SIRONA: Sustainable Integration of Regenerative Outer-space Nature and Agriculture

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I. Introduction

NASA has been exploring sustainable, regenerative food systems for missions beyond Low Earth Orbit (LEO).[1] SIRONA (Sustainable Integration of Regenerative Outer-space Nature and Agriculture) is a proposed design meant to address the most basic needs of Mars colonists through integrated biological systems modeled after ecologically-robust Earth agricultural systems, but modified to meet mission-specific challenges. These needs include survival, nutrition, socialization and psychological comfort gained from interaction with nature. Multiple studies suggest tangible benefits of gardening for humans.[2–4] These benefits range from cognitive improvement to increased social cohesion. There are measurable physiological effects, such as reduced cortisol levels and stress, which contribute to a healthy immune system. Furthermore, living systems with higher diversity are more resilient in novel conditions and provide more services for humans.[5] In addition to providing nutrition, phytochemicals found in crops treat and prevent medical issues such as radiative damage and micronutrient deficiency; these issues are likely to plague astronauts during long missions. SIRONA borrows from ecologically-robust agricultural systems that emphasize diversity as a significant contributing factor to increases in human benefits and overall system stability; this is demonstrated in the rich nutrient profile, redundant yields and relatively low risks expected.

SIRONA intends to provide comprehensive care of humans on Mars through the careful selection of food sources from multiple climate zones and horticultural therapy, which is implemented by promoting passive and active human-plant interaction. The well-being of humans is enhanced further enhanced by encouraging activities such as exercise, socialization, and meal preparation in the multi-purpose open space; this space allows humans to participate in recreation while surrounded by plants. Through a network of horticulture decision support tools referred to as AgQ and the Brain, gardening tasks that are not time-sensitive are to be assigned at optimal times; these are the times when the human can benefit the most by taking a restoration break from other critical and stressful tasks.

This work is organized in the following manner:

- Context of this design (Section II)
- Design considerations (Section III), including the design philosophy and crop selection methodology
- Detailed design concept of SIRONA (Section IV), including integrated system diagrams, sub-system details, the overall living system, and the decisions made to facilitate the experience of the crew members
- Concept of operation (Section V) required to deploy and maintain the greenhouse
- System summary (Section VI), including SIRONA's performance, power/mass summary, and a comprehensive risk matrix for the major aspects of this mission

II. Mars Arrival Assumptions

The proposed design discusses both the layout and viability of a Martian SIRONA to support a crew of four during a 600-day mission on an early Mars outpost. SIRONA attaches to the Mars Ice Home; several parameters were derived from the conceptual design of the Ice Home, including the launch parameters. The stowed configuration fits in the 8 m cargo shroud of the SLS launcher. SIRONA can be packaged and stowed within the volume and dimension constraints of the EDL (Entry, Descent, and Landing) aeroshell. As with the Ice Home deployment after landing, the SIRONA package will be transported to the Mars deployment location via robotic transporters already present.[6] The crew is estimated to arrive about 26 months after the launch of the SIRONA package.

III. Design Considerations

This study proposes a complete integration of biological components such that the astronauts, plants, and symbionts (aquatic life, algae, and microbes) remain healthy throughout the entirety of a 600-day mission. Components and technologies are carefully chosen to optimize benefit-to-mass ratios. Drawing from the stacking functions principle from permaculture, each element carries out multiple functions and more than one element can carry out each necessary function to ensure redundancy and security in a high-risk environment.

The nature of a regenerative system calls for a design that can continuously process fixed amounts of inputs and outputs from the system's various components. The system must be able to recycle and/or produce a portion of oxygen, carbon dioxide, food, greywater, and blackwater as generated by crew members and crops (Section VI, Table 8). The water and power interfaces for the greenhouse are similar to that of the Ice Home. The same goal of reducing GCR radiation is applicable here, as the crew will be spending a significant amount of time in the greenhouse working, eating, and recreating.

A. Design Philosophy

Design for SIRONA focuses on creating a highly integrated living system that is resilient, robust, and regenerative. This goal is achieved by drawing upon a unique approach which embraces the concept that the synergistic integration of all organisms is crucial to the well-being of the whole living system. The SIRONA greenhouse integrates proven concepts from the following design methodologies and technologies: permaculture, biophilia, biomimicry, Controlled Environment Agriculture (CEA), and vertical farming, Human Centered Design.

A major goal of this design is to maximize the use cases within the greenhouse volume to improve the habitability and human factors of the outpost beyond satisfying basic nutritional needs. Such use cases include relaxation, recreation, sensory stimulation, meal preparation, and supplemental Bioregenerative Life Support Systems (BLiSS) (e.g., food production, waste management, water reclamation, air revitalization, and access to nature). BLiSS is a specific acronym that embraces the concept that nature improves the health and well-being of the crew, and is a critical function of a bioregenerative life support system (Hava, 2013). It can be said that "Nature is BLiSS" (Hava, 2013) which embodies the intangible benefits of integrating nature into the habitat. Previous BLiSS designs focused on crew survival as their primary function; however, a BLiSS design such as that implemented in SIRONA provides support to the additional vital functions of keeping all of the living systems healthy and happy. To implement this unique overarching architectural concept in the SIRONA greenhouse, the layout is designed to mimic the feel of an outdoor garden or park; this provides a familiar Earth environment that promotes well-being, crew cohesion, relaxation and recreation.[8,9]

Additionally, SIRONA can be used as an emergency secondary habitat in case of catastrophic failure of the Mars Ice Home primary living quarters. SIRONA includes all of the subsystems necessary to function as a habitat, including a bathroom, kitchen, and emergency deployable sleeping quarters that are stowed during normal greenhouse operations. The Mars Ice Home and SIRONA are connected by an airlock; this allows the two systems to operate independently.

B. Diet Considerations

The estimated caloric requirements for this mission are approximately 6 million calories total. Given the limited size of the Ice Home, power constraints, and the current state of lighting technology, it is realistic to assume that the mission involves periodic resupplies of high-calorie staple foods from Earth. The role of SIRONA is to provide supplemental fresh crops and fish that enhance the micro-nutrient profile, palatability, and psychological attributes of the crew's diet.

The concept of "food as medicine" is adopted to guide crop selection. The crops grown on Mars play a critical role in providing micronutrients that address both the physiological deterioration of crew during long-duration spaceflight and the degradation of nutrients in foods stored for long periods. For example, vitamins D and K are key to counteracting the loss of bone mass.[10] Antioxidants such as beta-carotene, selenium, Vitamin E, and zeaxanthin may help to mitigate the effects of space radiation.[11] Certain spices and herbs long used in numerous cultures' traditional medicines have been clinically shown to have measurable positive effects on health,[12] in addition to livening up otherwise bland dishes.

Palatability is a key design driver because it can override all other attributes in influencing food consumption. Thus, a menu is required that not only supplies necessary nutrients but also is highly palatable. To this end, the design adopts aspects of highly effective techniques utilized by professional chefs in fine dining. Raw ingredients and cooking tools are chosen that create contrasting flavors and textures on the plate. To encourage the crew to engage with and be provoked by their meals, the selection of exotic crops is balanced with fruits and vegetables familiar to a Western diet.

C. Crop Integrated Value

A diverse roster of crops provides nutritional, medical, and psychological benefits to the crew, detailed in Table 7 of Section IV - System Summary. Rather than exporting the standard Earth agricultural definition of yield as biomass per area,[13] an amended metric is proposed (CY), to guide the crop selection process. In the SIRONA system, CY is the weighted value of all plant functions summed over the inverse harvest index (i.e., 1/harvest index). By this definition, the system favors those plants with the greatest number of functions and highest harvest index (Hx = edible biomass/inedible biomass) (e.g., high-scoring crops). Additionally, this equation is a flexible metric that can be adjusted based on mission constraints and priorities by adding, subtracting, or adjusting the weighting of the functions in the numerator. This re-definition of yield includes multiple axes of plant performance in a simplified metric that, while not perfect, better represents a complex system with multiple properties. Selection of robust, high value crops using the CY metric thus reflects the emphasis on optimizing each crop for complex and diverse gains.

$$CY = \sum [\frac{(v_1 v_2 ... v_x)}{Hx}]^{-1} \quad \text{(Eq. 1)}$$

In the above formula, v_i is a single plant function, and Hx is the harvest index (edible/inedible biomass). This metric can also be used to evaluate the total crop complement by summing CY and dividing by the area to get a composite crop yield density. This gives a more complete picture of the system functionality and provides the flexibility to include crops with other functions (i.e. psychological benefit, and medicinal value) than just nutrition and edible biomass to balance the overall system performance. In this design three primary crop functions in the numerator were used to evaluate each crop: nutrition, psychological benefit, and medicinal value. Table 7 provide the details for each crop.

D. Food Processing Considerations

Post-harvest processing is another factor that guides crop selection. Previous studies show that roughly 153 minutes (2.55 hours) of active crew time per day were dedicated to meal preparation, consumption, and cleanup in a resupply scenario.[14] Given the fresh food produced in the greenhouse and the processing equipment included in SIRONA, crew time is expected to increase slightly to accommodate post-harvest processing and cooking beyond simple rehydration and heating. While some of the highly perishable crops (e.g., salad crops) must be eaten fresh, other selected crops are amenable to long-term storage or preservation in order to compensate for seasonal variations in abundance and scarcity. Inedible plant and fish matter can be incorporated into other stages of the bioregenerative loop, such as serving as fish food in the aquaponics system.

IV. SIRONA Detailed Design Concept

A. Greenhouse Architecture

On Earth, technology and site-specific methods facilitate food production for nutrition and environmental habitability across vastly different ecosystems. Of the many food production approaches, the least resource- and time-intensive systems are agroecosystems, which provide nutrition under even extreme conditions by making use of evolved plant adaptations and mimicry of community-level biological processes.[15] For the mission at hand, the same principles important for stable agroecological systems on Earth (e.g., redundancy, reduction of resource waste, crop diversity)[16] are employed to improve efficiency of both biological and mechanical components. SIRONA is a BLiSS created to optimize system productivity of crops and crew members by mimicking terrestrial agroecological systems with use of permaculture principles.

