they are placed, and have rollers that allow them to move with minimal friction, removing any issues of trays ‘sticking’ and not flowing down their tracks.

When at the bottom of the track and ready for harvest, trays are removed by astronauts and placed on the workbenches to harvest and process the crops. The trays are then moved into a cleaning area, where they are cleaned and sterilized with UV light. After this, the astronauts reseed the trays and place them in a germination cabinet for a predetermined amount of time. Finally, when the germinated seedlings are ready to be moved into the track, they will be placed on the vertical lift in the central core and transported to the top of the spiral.

In the event that a tray needs to be removed before the end of the track, it can be lifted out of the track and carried down to the ground floor for adjustments or disposal. A set of small, triangular chocks will be used to prevent trays from filling the gap in a track when a tray is removed. Before removing the tray from its position, an astronaut will take the chocks and insert them in front of the wheels of the previous tray in the track. Once the tray is replaced, the chocks can be removed. This provides a simple, efficient way to remove trays anywhere in the spiral.

Section 4: Systems Engineering

4.1 Systems Engineering Approach

Five primary drivers play into the greenhouse design: food production, risk mitigation, human integration, energy minimization, and efficient utilization. First, the design was optimized space for maximum food production using a spiral design that grows with the plants. To mitigate risks, all systems were made redundant with the ability to be isolated as necessary. Humans were kept in mind at all times when it came to atmosphere control, maneuverability in the greenhouse, and the design of the top area for recreational activity. To ensure that the greenhouse was sustainable, many design decisions were made to minimize the amount of energy required for operation. For example, the tray system uses gravity instead of requiring moving parts and the atmosphere between the Ice Home and greenhouse support one another. Lastly, the team focused on implementing systems with dual purposes for efficient utilization of limited space such as the human factors area doubling as a reseeding area.

