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MarsGarden: Designing an Ecosystem for a Sustainable Multiplanetary Future
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MarsGarden
Designing an ecosystem for a sustainable multiplanetary future

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Abstract

Exploration of space has always held a certain fascination for humankind. Stepping foot on the Moon may have been the achievement of the century, and sending humans to Mars will be even more challenging and exciting. To achieve self-sufficiency off the Earth, humans will need a steady supply of food while also maintaining adequate mental health. We propose here a closed-loop ecosystem that accomplishes both while being feasible to transport, construct, and maintain on Mars. The resulting design, MarsGarden, is capable of providing a crew of four astronauts with all their dietary needs and also acting as a place of relaxation and restoration. MarsGarden is a scalable architecture that can be adapted to many deep space environments, or can be implemented on Earth as an agricultural solution for areas with land scarcity or extreme environments.

Keywords: Mars, Human Spaceflight, Life Support, Sustainable Architecture

1. Introduction

1.1. A multiplanetary vision for mankind

In more than 50 years of space exploration, human life outside our planet has been confined to small, uncomfortable environments, designed to protect astronauts from the threats of space rather than grant them a comfortable and healthy lifestyle. The module that brought the first man into space in 1961, the Vostok 1, was not much more than a small capsule shielding a single astronaut from the vacuum of space and the heat of reentry. The first space architecture experiment was the Skylab space station, launched by NASA in 1973. Despite previous astronauts' experiences in microgravity, Skylab was the first station where astronauts could experiment with relatively unconstrained movement in microgravity. The concept of the Skylab was later expanded with the existing International Space Station, operative since 1998. However, the poor physiological and psychological conditions of human life in space, together with the low degree of independence and self-sufficiency of space architectures, are still two defining traits of space habitation. The proximity to Earth, the relatively short duration of space missions and the training of astronauts have so far justified these limitations. Feasibility of deep space exploration strongly depends on the reduction of supplies from Earth, along with the improvement of mission safety and living conditions in space. Stressors for human spaceflight associated with habitability, confinement, and isolation can lead to degraded performance, feelings of claustrophobia, and lack of motivation. If humankind is willing to evolve into a multiplanetary species, we need to define a new paradigm of space life and space architecture.

1.2. Mars to stay

After returning to the Moon, as NASA confirmed with the announcement of the Artemis Program [1], the next step to human multiplanetary life will be set on Mars. Recent research missions and ongoing space exploration programs, such as NASA's Mars Exploration

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program [2] and Journey to Mars vision [3], ESA's Aurora program [4], and the Starship / Superheavy System by SpaceX [5], all confirm international efforts for the colonization of the Red Planet.

The recent international interest in space exploration has encouraged a broad rethinking and reshaping of design paradigms for human life in space. In particular, those designing for human life on Mars must take into account crew well-being for prolonged habitation in unconventional settings. In addition, self-sustainability will be the key enabler of an extended human presence on Mars. A self-sustaining settlement on Mars would be able to rely on independent production of energy and food without the need of supplies from the home planet. This could be achieved through intelligent use of the local resources, commonly referred to as In-Situ Resource Utilization (ISRU), as envisioned by the Russian rocket scientist Konstantin Tsiolkovsky long before the birth of space exploration [6].

1.3. A Mars Garden

We propose an original concept for a sustainable and human-centered life in space through a holistic approach to design. The holistic and integrated scope of the design allows the creation of a habitat for a long-term human presence outside our Home Planet, overcoming the limitations of current space architecture in terms of self-sufficiency, feasibility, safety and quality of life. In particular, we propose MarsGarden, a greenhouse conceived to couple with the residential module Ice Home design by NASA [7], to create a closed loop ecosystem capable of sustaining human life on Mars. The user needs and requirements for MarsGarden were derived from the same set of requirements used in the design of the Ice Home.

MarsGarden is designed for the production of food through hydroponic cultivation to support astronauts on their mission to Mars. The interior design of MarsGarden addresses psychological and physiological needs of the crew members, generating a safe, relaxing and ergonomic environment. The greenhouse module relies on the use of Martian water to feed the hydroponic system and to generate an ice layer able to protect astronauts from solar radiation. Plants grown in the greenhouse are used to recycle CO_2 and human waste and produce O_2 and food on site, while also providing astronauts with a familiar setting from their home planet. Moreover, MarsGarden is powered by nuclear reactors, granting a steady source of energy for a long-term mission on the Red Planet.

2. Concept and CONOPS

Many obstacles stand in the way of living on Mars, and our design must overcome each of them.

