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Martian Greenhouse Architecture: Enabling Habitability, Safety, and Aesthetics

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Abstract

A Greenhouse system in the partial gravity of Mars requires the integration of subsystems for air and water circulation and distribution, lighting, cultivation, and monitoring. According to NASA's Big Idea Challenge competition, Mars Ice Home should provide power, air, and water supply through an interface to an adjacent but separate greenhouse module. At large, the module will require Mars Ice House resources for building its structure and functionality. Although having a separate greenhouse structure may be the most efficient use of space, it will restrict the crew from regular interactions with nature, especially in a long-stay (conjunction class) mission to Mars and cause psychological deconditioning.

This paper presents a Martian greenhouse design based on human factors and aesthetics integration in the overall greenhouse architecture. Regarding the concept of operation, the greenhouse does not operate independently but has an independent closed-loop system. Therefore, adding water consumption for sanitary, laundry, and kitchen functions would not affect the overall amount of water storage. Besides, relocating a gym from the habitat to the greenhouse is beneficial for the air quality of the habitat, and excessive production of carbon dioxide is beneficial for plant growth. An indoor garden with public space for social interactions and personal space for a private time would support crew morale and improve their quality of life.

In summary, this paper presents the criteria for trade studies concerning the maximum cultivation area of a greenhouse with more human-centered spaces. Interior design examples are compared and qualitatively evaluated based on their effectiveness from the viewpoint of volume and area utilization, systems requirements, human activities, and psychological support and aesthetics.

Keywords: Greenhouse, Architecture, Habitability,

1. Introduction

This paper presents the Martian Integrated Nourishment Aid (MINA), a design for a greenhouse for partial gravity. This concept will provide 3000 kcal per day for four crewmembers during a 600-sol surface mission on Mars. Additionally, MINA integrates the need for a food production area with human factors. It does this through a combination of interior garden space with a gym, hygiene area, public lounge, and private garden, to increase the quality of life of the crew during a surface mission.

2. System Overview

The Logistic/Service Module (LSM), crew, and MINA 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 1 shows that this module generates power and provides water and air. The crew provides resources to MINA through their waste production and respiration. MINA 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

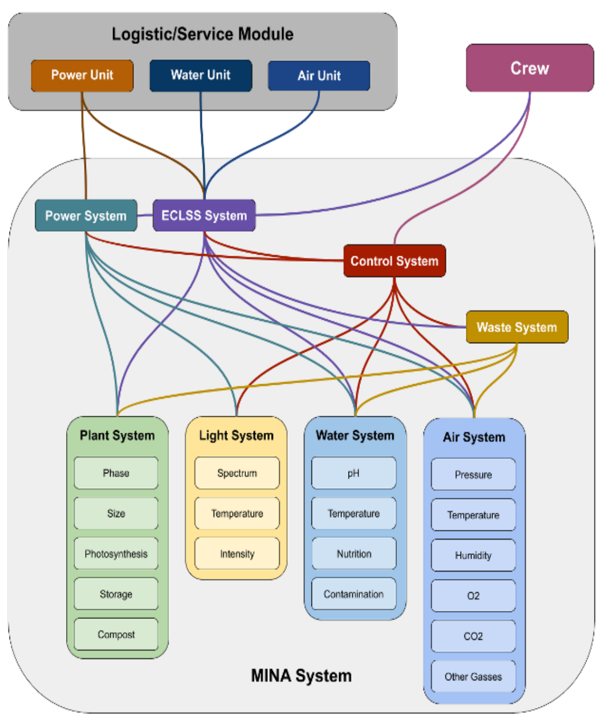

Figure 1 System Overview

independent Closed Environmental Life Support System (ECLSS). Two pressure hatches would connect MINA and the crew with a habitat module and/or pressurized rover.

3. Assumptions

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 [1].

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

MINA is assumed to be launched with the Space Launch System (SLS) Block 2 Cargo variant, which has a maximum payload of 18 tons[1]. 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.

