Utilizing the Pressure Gradients of The Greenhouse on Mars

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Dedication

To My Mother
To My Father

تقدیم به قهرمانان زندگی ام

مادرم و پدرم

ACKNOWLEDGMENTS

I want to appreciate all my professors at the Sasakawa International Center for Space Architecture (SICSA) for giving me the chance to gain knowledge in this program. Of course, this would not be possible without the patience helping of our program director, Dr. Olga Bannova.

ABSTRACT

Current models of greenhouse design primarily focus on enabling a means for water recycling, air revitalization, and food production. However, the enormous potential of using interior landscaping for positive psychological effects on the crew has been neglected. An indoor garden impacts living conditions within a confined environment of surface habitats in active and passive ways. Actively, from the human factors perspective, it diversifies the crew's diet and adds the enjoyment of on-site gardening to routine activities. Passively, it brings colors, textures, and aromas into the otherwise mundane interior environment.

This research by design process starts with plant selection based on their nutritional values using recipes from different cultures. Next, environmental requirements are considered for a hydroponic planting system for selected plants such as temperature, pH, and pollination methods. Afterward, the sizes of mature plants are reviewed to generate structural measurements of plant beds. Since architectural elements and design principles are linear, planar, and three-dimensional (3D), the integrated result is characterized into four categories: Plant Bracket, Plant Wall, Plant Trellis, and Plant Box.Finally, this project concludes by proposing the criteria for feasibility studies pertaining to the construction of a greenhouse on Mars surface at different stages of infrastructure development. Design factors for the evaluation of greenhouse module proposals are presented and categorized by the level of their impact on overall mission planning and success.

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1. INTRODUCTION

For humans to survive a 600-day mission on Mars's surface, the presence of a greenhouse module is essential. The crew cannot bring all the required food supplies with them from Earth and would have to grow food on Mars. To date, two categories of greenhouse designs have been proposed: an industrial-scale greenhouse, which prioritizes efficiency partly through maintaining a low-pressure environment, and a habitable greenhouse, which supports psychological wellness by maintaining a fully pressurized environment that crewmembers can move freely in. This project presents a hybrid approach in which a greenhouse module could support a variety of pressures, allowing for benefits from both types of designs and providing other advantages as well.

This project presents a design approach that combines both tactics — a series of trade studies aimed to find a feasible compromise between human factors and agricultural requirements.

1.1 Vision

Creating the multifunctional greenhouse space to support the physical and psychological needs of the crew during the long-term mission on mars.

1.2 Goals

Designing a complete and independent greenhouse module with pre and post-harvesting lab is the primary goal of this thesis. Maximizing flexibility and lowering redundancy in different modes (operation, hibernation, and power-off modes) would be the second priority, and taking advantage of utilizing human waste for the composting system is the ECLSS System goals.

1.3 Strategies

Towards the independent goals, utilizing one launch vehicle to deliver the system, minimizing site preparation are the strategies taken. Analyzing the folded greenhouse module in the payload shroud and the deployed architecture could lead to the maximization of greenhouse space and volume and optimization of the core size and the inflatable architecture. Increasing the quality of time spent at the greenhouse is considered as psychological strategies.

1.4 Constrains

Current Payload shroud size restrictions and exterior structure support for inflatables after deployment.

1.5 Questions

This thesis is trying to answer six main questions that answering to those could lead to the greenhouse design. Table 1-1 shows the questions. Three of these questions are about the greenhouse and three are about crew.

Table 1-1 Thesis Questions

Greenhouse	Crew
What to grow?	**What to eat?**
Plant List	Culture and menu diversity
How to grow?	**How to eat?**
Cultivation process, methods, and tools	Post-harvesting process, cooking, and recycling
Where to grow?	**Where to eat?**
The greenhouse architecture	The greenhouse human factors

2. WHAT TO GROW

2.1 Introduction

A greenhouse is an important component of the Mars mission infrastructure as plant-based life support systems offer self-sufficiency and possibly cost reduction. Resupply is prohibitive for long duration Mars missions as it increases the launch mass and consequently te launch costs. Risk toThe risk astronauts is also increased by relying on frequent resupply from Earth. Greenhouses cannot only be used for the production of edible biomass but also as air and water regeneration processors as physical human factors. This module could also support psychological support for the crew by providing a green region which resembles life on earth.

2.2 Human Factors

Human health has the physical and psychological aspects that are influenced by passive and active factors. Dynamic elements such as diet and meal diversity interact directly with human physical and mental health and are considered an active factor. Passive environmental aspects, such as aromas and color enrichment, are passive factors that affect cognitive conditioning.

2.2.1 Active Human Factors

2.2.1.1 Diet

Humans require nutrients and energy supplied in the form of calories. Insufficient calories and inadequate micronutrients trigger distinct health issues; for example, the Apollo 15 crew highlighted how an unexpected deficiency of one or more nutrients in a long-term space mission significantly affected mission success[1]. Therefore, it is essential to provide crewmembers with a required level of nutrition during their missions to prevent health deterioration. "Human-Systems

Integration Requirements," section 3.5.1.3.1 in the NASA Constellation Program (C×P) document 70024[2], thoroughly reviews nutritional requirements.

Additionally, the role of the greenhouse as a provider of various fresh food is more critical in long-duration mission scenarios. The use of fresh vegetables on Mars could enhance the nutritional intake of the crew and reduce the risk of vitamin and mineral deficiencies in their diet.

2.2.1.2 Menu Diversity

Food acceptance depends on the variety and adaptability of the food menu system. An extensive range of food items provides multiple choices to avoid menu fatigue. According to anecdotal reports, "healthier and tastier foods decrease the stress often experienced by the crew. Therefore, taste, menu variety, and an array of textures, colors, and flavors can contribute to the psychosocial wellbeing of the crew." [3]

Overall acceptability of the food is reduced when the food is challenging to prepare and eat [4]. Moreover, food acceptance can be affected by the social context and timing of meals. Food and mealtimes offer crews significant psychological and social benefits, such as reducing the stress and boredom of prolonged space missions and stimulating team-building behavior by sharing meals [4].

2.2.2 Passive Human Factors

2.2.2.1 Color, Texture, and Aroma

The current food strategy for International Space Station (ISS) prevents overly odiferous menus because other crewmembers could be disturbed in the pressure-tight habitat. In contrast, for a Mars mission, the introduction of recognizable and pleasant scents and tastes (through food) is being considered[5]. Documented testimonials about noxious smells in closed ECLSS space capsules suggest another critical function of plants onboard space habitat. Plants that indicate "freshness" can normalize the environment during long-term missions, neutralizing a certain amount of indoor "air pollution" caused by humans. "The aroma of the Earth" is a term often used by astronauts to describe the feeling of fresh fruit in the missions.[678]

2.3 Agricultural Factors

2.3.1 Plant Lists

In NASA's report "Nutritional and Cultural Aspects of Plant Species Selection for a Controlled Ecological Life Support System" [9], there are three scenarios of plant selection for a Mars mission: Minimum, Modest and Generous.

The "minimum" version represents the essential dietary requirements with less than ten plants. Nutritious plants with higher harvest index (ratio of edible portion to total biomass) are on this list, and the number of species has been dictated strictly by nutritional needs without regard for palatability and diversity.

The "modest" list has been derived from a vegetarian diet with 15 plants on the list. Simplicity is the primary driving factor, but the ability to create pleasing dishes was also considered.

The "generous" scenario pays attention to all the previous factors as well as better efficiency of nutrient recycling by the Controlled Ecological Life-Support Systems (CELSS) than the previous lists. This list has more than 35 plants making for the most variety.

Table 1 of the Appendix compares the diversity of the plant list provided by different countries. It categorizes plants into 8 types: Fruit, Grain, Herb and Spices, Leaf and Flower, Leguminous, Root and Tuber, Salad, and Sugar. The number of plants in each category reflects cultural preferences for flavor profiles in meals. Unexpectedly, the number of shared plants among the lists is not significant. For example, in the minimum list which provides for the basic needs of the crew, only peas, potato, and wheat are shared, 3 out of 13. This ratio increases in the generous list to 17 out of 36, or just above 47%.

2.3.2 Plant Selection

With just 30% of plants in common, an ultimate selection of plants does not exist and cannot be achieved due to the crew's personal preferences. Table 2-1 shows the most common plants between all the lists. This paper suggests a public greenhouse for these 24 plants and private chambers for other personal selections. To simplify the greenhouse systems, these 24 plants should have the most in common with regards to environmental needs.

Table 2-1 Most Common Plant List

Beans	Canola	Cucumber	Lettuce	Peanut	Radish	Strawberry	Taro
Broccoli	Carrot	Herbs	Onion	Peppers	Rice	Sugar Beet	Tomato
Cabbage	Chard	Kale	Peas	Potato	Soybean	Sweet potato	Wheat

2.3.3 Plant Requirements

One full life cycle of plants is shown in Figure 2-1. The cycle starts from seeding to flowering and ripening, then goes back to seeding again. Some plants bypass the formation of seeds to generate new plants by vegetative propagation. For example, potatoes can be divided into pieces, and each piece could germinate a new plant (fruiting to germination). The mature strawberry plant could reach its runners to the ground and germinate (maturing to germination).

There are various studies on genetically modified plants with more compatibility in extra-terrestrial missions[10][11]. For these 24 plants, however, the lack of information restricted this study to the non-genetically modified plants. Figure 2-2 shows the agriculture cycle from seed to seed in days. The minimum number of days for each plant cycle happens in the best environmental conditions, where the plant has the highest growth rate. The maximum number occurs in unfit conditions with the lowest rate of production.