A key principle in both permaculture and agroecological farming is the importance of perennial plants for stability and resource efficiency of the whole system. Fruit trees, for example, produce edible yields annually for years while simultaneously improving soil stability, habitat, and resource availability for other plants in a terrestrial ecosystem. This concept is implemented in the SIRONA system by utilizing fruit trees to passively process grey and blackwater via the Biowick. This system function, along with consistent, high-quality, composite yield (life support functions, nutrition, psychological and medicinal benefits) of fruit trees, suggests that an adapted food forest[17] will improve the long-term benefit/payout of SIRONA.

To account for time delays associated with perennial crops, successional planting of annuals provides quick and continuous fresh food while trees mature and develop fruits in the initial phases of the mission. Each individual tree can be transported at approximately age two years to further mature during the cold-temperature transit (see crop phasing in section V). Winter simulation through refrigeration during transit induces maturity and fruit production upon planting in SIRONA. Staging and intercropping annuals and perennials creates and artificial ecosystem analogous to agroecosystems, complete with successional resource management and growth-media remediation. SIRONA integrates these proven concepts (and others) from the following design methodologies and technologies: permaculture (food forests with polyculture food guilds), biomimicry, CEA, and vertical farming.

Figure 1 SIRONA Architecture Layout

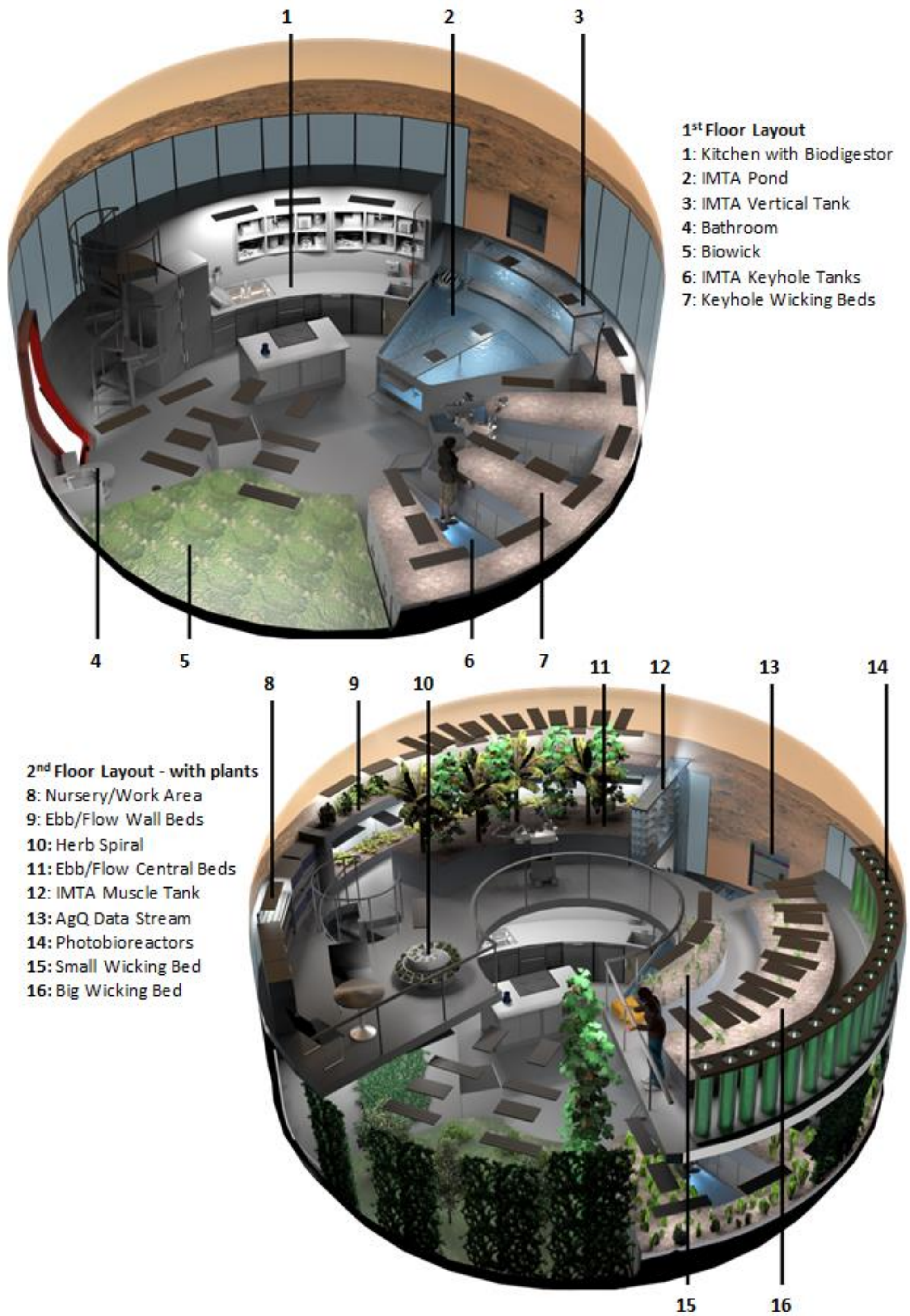


Figure 1 displays the entire greenhouse architecture. On the first floor, major subsystems include the Biowick, kitchen with biodigestor (bladder located under the kitchen floor), herb spiral, and the Integrated Multi-Trophic Aquaponics (IMTA) system reservoirs (pond and juvenile fish tanks) that water the keyhole garden (wicking beds) and Biowick. On the second floor, major subsystems include ebb and flow beds and wicking beds that are watered by the IMTA freshwater mussel tank, photobioreactors, herb spiral, plant nursery, and sitting area (which can be utilized to deploy the emergency sleep quarters). Multi-level features include high-wire trellising, programmable multi-spectrum LEDs, and the Himawari solar fiber optic lighting system. Section C Greenhouse Technologies provides detailed descriptions of each of these subsystems. Table 1 provides the major elements' (growth systems and IMTA reservoirs) areas, volumes and growth zones.

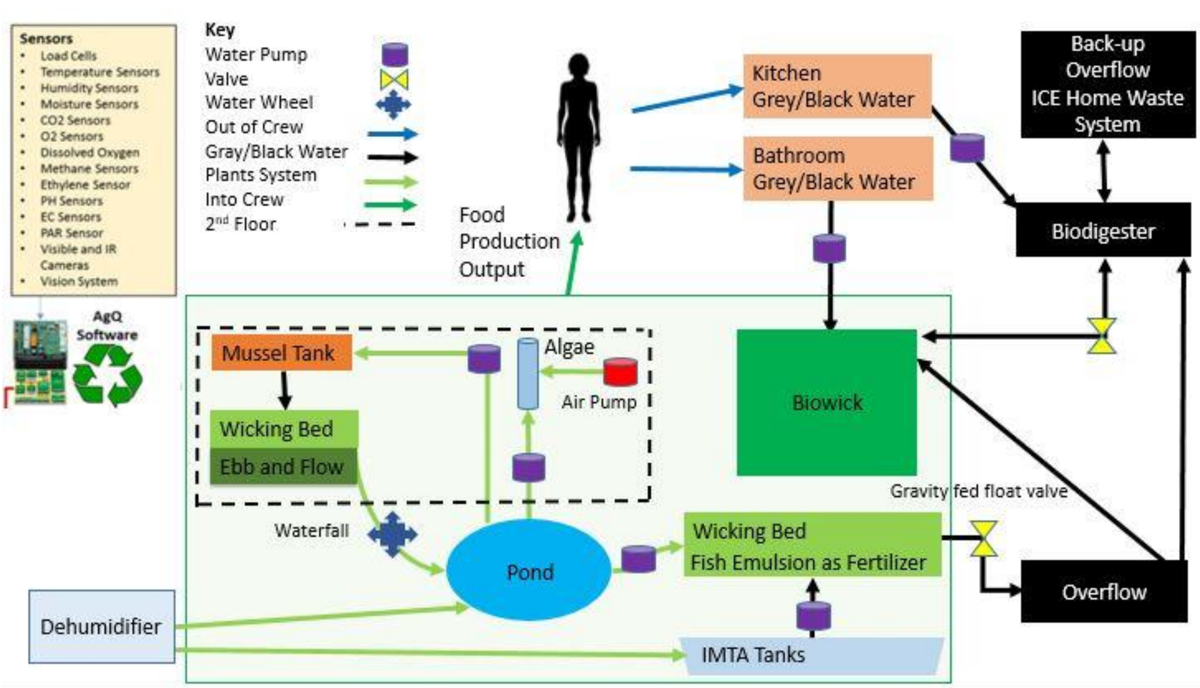
Table 1 - Area, Volume, and Zone of Major Growth and IMTA Systems

Label	Floor	Element	Area m^2	Vol. m^3	Zone
5	1	Biowick	13.926	9.508	2
7	1	Keyhole wicking bed	11.420	3.574	1
9	2	Ebb/flow vertical wall beds	9.347	1.899	2
11	2	Ebb/flow central bed	5.739	3.498	2
15	2	Small wicking bed	2.034	0.699	2
16	2	Big wicking bed	7.045	2.420	2
10	1&2	Herb spirals, both	2.36	N/A	1&2
		Subtotal	**51.870**	**21.599**	
14	1	Photobioreactor	1.484	0.7	2
IMTA Reservoirs					
6	1	IMTA keyhole tanks	3.178	1.965	3
2	1	IMTA pond	21.643	2.424	3
3	1	IMTA vertical tank	1.978	1.858	3
12	2	IMTA mussel tank	0.890	1.082	3
		Subtotal	**27.689**	**7.328**	

B. System Overview

As shown in Figure 2, the subsystems in SIRONA closely interact with each other. The land crops, trees, algae, aquatic animals, and crops all produce edible biomass for the crew members. The biodigester processes all of the kitchen's grey and blackwater, as well as inedible biomass produced by the greenhouse that is not used for other purposes like creating growth media. The grey and blackwater from the bathroom (i.e., from human output streams) is used as fertilizer for the Biowick; also, it can handle the overflow from the wicking beds. Bidirectional plumbing between the Biowick and biodigester mitigates the risk of overflow from either, as both are capable of processing grey and blackwater from any source. In the case that both systems are over capacity, the Mars Ice Home waste system

Figure 2 - SIRONA System Overview



serves as the backup overflow system. The first floor keyhole wicking bed is irrigated with IMTA pond water which contains nutrients from the fish that fertilizes the crops. Water from the pond is pumped up to the second floor mussel tank before it is used to irrigate the wicking beds and ebb and flow beds, then circulated to the algae photobioreactors. After irrigating the beds, the water returns to the mussel tank prior to cycling back to the pond via a waterfall that drives a water wheel both of which serve the function of aerating the water to increase the dissolved oxygen levels. Second floor systems are all interdependent with various water pumps and a water wheel to facilitate moving the water to and from the pond located on the first floor. All of these relationships are outlined in Figure 2.