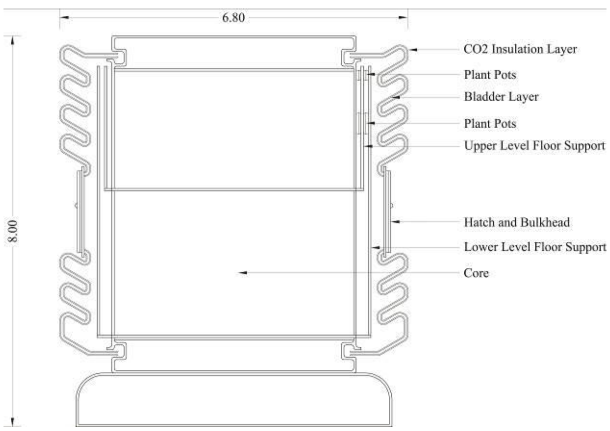

Figure 2 Schematic Packaging

3.2. Deployment, Outfitting, and Interface

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, MINA 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 MINA 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, MINA 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.

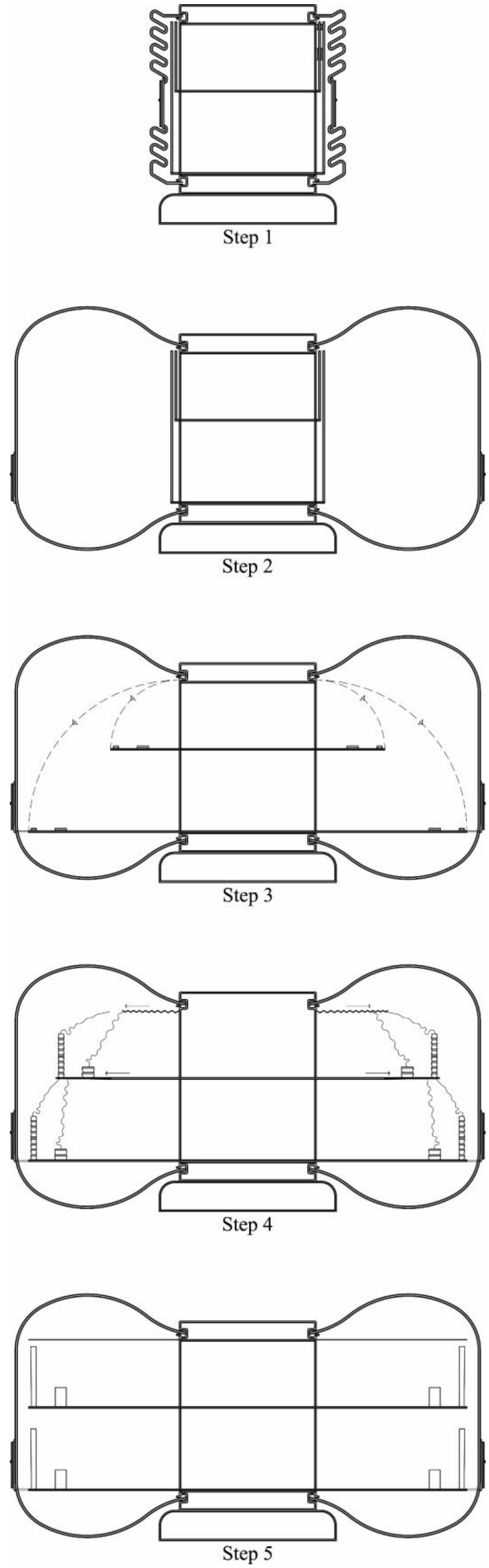

Figure 3 Deployment of MINA

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. Figure 3 illustrates the deployment steps.

MINA 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[2]. The Dual-Chamber Hybrid Inflatable Suitlock (DCIS)[3] in Figure 5 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[3]. These features make this airlock the best option for the greenhouse.

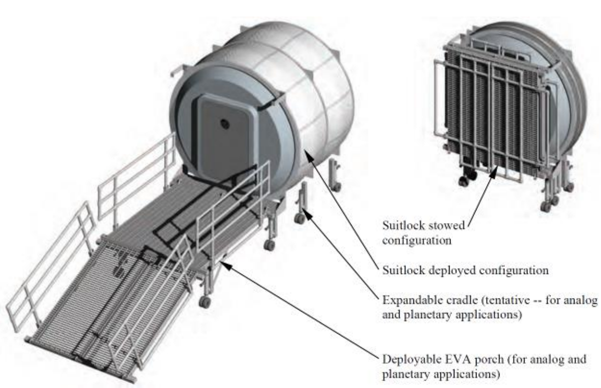

Figure 4 Suitlock In Deployed Configuration (Left), and Stowed Configuration (Right)[3]

4. Concept of Operation

There are three functional phases for MINA. First, pre-crew arrival and during the 3D printing of the shelter. Since radiation has no significant effect on beans [4][5][6], they can start growing as soon as the deployment is complete. The expansion of the cultivation region depends on the surplus water leftover from 3D printing consumption.