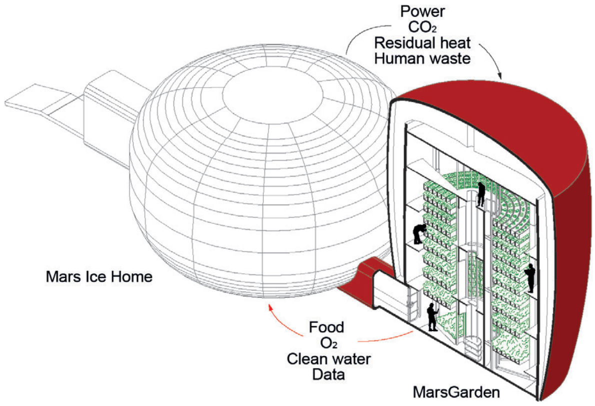

Figure 1: Axonometry of MarsGarden coupled with the Mars Ice Home

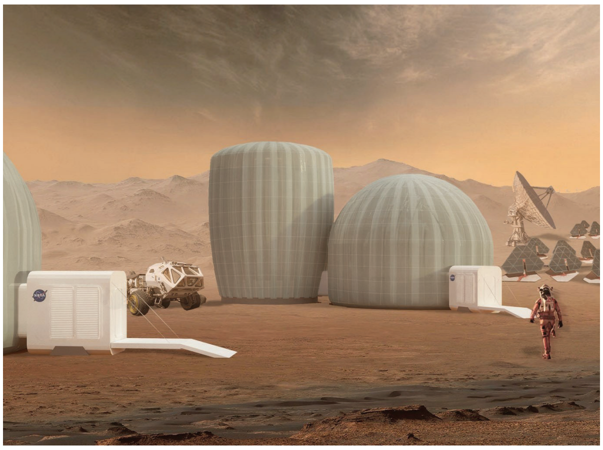

Figure 2: Rendered image of MarsGarden coupled with the Mars Ice Home

Figure 1 and 2 provide an overview of the MarsGarden concept. The greenhouse module is attached to the Mars Ice Home, allowing an exchange of material and energy between the two environments. This includes exchanging air, water, and waste to use the symbiotic relationship that exists between humans and plants. From the outside, the modules show the same inflatable shell, filled with water ice to shield astronauts from solar and space radiation. On the inside, MarsGarden is conceived as a vertical cylindrical volume revolving around a central spiral track, on which astronauts harvest crops for their self-sustenance.