C. Greenhouse Technologies

1. Integrated Multi-Trophic Aquaponics

Aquaponics makes up one of three grow zones in the SIRONA greenhouse. The aquatic aspect of the design is based on the Integrated Multi-Trophic Aquaculture (IMTA) system (Figure 3), which relies on aquatic organisms occupying different levels in the food chain to synergistically recycle nutrients, increase output, and achieve an overall stable ecosystem.[19] Ebb and flow media beds are paired with the IMTA to create an integrated *aquaponics* system. These beds use Growstone®, a lightweight, reusable, off-the-shelf growth media. The integration of hydroponics with aquaculture further increases the harvestable biomass and reduces the need for hydroponic nutrients to be resupplied in the long term.

Aquatic species and crop selection for the IMTA system is guided by symbiotic compatibility, capacity for ecological remediation, and consumer palatability. For example, all aquatic species (Table 7) selected must be able to thrive in environments with a temperature and pH that matches the growing environment of the crops grown in the aquaponics system. Three species of fish (barramundi, jade perch, and tilapia) have been selected along with freshwater shellfish (giant prawn, red claw crayfish, and mussels) and three aquatic crops (duckweed, watercress, and sacred lotus). The mussels, powerful filter feeders that ingest uneaten fish pellets and feces,[18] prevent particulates from accumulating in the ebb and flow grow beds. Prawns and crayfish carry out a similar function in the IMTA ecosystem as do the mussels, further increasing the utilization of nutrient inputs. The acceptability of the aquatic crops for human consumption is another key factor. Selected crops are featured in familiar seafood dishes from a variety of cuisines.

Figure 3 - IMTA pond and tanks nested within keyhole wicking beds.

2. Grow Beds

SIRONA uses both ebb and flow beds as well as wicking beds. Ebb and flow beds rely on the periodic flooding and draining of the grow bed to distribute nutrients and oxygen throughout the system. They are easy to set up and effective. Wicking beds act like a passive self-watering pot, operating on the principles of sub-irrigation and capillary action to deliver water and nutrients to the crops. Both types of beds rely on the highly porous Growstone® (lightweight, recycled foamed glass) as reusable growth media that serves as the water reservoir and is covered by a soilless media in which the crops grow. The grow beds receive nutrient-rich water from the aquaponics system and effluent from the biodigester.

Both the ebb and flow bed and wicking bed are selected for their resilience against pump failures. In case of pump failure, there is a long lag time (a couple to several hours) before crop death occurs in either of these media beds. In comparison, a pump or nozzle failure in the nutrient-film technique or aeroponic systems can lead to crop death in as little as 15-30 minutes. In cases where pumps cannot be repaired, both types of media beds can be hand watered. Resiliency is reinforced by the use of Growstone® as the aggregate media. At saturation (i.e., after all free water has drained away), Growstone® maintains a unique balance between moisture (30% of its volume through capillary action) and air (50% by volume), which reduces the chances of developing anaerobic conditions that can lead to root rot. An initial cache of organic soilless media (such as coco coir) is to be supplied for the start-up phase and replenished via *in situ* production of growth media from inedible biomass and biodigester effluent. To minimize launch volume and mass, grow beds and fish tanks are constructed from a deployable carbon fiber frame structure that is covered by Dura Skrim®, a food-safe, reinforced, flexible plastic sheeting.

As the Martian outpost expands and additional greenhouses are built, a scalable regolith remediation system can be developed to create additional growth media used in the Biowicks and wicking beds. The abundance of perchlorates in Martian regolith prevents the growth of many crops. Perchlorates are also a human hazard, and can cause goiter, thyroid hypoplasia, and a decreased metabolism if ingested. A possible solution to the problems caused by perchlorates is to reduce the concentration of perchlorates in Martian regolith through the utilization of enzymes. The reduction of perchlorate to chlorite is catalyzed by the enzyme perchlorate reductase (Pcr). The chlorite is then reduced to chlorine and oxygen in a reduction reaction catalyzed by the enzyme chlorite dismutase (Cld). Once both reactions are complete, the regolith is free of perchlorates and can then be used to grow crops. The procedure of perchlorate removal is environmentally safe and could serve as a supplemental source of oxygen for crew members.

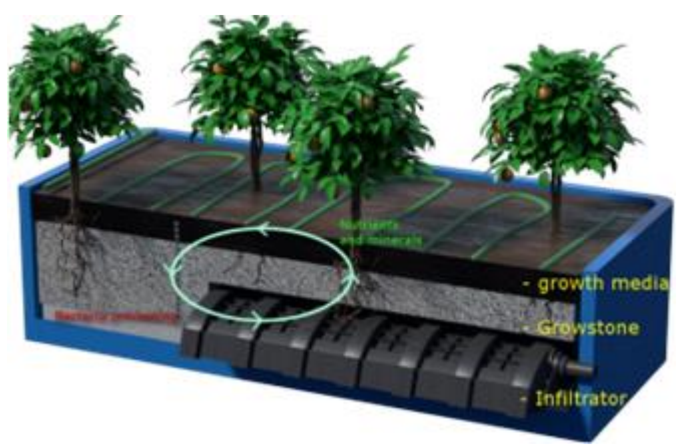
3. Photobioreactor

The photobioreactors (Fig. 1) produce algae as a nutritional supplement. Since the time between algal harvests is the shortest of any of the selected crops in this greenhouse, algae serves as a fresh food substitute when other crops have yet to reach maturity. Algae-based photobioreactors can simultaneously revitalize air (by consuming CO_2 and producing O_2) and manage waste (by consuming nitrogen and phosphorus byproduct streams from biological systems), in addition to producing edible biomass.

The genus *Spirulina* is selected for its high nutrient density, acceptability amongst consumers, and designation as food safe by the US Food and Drug Administration and the UN Food and Agricultural Organization. *Spirulina* occurs naturally in warm, tropical waters (~30 °C) with relatively high pH (pH 7-10); these conditions make it ideal for use in greenhouse systems.[20] The photobioreactor and the rest of the tropical zone are deliberately located on the second floor to take advantage of the natural heat gradient. Nutrients required for the algal culture is sourced from the fish tanks and/or biodigester.

The reactors are comprised of two concentric cylinders in an annulus configuration. A bank of LED tubes is inserted in the center cylinder, and algae surrounds the light in the annulus. The configuration allows for maximum utilization of light by algae and reduces stagnant flow and biomass build up by minimizing corners. Pumps sparge CO_2-enriched cabin air (or biodigester) through the bottoms of the reactors to mix and feed the culture. Non-reactive plastics, stainless steel, and carbon fiber are used as building materials. In the SIRONA design, reactors are primarily intended for the greenhouse, although there is potential for their installation in the crew quarters too.

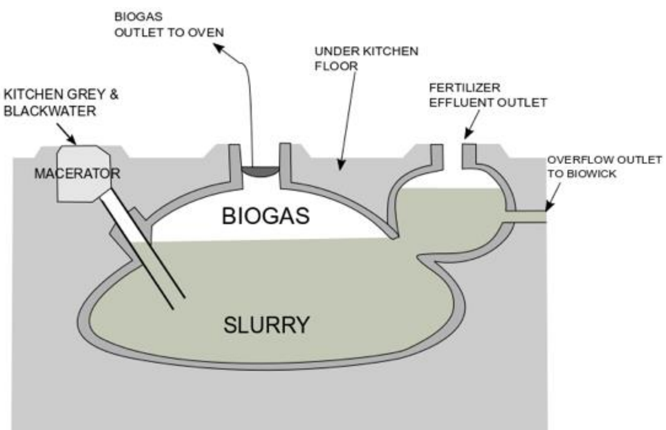
Figure 4 - Basic design of Biowick



4. Nutrient Recycling Technologies

A unique, passive aerobic Biowick system (Figure 4) optimizes the growth of fruit-bearing trees and vines in SIRONA. The closed-loop Biowick is adapted for space from the Watson Wick, an aerobic pumice wick invented by Tom Watson that relies on the symbiosis between microbes and woody plants to passively process grey and blackwater from human waste streams into nutrients for plants.[7,21] A half-cylinder infiltrator creates an open air volume buried under a layer of Growstone® aggregate, which itself is buried under a layer of growth media. The infiltrator allows water and human waste to surge into the system from an inlet, while providing an open space for air to infiltrate the media bed. The highly porous Growstone® houses primarily aerobic (and some anaerobic) bacteria that process incoming waste and acts as a medium through which air, liquids, and particulates percolate. Once processed by the bacteria, nutrients and minerals are then drawn up through the tree roots as moisture and fertilizer. Plant roots easily infiltrate the porous media bed, drawing water and nutrients up from the Growstone® into the woody tissue of the tree or vine. About 1-5% of the water is consumed by the tree in metabolic processes and growth, while the rest is returned to the atmosphere through transpiration. The purified water vapor produced by transpiration is then recaptured by dehumidification.

Figure 5 – Biodigester design



Biodigesters (Figure 5) are highly effective sources of renewable energy and fertilizer production which are inexpensive, easy to maintain, and simple. Methanogenic bacteria anaerobically process a mixture of organic waste, such as food scraps, inedible biomass, human/fish manure, and greywater.[22]The process produces a biogas composed of 55% methane and 45% carbon dioxide, as well as a nutrient-rich effluent that can be used as fertilizer for crops and algae, providing additional nutrient loop closure.[23] The biogas product can be used for cooking, heating, methane extraction, and carbon dioxide enrichment of plants.

5. Post-harvest Processing

The primary kitchen galley is deliberately moved from the crew quarters to the greenhouse and expanded into a fully functional kitchen adjacent to a dining/recreation area. Consequently, post-harvest processing, preservation, and cooking all take place in close proximity to the growing and harvesting sites. The relocation not only enhances crew efficiency, but also has the potential to improve physical and psychological well-being by increasing the amount of crewtime spent amidst nature.