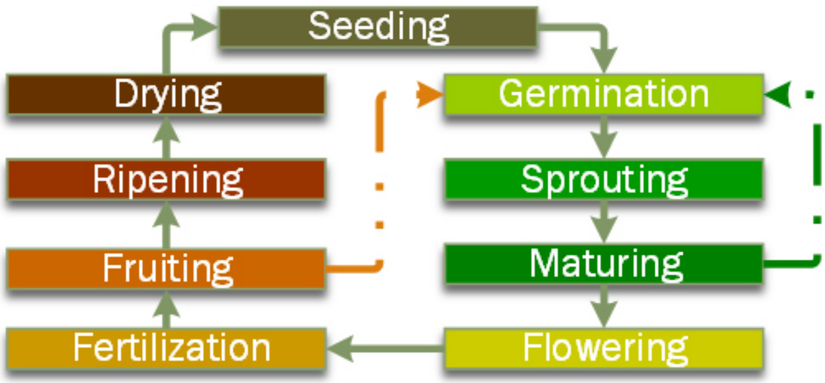


Figure 2-1 Plant Cycle

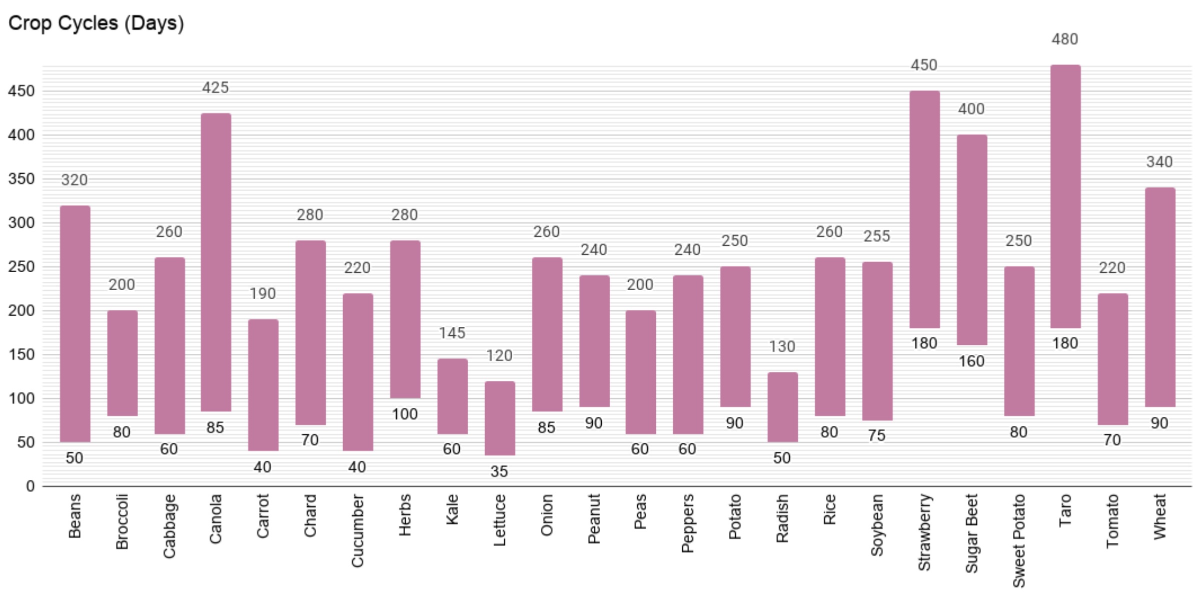


Figure 2-2 Crop Cycles Duration (Data from FAO[12])

2.3.4 Pollination

In a full crop cycle, pollen needs to be transferred from the male flower to the female in order to create the seeds for the next generation. Plants can be self-pollinating or cross-pollinating, which needs a vector (a pollinator or wind) to get the pollen to another flower of the same species. Figure 2-3 shows the pollination method for the common plant list. In the minimum plant scenario, only self-pollination plants are included to reduce the complexity of the greenhouse system. However, this approach reduces the diversity of plant types. The only wind pollination in this diagram is chard. Allergic reactions and the low rate of fertilization in a low-density plant greenhouse environment are the main two reasons that wind pollination is not recommended for a Martian greenhouse.

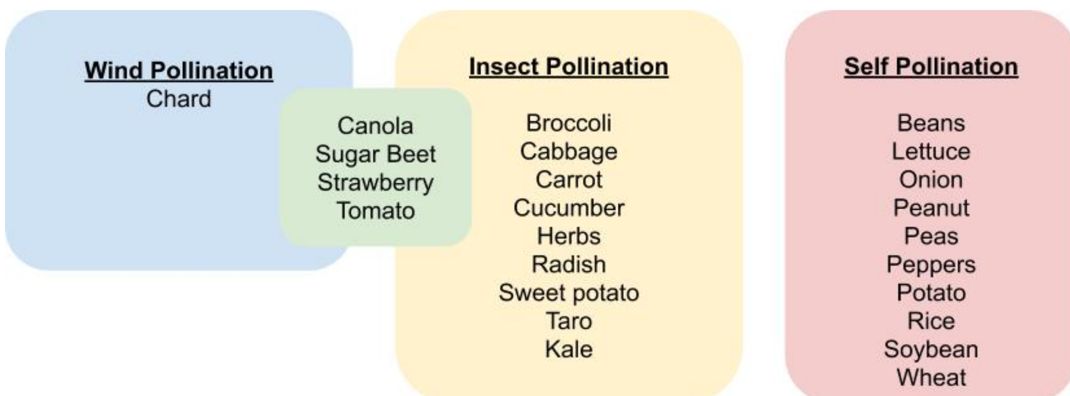


Figure 2-3 Pollination Method (Data from FAO[12])

2.3.5 Water

Since greenhouse on Mars uses closed system, the water is circulated to all plants. Therefore, it should have a pH level and nutrient value compatible with all plants. Figure 2-4 shows optimal pH levels for the common plants. Water with a pH level of 6 to 6.2 is suitable for all plants except canola and kale.

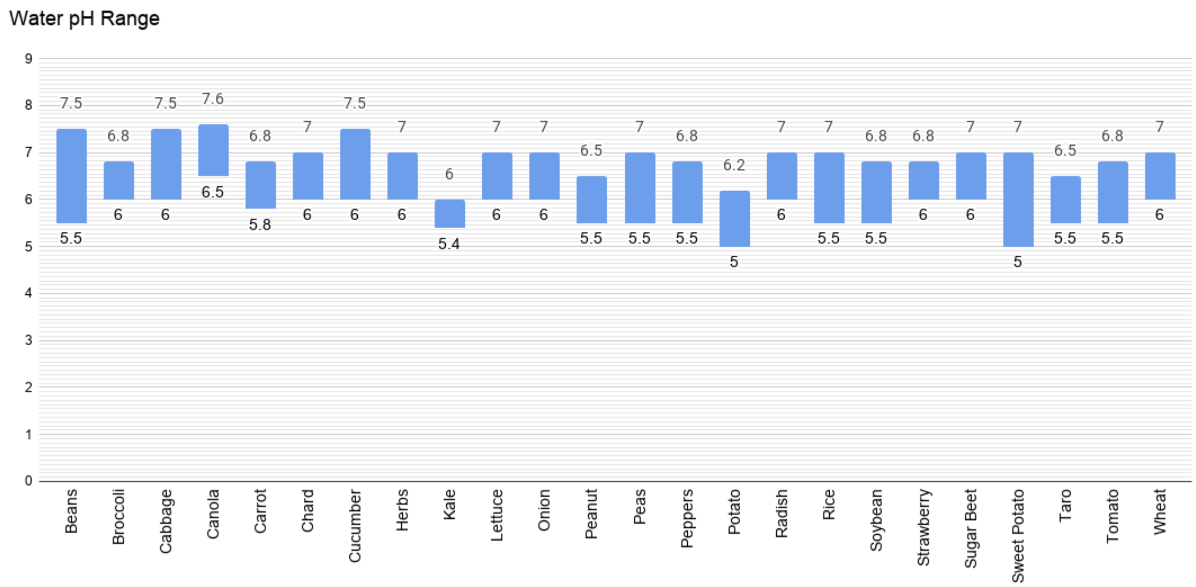


Figure 2-4 pH of Water (Data from FAO[12])

2.3.6 Air Temperature and Humidity

A temperature range of 18 to 22 centigrade is comfortable for humans. Figure 2-5 shows that most plants, except herbs and lettuce, can be productive in this temperature range. Since these

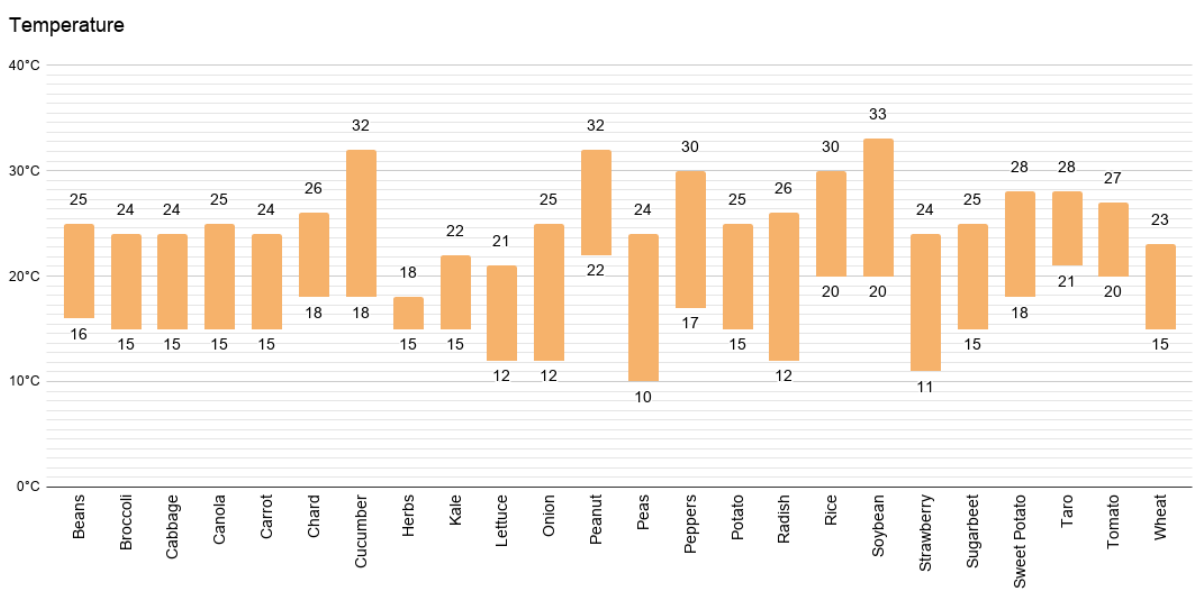


Figure 2-5 Crop Temperature (Data from FAO[12])

plants are essential for menu diversification, considering a more cooling zone or plant pots within a greenhouse could solve this issue. The overall humidity level should be 60-80% for healthy plant transpiration, and the pressure should be 101 kPa, the same as it is on Earth[13].

2.3.7 Plant Size

The part of the plant above the surface is called the shoot zone, and the part that is below the surface is the root zone. The junction of the root tissue and the shoot tissue is the crown of a plant. A crown exists at the interface of the medium and the air. Figure 2-6 describes the variety of plants size in the elevation. This chart reveals that a single plant pot module could not be compatible with all the plants. Previous studies suggest customizable plant racks to change the distance between pots vertically[141516]. However, harvesting the root vegetables with a deeper zone would not be productive.

Figure 2-7 defines three factors. The green circles represent the horizontal expansion of the individual plant. The rectangle describes the actual space that each plant needs through the whole crop cycle. Moreover, the distance between the rectangles shows the density of the crops. For example, onions can be planted extremely close together because they do not produce much foliage, and the foliage they do produce generally grows vertically. In contrast, broccoli grows a central flower that is surrounded by a lot of large leaves.

Insufficient spacing between plants reduces development speed, extends the growing period, and lowers the vegetative and reproductive development. Also, individual plant dry weight generally decreases as plant spacing decrease[17].