4.2 CONOPS

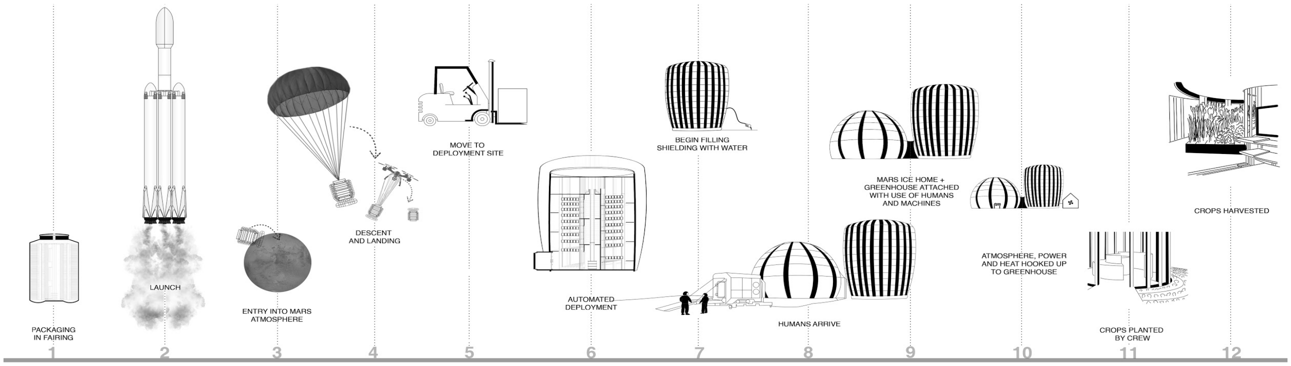


Figure 12: High level Concept of Operations (CONOPS) for the BEAVER system

4.3 Major Subsystems Designs

4.3.1 Environmental Control and Life Support Systems (ECLSS)

The greenhouse will be kept at 14.69 psia, a pressure .007 psia less than the Ice Home. This is done for three reasons: to keep pressure at a level humans are used to, to keep airflow in the direction of the greenhouse to prevent contaminants from entering the Mars Ice Home habitat, and to maintain a low D/P on the door for easy opening [46]. While there is a benefit of plant growth at higher pressures and CO_2 levels, these levels would neither be good for human health for extended periods of time nor keep airflow away from the living spaces in the Ice Home. Additionally, maintaining a higher pressure would require much more energy and an airlock system to separate the two buildings. Instead, a relief valve system will be installed to enable equalization between buildings in the event of pressure changes. Studies have also shown that both humans and plants can operate at lower pressures and higher concentrations of O_2 and CO_2, respectively. While this could provide structural benefits to the greenhouse by reducing the pressure differential between it and the Mars atmosphere, it would present several challenges. Chief among these is the effect it would have on greenhouse equipment; sensors, machinery, and other electronics would all have to be tested and characterized in low-pressure environments prior to launch. One of the selling points of this proposal is its use of non-specialty equipment with a high TRL on Earth; changing the atmospheric pressure that the equipment operates in essentially lowers its TRL, increasing mission risk and complexity. Therefore, the team concluded that the atmosphere should be operated at Earth pressure for the same reasons that the International Space Station is maintained at 14.7 PSI [47].

To obtain the benefit of higher CO_2 levels for plant growth [48], CO_2 will be kept at 800-1000 ppm. This is approximately twice that of Earth's atmosphere and is done to promote plant growth while also maintaining a safe level for human health [49, 50]. While O_2 levels will be kept consistent with the Ice Home, the temperature will be kept slightly higher at 23-26 °C. This temperature band is chosen to promote faster growth of the primary crops while not reducing the yield [51]. Residual heat produced from the humans and nuclear reactors will be used to increase temperature along with heaters spaced throughout the greenhouse.

To further provide benefits to both the Ice Home and the greenhouse, the connection between the two will allow the exchange of gases. CO_2 expelled by humans will aid plant growth, and the plants in the greenhouse will gradually take over as the primary means of recycling human-made CO_2 and converting it to O_2 via photosynthesis.

NASA reports show that astronauts consume roughly 0.84 kg of oxygen and produce 1.00 kg of CO_2 per Earth day [52]. The needs and effluents of plants are much more difficult to predict, as they depend on a large number of variables. However, an averaged value of 32 grams of oxygen released per 150 g of plant tissue grown can be used [53]. BEAVER produces roughly 7000 kg of plant material each Earth year, which translates into 19 kg of biomass produced per day. This, in turn, means that 4.1 kg of oxygen will be produced per day by the greenhouse. Using the stoichiometry of photosynthesis, the plants in BEAVER will consume 5.6 kg of CO_2 per day.

Table 8: Production and consumption of oxygen and carbon dioxide by astronauts and plants

Gas Consumption and Production	**Astronauts**	**BEAVER Plants**
O_2 Consumed/*Produced* per day	3.4 kg	*4.1 kg*
CO_2 Consumed/*Produced* per day	*4.0 kg*	5.6 kg

This means that all of the oxygen required of the astronauts can be produced by BEAVER, and over 70% of the carbon dioxide required by the plants can be produced by the astronauts. The excess CO_2 will be supplied from the Martian atmosphere by way of a scroll pump and compressor. Nitrogen will be supplied to both habitats from bottles until a less energy-intensive method of separating N_2 from the Martian atmosphere is optimized.

The greenhouse atmosphere will be monitored in the inner volume fan room, which will house a fan for air circulation and an atmosphere monitoring system. The system will utilize mass spectrometry to quantify contaminants by ionizing gas molecules with an electron beam and sorting them in a magnetic field. This allows astronauts to measure almost every aspect of the atmosphere including H_2, N_2, Ar, O_2, CO_2, and other hydrocarbons [54]. When levels are known, solenoid-operated valves can increase or decrease levels as desired from gas banks.