Figure 6 - Kitchen Layout, see Table 2 for label key

The layout of the kitchen in Figure 6 maximizes both functionality and aesthetics. Large pieces of equipment associated with long-term storage are located along the wall, with those for immediate post-harvest processing (a utility sink for initial cleaning of crops and fish, and a biodigester equipped with a macerator for breaking down inedible materials) located closest to the grow areas. Food residue on dirty dishes can be also discharged into the biodigester before being cleaned in the dishwasher or sink.

The bulk of meal preparation takes place at the central island. Stocked with cooking equipment, the island's size and barstool height allows two to four crew members to prepare meals together while facing each other and encourages cooking as a social, leisure activity. Two refrigeration and two freezer units are built into the island, maximizing storage space. On the island, four major pieces of equipment cover the gamut of possible cooking applications (Table 2). Some functional redundancy is built in to accommodate high processing volumes during seasonal harvests. For example, both the multi-cooker that includes an air fryer and the oven (which utilizes biogas from the biodigester) can be used to dehydrate surplus crops.

Table 2 - Kitchen Equipment

Label	Equipment	Mass (kg)	Power (W)	Comments
A	Induction burner + sous vide bath	7.5	1500	Used together or separately; ideal for cooking fish and large vegetables
B	All-in-one prep station	2.6	240	With attachments for blender, food processor, whisk
C	Dehydrator/ oven/broiler	10.2	15 w/ biogas	Contains fan for forced convection; runs off of gas from biodigester
D	Multi-cooker	11.7	1400	High heat (frying, searing)
E	Pantry	11	0	Stores grains, potatoes, etc.
F	Cold storage	352.4	486	Deep freezer (long-term storage); 2x freezers (short-term storage); 2x refrigerators
G	Dishwasher	32.7	1300	Greywater goes to biodigester
H	Herb spiral	5.0	60	Easily accessible for garnishes
I	Island	15.0	0	.8 m x 1.5 m x .9 m (height)
J	Dining table	15.0	0	.7 m x 1.4 m x .7 m (height)
K	Sinks	7.8	0	Food prep/dish sink; crop utility
L	Biodigester w/ macerator	10	540	Biogas connected to oven

V. Concept of Operations

The concept of operations details how the greenhouse is to be deployed and run while on the surface. The basic operational processes of all the major subsystems are listed below.

A. Control and Operations

1. Environmental Control

Three climate zones (Table 3) are outlined according to standard CEA methods and analogous terrestrial climate zones. While no single crop necessarily experiences optimal environmental conditions at all times, the polyculture guilds planned in each zone are productive and resilient under slightly variable conditions.[22] In permaculture, guilds are groupings of different plants, animals, and other components to create a symbiotic relationship to help them grow and stay healthy while providing useful resources to humans.

The selected crop complement is expected to uptake ~258 L of water/day, 96-99% of which is transpired. Humidity is maintained around 50-80%, depending on the grow zone temperature and the desired VPD to support plant growth at all stages (vegetative, flowering and fruiting simultaneously). In order to maintain the desired VPD, the dehumidification system recaptures the transpired water and recycles it back into the IMTA system.

Table 3 - Environmental Parameters

Zone	Hydroponic System	Earth Analog	Day Temp. C	Night Temp. C	Light (hrs/d)	DLI mol·m-2·d-1	pH	Day RH (%)	Day VPD (kPa)
1	Wicking Beds	Temperate	12.8-21.1 (55-70 F)	7.2-12.8 (45-55 F)	12	15.12	5.8 - 6.8	15 - 55	.8-1.08
2	Ebb/Flow, Wicking Beds, Biowick	Sub/ Tropical	21.1 -26.7 (70-80 F)	15.6-21.1 (60-70 F)	16-18	20.16 - 22.68	5.7 - 6.8	55 - 65	.83-1.12
3	Aquaponics Tanks	Freshwater	25.6-30 (78-86 F)	25.6-30 (78-86 F)	16-18	20.16 - 22.68	6.8 - 7.5	53 - 70	.83-1.13
4	Algae	Freshwater	30 (86 F)	30 (86 F)	24	30.24	7.0 - 10.0	N/A	N/A

The IMTA system dissolved oxygen level is maintained above 5 ppm through aeration provided by the waterfall and waterwheel. The waterfall also serves the function of humidification in the early startup phase before the crops reach their full transpiration rate. Because the wicking beds in the temperate climate Zone 1 require cooler temperatures, they are enclosed by a clear CO_2/O_2 permeable membrane curtain system that creates a microclimate for that zone. Multiple V-FloFans create airflow in the greenhouse and redistributes heat and humidity. By using a vertical airflow system, constant airspeed and desired microclimates can be achieved at the plant level.

2. Lighting Systems

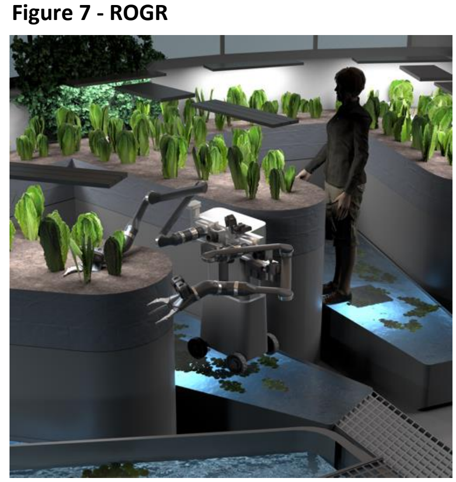
Lighting for crops comes from two sources: LED lights and a solar fiber optic Himawari system. Programmable Multi-spectrum LED lights made by AcroOptics provide the full Photosynthetically Active Radiation (PAR) spectrum as well as IR and UV. LED lights will be programmed to deliver short 'pulses' of 800-1000 $\mu mol/m^2/s$ for five minutes five to six times daily, which will increase photoprotective carotenoid content of leafy crops without compromising biomass production.[22] The Himawari solar lighting system provides half the total PAR input to the greenhouse, though it is subject to variability due to Mars weather conditions such as sand storms. The Himawari system is a mature commercial technology that operates as follows: a solar collection system utilizes fresnel lenses to concentrate and transmit sunlight into the greenhouse via thin optical fibers. The optical fibers enter the SIRONA structure through the same utility pass-through as the power system electric wires. Advantages to the Himawari lighting system include minimal power usage, an automatic tracking system that aims the lenses continuously at the sun, and colors that mimic natural lighting. The lighting panels from both systems are spaced such that the plants receive 350 $\mu mol/m^2/s$, which is sufficient for consistent carbon fixation.[24] The combination of these two systems optimizes power, mass, and controllability, resulting in a robust lighting system. Natural light that filters through the translucent shell of SIRONA helps to illuminate crew tasks and to entrain circadian rhythms.

3. AgQ, the Brain, and System Displays

The AgQ software carries out monitoring, alerting, diagnostics, and prediction functionality to provide plant care decision support. AgQ has a data processing pipeline that utilizes machine learning and aggregated data from the Brain (i.e., a multiple sensor system and the vision systems described below). The Brain provides data streams from the following sensors: pH, EC (electric conductivity), dissolved oxygen, water and air temperature, ethylene, methane, and other trace gases. It also provides the interface for wearable human health monitors. By pairing the plant care needs with the humans physiological stress state and psychological need for contact with nature, the system provides the alerts for plant care tasks at the optimal time that crew members can benefit from horticultural therapy. This is possible through the use of a dynamic pairing reinforcement learning algorithm that is fed the changes in measurable stress responses from the astronaut before and after being assigned a care task. Additionally, a Virtual Extension Service (Plant Telemedicine) is implemented to provide astronauts with plant care troubleshooting.

Organic Light-Emitting Diode (OLED) microdisplays are used on sections of the ceiling and walls in SIRONA.[25] These low power displays have advantageous features (e.g., high resolution display of the color black, long lifetime) that make them a viable image display technology. They will be used to display data from the AgQ system, views of Mars or scenes of clouds and birds from Earth to invoke a connection with nature.

Figure 7 - ROGR



4. Automation, Robotics and Vision

Robots are tasked with repetitive, time-consuming tasks, while activities that bring psychological and physical benefits resulting from human-plant interactions, such as harvesting, are left to the crew as well as tasks that robots are not well suited for. Daily and weekly plant health monitoring involve a program of robotic manipulation, stereoscopic imaging, and spectrum analyses using sensors embedded in the growth systems. In addition to health monitoring tasks, the robotics and automation system performs: pollination, nutrient management, and crop performance alerts (e.g., crew notification of harvest readiness, nutrient deficiencies, disease states and suggestions for corrective actions). These are included in the plant telemedicine module.

The Remotely Operated Gardening Rover (ROGR) (Figure 7) has two robotic arms, allowing for complete access to the crops. The Kinova JACO or a similar arm is outfitted with specialized custom end-effectors currently under development at CU Boulder's Correll Lab. Embedded finger sensors in the robotic hands provide sensitivity to textures and proximity, enabling fine motor skills crucial to manipulating delicate living systems.

The teleoperator and arm rely on visual input from four separate cameras:

1. A basic overview camera displaying the inside of the growth chamber.
2. An IR camera to monitor plant health and help diagnose problems.
3. A LIDAR sensor that maps plant positions and projects the chamber environment in virtual reality.
4. Two cameras on the end of the arm provide stereo vision for A.I. or a teleoperator to accurately manipulate the arm and interact with the plants.

Autonomous operations of the robotic system and teleoperators care for the system in between crewed missions.