The second phase is after the completion of the shelter and 6-8 weeks before crew arrival. Non-leafy plants can start growing, being harvested, and being stored in a food reservoir.

The third phase is for leafy plants, which need to be used fresh. This phase occurs during the 6-8 weeks before crew arrival.

Once the crew arrives in phase four, the full cultivation process can begin. However, there is no obligation for crewmembers to work in the greenhouse, as MINA can function autonomously. Therefore, the cultivation schedule in phase four is determined by the crew's needs and availability.

The last phase happens when the crew leaves. Depending on the next mission, the greenhouse can go into hibernation mode or continue working at a modified rate.

5. 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[7].

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[8], thoroughly reviews nutritional requirements.

The required energy for NASA's food system for Long-Duration Mission is based on body weight and height. The result is an average caloric requirement of 3000 (kcal) as opposed to 2500 (kcal) provided to the Apollo crew [8]. More recent studies agree on the minimum 3000 (kcal) for the Mars mission [9] [10].

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

6. Plant Selection

In NASA's report "Nutritional and Cultural Aspects of Plant Species Selection for a Controlled Ecological Life Support System"[11], there are three scenarios of plant selection for mars mission: Minimum, Modest and Generous.

The "Minimum" version represents the most basic 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. The simplicity is the primary driving factor, but that 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 would the previous lists. This list has more than 35 plants making for the most variety.

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 [11] shows that for 1130 kcal, each crew member needs 46.5 m^2 in a Controlled Environment Agriculture (CEA) area.

Table 1 compares the required area in NASA's plant list with the MINA 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.

Table 1 Energy and Agriculture Area

	ICPD (kcal)	TICPD (kcal)	I/T (%)	CEA (m^2)
NASA	1130	2700	60	46.5
MINA	3000	3000	100	123.5
	CEA: Controlled Environment Agriculture ICPD: Intake Calories Per Day TCPD: Required Calories Per Day I/T: the ratio of Intake to Required Calories			

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[12].

Table 2 Public Space Plants

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

7. Growth media

The hydroponic Nutrient Film Technique (NFT) is the chosen water system of the greenhouse. Compared to other hydroponic systems, 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.

Figure 5 shows four groups of plant pots: 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. The yellow color represents Rockwool, and 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[12].

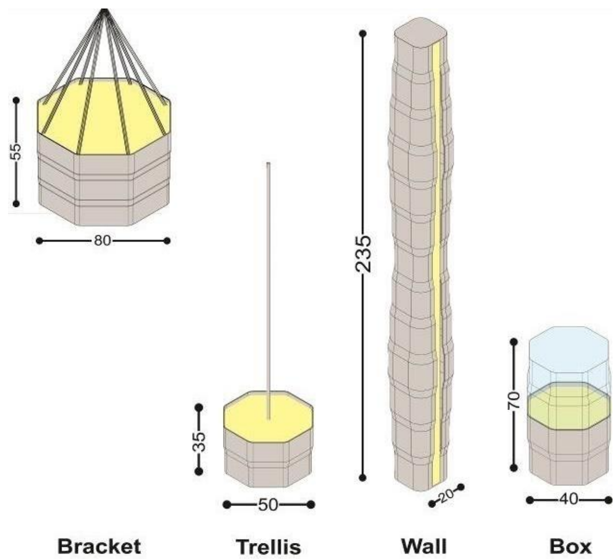

Figure 5 Plant Pots

8. Architecture

The backbone of the MINA structure is the core. The eight aluminum columns distribute the load and stabilize the structure. For increased stability, water tanks are located at the bottom of the core. These columns are also vertical ducts for water and power systems. At the lower level, there are three labs for plant studies and two storage areas for seeds and spare parts. A simple lift system enables transporting plant pots between the levels for the repair or customization of the greenhouse. The vertical circulation of the crew is enabled through a staircase connecting the public garden to the lounge area.

There are four water consumption facilities in the habitat module, which could be more efficient in the greenhouse: bathroom, an "aquatub" (an option for post space flight rehabilitation), laundry, and kitchen. These facilities are installed on the upper floor of the core and have a separate water cycle system. The ECLSS system manages the wastewater through a recycling system and returns clean water to the primary water cycle. In addition, allocating a gym within the structure can be beneficial for the plants due to the excessive production of carbon dioxide during exercise activities.