4.3.2 In-Situ Resource Utilization (ISRU)

ISRU of water and CO_2, and at a later stage of metals and silicates, is a critical aspect of this mission and accordingly a key driver of landing site selection. The recommended landing site is the Erebus Montes Exploration Zone (EZ), centered at 39.0N 192.1E with an elevation of -4,000 meters. It is one of the candidate EZ's identified in the 2015 NASA Human Landing Site workshops [55]. The pilot study [56] of the ongoing Subsurface Water Ice Mapping (SWIM) project [57] has identified nearby parts of Arcadia Planitia region as being consistent with the presence of excess subsurface water ice, thought to be abundant throughout this entire region. Water will be harvested from Mars for the greenhouse's shielding and hydroponic systems in the same way that it is harvested for the Mars Ice Home. A water production rate of 0.125 m^3 per day, half of the Mars Ice Home production rate, is assumed to support BEAVER. Initially, this limited water will be used to begin filling the ice shield starting from the top and to support plant growth in one track of the spiral. The water available will increase over time as less is needed for the Mars Ice Home shielding, allowing other tracks to be supplied and the greenhouse capabilities expanded. In addition, the team proposes to use solid oxide electrolysis (SOE) to produce oxygen from the Martian atmosphere for habitation pressure in the greenhouse. One of the MIT team members is on the science team for MOXIE, a science instrument flying to Mars in 2020 to prove this electrochemical concept. By using a scroll compressor to compress the Martian atmosphere to 1 bar and a scalable SOE stack, the required amount of 99.9% pure oxygen can be produced. This conversion would take place outside the habitat and be fed into the greenhouse through a triple-redundant valving system and pump. Thus, a significant portion of the up-front oxygen - along with resupplies that are needed due to the ice home's airlock air loss - can be produced with ISRU on Mars. Finally, the same scroll pump will be used to resupply the greenhouse with CO_2 by compressing the Martian atmosphere and feeding it into the greenhouse to maintain the required concentration of 800 ppm.

4.3.3 Power

Power is a potentially limiting resource on any space mission; therefore, the team carefully designed BEAVER to minimize power requirements. Systems that use power include the growth lighting, water recirculation, atmospheric conditioning, resource exchange between the greenhouse and Ice Home, tray elevator, and thermal control. The major consumers of power will be described in more detail in this section.

BEAVER will be powered with Kilopower reactors. This was chosen over solar power because of the added mass and maintenance required of solar panels, along with their variability due to Mars dust. Each Kilopower reactor is expected to produce 10 kWe [58]. The peak power demand of the greenhouse is 53.5 kW, while the average power demand is estimated at 38.9 kW. Therefore, four Kilopower reactors will be needed for nominal operations, with just over five required in extreme circumstances during peak power demands.

Six reactors are included in the design of BEAVER to cover peak power demand while still providing adequate margin and redundancy in the case of a unit failure. A summary of the calculated power requirements is given below.

Table 9: Power budget for the BEAVER system.

Component	**Peak Power (W)**	**Estimated Average Power (W)**
LED Lighting	48355	35520
Water Circulation System	325	325
Heaters	800	200
ECLSS	800	400
Power Conditioning	500	400
Controls and Computing Systems	1000	1000
Automation Equipment	1350	800
Exchange System with Mars Ice Home	200	200
Misc. (Valves, sensors, etc.)	200	50
Total Requirement	**53.5 kW**	**38.9 kW**

The power requirements for the LEDs, water circulation system, automation equipment, and exchange system were calculated for the greenhouse, while the rest of the numbers were estimates from the Mars Ice Home design. The total power was minimized to keep the greenhouse's needs comparable to the main habitat. This was accomplished through engineering solutions that minimize moving parts and employ dual-use systems. For example, the greenhouse tray system is designed to move with gravity instead of having a mechanized system that would require power. Another example is that the CO_2 scrubbers use passive amine beds instead of a powered system.

LED Lighting

The vast majority of the power requirement comes from the LED lighting used to provide adequate growing conditions to the plants, an unfortunately high but necessary number in any greenhouse architecture [59]. Standard LED lighting arrays used for indoor greenhouses are employed in this architecture to maximize the TRL of this subsystem. Calculations for the power required were fairly straightforward: the total plant growing area was multiplied by the average lighting requirements of the crops and divided by LED efficiencies in order to arrive at a total power requirement for the subsystem. While this number is high, it is unavoidable; plants require a certain amount of power to grow, and the purpose of the greenhouse is to grow these plants.