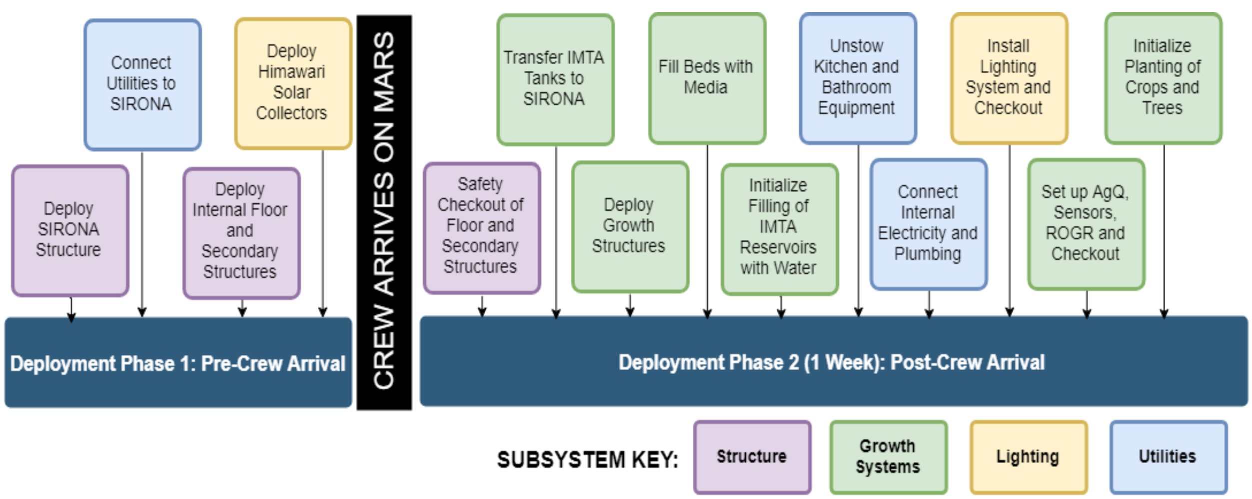
5. Martian crop science and adaptive breeding

A participatory breeding program, with collaborative input from both astronaut farmers and horticulturalist advisors, will be initiated to develop site-adapted cultivars for multigenerational crop sustainability on Mars. For example, some of the high-calorie crops (e.g., sweet potato, mashua, oca) may facilitate experimental cultivar development *in situ* due to the ability to select and propagate the 'best' clonal lineages over short time periods.[26] A plant laboratory facilitates basic and applied plant research *in situ*. Here, astronauts collect data on plants to assess crop performance. In addition to important internal leaf temperature measurements for intermittent adjustments of the vapor pressure deficit, phenotypic data (e.g., size, weight, flower and fruit occurrence, biomass ratios, seed weight, germination rate, pathogen load) is recorded on a biweekly basis or at the time of crop harvest. Additionally, nanopore sequencers are used to quantify differential RNA expression of key functional traits and genetic differentiation between preferred and non-optimal individual plants. These tools provide data for basic plant science and the Martian crop breeding program proposed above.

B. Deployment

Figure 8 summarizes the deployment sequence after the greenhouse lands on the Martian surface. Phase-1 of deployment refers to the time after the greenhouse landing, but before crew arrival. Phase-2 of deployment refers to the one week set-up period post-crew arrival. Due to the constraints of the Mars launch window, Phase-2 occurs 25-26 months after Phase-1 of deployment.

Figure 8 - SIRONA Deployment Timeline



1. SIRONA Deployment Phase-1

Phase-1 of deployment involves deploying the greenhouse structure and other major systems before the crew arrives on Mars. The robots deploy the external Himawari solar collectors and connect the utilities to the SIRONA shell. The airlock connecting SIRONA to the Ice Home habitat is deployed before the internal secondary structure deployment is complete.

SIRONA utilizes an inflatable system for the internal secondary structural components, including the floors and bathroom walls with vertical and horizontal tensioning cables or webbing for additional support. The bio-inspired flooring system imitates the opening of a flower such that the inflatable floors unfurl from the central hubs. Therefore, the flooring modules are referred to as petals. This design decision was made by considering past studies on inflatable support structures.[6,27,28] The inflatable beam components are rigidized with foam or Martian regolith for additional strength.

Figure 9 - Ice Home Deployment. Schematic of the inflatable structure's deployment of the first and second floors through the petal paradigm. (a) Collapsed structure at launch. The collapsed configuration allows for more usable empty space in the payload area. (b) Early stages of inflation and the unfolding of the multiple flooring petals. (c) Fully expanded petals with enough space for the Biowick and IMTA tank.

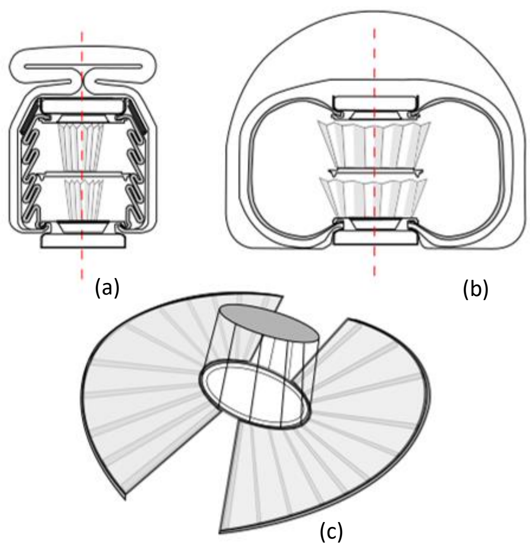


Figure 9 shows the deployment of the floors within the SIRONA structure. Vertical tension cables allow the second floor central hub to be suspended between the two toroid ceiling and floor hubs. Stage (a) of the figure displays the petals in the stowed position. In stage (b), as the inflation process proceeds, each petal pivots at the central hub as it is lowered into position and unfolds like a fan. Upon unfolding, the floor petals are secured to the SIRONA shell. Additional horizontal support webbing is attached at the central hub and is pre-strung along the inflatable beams that support the petal floor surface. Once the petals are deployed, these horizontal stabilization straps (which are attached to the toroid shell) are tensioned to provide additional structural support.

A similar process happens for the first floor. For example, collapsible growth system components such as the Biowick and IMTA pond are also stowed and unfolded in a similar process as the floor petals; as the flooring expands, these components are pulled into place and deployed. Other heavy items such as the kitchen island with refrigerators are stowed on the first floor central hub on castors and can easily be moved into place when the crew arrives.

2. SIRONA Deployment Phase-2

The deployment timeline (Fig. 8) details the order of the major steps taken to reconfigure and start the systems in SIRONA. After a safety checkout of the systems that were deployed in Phase-1, small equipment and hardware (e.g., light panels, cooking equipment and tools) and growth systems are unstowed from the launch configuration to the deployed SIRONA location by the crew in Phase-2. Hardware, such as furniture and equipment, is designed to be both easily stowed and deployed. For example, tables, chairs, storage areas (shelves and cabinets), growth systems, plant nursery equipment, photobioreactors, and the staircase can all be collapsed for transport. Once all of the systems are reconfigured, the initialization process can occur which includes connecting the utilities to the internal systems, a system checkout process and planting of the living organisms (seeds, trees, tubers and aquatic species) is completed. Eq. (2) presents a metric, called the packing factor, which estimates the deployment potential for structures.

$$r_{deployment} \approx \frac{Total\ Volume\ Deployed}{Total\ Volume\ Collapsed} \qquad \text{(Eq. 2)}$$

A detailed breakdown of sub-system volumes pre- and post-deployment can be found in Table 4. It is estimated that the ratio between the deployed volumes and the stowed volumes is at most a packing factor of 4.7 overall (including the greenhouse structure) and 1.84 for the combined internal sub-systems. The stowed volume is estimated by applying the packing factor to the deployed sub-system volume. The estimated post-deployment volume takes into account empty interstitial space created during expansion. For this reason, sub-systems such as the IMTA system undergo a dramatic increase in volume. The estimated component volumes and dimensions either come from Table 1 or *BVAD.*[29] Based on estimates of worst case volumes, there is a margin of 20.3 m^3 (11.56%) of available in payload volume in SIRONA in the launch configuration.

Table 4 - Deployment Volumes

Sub-system (or component)	Est. Stowed Vol. m^3	Est. Deployed Vol. m3*
Mars Ice Home	327.9	1986.5
First floor system	6.5	39.3
Second floor system	6.8	41.2
Kitchen equipment	25.4	25.4
Photobioreactors	0.1	0.7
All wicking beds	2.2	6.7
Ebb and flow beds	1.8	5.4
IMTA System	1.8	7.3
Misc. (bathroom walls, furnishings, etc.)	21.3	64.0
Biowick	3.2	9.5
Growth media	21.6	21.6
Lighting panels	3.1	3.1
Himawari solar collectors	61.1	61.1
Photobioreactor bulbs	0.04	0.04
Total SIRONA Vol.	**482.9**	**2271.9**
Total Sub-System Vol.	**155.0**	**285.4**
Available Payload Vol.	**175.3**	**N/A**
Launch Config. Margin:	**20.3**	**11.56%**

3. Robotic Tasks During Deployment

Multiple robotic agents help to deploy the inflatable structure and to place individual heavy components within the habitat. A system of pulleys and cables, accompanied by independent motors, place heavy objects near the desired areas to reduce crew time and mitigate the risk of crew injury. Rovers help to secure heavy objects using cables and redirect the petal components of the flooring during deployment. During the intermediate stages of inflation, instead of having robots move to the second floor before this is completely deployed, the robots ensure that the second floor deploys in an efficient and secure manner by fixing cable endings on the second floor that later serve as support. The deployment robots are later used for maintenance, crop monitoring, and other tasks.

4. Food Production Phasing

The following guidelines estimate the crop output over the entire duration of the mission; some variation in production schedules for each of the land crops and aquatic food sources is expected.

<u>Phase 0: Transit from Earth to Mars</u>

Crops with a dormant stage are transported as seeds in an airtight, dark, and cool container to preserve seed viability. Dwarf woody fruit trees are transported as two-year-old grafted individuals. Young trees are wrapped in wicking material and kept in cold, climate control areas to minimize risk of tree damage. During transit, fruit trees will age through their third 'winter,' thus decreasing the expected wait for fruit production once planted in the SIRONA system. Tuber crops are transported as roots, to be split for clonal reproduction upon arrival.

The starting stock of freshwater seafood (fish and shellfish) are launched in the juvenile life stage (live young and eggs) and transported from Earth in roughly 3 m^3 of water (sufficient for ~20 of each species), split between the IMTA keyhole tanks and the mussel tank. These water reservoirs also irrigate the dormant dwarf trees during transit. All aquatic species will mature during transit and reach adult life stage by arrival on Mars; however, their growth rate can be reduced during transit by regulating temperature and feeding rates to ensure that they do not outgrow their transit tanks.