A flexible open-plan and mobile furniture in the greenhouse respond to the various needs of the crew. Therefore, there is no exact spot for the gym or lounge area, and the crew can modify the space to their personal and group preferences.

Wall plant pots shape radial walls on the upper floor, which holds four private spaces in between the walls. These rooms do not have a door or wall from the floor to the ceiling, but they can isolate a crewmember(s) from the public area. Plant boxes in each room shape the private garden for each crewmember, allowing them to grow their preferred plants there. The use of mobile furniture in these areas also can convert the space into a private working office or even a bedroom if needed.

9. Comparison

There is a spectrum of greenhouse designs in an extra-terrestrial world from a food factory to an interior garden. The five winners of the Big Idea Challenge 2019 are spread in this band[13][14][15][16][17]. MINA has some advantages over the designs of these five winners.

The most significant advantage is the consideration of human factors. For example, having a longer plant list and private cultivation areas increases the life satisfaction of the crew. Fruits and herbs add color and aroma in the garden area as well as in their cuisine. Also, a private garden could fill the gap between the common plant list and the different cultural tastes of the crewmembers.

Besides, this variety of plants requires plant pots that can be used as interior design elements[12]. The mobility of the pots enables the crew to rearrange the interior according to their needs. Moreover, wall pots can partition the space and separate areas for different tasks. Aesthetically, it allows those spaces to have their own identity[18].

The second improvement is the planting area. Table 3 shows that 1784 plant pots cover 497.54 m^2 of cultivation area, which is slightly above the crew's requirement of 494 m^2. This cultivation area covers the calorie needs of four crewmembers. However, other proposals would not fulfill even 60% of the calories required, which would be 296.4 m^2 for four crewmembers.

The third benefit of MINA is the reduction of system requirements. By providing 100% of the crew's food on-site, the required cargo mass is reduced. This allows more utilities and support materials to be included in the mission.

Table 3 Cultivation Details

	Bracket	Box	Wall	Trellis	Total
Pots in Upper Level	0	288	528	62	878
Pots in Lower Level	64	556	222	64	906
Total Number of Pots	64	844	750	126	**1784**
Area of Each Pot (m^2)	0.64	0.16	0.38	0.29	
Total Cultivation Area (m^2)	40.96	135.04	285	36.54	**497.54**

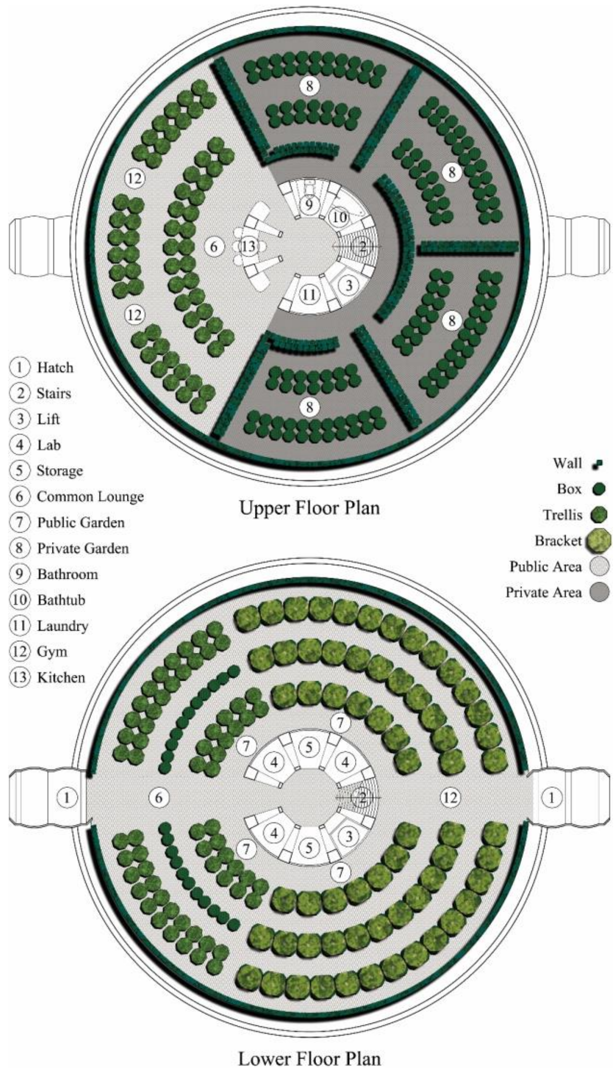

Figure 6 Floor Plans of MINA

10. Technical Estimates

Table 4 displays the mass estimation of the structure and the systems. The roughly 17.6 tons of this design is compatible with all the current rocket payload capacity.