Water Recirculation

A key innovation of BEAVER is its minimization of mass in the plant spiral. A heavy spiral would require large support struts that would add to the system's mass, raising costs. With this in mind, the spirals were created to hold a small mass of water at any given time while still meeting the needs of the plants. Rather than hold plants in trays that constantly carry a pool of water – which would be heavy and expensive – the system instead uses a small, constantly flowing stream of water that runs down the spiral. The stream is 0.8 cm deep, providing significant margin to the 0.2 cm of depth that plant roots generally require in a hydroponics system. The power required to continuously pump water in recirculation loops to feed each of the hydroponics tracks in the spiral can be calculated as follows:

$$P = \rho Q g h / \eta$$

where ρ is the density, Q is volumetric flow rate, g is gravity, h is height, and η is pump efficiency. ρ, g, and η are all known constants. The height is taken from the greenhouse design. The volumetric flow rate can be calculated using Manning's Equation [60]. These calculations all result in a power requirement of roughly 325 W. This is a very conservative estimate, as it overestimates the required water depth needed and includes a 30% margin.

4.3.4 Thermal

The thermal system is designed to optimize natural sources of heat in order to minimize the input required to maintain the greenhouse operating temperature. Residual heat from the Kilopower reactors will be transported to the greenhouse via liquid heat exchanger tubes. This heat will be routed to the bottom level of the greenhouse in order to create a natural convection cycle, forcing air circulation to supplement that which is already supplied by fans. In addition, residual waste from LED inefficiencies and humans will be a natural heat supply. Finally, the greenhouse floor and all areas where the outer spiral contacts the greenhouse walls (and thus already blocks incoming light) will be covered in aerogel insulation, which will reduce the amount of heat exchange between the greenhouse interior and exterior. Extra heaters will be available as a backup system in case they are required.

4.3.5 Structure: Radiation Shielding

Radiation shielding will mimic that of the Ice Home. Pure water ice will fill the outside walls of the greenhouse and provide 1-2 meters of shielding at all levels. The top level, where the human recreation area is located, will have the most shielding due to 2 meters of top ice shielding and 1 meter of water shielding from the reservoir. These levels of shielding are expected to reduce the amount of incoming radiation by between 40% and 60% [61].

4.3.6 Hydroponics: Water and Nutrient Feed System

A novel piping and isolation system was designed to allow water and custom nutrients to flow down the hydroponics spiral while providing quarantining capabilities to eliminate disease spread. A water reservoir will be the primary source of water for each track with a backup reservoir available to be placed online in the event of primary contamination or damage. A reinforced Tygon tubing piping system will connect each loop to the water reservoir system, and a nutrient delivery system will be attached to the top of the piping system below the water reservoirs. All three systems will be double valve isolated from one other to ensure robust contamination and leak isolation.

In order to fill a loop with nutrient-laden water, solenoid-operated valves will open in sequence by a computer signal (primary) or manually by a human (backup). In order, the track valve and reservoir valve will open to allow water to flow from the reservoir into a track and down the spiral. This valve operating sequence was chosen to minimize D/P on each valve to extend their life and to ensure water only goes into the appropriate loop. The shutting sequence will be the reverse of the opening sequence to ensure no water gets trapped in the piping system. Gravity is used to flow the water, and thus no pumps are required in this part of the system.

Since each loop can have a different type of plant at different levels of development, different nutrient mixtures will be fed into each track. The primary types of nutrients are stored as aqueous solutions in separate bottles, which are all connected to the piping system. When nutrients need to be delivered to a track, a central computer (primary) or human (backup) will open the nutrient valves to allow appropriate custom mixes to be sent to the correct part of the spiral. The nutrient valves will open in sequence with the water reservoir system and piping system valves to enable water and nutrients to flow to the desired loop simultaneously.

Once water flows from the reservoir at the top of the greenhouse and around the spiral, it eventually reaches the ground floor. Here it is collected in a water reservoir that is treated with filtration, UV sterilization, and optionally passed through a reverse osmosis unit. Once cleaned, the water is pumped back up to the top of the greenhouse with pipes located inside the central column of the greenhouse. The cycle then repeats, creating a simple, safe, and effective water circulation loop that feeds the hydroponics system. The piping and pumping systems have been designed in detail but are omitted from this report for the sake of brevity.