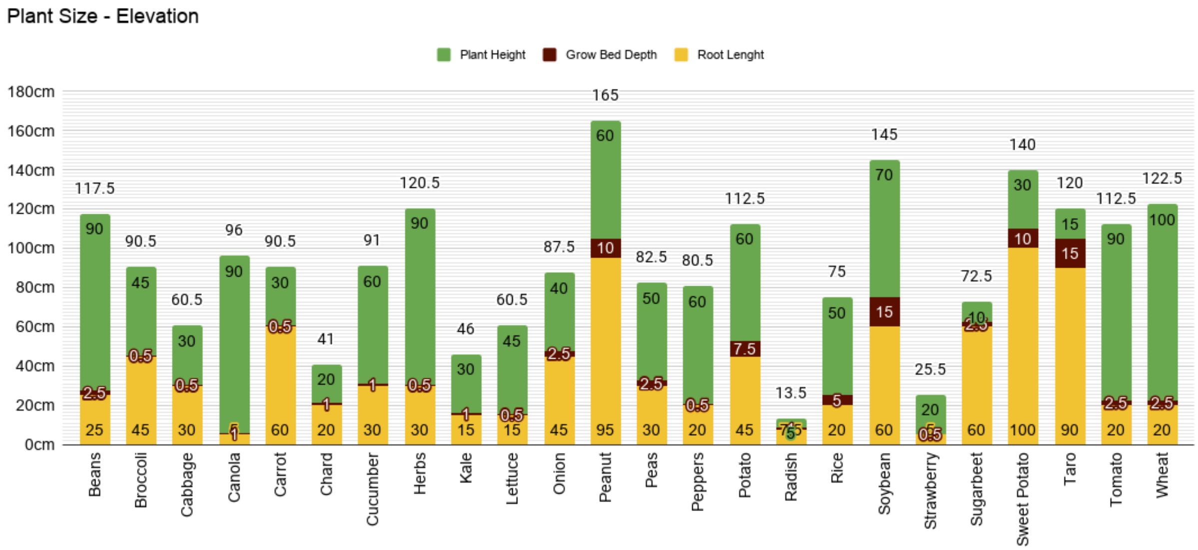


Figure 2-6 Plants Size and Spacing in Elevation

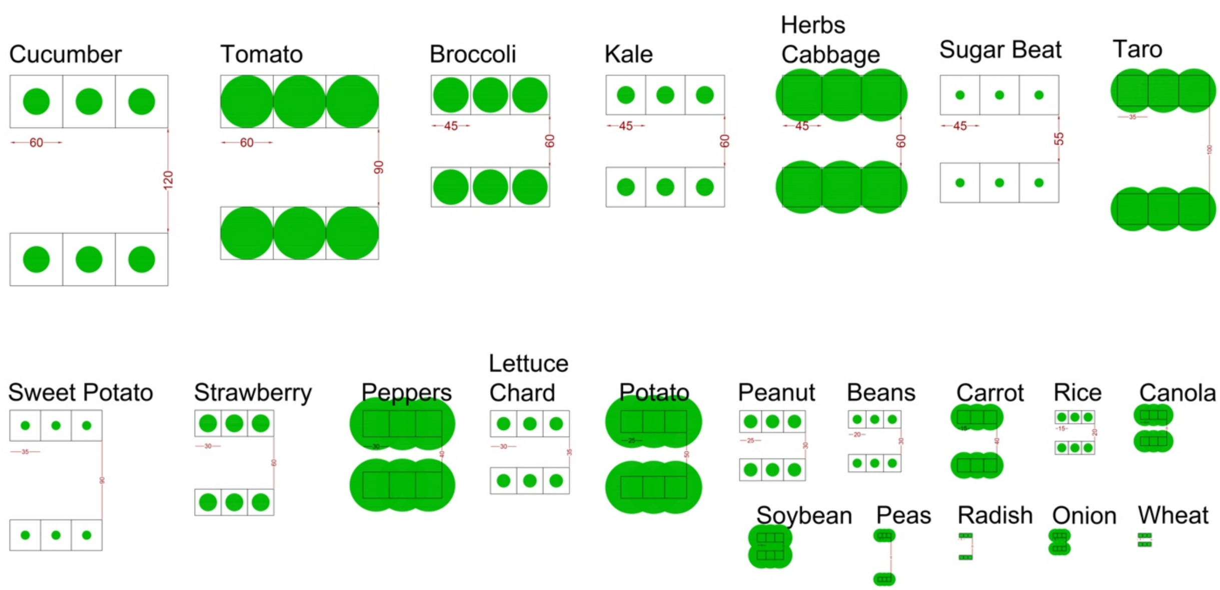


Figure 2-7 Plants Size and Spacing in Plan

2.4 Results

2.4.1 Public Plant List

By excluding canola, chard, and kale, the proposed public space plant list contains 21 plants (Table 2-2). Since a one- size modular plant pot for the public space list would not be practical, dimensions driven from human factors are considered.

Table 2-2 Public Plant List

Beans	Carrot	Lettuce	Peanut	Radish	Strawberry	Taro
Broccoli	Cucumber	Onion	Peppers	Rice	Sugar Beet	Tomato
Cabbage	Herbs	Peas	Potato	Soybean	Sweet potato	Wheat

2.4.2 Plant Pots Design

Table 2-3 groups the plants by their dimensionality and shape, forming four groups: Bracket, Trellis, Wall, and Box. These groups were obtained by considering the height of the plant, the depth of the plant, and the spacing required. For example, low growing, low depth, and high-density plantings naturally form a wall structure. On the other hand, the high height plants naturally form a columnar structure.

Table 2-3 Public Space Plants Grouping

	Bracket	Trellis	Wall	Box
Height	Low Medium	High	Low	Low
Depth	Low Medium	Low Medium High	Low	Low Medium High
Spacing	Medium	Low Medium High	Low	Low Medium High
Plants	Potato Peanut Sweet Potato Taro	Beans Cucumber Peas Soybean Tomato Peppers	Herbs Radish Lettuce	Carrot Onion Sugar Beet Broccoli Cabbage Rice Wheat Strawberry

The drawing in Figure 2-8 shows how all plant pots can be expanded out of the envelope. Figure 2-9 shows height lines to divide the space into horizontal zones based on the height of humans[18]. Each plant grouping ranges over multiple horizontal zones. For example, the pot of plants in the trellis grouping is in zone D, but the plant grows from C to B. This natural division of the space allows for forming different interior design elements. Proposed plant pots based on the zones are shown in Figure 2-10. The yellow color represents the plant bed in the NFT method. Blue is the transparent cap for the boxes used for the pollination period. The horizontal lines on the body of pots represent the foldability of the pots for ease of deployment.

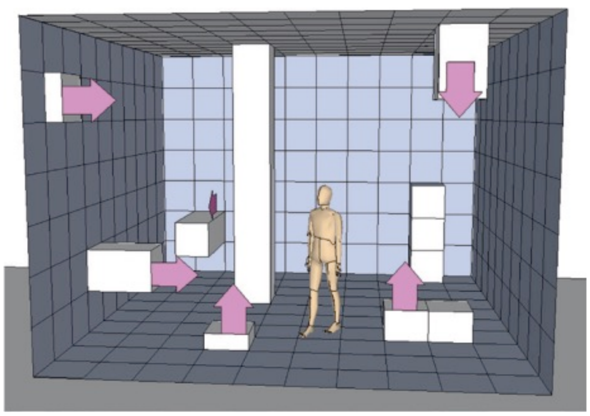


Figure 2-8 Conceptual 3D Origins [18]

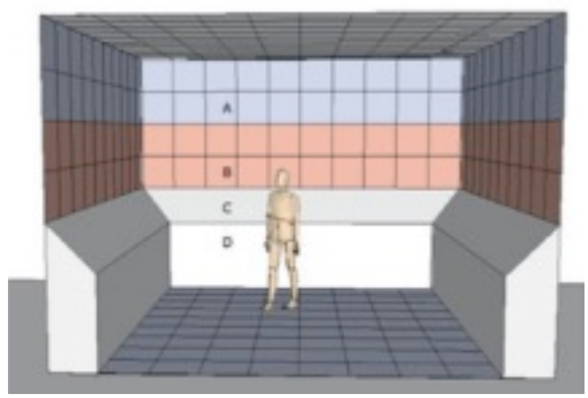


Figure 2-9 Height Lines and horizontal zones [18]

2.4.3 Cultivation Area

Industrial mass production of food, which is the approach previously taken, might show an impressive number in theory but ignores human needs. Typically, the mass production approach has used a small plant list to achieve these goals. One might think that increasing the number of same plants might help the situation. However, changing the plant list alone does not address human needs unless accompanied by responsive interior design, especially when cultural differences are considered. Additionally, by considering plant geometry, we have categorized the plant lists so that their pots can convert the over-engineered industrial interior into a comfort hub with a unique interior perspective in the extra-terrestrial world.

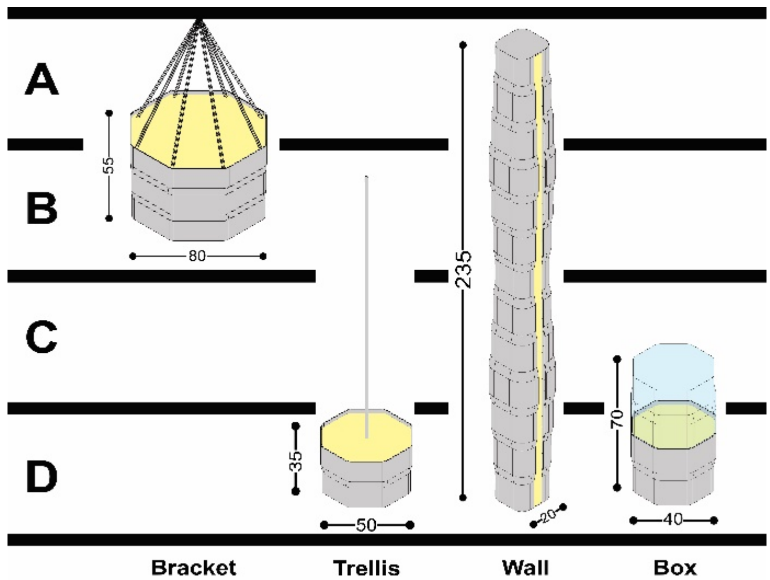


Figure 2-10 Proposed Plant Pots

All of the Minimum, Modest, and Generous plant scenarios are based on 2700 kcal per day per person to support 60% of the daily diet. The report [9] shows that for 1130 kcal, each crew member needs 46.5 m^2 in a Controlled Environment Agriculture (CEA) area.

Table 2-4 compares the required area in NASA's plant list with the greenhouse project. By increasing the total intake calories from 2700 kcal to 3000 and from 60% dietary support to 100%, the total area for CEA jumps to 123.5 m^2 per person. Therefore, for four crew members, 494 m^2 is required. An ultimate selection of plants does not exist and cannot be achieved due to the crew's personal preferences. Table 2 shows the most common plants between all the lists after analyzed by water pH, air temperature, and pollination method. This paper suggests a public greenhouse for these 21 plants and private chambers for other personal selections[19].

Table 2-4 Intake Calorie and Cultivation Area

	Intake Calories Per Day (kcal)	Required Calories Per Day (kcal)	The Ratio of Intake to Required Calories (%)	Controlled Environment Agriculture (m2)
NASA [9]	1130	2700	60	46.5
Greenhouse	3000	3000	100	123.5
4 Crew Need 494 m^2 Cultivation Area				

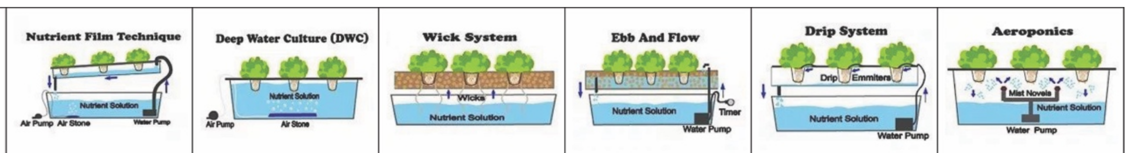
3. HOW TO GROW

3.1 Organic Cultivation Process

Organic cultivation practices specifically aim at getting plant environment into healthy shape by using nonchemical, pesticide-free methods and by encouraging the natural ecosystem to thrive. The aim of cultivating is to help your plants grow better. And you want good drainage so you don't drown your plants.