MINA has a central core with eight columns and 16 beams in each floor to support all of the loads as the structure. It should be mentioned that the pressure difference of about 100 kPa stabilizes the inflatable and the hatches in their place. Therefore, those weights are not included in the structure mass.

The agriculture system in this estimation weighs less than 5.1 tons for all the seeds, nutrients, plant pots, and their appurtenances. The estimation of other systems covers all the light, air, control, and the ECLSS system.

The National Greenhouse Manufacturers Association's structural design manual suggests 73.23 kg of live load per square meter for the functional hydroponic system[19]. For the 407.54 m^2 of MINA, as Table 5 illustrates, the number is 40.32 kg/m^2 as a starting point. This is the total mass of all the systems and subsystems included in Table 4, except the structure, on 402.13 m^2 of both floors. The efficiency of this design, despite the density of the plant pots on the floor, is recognizable.

The ratio of live load to dead load is the critical number in the structural analysis and design. In MINA, this proportion is 2.04, which enables adding more plant pots to the agriculture system to have reservoir food support.

Table 4 Mass Estimation of MINA

	Material	Volume (m³)	Density (kg/m³)	Total Mass (kg)
Beams	Aluminum Alloy	0.301	2700	812.2
Core	Aluminum Alloy	1.008	2700	2721.6
Floor	Aluminum-Mesh	4.021	450	1809.5
Inflatable	Kevlar	3.942	1440	5677.1
Hatches & Bulkheads	Various	-	-	204
Total Mass of Structure				**11224.4**
Seeds	Various	-	-	31.8
Plant Pots	Polyethylene-LD	3.568	910	3246.6
Plant Caps	Polycarbonate	1.0128	1200	1215.4
Accessories	PVC-Flexible	0.108	940	101.1
Plant Beds	Rockwool	5.088	22	111.9
Pipings	PVC-Flexible	0.271	1290	349.1
Nutrients	Various	-	-	246.28
Total Mass of Agriculture System				**5056.0**
Electronic Supplies	Various	-	-	671.1
Mechanical Supplies	Various	-	-	575.1
Total Mass of Other Systems				**1246.2**
Total Mass Of MINA				**17526.5**
Water Usage	Water	2736.47	1	2736.5
Water Reservoir	Water	1840.9	1	1840.9
Total Required Water				4577.4

Table 5 Loads Analysis

	Total Live Load (kg)	Total Dead Load (kg)	Live /Dead Load
	10879.6	5343.3	**2.04**
Total Area	Live Load/Area (kg/m²)	Dead Load/Area (Kg/m²)	Total Load/Area (kg/m²)
402.1238	27.06	13.29	**40.34**

11. Conclusion

This paper has introduced the Martian Integrated Nourishment Aid (MINA), a greenhouse design for the partial gravity on Mars. It was designed to both provide 100% of the crewmembers' nutritional requirements as well as address human psychological needs. On the spectrum from a food factory to an interior garden for greenhouse design, this project is closer to a garden concept

This design concept brings several advantages over other greenhouse proposals. First, the foremost attention is paid to human needs. Using various plant pots accommodates spatial requirements of the individual plants while simultaneously allowing for interior design elements and wall installations for the benefit of the crew. Private garden areas provided by these pots fill the cultural gap in cuisine and offer a personal and private environment. Second, this design has a large cultivation area that is designed to feed crewmembers completely. This, combined with the fact that MINA is semi-autonomous, means that producing and storing food sources can begin before crew arrival. Finally, because MINA does provide 100% of the crew's calorie requirements without the necessity of additional food supplies, there is a reduction in cargo mass.

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Appendix

Table 1 Various Plant Lists

	Russian Academy of Sciences [20]	**NASA** [21]	**ESA/Canada** [22]	**University of Utah** [23]	**NASA** [24]	**Institute for Environmental Sciences in Japan** [25]	**ESA/Canada** [22]	**NASA** [21]	**University of Utah** [23]
	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**