4.4 Ice Home - Greenhouse Interface

A dual pressure door system is employed between the two structures; one door opens inward to the Mars Ice Home, the other opens inward to the greenhouse, and a small passageway exists between the two. This is similar to an airlock but without the air-cycling capability. An airlock was avoided because trade studies determined that it would require too much additional space, power, gas, and time to operate. With the proposed configuration, the atmospheres of the two structures are kept mostly isolated from one another. In addition, in the event of a sudden depressurization or emergency in one of the structures, the second structure is protected by the pressure doors. Access to the damaged structure for repairs is possible without compromising the second due to the dual-door setup.

Many resources will be exchanged between the two systems. These include food, power, data, gases, residual heat, wastewater, clean water, biomass, and waste. The majority of these resources will be transferred via pipes or tubes parallel to the pressure doors and isolated with dual-redundant solenoid valves. The food will be transferred manually by humans through the pressure door passage.

Of particular importance to this design is the exchange of gases across the interface. CO_2 and O_2 will be exchanged between the Ice Home and BEAVER in order to utilize the mutually beneficial gas exchange process between humans and plants. CO_2 will be removed from the Ice Home by a continuous rotating scrubber using temperature swing adsorption and released into the greenhouse with the addition of heat [62]. The O_2 from the greenhouse will be pumped into the Ice Home by a pipe and valve system that periodically moves filtered gas across the habitat interface. This was favored over fractional distillation of oxygen as it is a simpler and less power-intensive method of moving oxygen from BEAVER to the Ice Home. Thus, the inhabitants of the Ice Home (astronauts) and BEAVER (plants) can utilize a mutually beneficial gas exchange system enabled by the design of the pressure door.

4.5 Sensors and Automation

In order to minimize human labor time, portions of the Greenhouse operation will be automated. These automations all exist within the growing system, leaving the pre and post processing systems to human labor. A roadmap for the post-deployment evolution of BEAVER into a fully automated greenhouse is in Section 4.11.

The primary work during plant growth is in control of water, environment (light, temperature, atmospheric conditions), and nutrients. Automated environmental control is straightforward, as the primary Greenhouse computer needs only to be programmed with how the LEDs are to be cycled and temperature being monitored as well by the computer and using bang-bang control to turn on the backup heaters if active measures are needed. The atmospheric control has been discussed and using commercially available CO_2, O_2, and humidity sensors will allow this control to be automated. Automated control of the hydroponic water and nutrient feed is achieved through pH and electrical conductivity sensors placed throughout the feed system. This will allow tight control of the solution fed to each track, giving a robust estimate of the solution state. These systems have all been commercially demonstrated by groups such as Postscapes and Freight Farms.

In addition to the above commercially available sensor systems, cameras will be placed throughout BEAVER and make use of modern computer vision techniques to monitor plant health. This will streamline astronaut tasks within the Greenhouse by removing visual inspection tasks that would be highly time-consuming for astronauts.

4.6 Launch and Landing Loads

BEAVER will be packaged in a stowed configuration to fit inside a large rocket fairing, as discussed in Section 3. The system will be subjected to normal pre-launch checks (acoustic, vibration, shock, TVAC, EMI, EMC, etc.) to ensure compatibility. In its stowed configuration with its use of high TRL, space-rated materials, and given its similarity in structure to the Mars Ice Home, which has been analyzed for launch loads, BEAVER is expected to survive all launch and landing loads on its journey to the Martian surface.

4.7 Mass Budget

The total projected mass of the greenhouse system, which includes the outer structure, inner spiral structures, central core, upper and lower floors, plant trays, LED fixtures, water and air circulation systems, life support systems, Kilopower modules, furniture, batteries, plant nutrients, and command and control is 13,380 kg. A summarized version of the full mass budget is shown in the table below.

Table 10: Mass budget for BEAVER system.