3.1.1 Cultivation Method

The hydroponic Nutrient Film Technique (NFT) is the chosen water system of the greenhouse. Compared to other hydroponic systems in figure 3-1, NFT needs less growth medium, is more energy-efficient, and has less complicated systems. Besides, the entire greenhouse, when fully installed, requires less water than other systems.



	Nutrient Film Technique	Deep Water Culture (DWC)	Wick System	Ebb And Flow	Drip System	Aeroponics
Air Pump	Yes	Yes	No	Yes	Yes	Yes
Water Pump	Yes	No	No	Yes	Yes	Yes
Timer	No	No	No	Yes	Yes	Yes
Grow Medium	No	No	Yes	Yes	No	No

Figure 3-1 Cultivation Methods

3.1.2 Crop Cycle

As mentioned in 2.3.3 plant requirements, the process by which one part of an embryo causes adjacent tissues or parts to change form or shape, as by the diffusion of hormones or other compounds. In general, high temperature and strong light intensity are required for bud growth and floral induction Temperature plays an important part in floral initiation. When summer temperatures are lower than normal the inflorescence develop in autumn, while normally inflorescence develop in summer. Large amounts of fruit or nuts on the tree tend to reduce initiation. Fruit thinning can be used to manage for even cropping levels between season.

The stage when the flowers (and floral organs) are formed. There is a requirement for a minimum temperature in most crops. Prolonged cold weather during the time when the flower buds are developing rapidly can have detrimental effect on flowering, pollination and fruit set.

Water and nutritional stresses at this time can reduce flower numbers.

The period during which a flower is fully open and functional. It may also refer to the onset of that period. Anthesis is the time and process of budding and unfolding of blossoms.

Timing of flowering depends on rate of temperature increase and temperature distribution. Soil moisture tends to play an important role in the flowering processes. Most stages of flower development require light. Canopy management to let light penetrate to the buds and fruit/nuts is an important aspect of orchard management. Understanding the environmental effects (e.g. light, water, nutrients, diseases) on the crop production cycle specific to the crop you grow will help to formulate effective orchard and tree management actions.

3.1.3 Harvesting Process

Harvesting is the process of gathering a ripe crop from the greenhouse. Reaping is the cutting of grain or pulse for harvest, typically using a scythe, sickle, or reaper. On smaller greenhouses with minimal mechanization, harvesting is the most labor-intensive activity of the growing season. On large mechanized farms, harvesting utilizes the most expensive and sophisticated farm machinery, such as the combine harvester. Process automation has increased the efficiency of both the seeding and harvesting process. Specialized harvesting equipment utilizing conveyor belts to mimic gentle gripping and mass transport replaces the manual task of removing each seedling by hand. The term "harvesting" in general usage may include immediate postharvest handling, including cleaning, sorting, packing, and cooling.

The completion of harvesting marks the end of the growing season, or the growing cycle for a particular crop, and the social importance of this event makes it the focus of seasonal celebrations such as harvest festivals, found in many religions.

3.1.4 Post-Harvesting Process

In agriculture, postharvest handling is the stage of crop production immediately following harvest, including drying, storing, primary process, secondary process, evaluation, packaging and storing. As figure 3-2 shows, the instant a crop is removed from the ground, or separated from its parent plant, it begins to deteriorate. Postharvest treatment largely determines final quality for fresh consumption, or used as an ingredient in a processed food product.

The most important goals of post-harvest handling are keeping the product cool, to avoid moisture loss and slow down undesirable chemical changes, and avoiding physical damage such as bruising, to delay spoilage. Sanitation is also an important factor, to reduce the possibility of pathogens that could be carried by fresh produce, for example, as residue from contaminated washing water.

Initial post-harvest storage conditions are critical to maintaining quality. Each crop has an optimum range of storage temperature and humidity. Also, certain crops cannot be effectively stored together, as unwanted chemical interactions can result. Various methods of high-speed cooling, and sophisticated refrigerated and atmosphere-controlled environments, are employed to prolong freshness, particularly in large-scale operations.

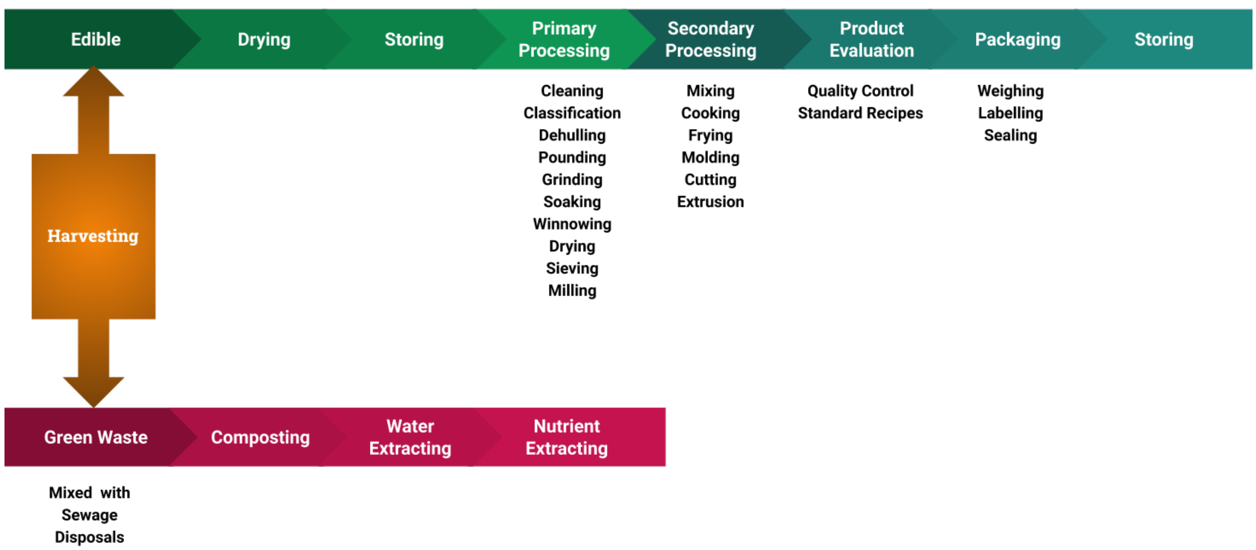


Figure 3-2 Post Harvesting Process

3.2 Systems

Various systems should integrate and work ultimately perfect together to make the greenhouse functional. First, we need to know the assumptions about the resources that support the greenhouse module. Then by locating each system in core or inflatable, we could estimate the distribution of the different systems in its architecture.

3.2.1 Assumptions

The Logistic/Service Module (LSM), crew, and the greenhouse are the three main elements of this project. The LSM has been derived from the Big Idea Challenge 2018 competition but could have any characteristic features. Figure 2-3 shows that this module generates power and provides water and air. The crew provides resources to the greenhouse through their waste production and respiration. The greenhouse also connects to the LSM through an interface to access resources and offers food support, a hygiene area, and a private garden for each crew member with the independent Closed Environmental Life Support System (ECLSS). Two pressure hatches would connect the greenhouse and the crew with a habitat module and/or pressurized rover.

The Mars Ice House (MIH) produces 100 liters of water in each sol and has five generators that produce power. The internal pressure of the greenhouse and habitats are 101 kPa, the same as on Earth [20].

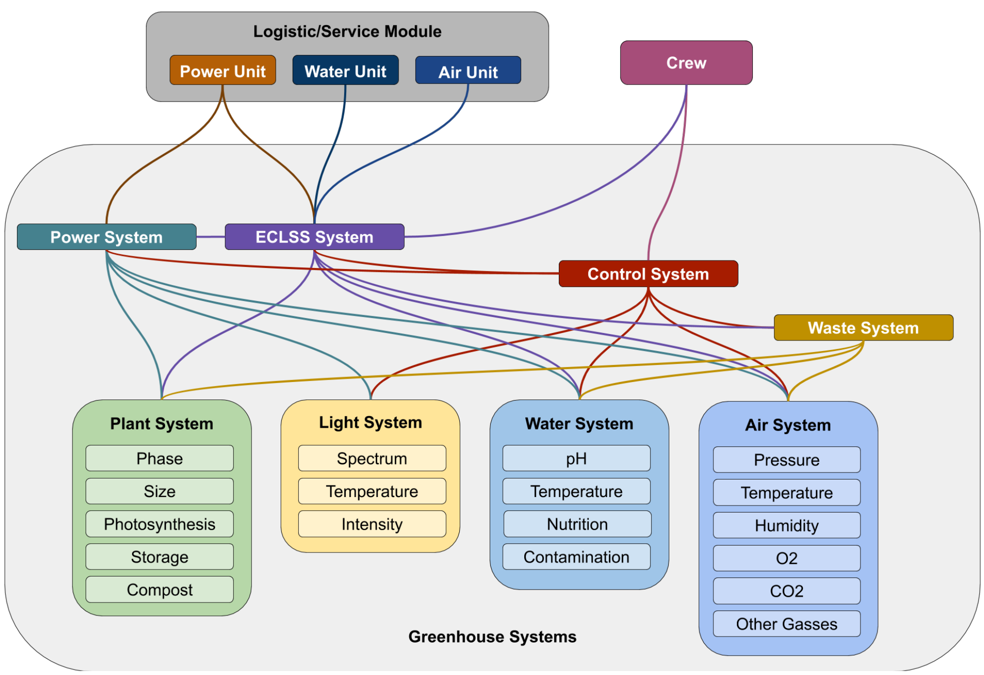


Figure 3-3 Greenhouse System Overview

3.2.2 Agriculture Systems

In this thesis agriculture system is called to all the system and subsystems interacting with plant from the crop cycle to the final outcome from post harvesting as a food package or seed storage. Figure 3-4 shows the distribution of agriculture systems in core and inflatable. The crop cycle starts at the pre-growth section as seedlings in germination phase. After reaching the maturation, they are transferred into hydroponic pots to reach fruiting and end the cycle. Equipment for pollination and harvesting is also available as a form of a robot or hand tools for the crew. After the harvesting, the crop is taken to the cleaning section and the usable parts are separated and transferred to the lab. Other remainders will be thrown into the compost bin. The seed storage and the freezer for storing the fully prepared food or ingredients has heavy weight for cooling. Therefore, they are located at the core.