<u>Phase 1 (0-6 months): Production of fast-growing and continuous harvest crops</u>

After deployment, the keyhole and mussel tanks are transferred into SIRONA and the remaining IMTA tanks are filled with water produced via ISRU. Assuming a water extraction rate of 4.2 kg/hr (~100 kg/day), the remaining tanks will take 1.4 months to fill after crew arrival. The water used for fish transport is a sufficient quantity to start the initial phase of crop production.

Land crops and *Spirulina* that continuously produce edible yield and other crops that quickly reach harvestable maturity are the primary source of fresh food during the first six months of this mission. There is an expected delay of 21 days to first harvest of any crop because of the time lag between planting and harvest.

Phase 2 (6-12 months): Production of mid-mission harvestable crops

Crops that are continuously producing and have quick maturity (Phase 1 crops) continue to be planted and harvested. The first seafood harvest occurs during this phase as the fish population reaches full capacity. Table 7 provides a detailed analysis of seafood yield.

Phase 3 (12-48 months): Production of woody crops

In addition to crops harvested during Phases 1 and 2, which will be continuously produced after initial harvest, mature fruit from trees will yield harvestable fruits throughout Phase 3. Trees left for subsequent missions will provide fruit immediately if interim care is automated and remote.

C. Crew Time

Table 5 summarizes the daily average time the crew spends taking care of the crops. The estimated crew time spent on greenhouse tasks is based on a previous study that track task timing.[30] The following care task times are derived by finding the task time per area and then applying the SIRONA area to those values. The area scaling factor between the two systems is 4.167 and is applied to the task timing to find the estimated time it takes to care for the crops in SIRONA. Tasks were then allocated as either a crew task or automation task.

Table 5 - Crew and Robotic Care Tasks

Tasks	Crew Time min/d	ROGR (Crew Time Savings) min/d
Crop specific tasks	49.1	24.05
Preparation tasks	38	0
General horticulture tasks	32.8	131.2
IMTA nutrient management tasks	0	6
Infrequent tasks equivalent	8	0
Total	78.8	137.2

Tasks are divided into two types, daily and infrequent. Daily tasks include:

- Crop specific care tasks performed by the crew: thinning, pruning and training of plants, harvesting, quality checkout of plants, and cleaning.
- Crop specific care tasks performed by ROGR: seeding germination trays, transplanting, and pollination.
- Preparation tasks, including: gathering the necessary tools, cleaning work area, or disposing of trash or inedible biomass.
- General horticulture tasks, including: verifying AgQ sensor readings are correct or minor crop management such as removing damaged leaves.
- IMTA nutrition management system tasks, including: verifying pH levels of water and PAR measurement of lights.

There are other infrequent maintenance tasks that need to be completed that vary in from 30-180 days depending on the task. The times required to complete these tasks was calculated, and divided by the cycle time to obtain an equivalent daily average of the tasks. On average, the crew will spend 8 minutes completing these infrequent tasks in a task rotation and the actual time may vary day-to-day. These tasks include changing and cleaning air filters, sensor calibration, IMTA tank cleaning, and cleanout/disinfection of HVAC and dehumidification systems.

The estimated time the crew will spend completing the greenhouse related work is 78.8 minutes/day, or just about 20 min per crew member. The total equivalent crew time saving the automation systems provide is 137.2 min/d; however, there robotic systems will likely take a much longer time to complete these tasks than the crew time savings.

VI. System Performance Summary

A. Food Production

Table 7 presents details of the crop complement. SIRONA provides approximately 51.65 m^2 of land crop production (excluding the aquatic crops and freshwater seafood), which is broken into two climatic zones of 40.09 m^2 for the sub-tropical and 11.56 m^2 for the temperate analog zones. The overall average edible biomass density (i.e., yield (kg)/total growth area) for the land crop production system is 33.21 kg/m^2.

Table 7 – Food Production Summary

Crop	Diet Target	Total Area	Edible Mass	Key Nutrients	Key Functions			O2 Output	CO2 Uptake	Avg. H2O Uptake
	CM-d	m2	kg/yr	Vit = Vitamin; Min = Mineral	Diet	Psych	Med	kg/yr	kg/yr	kg/yr
Zone 1 - Keyhole Wicking Beds										
Lettuce	4	0.64[**]	30.66[††]	Vit (C), Min (Mn, K, Cu, Fe), fiber	x			1.816[‡‡]	2.498[‡‡]	490.187[‡‡]
Spinach	2	1.096[**]	29.2[††]	Vit (A, B, E, K), Min (Mn, Mg, Fe, Cu), folate	x			3.113[‡‡]	4.282[‡‡]	708.291[‡‡]
Kale	4	1.965[§§]	30.66[***]	Vit (A, B, K), folate, protein, fiber, α-linolenic acid, lutein, zeaxanthin	x			29.412[†††]	37.303[†††]	1506.467[‡‡‡]
Ground cherry	3	0.496[**]	0.477[***]	Vit (A, C), Min (Fe, Ca, P), niacin, thiamin, riboflavin	x	x		7.417[†††]	9.407[†††]	501.126[§§§]
Sorrel	2	1.381[§§]	15.33[***]	Vit (C), Min (P, Fe), fiber, oxalic acid, flavonoids	x	x	x	20.668[†††]	26.213[†††]	1058.599[‡‡‡]
Green onion	3	0.165	4.928[††]	Vit (B, C), quercetin, fiber	x			0.643[‡‡]	5.870[‡‡]	104.792[‡‡]
Bok choy	4	0.834	21.921[****]	Vit (A, V)	x			12.481[†††]	15.829[†††]	639.261[‡‡‡]
Carrot	3	1.464	39.986[††]	Vit (K), fiber, lutein, α- and β-carotene, lycopene	x	x		8.742[‡‡]	12.023[‡‡]	945.817[‡‡]
Radish	3	0.294	9.837[††]	Vit (A, B, K), Min (P), folate, α-linolenic acid, lutein, zeaxanthin, fiber, protein	x			1.273[‡‡]	1.750[‡‡]	189.939[‡‡]
Potato	2	3.229[**]	124.1[††]		x			37.984[‡‡]	53.305[‡‡]	4714.150[‡‡]
Zone 2 - Ebb and Flow Beds										
Strawberry	4	2.48	130.448[††††]	Vit (C), Min (P), folic acid, fiber	x	x		101.680[†††]	128.960[†††]	3665.754[§§§]

[**] Value derived from edible biomass value in BVAD table 4-99 and crop production value in BVAD table 4-64

[††] Value derived from the calculated area and from the edible biomass value in BVAD table 4-99

[‡‡] Value derived from the calculated area and from the oxygen production value in BVAD table 4-98

[§§] Value derived from BVAD

[***] Value derived from BVAD and the calculated area

[†††] Value derived by assuming from BVAD that 0.82 kg/m^2-d of oxygen is required per crew member and that 1.04 kg/m^2-d of carbon dioxide is produced per crew member

[‡‡‡] Value derived from assuming the water uptake value of leafy greens and herbs is the same as that of the lettuce water uptake value in BVAD table 4-98

[§§§] Value derived from assuming the water uptake value of small fruits is the same as that of the tomato water uptake value in BVAD table 4-98

[****] Value derived from the calculated area and the crop yield value from reference 3

[††††] Value derived from the calculated area and the crop yield value from reference 3

Tomato	3	3.626[**]	229.95[††]	Vit (A, C), lycopene, lutein, α- and β-carotene	x	x		34.884[‡‡]	47.959[‡‡]	3665.754[‡‡]
Pepper	4	1.665[‡‡‡‡]	90.52[††]	Vit (A, C, E, K), fiber	x			14.690[‡‡]	20.652[‡‡]	1683.499[‡‡]
Ginger	4	0.52	6.921[***]	gingerol		x	x	77.818[†††]	27.040[†††]	759.200[§§§§]
Turmeric	4	0.52	4.55[***]	curcumin		x	x	77.818[†††]	27.040[†††]	759.200[§§§§]
Aloe	2	0.26	0.139[***]	Vit (C), anthraquinones		x		3.891[†††]	4.935[†††]	474.500[†††]
Marigolds	4	0.52	0.064[***]	calendulin, linolenic acid, carotenoids	x	x		7.782[†††]	9.870[†††]	398.580[‡‡‡]
Banana	4	2[*****]	48.48[***]	Min (P), carbohydrates, fiber	x			299.30[†††]	104.0[†††]	7300.0[†††††]
Oca	4	3.229[‡‡‡‡‡]	43.913[***]	antioxidants, starch, fiber	x			48.320[†††]	61.284[†††]	4714.150[§§§§]
Cilantro	4	0.52	5.2[***]	lutein, zeaxanthin, β-carotene	x	x	x	7.782[†††]	9.870[†††]	398.580[‡‡‡]
Chamomile	2	0.74[§§]	0.37[***]	terpenoids, flavonoids	x	x		11.074[†††]	14.045[†††]	567.210[‡‡‡]
Basil	4	0.52	12.199[***]	Vit (A, K), Min (Mn, Mg)	x	x		7.782[†††]	9.870[†††]	398.580[‡‡‡]
Mint	3	0.39[§§]	1.685[***]	Vit (C), rosmarinic acid	x	x	x	5.836[†††]	7.402[†††]	298.935[‡‡‡]
Zone 2 - Wicking Bed										
Nasturtium	4	0.52	1.596[***]	Vit (C), Min (Fe)		x		7.782[†††]	9.870[†††]	949.000[†††]
Mashua	2	1.614[‡‡‡‡‡]	21.956[***]	antioxidants, starch, fiber	x			24.160[†††]	30.642[†††]	2357.075[§§§§]
Sweet potato	2	6.961[**]	131.4[††]	Vit (A, C), Min (Ca, K)	x			104.470[‡‡]	143.646[‡‡]	3811.326[‡‡]
Zone 2 - Biowick										
Dwarf lemon	1	1[*****]	45[***]	Vit (C), Min (K)	x	x		14.965[†††]	52.0[†††]	3650.0[†††††]
Barbados cherry	3	3[*****]	39.6[***]	Vit (A, C), niacin	x	x		44.895[†††]	56.940[†††]	10950.0[†††††]
Kumquat	1	2[*****]	119[***]	Vit (C), fiber	x	x		14.965[†††]	18.980[†††]	3650.0[†††††]
Dwarf plum	3	3[*****]	110.1[***]	Vit (C), zeaxanthin	x			44.895[†††]	56.940[†††]	10950.0[†††††]
Passionfruit	3	2.5[*****]	64[***]	Vit (A, C), fiber, β-carotene	x	x	x	44.895[†††]	56.940[†††]	10950.0[†††††]
Kiwi	3	2.5[*****]	68.1[***]	Vit (C, K), Min (Ca), fiber	x			44.895[†††]	56.940[†††]	10950.0[†††††]
Crop Totals & Avg.	3.1	51.65	1715.39	Avg. Edible Biomass Density (kg/m^2):	33.21			1168.127	1124.3	94160.0