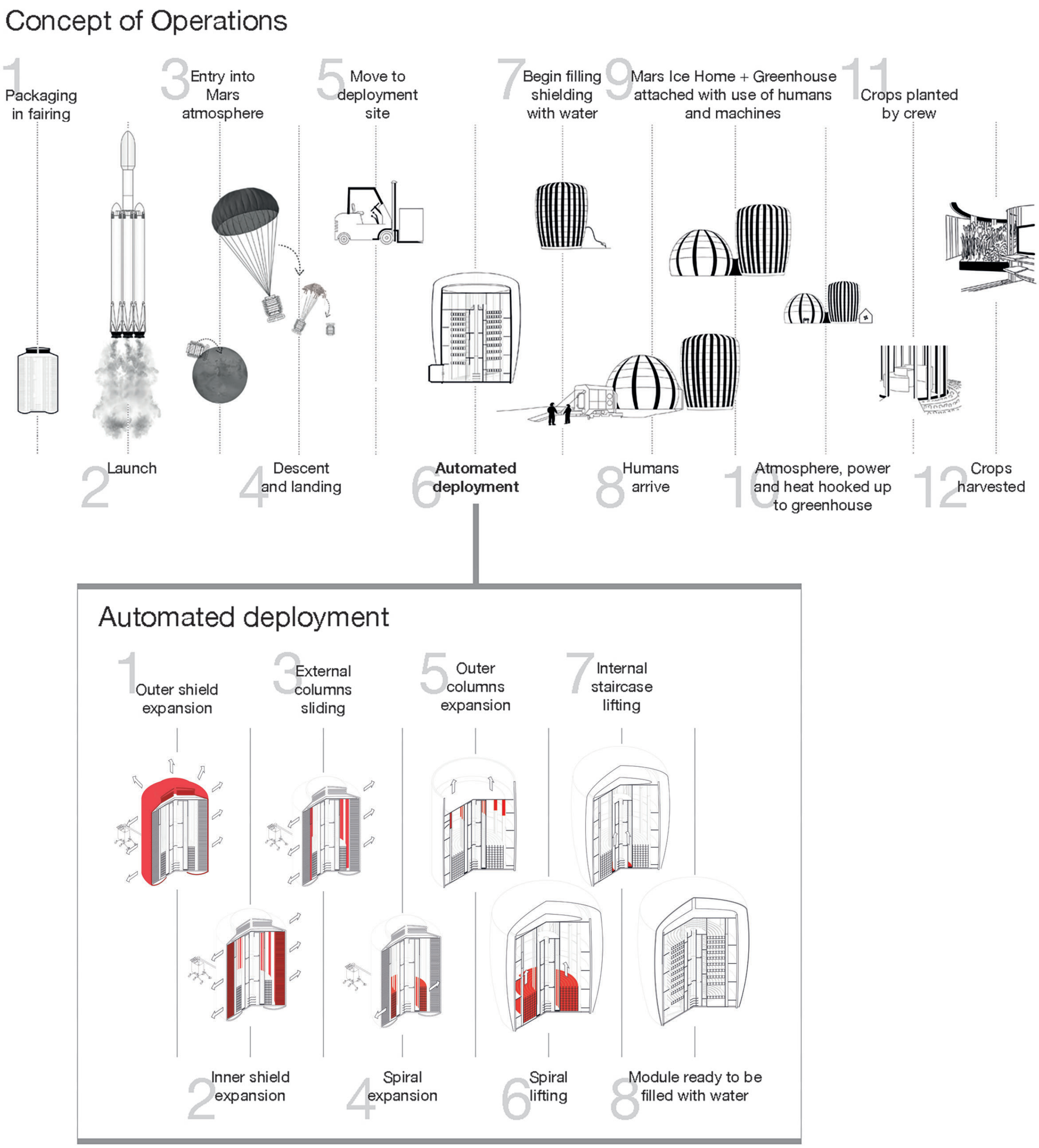

Figure 3: Concept of Operations for MarsGarden

Figure 3 shows the Concept of Operations for MarsGarden, describing the main steps of its journey to Mars. MarsGarden will be launched to Mars after the Mars Ice Home, as it reuses the support systems designed for the Mars Ice Home. The greenhouse is designed to produce food on Mars for astronauts, but not during its transport to Mars through deep space, as it will be launched separately from the crew. After design optimization, the final configuration of the MarsGarden module is 13.4 m tall and has a maximum diameter of 11.3 m. The long concept of the 8.4 m SLS fairing is 7.5 m in diameter and 11.46 m in height for the cylindrical section of the fairing, with a nosecone of decreasing diameter that is 6.65 m in height [8]. The greenhouse module must be properly compacted and stored for launch to fit within this envelope, while allowing sufficient space for the cruise system, landing system, and any small robotics necessary to help deploy the greenhouse.

Before placing MarsGarden into a rocket, the top portions of the inner core and of the columns are compressed, and the outer row of columns is retracted towards the center of the module, leaving space to fold the shield layers. The outer spiral is deflated and folded together with the shield. The inner helix is compressed vertically and horizontally. This shrinks the module down to a size of 9.0 m in height and 6.8 m in diameter, an acceptable volume for launch that leaves approximately 50% of the available fairing volume unused. The in-space transit and Mars entry, descent, and landing phases of the mission are not designed here, as they are out of scope for this work. It is assumed that the mission will use the same trajectory and landing systems as those designed for the Mars Ice Home by NASA. After landing on Mars, the greenhouse module is moved to its final location, next to the pre-deployed Mars Ice Home. The transportation of the module is carried out with the help of deployment rovers, which are landed on the planet together with the Mars Ice Home. The design of these rovers is outside the scope of this work, but their primary functionality will be to move the greenhouse into place for deployment, and to hook up power and air sources so that deployment can begin. Once MarsGarden is in place, the automatic deployment begins. The top portions of the inner core and the columns are activated and expanded via a standard telescoping mechanism. The outer shielding layers and helical ramp are then inflated with air. The outermost circle of columns is pulled outwards to its original position, while also decompressing the inner helix. Once the structure is in place, the helical track is lifted into position with a controlled and remote activation of gas springs. The horizontal compression and expansion of the helical track are accomplished through a double telescoping structure. Once the module is expanded, it will take up to 24 months to fill its outer shell with Martian water that will be frozen as ice. This time span is related to the extraction capabilities of a drill and pump designed to harvest water for the Mars Ice Home. At the next available launch opportunity, which occurs every 26 months, astronauts will travel to Mars, arriving after the ice shield is completely filled. The crew will carry out the final setup activities manually: connecting the Mars Ice Home to MarsGarden and starting the main life support systems of the two modules.

The design of MarsGreenhouse is driven by a few high-level design objectives: providing a feasible solution for the sustenance of life in space; obtaining a self-sustainable module for space exploration; enhancing reliability and safety of the designed solutions; and granting a higher quality of life to astronauts with respect to currently existing and under-study space dwelling solutions. A systems thinking approach allowed us to design integrated capabilities and functionalities for MarsGarden. Our efforts are channeled into three design thrusts, considered as interdependent and coexistent in a holistic fashion: Ecology, Architecture, and Systems Engineering. Together, these thrusts enable a design that will allow astronauts to grow crops inside an ergonomic and safe environment. The physical, psychological and chemical interaction between crew members and plants sustains an artificial ecosystem and shapes a new paradigm of human multiplanetary life.

3. MarsGarden Ecology

MarsGarden is designed to provide enough sustenance to make astronauts food-independent of Earth for the entire duration of their mission on Mars. Nutritional requirements for the greenhouse design were derived from NASA's technical standard on human factors, habitability and environmental health [9]. The sizing of the greenhouse system and the selection of the crops to be harvested inside it are therefore based on the assumption of a daily caloric intake per crew member of 2,700 calorie. Table 1 shows the nutritional requirements considered in the design process for an individual on a daily and annual basis, along with numbers for a four-person crew on an annual basis.

3.1. Crops Selection

We selected eight archetypes of plants to provide a balanced diet for the crew: wheat, oats, rice, rapeseed,

Requirement	Calories (cal)	Corbohydrates (g)	Protein (g)	Fat (g)
Single Astronaut - 1 day	2,700	500	80	30
Single Astronaut - 1 Earth year	985,500	182,500	29,200	10,950
Four Astronauts - 1 Earth year	3,942,000	730,000	116,800	43,800

Table 1: Breakdown of crew's nutritional needs

potatoes, peanuts, tomatoes and lettuce. The crops were carefully chosen to satisfy dietary requirements while also minimizing food storage requirements and maximizing the efficiency of harvesting cycles. Additional factors were considered when ranking crop options, including yield rates, resistance to disease, pollination requirements, and maintenance needs of each species. Table 2 shows the nutritional content of the eight selected crop archetypes.