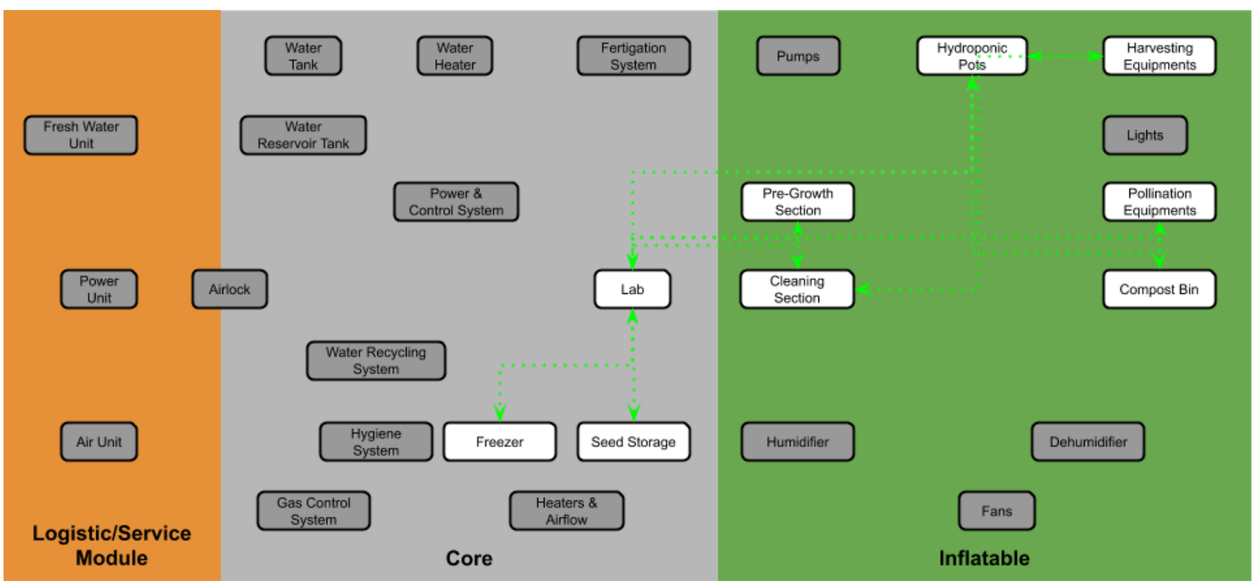


Figure 3-4 Agriculture Systems

3.2.3 Air and Water Systems

The logistic and service module gives air and water supply to the greenhouse module through the airlock piping system. To prevent contamination of the whole system in case of a hazard, water goes to the water reservoir tank first to be examined for any abnormality. As figure 3-5 shows, then it continues through the water tank and the water heater to reach to the comfortable temperature for the plants. Fertigation system at this point controls the nutrient of the water and inputs the chemicals to reach the desired level. Pumps will push the water through the pipes to reach even the farthest plant pots. The returning pipes will pour the used water to the water recycling system. Parallel to this, clean water goes to the lab, cleaning section and humidifiers. Final destination of the water is water recycling system. Therefore, All the water from dehumidifiers, hygiene system will end up there too.

The air unit in service module supports the greenhouse with not only the CO_2, but with nitrogen and other gases used to stabilize the pressure. The gas control system has

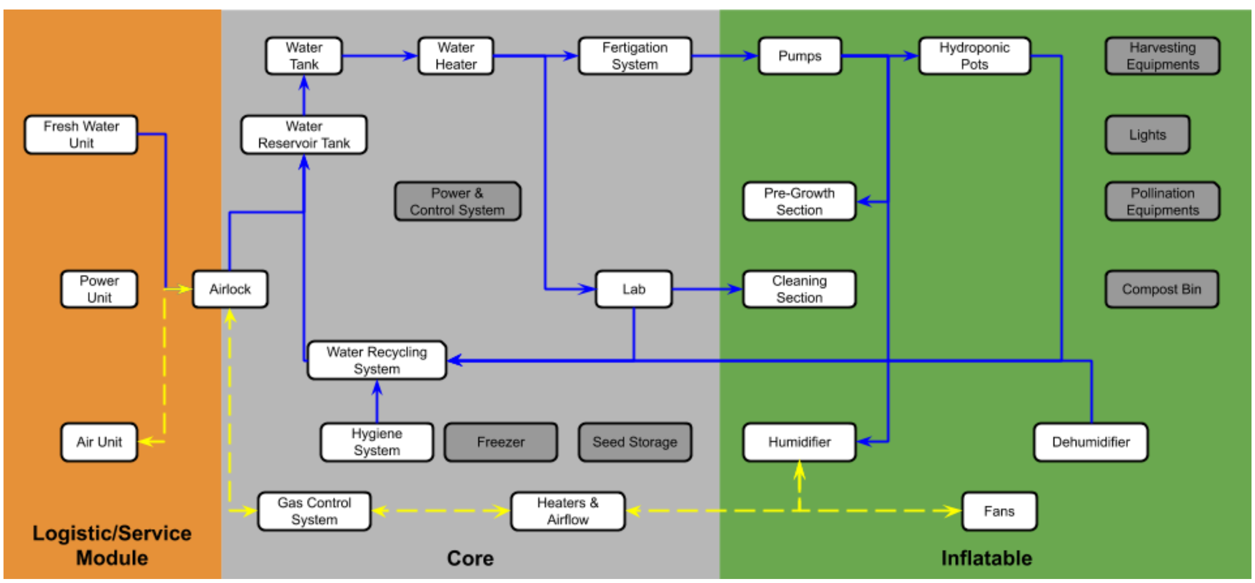


Figure 3-5 Air and Water Systems

sensors to measure all the aspect of the incoming air for pollution or other insalubrious gas combination. Since the desired temperature for plants is between 18 to 22 centigrade, it needs to be warmed up. Heaters are located at the airflow canals and fans help them to through the air to the inflatable.

3.2.4 Power and Control Systems

The power unit which is assumed is working with nuclear energy is the main source for the electricity. Almost all the greenhouse systems, subsystems and parts use power to be controlled and monitored with sensors. The only system that is added to this section is lights (figure 3-6). The LED lamps not only provide desired spectrum for the plants but also have the option of color selection for different modes of the greenhouse. For example, in the plant lighting time it should be purple and in the use of the crew it should turn into white.

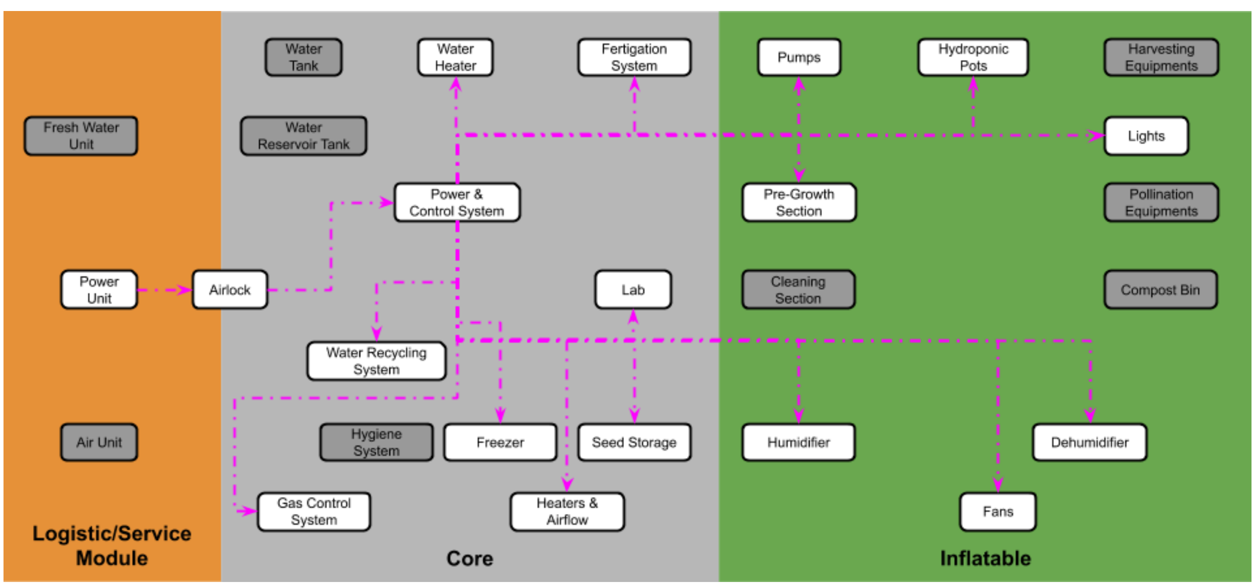


Figure 3-6 Power and Control Systems

3.3 Results

Distribution of the systems and subsystems show that if we could place only the end point of the systems in the inflatable and locate the main parts at the core, it could be the optimum situation. Deployment restrictions limits transferring heavier system parts and hatch and airlock size confines the dimension of the objects that could be passed from the core to the inflatable.

This analysis shows that the required volume for the greenhouse to place all the mentioned systems and subsystems is about 1100m^3 (figure 3-7).

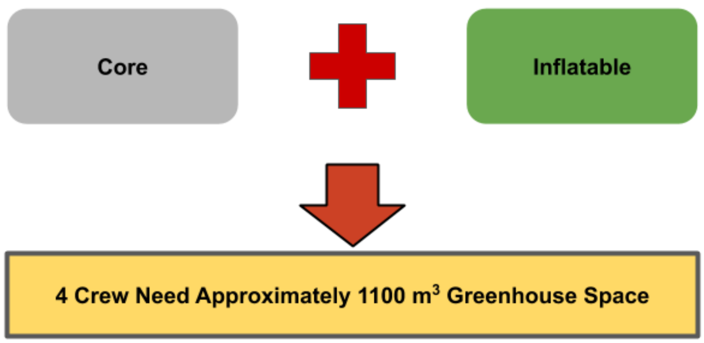


Figure 3-7 Volume Estimation

4. WHERE TO GROW?

4.1 Greenhouse Case Studies

In the assumptions of NASA's Big Idea Challenge Competition 2018 [20] and other recent projects [14][21][22][23][24]. It is assumed that the greenhouse connects to the habitat after crew arrival and integrates into the logistics/service module. In this scenario, the habitat connects to the greenhouse directly or through an inflatable tunnel allowing the crew to access the greenhouse at any time.

This approach assumes that the habitat and greenhouse utilize a similar structure and function under equal pressure [25]. That simplifies an overall system and enables modules' individual ECLSS systems to unify as one expanded system. Since there is no airlock in between, all atmospheric parameters such as pressure, temperature, humidity, etc. would be the same in all modules and similar to earth conditions.

Psychologically, the ease of access to the greenhouse creates a feeling of it as a backyard or a garden. In the Martian Integrated Nourishment Aid (MINA) project [26], we proposed a greenhouse with a private area for each crewmember to enhance living on Mars with improved design and culturally compatible food selections.

A traditional approach to industrial greenhouse design aims to maximize crop yields and daily calorie intake while producing fewer plants. A cultural aspect of the food, in this case, is neglected, and cuisine variety or food customization is not considered [19]. Such an approach ignores physiological and psychological human factors associated with food preparation and consumption behavior.

4.1.1 NASA

The most recent NASA's greenhouse project is the Big Idea Challenge 2018 which was based on the Mars Ice Home prototype. Deployable Enclosed Martian Environment for Technology, Eating, and Recreation. DEMETER incorporates ice shielding from the Mars Ice Home habitat design and will provide sufficient nutritious food for a four-person astronaut crew on a 600-sol surface mission to Mars. The design has been conducted in five primary phases: determining the nutritional need of the astronaut crew, selecting a plant-based diet to meet the nutritional need, sizing the greenhouse architecture to grow the plants, developing the necessary subsystems to support the growth of the plants, and iteration using the knowledge gained during the prototyping process. The design is an automated hydroponic growing system which utilizes a cylinder inside a torus. This cylinder stores the system that dispenses and recycles the water and nutrients. The greenhouse also provides a circular track for exercise and recreation.