‡‡‡‡ Value derived by assuming it should be double that of the area value derived from edible biomass value in BVAD table 4-99 and the crop production value in BVAD table 4-64

§§§§ Value derived from assuming the water uptake value of root crops is the same as that of the potato water uptake value in BVAD table 4-98

***** Value derived from assuming that 1 m^2 would be enough room for a dwarf tree to grow BVAD

††††† Value derived from assuming the water uptake value of dwarf trees is double that of the large crops' uptake value in BVAD table 4-98

‡‡‡‡‡ Derived this area value by assuming that it is half that of the area value of potato, which was derived from edible biomass value in BVAD table 4-99 and the crop production value in BVAD table 4-64

Aquatic Crops: Photobioreactor and IMTA Crops										
Spirulina (Dry mass)	4	400L	3.65	Vit (B), Min (Ca, K, Mg, Fe), niacin, essential amino acids	x			21.90	53.290	N/A
Duckweed	N/A	N/A	3.37	protein, antioxidants	x			N/A	N/A	N/A
Watercress	N/A	N/A	2.56	Vit (C, K), carotenoids	x	x		N/A	N/A	N/A
Sacred lotus	N/A	N/A	8.27	TBD	x	x		N/A	N/A	N/A
Aquatic Crop Totals & Avg.	4.0	400L	17.86					21.90	46.720	N/A
IMTA Seafood Species										
Tilapia	N/A	N/A	36.31	Protein	x	x		N/A	N/A	N/A
Jade perch	N/A	N/A	54.46	Protein, omega-3 fatty acids	x	x	x	N/A	N/A	N/A
Barramundi	N/A	N/A	54.46	Protein, omega-3 fatty acids	x	x	x	N/A	N/A	N/A
Prawn	N/A	N/A	10.14	Protein	x	x		N/A	N/A	N/A
Crayfish	N/A	N/A	24.31	Protein	x	x		N/A	N/A	N/A
Mussel	N/A	N/A	17.64	Protein	x	x		N/A	N/A	N/A
Seafood Total			197.32							
Total SIRONA Edible Biomass (kg/yr)			**1930.56**	**Avg. Total SIRONA Edible Biomass = (kg)/CM-d**	**1.32**			1190.027	1171.0	94160.0

Table 6 presents a detailed dietary nutrient profile of the total food production system. The dietary target per crop is derived from previous studies. The area allocated to each crop is determined through an iterative process that first aims to achieve the highest dietary target for crops that must be eaten fresh (e.g., salad crops and fruits). Then, the remaining area is then split amongst the other crops by balancing factors including biomass production, nutrient profile, and culinary, psychological, and medicinal considerations.

The overall biomass yield for land crops is 1408.29 kg/yr, 17.86 kg/yr for the aquatic crops and spirulina, and 197.32 kg/yr for seafood (e.g., fish, mollusks, crustaceans). The total biomass yield of the entire ecosystem is 1930.56 kg/yr, or 1.32 kg/CM-d. The entire ecosystem provides 77.81% of the total dietary mass (Table 8), or 18.59% of the total metabolic energy for a crew of four (or approximately one crew member's provisions) over the course of the 600-day surface stay (Table 6). While SIRONA provides a high dietary mass, most of it comes from fruits and vegetables, which have a high fiber and water content. Carbohydrate crops and seafood contribute the majority of the metabolic energy provided by SIRONA. Seafood (e.g., fish, crustaceans, mollusks) provides approximately 4% of the total caloric needs; the yield results in the equivalent of four 8-oz meals of seafood per crew member per week (Table 8) and presents a readily available source of fresh protein and omega-3 fatty acids. The photobioreactor produces 10 g/CM-d of dry edible spirulina biomass, which is included in the total edible biomass reported above.

Table 6 - Total Dietary Nutrient Profile

Nutrient	Target Qty.	Unit	SIRONA Total	% of Target Achieved
Water	825	g/CM-d	911.20	110.45%
Energy	3033	kcal/CM-d	563.80	18.59%
Protein	125	g/CM-d	37.19	29.75%
Fat	104	g/CM-d	4.81	4.62%
Carbohydrate	400	g/CM-d	106.68	26.67%
Dietary fiber	42	g/CM-d	24.81	59.08%
Calcium, Ca	1000	mg/CM-d	333.78	33.38%
Iron, Fe	10	mg/CM-d	12.78	127.81%
Magnesium, Mg	350	mg/CM-d	219.73	62.78%
Phosphorus, P	1000	mg/CM-d	510.82	51.08%
Potassium, K	3500	mg/CM-d	2977.78	85.08%
Sodium, Na	2400	mg/CM-d	220.10	9.17%
Zinc, Zn	15	mg/CM-d	4.01	26.71%
Vitamin C	100	mg/CM-d	984.56	984.56%
Thiamin	1.5	mg/CM-d	0.48	32.08%
Riboflavin	2	mg/CM-d	0.60	30.10%
Niacin	20	mg/CM-d	7.87	39.33%
Vitamin B-6	2	mg/CM-d	1.31	65.72%
Folate, DFE	400	µg/CM-d	223.47	55.87%
Vitamin B-12	2	µg/CM-d	1.73	86.25%
Vitamin A, IU	5000	IU/CM-d	26855.22	537.10%
Vitamin E	30	IU/CM-d	4.51	15.05%
Vitamin D	400	IU/CM-d	74.85	18.71%
Vitamin K	80	µg/CM-d	316.78	395.98%

The greenhouse design achieves the goal, previously stated in Section III Design Considerations, of providing a moderate amount of metabolic energy and a high quantity of micronutrients, phytonutrients, and antioxidants.

B. Living Systems Input/Output - CO_2, O_2, Water

Table 8 summarizes the loop closure percentage of the crew input and output requirements met by the SIRONA design. The SIRONA crop complement (including the photobioreactors and land crops) produces 3.20 kg/day (97.56%) of the oxygen and consumes 3.08 kg/day (74.05%) of the carbon dioxide needed for a four-person crew. The photobioreactor, on its own, consumes 128 g of CO_2/day, assuming a photosynthetic efficiency of 67%,and produces 60 g of O_2/day based on a conservative temperature assumption of 30 °C, with the remainder being produced by the land crops.[20] The total CO_2 and O_2 figures reported above do not include contributions by the aquatic species.

The total water uptake by the growth system is 258 L/day. Of this total, the Biowick has an uptake capacity of 140 L/day, which is 355% of the expected grey and blackwater production in the bathroom (including hygiene, laundry, and toilet wastewater). In cases where the wastewater from the bathroom is not able to meet the total Biowick requirement, the remaining crop water requirement is provided either by the kitchen or the IMTA system. However, the biodigester is capable of processing 100% of the grey and blackwater produced in the kitchen. It is assumed that ISRU is the primary source for drinking water. The dehumidification system in SIRONA acts as a secondary source of drinking water.

Table 8 - Living Systems Inputs/Outputs

	O2	H2O	CO2	Food	Metabolic Energy	Bathroom Wastewater	Kitchen Wastewater
Units	**kg/d**	**kg/d**	**kg/d**	**kg/d**	**MJ/d**	**kg/d**	**kg/d**
Human (In/Out)	**In**	**In**	**Out**	**In**	**In**	**Out**	**Out**
Required (CM)	0.82	2.5	1.04	1.51	12.71	9.853	5.41
Total Required (4 CM)	3.28	10	4.16	6.04	50.84	39.412	21.64
SIRONA	**Out**	**In**	**In**	**Out**	**Out**	**In**	**In**
Total Output/Input (4 CM)	3.2	10	3.08	4.70	10.04	140	21.64
% Provided by SIRONA	97.56	100	74.05	77.81	19.75	355.22	100

C. System Power and Mass Summary

Figure 10 and Table 9 present a first order mass and power analysis based on values derived from a combination of commercial hardware and past space flight systems.

Of the 40 kW allotted to the greenhouse, SIRONA uses 35.35 kW when 100% of the equipment is running, leaving a raw power margin of 11.62%. However, this is generally unrealistic and represents a maximum estimate. A more realistic scenario is one in which 50% of the equipment runs simultaneously along with the crop lighting system; in this case, the 50% power use margin is 12.29 kW, or 30.71%.

The total mass of the greenhouse system is 15,087 kg. This leaves a 16.18% margin of the budgeted 18,000 kg. The food production system, excluding crop lighting, is the component with the highest mass and accounts for 48.5% of the total system mass. It utilizes 4.8% of the total power to run pumps and heaters.

LEDs have a high degree of controllability, are power intensive (50% of total power) but are mass efficient (.8% of total mass). The Himawari solar tracking system accounts for only .2% of the entire greenhouse power consumption, which makes it an excellent power-saving light source. The result is the ability to provide double the crop area with very little additional power. However, the Himawari accounts for 8.7% of the total greenhouse mass, as compared to the .8% taken up by the LEDs. Thus, pairing the LED system with the low power Himawari optimizes controllability, power efficiency, and mass. The photobioreactors consume an additional 7.6% of the power, of which the majority is used by LED lighting. The total lighting for the food production systems accounts for 57.8% of the total power consumption.

Appliances in the kitchen subsystem consume 5% of the total power (assuming only one third of the non-refrigeration equipment runs simultaneously and the refrigerators and freezers are running continuously) and take up 2.7% of the total mass.