3.2. Growth System Selection

Four methods of plant growth were considered and compared for this study: soil-based systems, aquaponics, hydroponics, and aeroponics. Soil-based systems were removed from consideration due to the inherent difficulties of autonomous regolith transport and treatment. Bringing soil from Earth would drastically increase the launch requirements, while using Martian regolith presents a complex logistical situation and scientific uncertainty regarding the properties of the regolith [10]. Aquaponics, which uses a symbiotic relationship between crop growth and fish breeding, was considered because of the additional protein that would be provided by the fish. However, long-duration transport of fish to Mars presents a significant unknown, as does the response of fish to Mars gravity or microgravity environments [11]. Aeroponics presented a compelling alternative, as it overcame the mass problem of soil-based systems and the technical unknowns of aquaponics. Despite having been demonstrated successfully with root crops [12], aeroponics has a relatively low Technology Readiness Level (TRL), and thus presented an increased mission risk.

A hydroponic system was ultimately chosen because it overcomes the majority of the limitations of the other options. It has reduced mass compared to soil-based systems and a higher TRL than aeroponics. In addition, hydroponic systems have higher yield rates and allow for precisely-tuned control of nutrient concentration, pH, oxygenation, and more [13]. Importantly, it also optimizes water use, making it conducive to closed-loop environmental control systems in the greenhouse. Hydroponic systems have been developed for many industries and research studies on Earth. The Prototype Lunar Greenhouse (LGH), for example, is a hydroponic chamber jointly designed by NASA's Kennedy Advanced Life Support Research and the University of Arizona's Controlled Environment Agriculture Center (UA-CEAC) [14].

A second example of plant growth systems that has been in development for use in space is the Veggie Plant Growth System from Orbital Technologies Corp. Veggie was delivered to the International Space Station (ISS) in April 2014, and has been put to use consistently since then. It is a research study aimed at understanding plant growth in microgravity environments [15].

3.3. Sizing of the Growing System

The helical design of the MarsGarden growing system minimizes the required growth and storage space inside the module, as the amount of cultivated and harvested plants is always limited to periodical needs of the crew. Both the evaluation of the space required for plant growth and the assessment of daily human operations play a key role in constraining the design of the greenhouse system. We developed a parametric model to simulate the dynamics of human operations, the associated flow of food demand and the overall surface area required for crop cultivation. A detailed analysis was conducted for each crop to determine its associated maintenance requirements, pollination method, water and fertilizer needs, water consumption, harvest cycle, and growth yield. Armed with these data for each crop across their growth cycles, the model computes the required surface area to grow each crop and the average hours of labor to maintain the crop. The model uses a basic optimization scheme to space out labor requirements and avoid sharp peaks on any given day, as astronauts will have other daily tasks that will demand their time.

Crop	Dry mass (kg/yr)	Calories (cal/yr)	Carbohydrates (kg/yr)	Protein (kg/yr)	Fat (kg/yr)
Peanuts	30	170,100	5	15	8
Rapeseed oil	20	175,000	0	20	0
Rolled oats	20	778,000	132	20	34
Wheat flour	600	2,040,000	432	15	78
Potatoes	600	522,000	120	1	12
Tomatoes	500	90,000	20	0	5
Lettuce	150	22,500	4	0	2
Green beans	550	170,500	39	1	10
Total	2,470	3,968,100	751	71	148
Requirement	N/A	3,942,000	730	44	117

Table 2: Total greenhouse food production summary

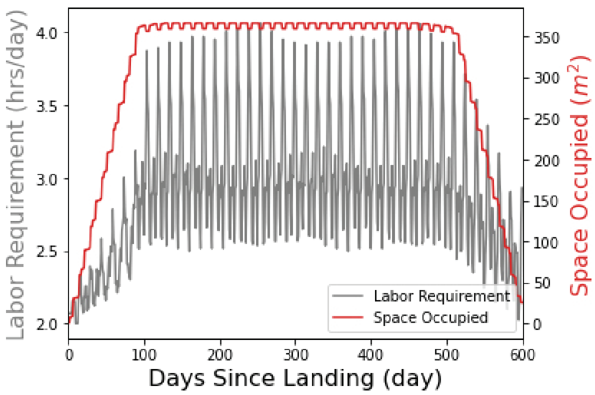

Figure 4: Dynamics of the required human labor (hours per day) and required growing surface area (square meters) over a 600 Earth day mission on Mars for a crew of four astronauts

Figure 4 illustrates the dynamics of the required human labor (hours) and required growing surface area (square meters) over a 600 Earth day mission on Mars for a crew of four astronauts, which are the mission duration and crew composition indicated by NASA for human exploration of the Red Planet [16]. The maximum space required for crop harvesting is 360 m^2, and the labor required is 3 person-hours/day. MarsGarden is designed for reuse over subsequent mission cycles; the commissioning and decommissioning of the module are marked by a ramp-up and a ramp-down of the demand for space and labor. The peaks in the labor requirement line correspond to harvesting days in the greenhouse. On these days, which occur once every two weeks, astronauts harvest mature crops from the helical system to meet their short-term nutritional needs.

3.4. Plant Movement Throughout Life Cycle

The majority of the plants in MarsGarden are grown on the main spiral system. They begin their life at the top of the spirals as seedlings, and as they grow in size, they move down the spiral under the influence of gravity. By the time they reach the bottom of the spiral days, weeks, or months later, they are fully grown and ready to be harvested. Of the eight archetypes of plants chosen to support the crew, six archetypes are expected to be grown on this main spiral system. Each archetype has its own dedicated track, or path, in the spiral. The tracks are segmented to prevent the spread of disease. More detail on disease prevention can be found in Section 5.2. The remaining two archetypes are viney plants that will be grown in the central core of the module. These two archetypes are grown in the central core to provide the appropriate vertical and horizontal space needed by viney plants. LED lighting and nutrient delivery systems are present in the central core to support the growth of these plants.