The primary purpose of the greenhouse is to feed the crew, but it will also support the effort to create a closed loop habitat by recycling biomass, energy, water, oxygen (O2), and carbon dioxide (CO2) with the Ice Home. With consideration for future missions, the targeted operating lifespan of DEMETER is 15 Earth years. This greenhouse will be part of the first effort to establish a human presence on Mars, which has only been visited by probes and rovers. Similar technologies used in this series of Martian missions will be tested in cislunar and lunar missions, providing opportunity for improvement and astronaut practice.

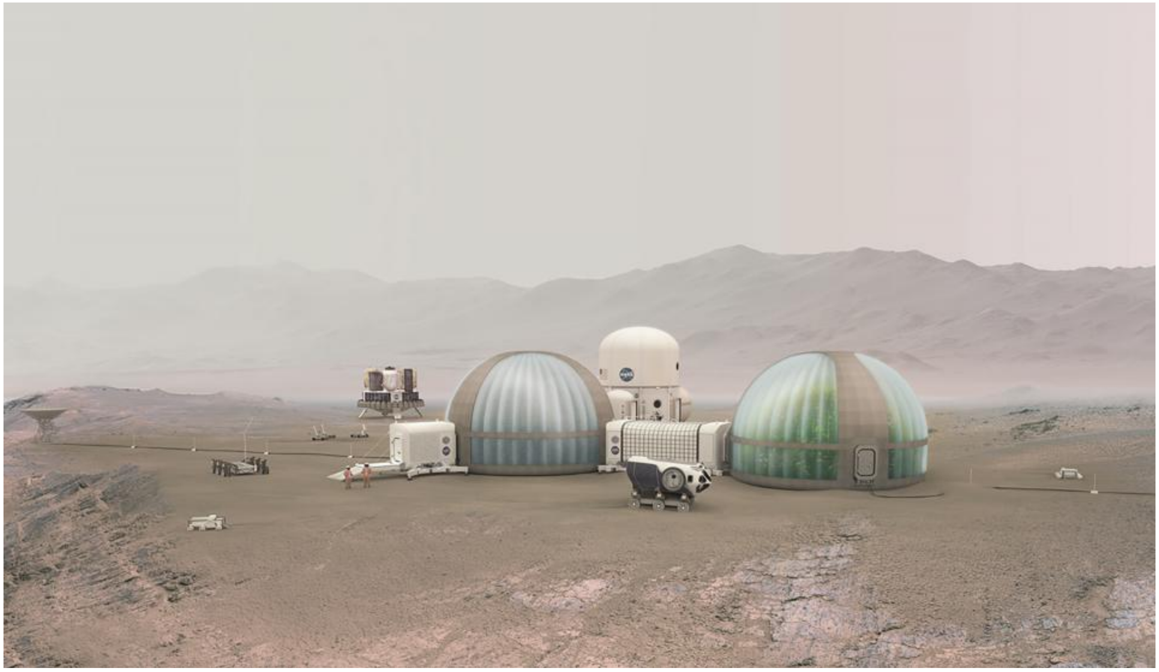


Figure 4-1 NASA's Big Idea Challenge Greenhouse

4.1.2 ESA

The project Greenhouse Module for Space System was one part of European activities focused on developing a regenerative life support system (LSS). The bulk of these activities take place within the ESA Micro-Ecological Life Support System Alternative (MELiSSA) framework [27]. The MELiSSA framework aims to develop a micro-organism and higher plant-based ecosystem, which would function as a closed-loop bio-regenerative life support system, required for future long-duration human space flight.

MELiSSA is based on an "aquatic" ecosystem consisting of five distinct sections, or compartments[28]. The goal of the project was to perform a preliminary sizing of a greenhouse module (GHM) capable of producing the MELiSSA menu for six crew and to compile the associated data for oxygen and water production. This greenhouse module could be deployed independently of other lunar base systems and then be integrated into an already-established lunar infrastructure. The long-term goal of such a GHM is to decrease overall mission (resupply) launch masses.

The main objective of the GHM was in-situ crop production to provide 100% of the dietary requirements for a crew of six via the production of specific quantities of selected plants. In addition, the facility was developed for atmospheric revitalization, water purification and to support crew well-being. The GHM is integrated into the MELiSSA loop, which constitutes the secondary life-support system of the habitat in the initial phase. When operations within the GHM reach a steady state, the MELiSSA loop will become the primary LSS. The GHM receives its inputs (e.g. water, air, CO2, nutrients) from the MELiSSA loop and sends its outputs (e.g. harvested crops, inedible parts of the plants, O2, fresh water) to the loop. Overall wastes from the GHM are managed by the MELiSSA loop or by the physical/chemical backup LSS. Therefore, the GHM does not include a waste management system, only a short- term waste storage unit.

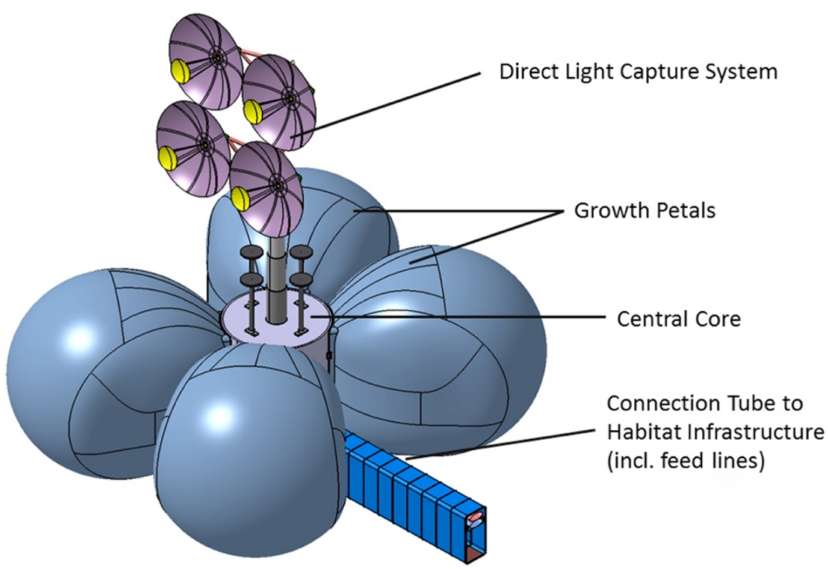


Figure 4-2 ESA GHM System [27]

4.2 Greenhouse Design Obstacles

The current studies show the launching mass restrictions and the food independency of the mission would not be possible with current rockets. So, if we want to aim for TRL 8 with more feasible plan, we need to reduce the size of the greenhouse or decrease the total mass. One of the realistic solutions is using the genetically modified plants that need smaller space to grow. These GMO plants could even be more productive and give more biomass.

4.2.1 Mass Reduction

Previous studies show that there is a linear relationship between the mass and the pressure the inflatable is bearing. Table 4-1 shows that when the interior pressure of the greenhouse is the same as the pressure on earth by the sea, 101.3kPa, the inflatable structure needs 4 times more thickness than the pressure is about the third and 30.0kPa. since there is no study or evidence of the radiation on the plants, even decreasing the size of the radiation shield could lead to lighter mass. But the question is how low is possible for the current greenhouse needs?

Table 4-1 Effect of Pressure Difference on Structure

Pressure (kPa)	101.3	59.2	30.0
Kevlar Weight (kg/m^2)	2.54	1.31	0.66
Reference	29	30	30

4.2.2 Total Pressure

The major problem of transfer from a cabin atmospheric pressure (101.3 kPa) to lower pressure is the threat of aerospace bends-decompression sickness. (Nitrogen gas comes out of solution in the bloodstream and forming bubbles that collect painfully in the joints of the body). To avoid this problem, astronauts "pre-breathe" pure oxygen for at least three hours before donning into the suit to purge the nitrogen from their bloodstream [31]. Table 1 shows different pressure and atmospheric compositions used in space missions. A prebreathe time of 1 hour is assumed as a tentative upper bound for surface exploration EVAs to denitrogenate the brain and spinal cord and prevent (Type II) DCS symptoms[32]. Long pre-breathing periods diminish productive crew time and maybe unacceptable during lunar or Mars missions when EVAs will be more frequent and should be easy, simple, routine, and safe.

For surface missions, the pressure in a Multi-Mission Space Exploration Vehicle would be lowered from the normal 101.3 kPa of habitat to 56.5 kPa to minimize the rate of nitrogen return while breathing cabin air - a nitrogen/oxygen mixture. This technique allows for a short 30-40 minute pre-breathe time in the Extravehicular Mobility Unit just before starting an EVA[33].

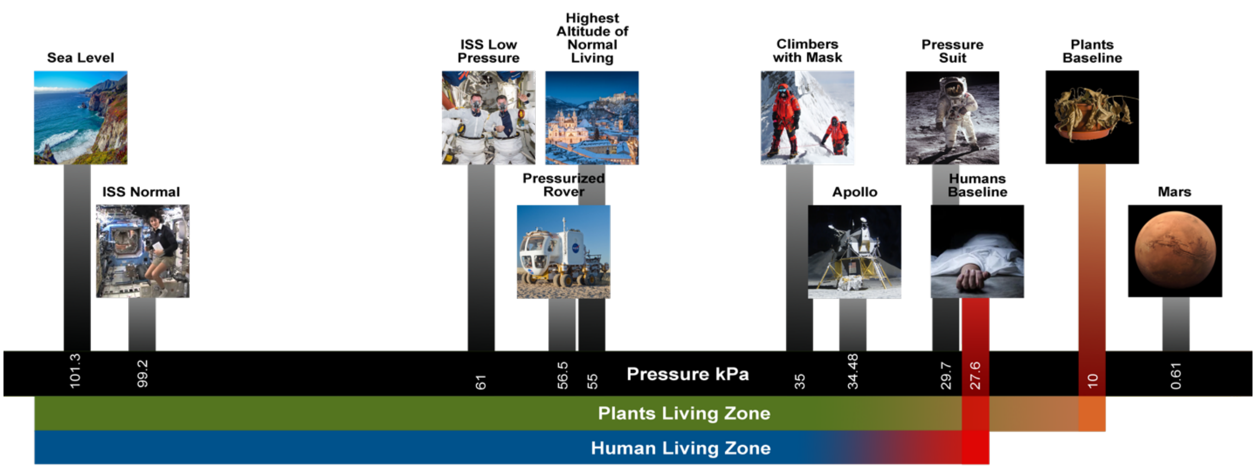


Figure 4-3 Pressure Gradients and Living Zones

4.2.3 Partial Pressure

Human body reacts to two factors in the atmospheric pressure. The total pressure on the body and the partial pressure of the gases he breathes. Figure 4-4 shows partial pressure of O2 and CO2 and the total pressure of various environment. Despite the same CO2 range, increasing the partial pressure of oxygen is vital when lowering the total pressure.