Greenhouse Component	**Mass**
Combined Structural Mass	9321 kg
Kilopower Modules	1575 kg
LED Arrays	906 kg
Plant Nutrients and Equipment	553 kg
Command and Control	300 kg
Water and Air Distribution	620 kg
Misc. (batteries, furniture, etc.)	103 kg
Total Launch Mass of BEAVER	**13378 kg**

This total is well under the 18,000 kg allowance, allowing several metric tons of margin. The BEAVER team suggests that 3,000 kg of this margin be used to take water to significantly jumpstart the timeline of the greenhouse operation. This would also serve to mitigate the risk that ISRU production may be less efficient than initially expected. One of the main strengths of this proposed design is the low mass; a strength which can be utilized to mitigate more mission risk and begin plant production sooner than other designs considered.

4.8 Risk Management

The first goal of the greenhouse design was to optimize food production, but minimizing risk is essential for continued safe operations. This means that all parts of the greenhouse are designed with redundant features. In addition to the risk management measures previously mentioned, several more are included in the BEAVER design. There is a primary and backup water reservoir for the crops in case a water supply becomes contaminated. Two backup pumps support pumping water into the reservoirs with LVR motor controllers connected to an ABT switch so that one pump can always be running for each track. Furthermore, each section of the tray beds has the capability to be isolated from the rest of the greenhouse water supply to prevent the spread of waterborne disease while continuing operation. All features throughout will be double-isolated or have a backup system available to continue food production to the maximum extent possible. The team understands that minimization of risk is one of the primary drivers for space-rated designs, and that is why reliability was one of the five key design drivers for BEAVER.

In the case of a power outage, BEAVER's two battery backups will enable continued operation for approximately 3 hours, but this time is expected to increase with graphene and other advanced material research ongoing. If required, the Emergency Nutrition System, which requires no electrical power, will automatically start. Upon sensing power failure to the pumps, the backup water reservoir and emergency nutrient mix container will open and begin to feed the six tracks. The emergency nutrient mix will include a premixed solution capable of providing nutrients to all six tracks until power can be restored. Valves will also fail open to ensure proper flow, and the water will be pooled in the collection basin at the bottom of the greenhouse until power is restored and it can be pumped back to the top. As for atmosphere control losing power, Dräger sampling tubes and systems [63] can be used by astronauts to measure atmospheric composition and gas tanks can be adjusted manually.

In case of a rupture in the greenhouse shell, the pressure door will isolate the two habitats to ensure safety to the astronauts. To access and repair the greenhouse, astronauts will use the main airlock to the Ice Home to access and repair the greenhouse from the outside. Once fixed, the greenhouse can be pressurized through the Ice Home connection to BEAVER and the backup gas tanks if required. Altogether, these redundant and automated emergency systems allow BEAVER to have a robust design against all major risks. BEAVER can survive autonomously for multiple days since no major tasks rely on astronauts apart from harvesting and planting, which are non-mission critical. If an emergency does occur, however, emergency systems automatically isolate issues and provide enough time for astronauts to act to prevent loss of crops and continued operation.

4.9 Dual-Use Capabilities

A major design driver for BEAVER was the incorporation of dual-use capabilities into the system. By including subsystems and processes that serve multiple purposes, the greenhouse becomes more efficient. One example is the dual use capability of plants: to produce food, enhance crew mental well-being, and recycle air, all at the same time. A large consideration was given to enhancing the user experience of the greenhouse to improve the mental well-being of the crew. Additionally, the oxygen produced by the plants is periodically transferred to the Ice Home habitat for astronauts to breath. In a similar vein, the astronauts themselves have dual-use capabilities with regards to the plants; they are used to convert oxygen into carbon dioxide and their waste is used to provide nutrients to the plants.

From a systems standpoint, many systems serve multiple functions. For example, the LEDs provide light to the plants but are also used to provide extra heat to the greenhouse to maintain its temperature. Likewise, for the Kilopower reactors, their primary output is electrical energy but waste heat is also captured via a system of heat exchangers and transferred to the greenhouse via natural circulation to maintain its temperature.

From an architectural standpoint, the human factors areas serve as both a relaxation area and the prime location to load trays into the spiral. The waterfall in the human factors area creates an aesthetically pleasing environment while also feeding the hydroponics system. The water tank on top of the greenhouse supplies gravity-fed water for the system while also providing additional radiation shielding for the crew and plants.