Figure 5 shows a schematic of the crops cultivation concept. Each major stage of the lifecycle of a crop is labeled in the figure, showing where crops are in the greenhouse during each stage of their life. This includes initial seeding, germination, growth, harvesting, and storage. The distance between successive rounds of the spiral track on which the crops grow decreases with height; at the top of the greenhouse, the spiral loops are closer vertically, since the plants are young and short; at the bottom, the spirals are farther apart, since the plants are mature and tall. Plants spend their entire post-germination lifecycle in the same tray. The tray is initially slotted into its appropriate track at the top of the spiral by a crewmember. As trays at the bottom of the spiral are removed for harvesting, the trays farther up in the spiral will shift down the spiral to fill the space left

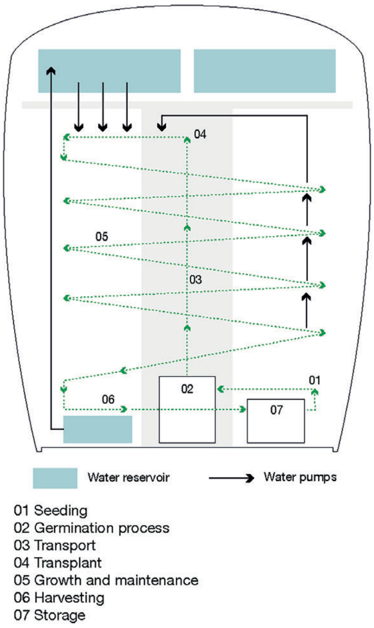

Figure 5: Crops cultivation concept

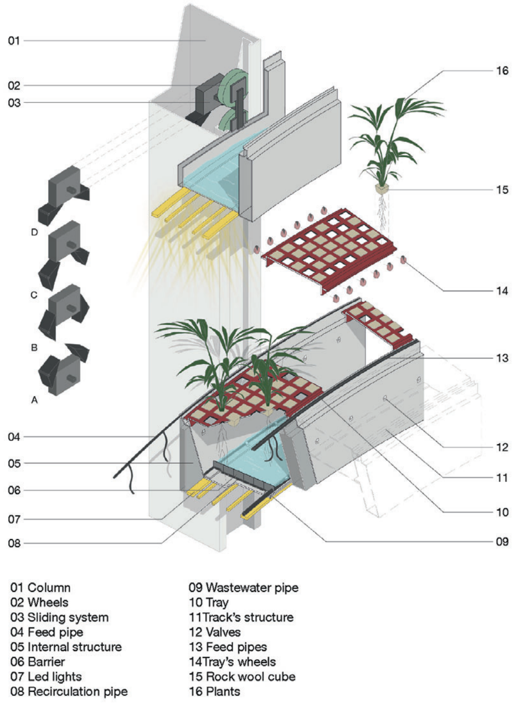

Figure 6: Detailed section of the helical hydroponic system

by the freshly harvested trays. In this way, each track in the spiral will have plants ranging from initial seedlings (at the top) to adolescent plants (halfway down the spiral) to fully grown plants (at the bottom of the spiral). The fact that no moving parts or machinery are needed to move the plants through their entire lifecycle down the spiral is one of the primary innovations of this design.

The trays the plants reside in are made of polyethylene plastic and are sized to allow crewmembers to remove and carry them when necessary. They are no larger than 30 cm in height, depending on the crop, to support the hydroponic system's water and nutrient delivery system and to house the roots of the crops. The trays are lightweight and supported by rollers that connect to the track to allow downwards movement along the spiral. They are constrained laterally by the sides of the track but can be removed easily by a crewmember for maintenance, inspection, or harvesting. These aspects of the trays and the tracks on which they travel are shown in detail in Figure 6.

Figure 7 better details the dynamics of the harvesting system and the interaction between astronauts and plants. Astronauts manually load trays with plant seedlings and place them at the top of the helical track. Similarly, astronauts manually remove trays bearing fully-grown plants from the bottom of the spiral track to harvest. When a tray is removed, either because its crops need to be harvested, or for purposes of maintenance or disease control, triangular chocks can be used to hold the other trays in place. When chocks are removed, trays slide down the track, filling the gap and leaving free space at the top of the spiral for a new tray to be placed in the system.

4. MarsGarden Architecture

The growing system determines the overall shape and the internal layout of MarsGarden. We investigated and assessed several state-of-the art structural alternatives. Skidmore, Owings and Merrill, together with the MIT Media Lab [17] proposed pressurized inflatable modules for a Moon Village, while SEArch+ and Apis Cor [18] envisioned a 3D printed tower on Mars. Foster and Partners [19] proposed a combined solution: an inflatable dwelling module protected by a 3D printed regolith radiation shield. Ultimately, we selected inflatable structures as the most efficient and suitable solution; NASA identified inflatable structures as a key enabling technology to realize very lightweight structures at a low cost. It has been demonstrated that the flexible membranes of inflatable (or pneumatic) structures efficiently resist tensile stresses induced by internal pressurization. The major benefits introduced with the adop-