Figure 10 - Subsystem Power and Mass by %

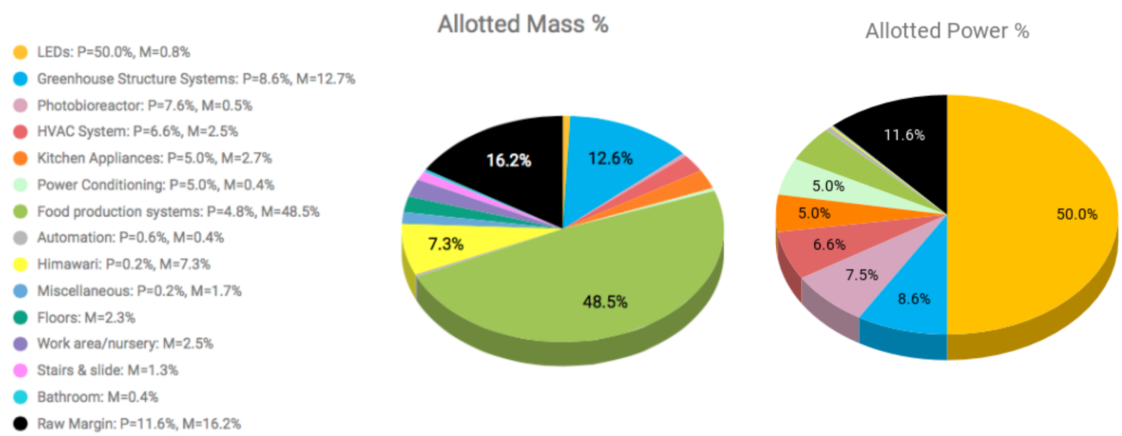


Table 9 - Subsystem Power and Mass Summary

Sub-System	Power (W)	Mass (kg)	Qty	Total (W)	Total (kg)	Comments
Allotted	40,000	18,000	1	40,000	18,000	Starting power and mass budget
Power conditioning	500	20	4	2000	80	Assumes power goes to SIRONA at 95% efficiency
SIRONA Greenhouse - Assumes the greenhouse structure requires the same systems as the Ice Home Habitat						
Greenhouse structure	0	1887	1	0	1887	Total value from Ice Home ConOps Table 5
Air pumps	75	10	4	300	40	Ice Home air circulation
H2O pumps/heaters	880	80	1	880	80	Ice Home water pumps/heaters
Data, controls, sensors	2255	269.2	1	2255	269.2	Assumes same data collection, control system, and deployment sensor as Ice Home
Internal SIRONA Greenhouse Systems						
Biowick	0	581.4	1	0	581.4	Structure and infiltrator (excluding media)
Aquaponics	1920	2432	1	1920	2432	Tanks/structure, pumps, heaters (excluding lights)
Wicking beds	0	709.6	1	0	709.6	Structure only
Ebb/flow beds	0	500	1	0	500	Structure only
Growth media	0	4141	1	0	4141	Growstone®/growth media for Biowick & beds

Start-up nutrients	0	90	4	0	360	1 yr/CM of nutrients supplied prior to aquaponics/biodigestor supply availability
Photobioreactor	3019	84.4	1	3019	84.4	Algae system pumps and 21 LED tube lights
Work area/nursery/displays	0	454.2	1	0	454.2	Work benches, germination racks, tools, supplies, 3D-printer, OLED displays
LED grow lights	400	2.7	50	20000	135	AcroOptics; 400W Grow lights: multispectral LED w/ 6 controllable channels
Himawari	5	88	15	75	1320	Equivalent to a 400W LED Light = 350 PPFD
Robotics/vision	55	13.6	4	220	54.4	JACO arm and vision/sensing systems
Controls	0.3	1	8	2.4	8	Based AgQ/Brain system developed at CU
Grow system fans	205	13	4	820	52	V-Flow Vertical Ventilation Fans for Grow Systems, 1 per grow area
Air temp	360	80	2	720	160	Two climate zones w/ separate control
Humidity control	360	80	3	1080	240	Two climate zones humidity control; an extra unit to handle transpiration load
Kitchen (all appliances)	5055	462.6	0.3	1516.5	138.78	Total power assume only 1/3 of appliances are on simultaneously
Refrigerators/freezers	486	352.4	1	486	352.4	Freezers, refrigerators
Bathroom	0	68.2	1	0	68.2	Plumbing fixtures and storage
Misc. plumbing & equipment	60	300	1	60	300	Bath/kitchen pumps & plumbing, small equipment
Stairs & slide	0	227.3	1	0	227.3	Slide is a secondary exit and recreational
Floors	0	412.3	1	0.0	412.3	1st and 2nd inflatable floor structures
Total				**35,353.9**	**15,087.2**	
Total Raw Margin				**4,646.1**	**2,912.8**	Remaining power and mass from allocation
Total Raw Margin %				**11.62%**	**16.18%**	Assumes 100% of electrical items are running
50% Power Use Margin				**12,285.6 30.71%**		Assumes only 50% of non-lighting systems are running simultaneously

D. Risk Reduction

Table 10 summarizes risks associated with the SIRONA system. Numbers in blue represent the initial likelihood and consequences. Numbers in black represent the final likelihood after accounting for mitigation measures.

Table 10 - Risk Matrix: blue (initial); black (final)

Likelihood	Risk Matrix				
5	11	11			
4					
3	5,10	5, 6, 10	1,3		
2	2,6,7,8,12,19	2, 7, 8, 16, 18, 19	4,12, 19, 20		
1	1,3,18,20	4,9,15,16	13,14, 9, 15	17, 13	14, 17
Consequences	**1**	**2**	**3**	**4**	**5**

The SIRONA Greenhouse should be one-fault tolerant for catastrophic failure of any system. This can be seen in the design choices of SIRONA, such as: dissimilar lighting technologies, the Biowick and biodigester acting as an overflow for each other, and a second bathroom in case of airlock failure, to name a few of the design fail safes. Passive systems were implemented wherever possible to reduce the possibility of mechanical failures thereby increasing the robustness and resiliency of the system. When selecting technologies and growth medias, we selected systems with low risk and low failure. Additionally, multiple spare replacement parts for every system will be provisioned for the crew. Many of the parts should be designed for 3D printing in space. All of the technologies can be maintained *in situ*. The likelihood and consequence definitions from Peeters et al.[31] were used to develop Tables 10 and 11.

Table 11 - Risk Assessment and Mitigation Strategy

System	#	Risk	Likelihood: Consequence		Mitigation
			Start	Result	
Biowick	1	Overflow	3 : 3	1 : 1	Overflow goes to biodigester.
Biowick	2	Tree loss	2 : 2	2 : 1	Plant alternate crops from seed.
Biodigester	3	Overflow	3 : 3	1 : 1	Divert to Ice Home waste collection system.
Biodigester	4	Microbe failure	2 : 3	1 : 2	Pre-mission: select microbes to digest cellulose; test radiation exposure. During mission: Use masticator to breakdown waste.
All systems	5	Pump failure	3 : 2	3 : 1	Provide multiple spares. Design parts w/ high probability of failure to be 3D printed. In case of catastrophic failure, hand water.
Aquaponics	6	Fish loss	3 : 2	2 : 1	Hydroponic nutrients & biodigester fertilizer replace fish-based fertilizer; test fish on Deep Space Gateway to ensure transit survival.
Food system	7	Cold storage failure	2 : 2	2 : 1	Utilize dissimilar cooling technologies. Store food in outside storage box in the Martian environment if catastrophic failure. Utilize other food preservation (ex. dehydration & freeze-drying) methods
All systems	8	Parts failure	2 : 2	2 : 1	Spare parts are provided or designed for on-site 3D printing.
Robotics	9	Catastrophic failure	1 : 3	1 : 2	In case of failure, the crew will complete robotic tasks & will be restructured for crewtime considerations.
LED Lighting	10	Light failure	3 : 2	3 : 1	LEDs are in parallel and can be repaired individually. Replacement LEDs, ballasts, and lighting arrays are supplied.
Himawari	11	Dust on collectors	5 : 2	5 : 1	Collectors include a cleaning mechanism to remove dust. As needed, EVA can be conducted for cleaning & maintenance post dust storms.
Oven Burner	12	Methane usage	2 : 3	2 : 1	Biodigester methane is stored at low-pressure outside of SIRONA. Gas is scrubbed for contaminants before use. The Martian atmosphere is a secondary source in case of inadequate supply.
Oven Burner	13	Fire	1 : 4	1 : 2	Smoke detectors, fire extinguishers, & suppression systems (pond is a fire suppression backup) are installed. Flammable objects are stowed away from oven. Cooking equipment w/o an open flame is provided.
Crop Systems	14	Crop loss	1 : 5	1 : 3	Stored food provide bulk calories. Supplements provide key nutrients to maintain adequate health for the remainder of mission.
Crop Systems	15	Crop disease	1 : 3	1 : 2	Cultivar selection for disease resistance. Plant diversity decreases likelihood of a single pathogen causing disease in many hosts. Regular monitoring eliminates infected tissue quickly after detection.
Crop Systems	16	Crop nutrient deficiency	2 : 2	1 : 2	Continuous monitoring using sensors and visual inspection prevents nutrient deficiency or excess. Liquid nutrients (e.g., fish emulsion fertilizer, carbon biomass byproducts, water) are added.
Power Systems	17	Power failure	1 : 5	1 : 4	A back up power system can power the Himawari to provide crop lighting & run pumps. The oven is functional without power.
Growth Systems	18	Sensor failure	2 : 2	1 : 1	Spare sensors are provided. In case of failure, frequent visual inspection is utilized.
Biowick	19	Clog	2 : 2	2 : 1	A manual port allows the crew to remove the clog.
Sinks	20	Hygiene	3 : 2	1 : 1	Separate sinks are provided for cooking and preprocessing of crops.

VII. Concluding Discussion

SIRONA is a multi-functional design that enhances both the physiological and psychological well-being of the crew while minimizing sub-system mass and power. It draws upon principles of bioregenerative ecosystem design to naturally recycle inputs and outputs between the integrated subsystems. This can be seen in the selection of crops as well as their integration with systems such as the Biowick, the IMTA system, and the biodigester. Future development of the SIRONA system technologies will include design iteration, prototyping, and deep space testing. SIRONA is capable of producing a wide variety of food sources -- land crops and aquatic species (algae, crops, fish, crustaceans, and mollusks) -- that provide health benefits beyond fulfilling basic nutritional needs. Versatile and powerful kitchen tools allow for effective post-harvest processing and cooking to improve nutritional intake, crew well-being, and group cohesion. SIRONA provides the full benefits of a bioregenerative life support system including: nutrient and water recycling, air revitalization, access to nature, and nutritious food production.

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