4.10 Future Automation and Efficiency Considerations

BEAVER is designed as the first iteration of a system that will fulfill a longer and greater purpose than simply serving the first few crews on Mars. As such, it is designed with extensibility in mind to improve efficiency and autonomy.

Two options for architectural extensibility of BEAVER are (1) to bury part of the greenhouse structure underground and (2) to fabricate a significant part of the structure from ISRU systems on Mars. Partially burying the structure would require additional up-front excavation but would reduce the amount of water needed for ice shielding. The door between the habitat and greenhouse would be moved to the second or third level of the greenhouse to accommodate this vertical shift. In addition, the team acknowledges that in future, with broad-based ISRU and manufacturing capabilities on Mars, the spirals that comprise the majority of the greenhouse could be 3D printed on Mars rather than made of an inflatable material and packaged on Earth. This could improve the strength of the spirals, use local resources to make BEAVER scalable, and add flexibility into the design and its transport.

From an ecological standpoint, custom temperature controls for each track in the spiral could be added. Different plants grow optimally at different temperatures. For these, it is proposed that a future iteration of BEAVER include parabolic-style controllable heating apparatuses and cooling fans that are mounted above specific tracks. These would allow the temperature of each track to be optimized with respect to maximizing crop yields while staying within any hard temperature constraints of the crops.

Options for increasing BEAVER's autonomy and reducing its demands on crew labor time can be designed and tested in advance in Mars analog simulations and gradually introduced as upgrades after the initial crew deployment. In the first synod after crew arrival, an automated sorting concourse would be installed at the top level to automatically direct trays from the elevator to the entry point of the appropriate spiral ramp. With the second synod opportunity, a second sorting concourse would be added at ground level to direct trays to newly automated processes for harvesting, tray cleaning, and seeding. Both sorting concourses would be assembled from the same basic modular element for ease of maintenance and support and would significantly reduce the astronaut labor requirements.

Finally, another automation option that can be gradually introduced is a set of portable devices that sync with the planning and communication software. This can be done using analogs of Apple Watch or additional displays along the spirals. One of the most promising solutions that can be also used to remind the procedure *ad hoc* as well as be updated with temporal and spatial directions from the system is an Augmented Reality Headset and relevant planning and work environment software. In late May 2019, one such type of software designed for Microsoft HoloLens will be publicly available and would serve as a good option for this proposed system [64].

Section 5: Prototype

The design, fabrication, and testing of a prototype was a key step in the development of the BEAVER concept. It helped focus the team's attention on the difficulty of packaging and deployment while also validating key innovations in the design. The following section will describe the design process of the prototypes, reveal their final designs in the finished products, and discuss how the prototyping process helped shape the BEAVER architecture.

5.1 Design Process of the Prototypes

The primary goals of the prototypes are to: (1) physically model the greenhouse structures relative to one other, (2) further elaborate on the deployment of the spirals, and (3) show the plant tray movement in greater detail.

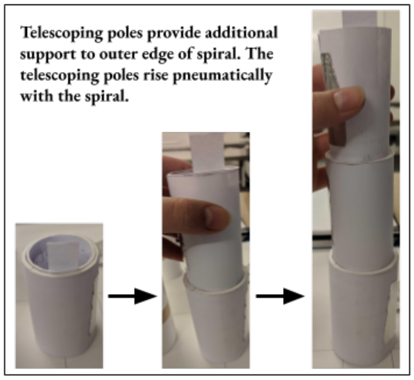


Figure 13: Telescoping poles in the prototype

A 3D-printed model of the greenhouse was created to show all components in relation to each other. Each key component of the greenhouse is removable from the model to allow for further inspection.

A second, simplified inflatable prototype of the greenhouse was built to demonstrate the feasibility of deployment, particularly the expansion of the internal spiral structure. As the exterior of the dome inflates, the attached spiral rises from its folded to the deployed formation. Along the outer edge of the spiral are several telescoping poles that provide it with further support.

A third prototype, consisting of a flat spiral with modular trays, was laser cut to show the movement and shape of the trays along the spiral.