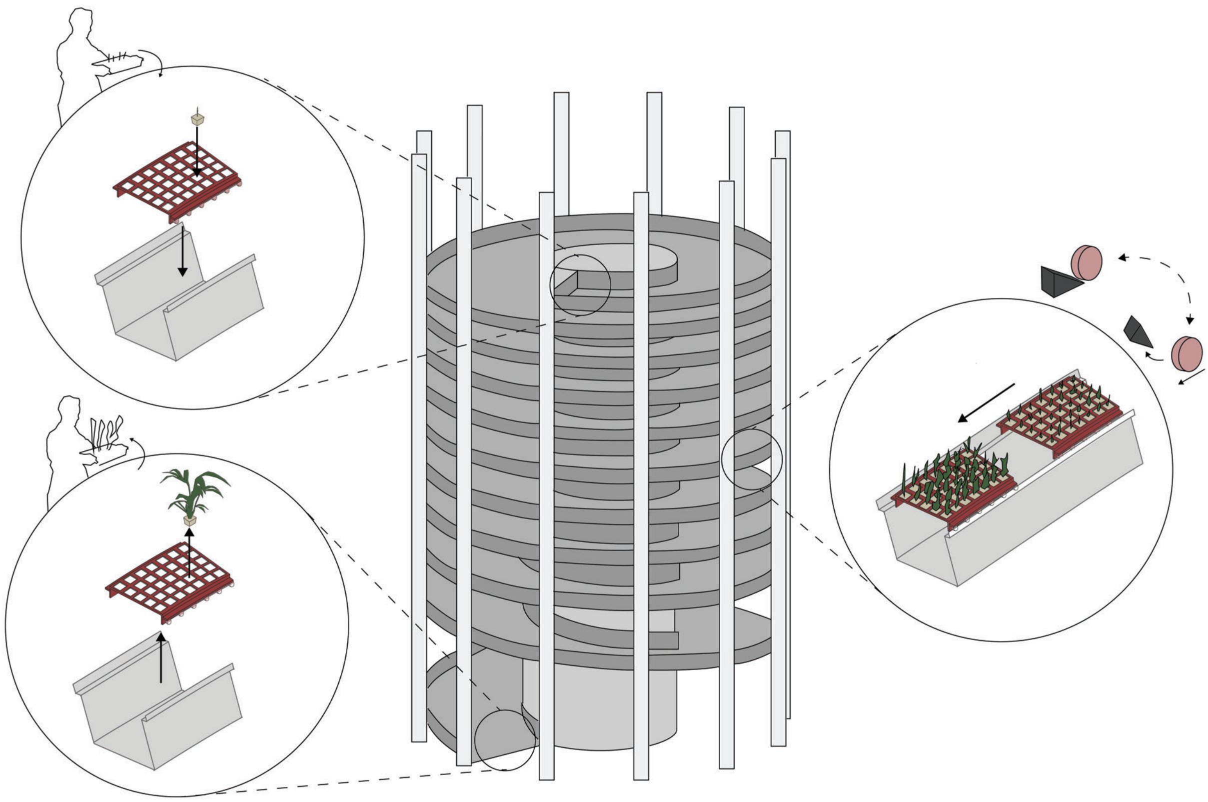

Figure 7: Trays movement detail: astronauts place the trays on the spiral track with fresh seedlings (top left), trays passively shift down the track over the course of the crop's lifetime (middle right), and astronauts lift the trays out when plants are mature and reach the bottom of the spiral (bottom left).

tion of inflatable solutions are the dramatic containment of the overall structural mass and the possibility to fold the structure into very compact volumes for launch and transportation to the target location [20].

4.1. *Materials Selection*

The inflatable layers are attached to a top and bottom aluminum plate and are designed to filter out 40% to 60% of the incoming harmful solar radiation [21]. The filtering effect is achieved with an ice shield embedded between the inner layers of the shell of MarsGarden; this solution is also adopted for the Mars Ice Home residential module [7] to which MarsGarden is coupled. The ice shield of the two modules is filled with water drawn from the Martian subsurface by a drill. The outer cover of the inflatable structure is reinforced with high abrasion and tearing resistant materials (Beta cloth reinforced with Chromel R) to survive Martian sandstorms.

4.2. *Structural Analysis*

The outer shape chosen for the MarsGarden module is a cylinder with a diameter reduction at the base to transmit horizontal loads onto the ground support. The cylinder shape: (A) optimally distributes the stress field induced by the internal pressurization, (B) is efficient in terms of volume to surface area ratio, and (C) allows for a vertical development of the internal layout for the growing system (see Figure 5).

The load-bearing structure is primarily based on a cylindrical core and two circular series of aluminum columns. The structure supports an upper floor, the helical growing track and a second helical element connecting the two floors of the module.

Structural analysis and assessment of the alternative design solutions have been conducted through the use of digital engineering and numerical simulations. In particular, we developed parametric models of the complex structural assemblies for high fidelity numerical analysis based on the finite element method (FEM). We defined a baseline design: a cylindrical inflatable outer shell with a system of columns to support the inner structure of the module. Alternatives were explored by varying dimensions, shapes, and positions of structural components through the use of Grasshopper and Karamba parametric design programs [22].