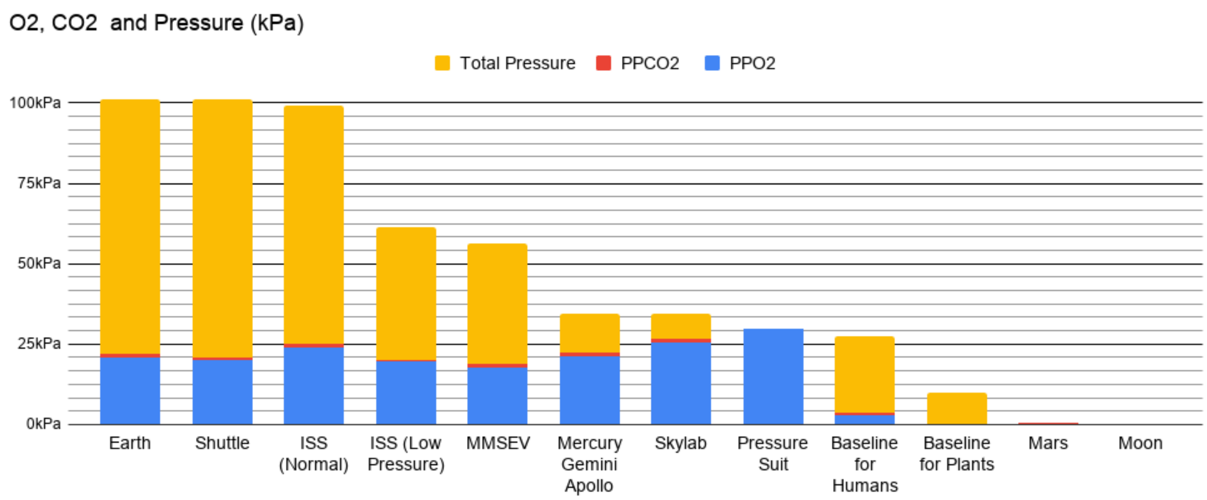


Figure 4-4 Total Pressure and Partial Pressure of Various Environments

4.2.4 EVA Scenarios

There are four different protocols for surface EVAs. Table 2 displays that protocols A and B are straight 8 hours of EVA, and protocols C and D have two hours duration. While protocols A and C have 80% of oxygen, the B and D protocols have 95%. These protocols show the depressing process from the assumed cabin pressure of 56.5 to 29.7 of the spacesuits, which takes 25 minutes. In the protocols C and D, there is one hour of the hold before starting each EVA that increases each prebreathe cycle to one hour and 25 minutes and a total of 4 hours and 15 minutes.

In the current mission scenarios, the crew would spend the pre-breathe time in an airlock module that is equipped with gym facilities for severe physical activity. A proposed low-pressure greenhouse can enhance the crew's pre-breathing routine and reduce stress levels by offering interactions with plants or doing daily agricultural chores. Besides, exercising around plants is beneficial for the plants, the ECLSS system, and the crew.

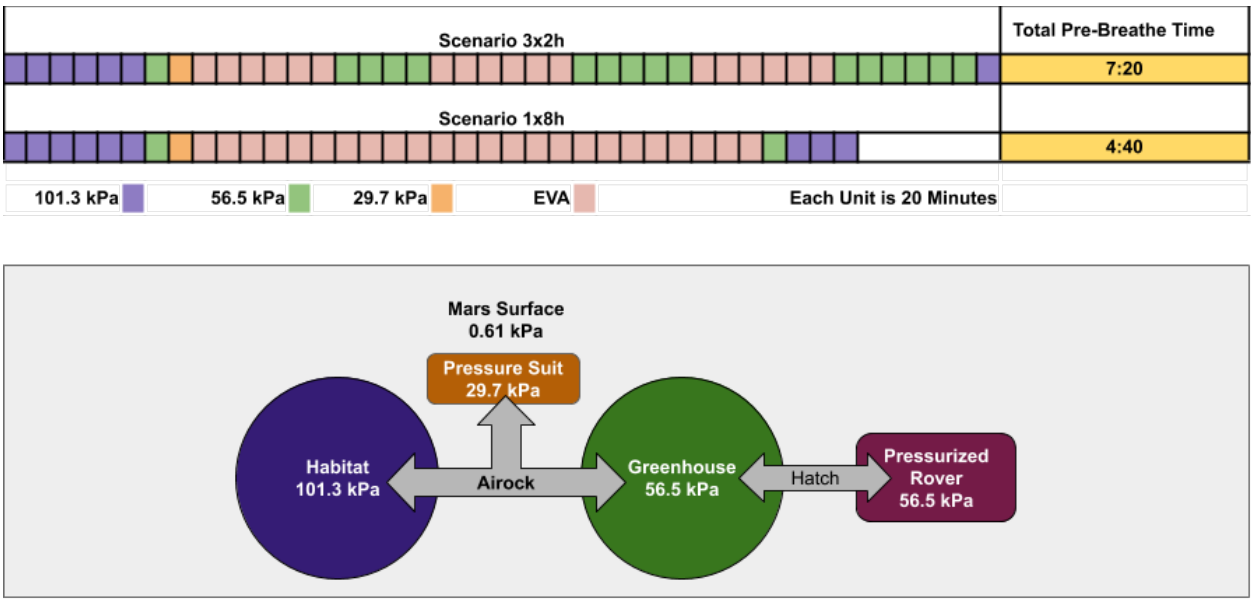


Figure 4-5 Pre-breathe Scenarios

4.3 Greenhouse Geometries

There are four geometries used in the previous greenhouse studies. The mushroom is a core with an inflatable on top. The size of the core is the maximum payload shroud fit which would be about 8 meters in diameter. With a 9meter height it has the largest core. The torus, 2-petals and 3-petals geometries use the same minimum core size with 5meter in diameter and 7meter height. Height of all the inflatables is about 6.5meter which shapes 3 story or level. Table 4-2 shows the mass estimation of the geometries. The considered material for the core is the aluminum and the inflatable is a complex layered bladder, Kevlar and isolation [34].

Table 4-2 Estimation of the Total Mass of the Greenhouse Geometries

	Mushroom	Torus	2 Petals	3 Petals
Inflatable Mass (kg)	1024	1462	1606	1719
Core Mass (kg)	15176	8135	8135	8135
Airlock/Suitport (kg)	600	600	600	600
Hatch (kg)	230	230	345	460
Total Mass (kg)	17030	10427	10686	10914
Total Mass (ton)	**17.0**	**10.4**	**10.7**	**10.9**

4.3.1 Deployment

The Mars greenhouse is assumed to be launched with the Space Launch System (SLS) Block 2 Cargo variant, which has a maximum payload of 18 tons[20]. The maximum dimensional limits when packaged and stowed in the Entry, Descent, and Landing (EDL) aeroshell are 6.8m in diameter and 8m in height. Figure 2 schematically shows how it will be packaged.

In a long-stay mission scenario, the crew is estimated to arrive 26 months after the greenhouse deployment and at the first conjunction opportunity. Therefore, the greenhouse is designed to be fully autonomous in deployment, outfitting, and interfacing.

Robots and 3D printers, which are assumed to have made a flat foundation for MIH, will likewise prepare the deployment site for the arrival of MINA. After greenhouse module reaches the surface, robots and cranes will transport and dock it to the LSM. The power and data cables will connect to MINA, and after confirmation of proper connections, air pumps will fill it by bringing filtered Martian atmosphere into the inflatable. After pressurization, greenhouse module will get its water and air supply. Ground operators, with the assistance of on-site computers, will monitor and adjust all the steps of the process. The agriculture system is pre-integrated and folded around the core, and the beams, which support the floor mesh, accommodate all pipes and wires. Foldable plant pots are fixed to their positions on the floor beams and will be unfolded through the opening of these beams. All human facilities are fixed in their locations in the core and are ready for use upon deployment.

The greenhouse module has dual egress capability and can interface with any pressurized module through two hatches and an airlock. The International Berthing Docking Mechanism (IBDM) enables mechanical connections as well as power, air, water, and data[35]. The Dual-Chamber Hybrid Inflatable Suitlock (DCIS)[36] in Figure 4-6 is the chosen airlock. A dual compartment suitlock will allow for dust and contaminant control, suit maintenance, and efficient egress/ingress; and the inflatable will allow the unit to stow in a compact package for transport. This module has a triple bulkhead and is dual-chambered, with one continuously pressurized compartment (either at cabin pressure or transitional pressure from high-pressure habitats) and a nominal, unpressurized second compartment where the suits will be kept for normal operations. The advantages include quicker egress/ingress, capacity for 'shirt-sleeve' suit maintenance, and portability of the entire unit[36]. These features make this airlock the best option for the greenhouse.

Figure 4-7 shows the deployment of the geometries. Since mushroom has the inflatable on top that connects to the core only through a hatch, it has the simplest deployment. Torus has a hatch and airlock which is attached to the inflatable. By pressurizing the inflatable and increasing the space, these openings need to be pushed away. The airlock weighs 600kg and the hatch 115kg and it is too heavy to be carried by the crew. Therefore, a rover or a crane is needed.

In the petal versions, each petal has its own hatch and there is an airlock to access outside. All of them are located at the core. Despite it reduces the accessible area of the core but it increases the easiness of deployment.

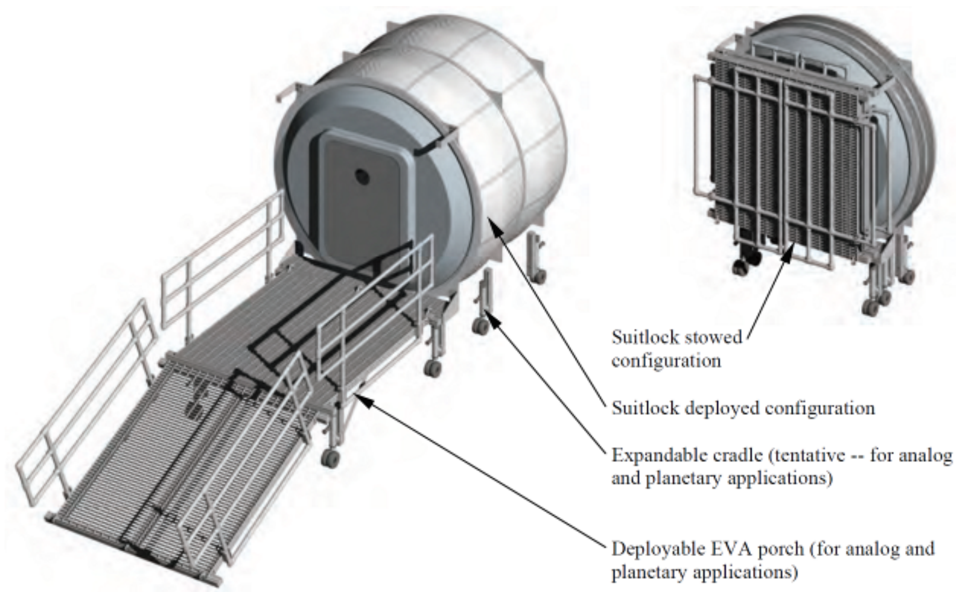


Figure 4-6 Suitlock In Deployed (Left), and Stowed Configuration (Right)[36]