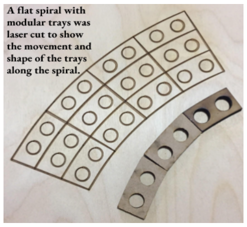
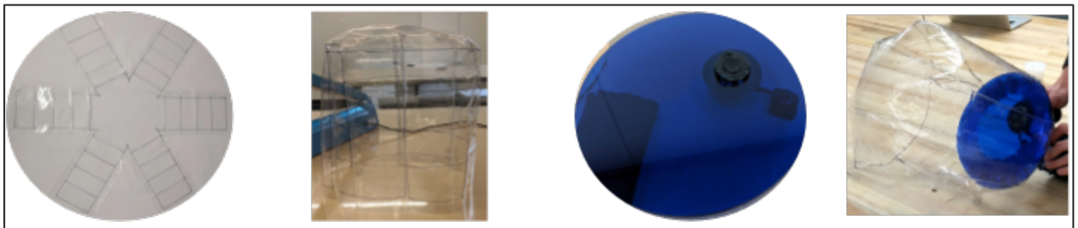


Figure 14: Laser cut plant trays

5.2 Development of the Prototypes

The evolution of the prototypes was fueled by two factors: developability and scaling. The process of fabricating the doubly curved outside structure of the greenhouse for the deployment prototype from a flat vinyl sheet initially resulted in a large, complicated, non-airtight inflatable structure. However, after re-evaluation, the flattened greenhouse was simplified into one large piece of vinyl (shown below), with double seams heat sealed together to make the entire structure airtight. This inflatable structure is attached to an acrylic base with an air valve to actuate the entire structure.

The scale of the prototype also changed because of the fabrication process; initially, the deployment prototype was about 18 inches tall; due to material and tool limitations, this height was reduced to about 12 inches. Similarly, because of 3D printing time constraints, the solid model of the greenhouse was reduced in size.



Dome and side panels cut out of single piece of vinyl.

Outer shell assembled and sealed with heat sealer.

Acrylic base with air valve attached.

Shell attached to acrylic, air sealed, and inflated with air pump.

Figure 15: Development of the inflatable prototype

5.3 The Influence of the Prototype on BEAVER

The design and fabrication process of the prototypes provided useful feedback about the viability of the original greenhouse concept. The prototype impacted all areas of the design but had a particularly pronounced effect on the structure and deployment method of the plant spirals. The original deployment method for the individual spirals called for multiple telescoping poles between each level; this proved difficult to implement in the prototype, so the design was changed to include telescoping poles through spiral layers. The method of actuation changed as well, from pneumatically actuated telescoping poles between layers to the inflation of the outer layer of the greenhouse structure itself. The spirals were connected to the outer shell to simplify deployment and provide further structural support. These are just a few examples of how prototyping influenced the overall design development of BEAVER.

Section 6: Conclusion

The MIT team is excited to help NASA pave the way towards human exploration of Mars. BEAVER was designed to satisfy all criteria for this competition and represents a well-thought-out systems engineering design. Its architecture is centered around an elegant and purposeful spiral that takes seedlings as inputs at its top and produces plants ready to harvest at its bottom. The heights between levels of the spiral begin small and increase as one moves down the spiral in order to match the growth of plants and thus maximize vertical space. The greenhouse is stowable in a standard rocket fairing while autonomously deploying to a large enough size to produce 100% of the astronauts' nutritional needs and provide adequate working and relaxation areas for psychological well-being. BEAVER grows eight unique crop archetypes, giving the astronauts variety in their diet. It requires minimal labor to maintain - on average, 3 total hours per day split amongst the crew - and is equipped with an automated sensing network that produces an optimized Daily Task List to maximize astronaut efficiency. The greenhouse was designed to minimize risks with redundant systems and simplicity, minimize labor, and maximize production so that the crew can spend time on what counts: exploring Mars.

A significant number of trade studies, analysis, and calculations were completed prior to arriving at the final design of this system. Many of these had to be omitted from this report for the sake of space. In addition, the full CAD for this design has been completed and is available upon request. Thank you very much for your consideration of this design proposal.

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