The final solution is the result of a process of sizing and structural optimization, mostly conducted in an automated fashion. All the components of the greenhouse structure (outer shell, internal core bearing structure, and spirals) are designed to minimize the overall mass of the module, comply with launch and transportation requirements, and withstand loads due to internal pressurization, loads associated with the ice-shield, and the reduced gravity.
Figure 8 shows the results of the finite element analysis (FEA) conducted on the model of the final configuration of the inflatable shell. This structure is primarily subject to tensile stresses: this is due to the pressure differential of 101 kPa between the pressurized inner space of the module and the outer Martian environment. The analysis suggests that the maximum displacement of the membrane is approximately 5 cm. This value can be considered acceptable with respect to the maximum displacement required by EN 1990:2002+A1:2005 [23] standard for roofing systems (1/00 of the span - 7 cm in this case). In addition, the utilization factor does not reach the yield limit of the inner layer of the greenhouse, a Kevlar mesh, resulting in a stable structure that can withstand the internal atmospheric pressure. The FEA of the inner structures demonstrates the combination of both compression and tension forces acting inside the elements. The analysis shows a maximum deflection of 0.219 cm, located in the top portion of the runway connecting the end of the spiral track to the inner core at the top of the module. This value is acceptable given the limit of 1/300 of the span, prescribed by EN 1990:2002+A1:2005 standard, which is equal to 0.8 cm.

4.3. Human Factors

The harsh living conditions of space explorers have been documented since the beginning of space exploration [24]: isolation and uncertainty are frequent, which we ourselves have experienced during the recent COVID-19 outbreak. Space research is focusing on how to address the psychological downsides of deep space exploration, and astronauts have given insight on how to cope with boredom and seclusion [25, 26]. A tight schedule helps astronauts to keep track of time and keeps them occupied with tasks that can stimulate their attention. On the other hand, occasional changes in their living patterns can uplift their morale. Astronauts describe food and cooking as some of the best solutions to breaking the monotony of space life. Moreover, the sense of smell and the presence of plants are agreed upon by astronauts to be two possible beneficial factors in space missions. Communication with Earth is another critical aspect for the preservation of mental wellness, as is the practice of physical exercise to prevent muscular atrophy caused by reduced gravity. Finally, a comfortable environment that is organized and operational helps astronauts perform daily tasks with minimal frustration, and the reservation of customizable, personal space allows them to relax and rest. We tuned our interior design of MarsGarden with these needs in mind to generate a space meant for working efficiently and for living healthfully [27].

The internal space of MarsGarden is organized around the helical growing track and exploits its vertical layout. On the bottom floor, the greater vertical distance between successive rounds of the helix allows for a customizable workspace for the astronauts, as shown in Figure 9. The workspace is equipped with two desks and two closets, together with screens displaying information about the specific health conditions of crops and systems of the module. The furniture is movable and expandable; it can be adapted to the needs of the crew members and ease their operation (management of the crops, maintenance of the module, plant harvesting and seeding) while providing important psychological benefits. Figure 10 shows design sketches of the different possible configurations of the furniture.

From the first floor, astronauts can also access the germination chamber for crop seedlings, located inside the inner structural core of the module. A staircase revolves between the core and the inner round of columns. It leads to the top floor of MarsGarden as well as to intermediate rooms, where astronauts grow vine-like crops, such as tomatoes, on the inner walls of the core. At the top floor of MarsGarden, above the inner core, we reserved space for a relaxation area for the astronauts, shown in Figure 11.

The area is arranged around the lift, connecting the germination room to the top end of the helical track. It is composed of inflatable benches with integrated screens and is surrounded by the natural element of crops grown on the helical track. A second natural element is introduced by a small waterfall fountain that pours water into the helical track from the water reservoir located above the relaxation area, at the top of the module. Water then flows down the helix and brings nutrients and hydration to the crops, while also providing a relaxing environment for the crew.