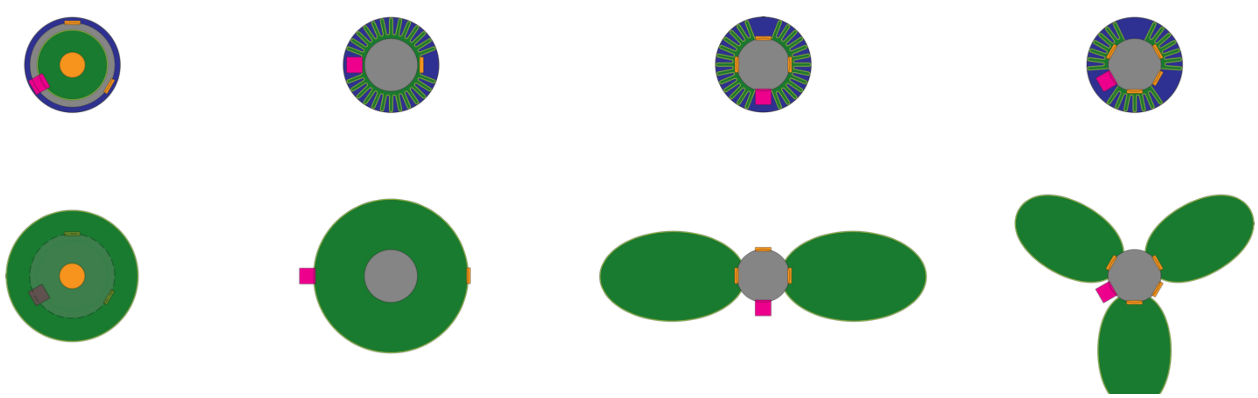


Figure 4-7 Payload Shroud and Deployment of the Geometries

4.3.2 Space Efficiency

having the larger volume does not lead to having larger usable area. Figure 4-8 shows the usable area in each floor of the geometries. It is clear that the larger the area of each floor, the larger the corridors to access to the plant pots. In this design the width of the corridors is 0.9m to enables the walking of the crew and movement of the robots. Table 4-3 shows the ratio of the total area of each geometry and the usable area of it. Petals are the winners of this part with more than 10% difference to mushroom and torus.

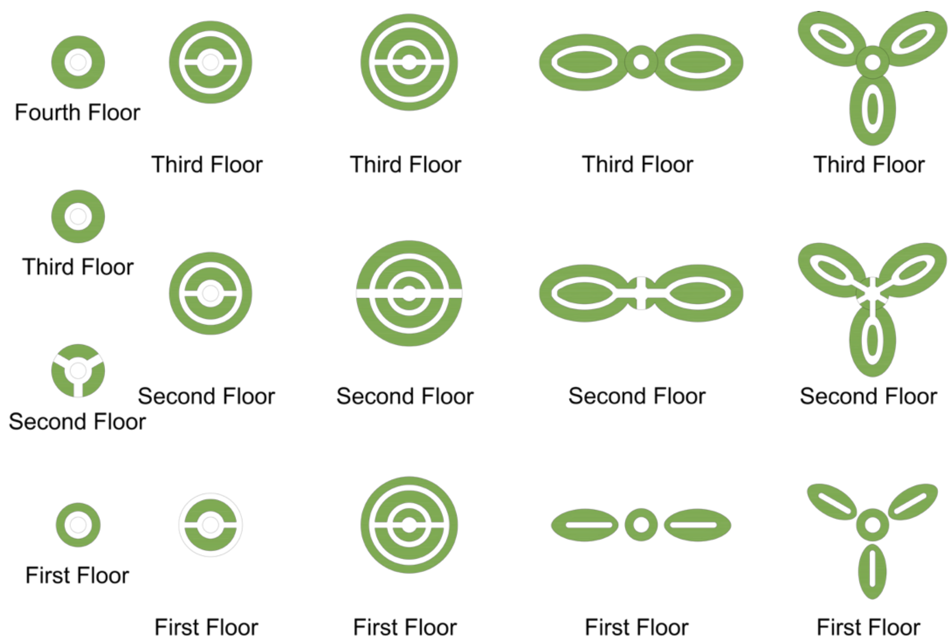


Figure 4-8 Space Usable Area in Geometries in Plan View

Table 4-3 Space Efficiency of the Geometries

	Mushroom	Torus	2 Petals	3 Petals
Total Inflatable Area	316.7	476.64	437.82	434.52
Total Core Area	185.46	77.78	77.78	77.78
Total Area	**502.16**	**554.42**	**515.6**	**512.3**
Usable Area Level 1	30.67	108.71	77.82	81.04
Usable Area Level 2	80.33	121.92	149.89	141.15
Usable Area Level 3	80.33	108.71	158.36	152.21
Usable Area Core	122	0	0	0
Total Usable Area	**313.33**	**339.34**	**386.07**	**374.4**
Space Efficiency (%)	**62**	**61**	**75**	**73**

4.4 Greenhouse Modes

Most of the studies and the papers written about the greenhouse happens in the operation mode. This means using the complete capacity and non-stop working. Whereas in most scenarios there is a hibernation mode which describes the greenhouse without the presence of the crew. This could be the result of completion of the surface mission or a temporary leaving of the crew for a long distant mission. There is always the emergency mode for every module too. That the loss power or leakage of water or pressure could lead to a total or partial crop loss. Mushroom and torus have one connected space. Therefore, they work efficiently in the operation mode but they could not be used partially for hibernation mode and in case of any emergency, they would face the total plant loss. The petals have lower redundancy and they have better performance in the accident.

4.5 Human Factors

As mentioned in the partial pressure section, crew needs to wear oxygen mask and carry oxygen tank on their shoulder. This means the circulation of crew would be easier while moving horizontally than vertically and through the ladders. Therefore, the mushroom with 7story height is the most difficult in this aspect. Even using electronic elevators is easier and more light weight when supporting just the 6.5 meters of the others.

4.6 Results

Various factors are playing the roles in the greenhouse design and based on the priority of the mission or the designer it could give different results. Table 4-4 describes the design criteria of the geometries. This analysis does not numerically value the criteria because it needs more investigation with more accurate mission scenarios. But it gives a good estimation about the hidden aspects of the design. In this table both petal versions are the same in every aspect. Torus and mushroom perform better in the operation mode but mushroom is the most feasible in deployment and assembly.

Table 4-4 Greenhouse Design Criteria

- Green: Most Preferable
- Yellow: Moderately Preferable
- Red: Least Preferable

		Mushroom	Torus	2 Petals	3 Petals
Operation	Space Efficiency	Red	Yellow	Green	Green
	Space Modification	Red	Red	Green	Green
Hibernation	Partial Operation	Red	Red	Green	Green
	Resource Consumption	Red	Red	Green	Green
Emergency	Crop Loss	Red	Red	Green	Green
	Functionality	Red	Red	Green	Green
Physical Properties	Mass	Red	Green	Green	Green
	Deployment	Green	Red	Yellow	Yellow
	Structure Assembly	Green	Yellow	Red	Red
	Systems Assembly	Green	Green	Red	Red
Human Factors	Accessibility	Red	Green	Green	Green
	Personal Area	Yellow	Yellow	Green	Green

5. CONCLUSION

This thesis summarizes the detailed analysis of a phase A design project performed on a subsystem level on a Martian greenhouse concept. The result is a hybrid rigid-inflatable greenhouse which can fulfil the function of the higher plant compartment sized to sustain four crew, within a larger closed loop system over a mission period of 600 days. The greenhouse design parameters, including margins to account for the uncertainties inherent in early design efforts, indicate that the greenhouse structure, along with the internal equipment and outfitting, could be delivered to LEO using a single SLS launch. However, the initial supply of resources, such as water and power, necessitate the presence of substantial infrastructure on the Mars, prior to arrival of this greenhouse.

Such a greenhouse module would be an essential part of a Mars Village-like permanent base, where humans would work and live and therefore need to sustain their basic metabolic needs. While an actual Mars mission incorporating significant habitat, infrastructure is still decades in the future and technologies at that time will likely allow for a reduction in these budgets, this was not considered during this phase of the design. It also provided the basis to generate a list of recommendations to complete all the remaining activities required for the further development of the concept and to identify the activities required to address the critical areas in technological maturity, tool availability and scientific knowledge.

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Appendix

Table 1 Various Plant Lists

	Russian Academy of Sciences [37]	NASA [38]	ESA/Canada [28]	University of Utah [39]	NASA [40]	Institute for Environmental Sciences in Japan [41]	ESA/Canada [28]	NASA [38]	University of Utah [39]
	Beets	Beans	Beans	Broccoli	Beets	Beans	Alfalfa	Banana	Beans
	Carrots	Broccoli	Beets	Canola	Broccoli	Cabbages	Beans	Barley	Beets
	Cucumber	Corn	Broccoli	Carrots	Corn	Carrots	Beets	Beans	Broccoli
	Dill	Kale	Cabbages	Chilies	Cucumber	Cucumber	Broccoli	Beets	Cabbages
	Earth Almond	Mustard Greens	Carrots	Kale	Kale	Komatsuna	Cabbages	Broccoli	Canola
	Kohlrabi	Oats	Cauliflower	Lentil	Lettuce	Lettuce	Carrots	Cabbages	Carrots
	Onions	Peanuts	Kale	Lettuce	Mustard Greens	Mitsuba	Cauliflower	Cantaloupe	Chard
	Peas	Peas	Lettuce	Onions	Oats	Onions	Chard	Carrots	Chilies
	Potato	Potato	Onions	Peas	Onions	Peanuts	Chilies	Cauliflower	Chives
	Radishes	Rice	Potato	Peanuts	Peanuts	Peas	Cucumber	Celery	Fennel
	Tomato	Soybeans	Rice	Rice	Peas	Peppers	Herbs	Chard	Flax
	Wheat	Turnip	Soybeans	Soybeans	Potato	Radishes	Kale	Chives	Garlic
		Wheat	Spinach	Sweet Potato	Rice	Rice	Lettuce	Corn	Ginger
			Sweet Potato	Tomato	Soybeans	Shiso	Mushrooms	Garlic	Kale
			Wheat	Wheat	Spinach	Shungiku	Onions	Grape	Lentil
					Strawberries	Soybeans	Peanuts	Kale	Lettuce
					Sugar Beets	Spinach	Peas	Lettuce	Melons
					Sweet Potato	Sugar Beets	Peppers	Mint	Millets
					Tomato	Tomato	Potato	Oats	Mushrooms
					Wheat	Turnip	Rice	Onions	Oats
							Soybeans	Parsley	Onions
							Spinach	Peanuts	Oregano
							Squash	Peas	Parsley
							Sweet Potato	Peppers	Peanuts
							Tomato	Potato	Peas
							Wheat	Rice	Potato
								Rye	Pumpkin
								Soybeans	Quinoa
								Spinach	Radishes
								Strawberries	Rice
								Sugar Cane	Sage
								Sweet Potato	Sorghum
								Taro	Soybeans
								Tea	Squash
								Tomato	Strawberries
								Wheat	Sunflower
									Sweet Potato
									Thyme
									Tomatillo
									Tomato
									Wheat
Fruit	0	0	0	0	1	0	0	4	3
Grain	1	4	2	3	4	1	2	6	6
Herb and Spices	1	0	0	1	0	4	4	6	9
Leaf and Flower	0	3	5	2	4	3	7	6	6
Leguminous	1	4	2	4	3	4	4	4	6
Root and Tuber	6	2	4	2	3	3	4	5	5
Salad	3	0	2	3	4	4	5	4	5
Sugar	0	0	0	0	1	1	0	1	1
Total	12	13	15	15	20	20	26	36	41