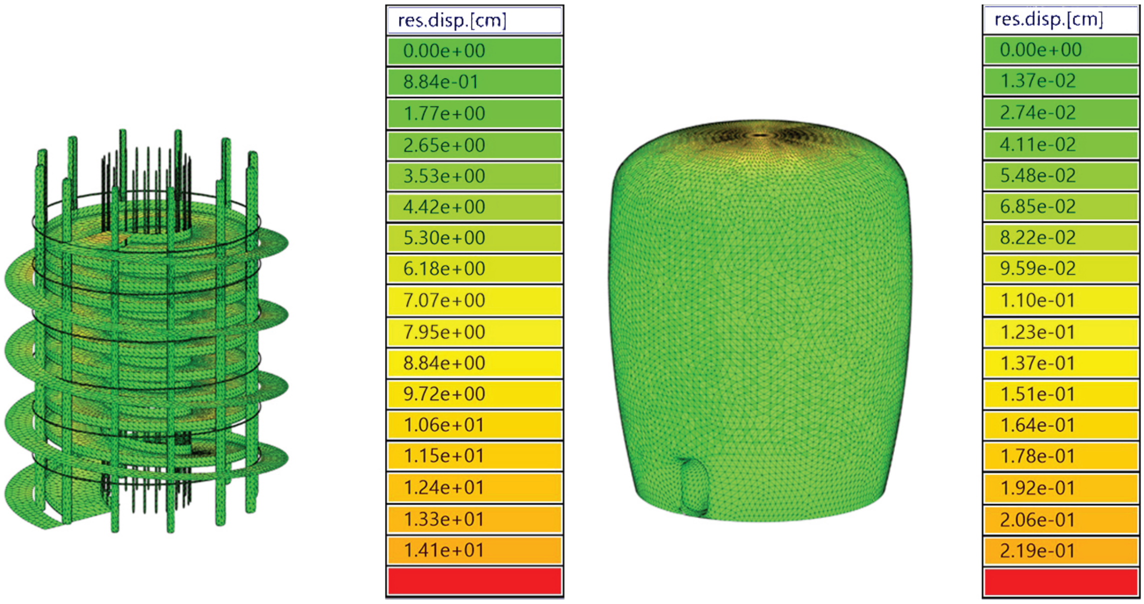

Figure 8: Results of the FEM simulation of the module

Figure 9: Rendered image of the working area

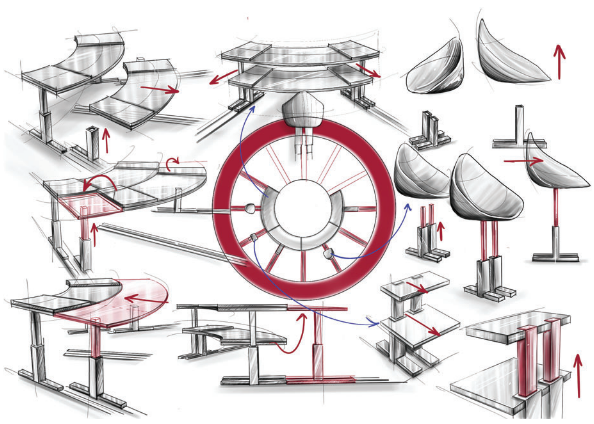

Figure 10: Study of different configurations of the workplace

5. MarsGarden System Engineering

MarsGarden is designed for sustainability, self-sufficiency, human well-being and safety. System thinking was adopted to approach the design in a holistic fashion: the three design thrusts of Ecology, Architecture and Systems were integrated and considered simultaneously. This allowed the designers to leverage these domains' interdependence so that novel design concepts could emerge [28].

Livable conditions are maintained in the modules with both active and passive solutions. This means that the Environmental Control System (ECS) of MarsGarden, which actively monitors and regulates the air composition, temperature and pressure of the greenhouse, is backed up by different components which passively contribute to the environmental quality, such as plants, which produce O_2 through photosynthesis. The design of a highly insulating and radiation-resistant shell is not sufficient to grant a safe and feasible mission on Mars. Once the system is fully isolated from the outer environment, the need arises to create an artificial ecosystem inside the two modules (Mars Ice Home and MarsGarden) to allow life to survive indoors.

Figure 11: Rendered image of the top floor of the module

5.1. O_2 and CO_2 Production

The ecosystem is based on the mutual relationship between the astronauts and the plants: the survival of one species is strongly related to the survival of the other. As an example, on the one hand, plants provide food for astronauts while also producing all the O_2 needed by the crew. On the other hand, human waste is partially reused as a nutrient supply for the plants, and the CO_2 exhaled by astronauts is used by plants for their photosynthesis. Studies carried out by NASA on the Recycling Life Support Systems of the ISS, together with chemical computations and botanic studies on photosynthesis, detail the amount of CO_2 and O_2 the greenhouse and the crew are expected to exchange [29]. We expect the greenhouse to produce 4.1 kg of O_2 per day, fulfilling the 0.84 kg of O_2 needed daily for each crew member. The estimated consumption of CO_2 from plants in the module is 5.6 kg per day: 70% of this can be obtained by CO_2 exhaled from astronauts, who each produce 1.00 kg of CO_2 per day. The remaining carbon dioxide can be obtained from the Martian atmosphere. Gas levels inside the greenhouse are regulated by the ECS, which controls dedicated gas banks. The CO_2 concentration in the greenhouse is twice that of Earth (800-1000 ppm) to stimulate plant growth, and the inner temperature is kept at around 23-26 °C. In addition to the production of O_2 through photosynthesis, the system can rely on oxygen reserves created from the Martian atmosphere through Solid Oxide Electrolysis (SOE). The Massachusetts Institute of Technology (MIT) and NASA are currently investigating this technology with the Mars Oxygen In Situ Resource Utilization Experiment (MOXIE) on board the Mars 2020 Perseverance rover [30, 31].

5.2. Disease Prevention and Waste Management

The key role played by plants in the success of the proposed mission architecture justifies the use of exceptional safety measures for crop disease control and prevention. Plants are the main source of nutrition for the crew, and they also provide astronauts with contact with natural elements from the home planet [32], among other benefits. A passive filtration system, composed of fine mesh, is used to filter out particulates such as roots before the sterilization step takes place. The sterilization of the trays and of the helical track is a critical function, and is accomplished through the use of UV light to eliminate pathogens from the recirculating nutrient solution. The helical track is divided into several compartments that can each be isolated to prevent a disease from spreading if detected. The identification of diseased crops is managed via image recognition techniques by fixed cameras. Furthermore, a reverse osmosis, deionization system is also used by the crew on a periodic basis to eliminate any build-up of minerals and allelopathic compounds. Finally, the crew will wipe down each tray with a disinfectant solution after harvesting, prior to reseeding with a new plant. Ongoing botanical research suggests that safety measures must also extend to pre-mission preparation; NASA has recently started a breeding program to select the most suitable crops to be cultivated in space [33]. We envision a similar premission program, able to generate high yielding plants, resistant to fungi and diseases. It could also be possible to study the growing conditions of plants on the Red Planet through the use of smaller greenhouse modules, such as the "Veggie" plant growing systems currently used on the ISS [15]

Plant waste will be generated by the growing system and must either be disposed of or used. Plant biomass has valuable chemicals that could be extracted to aid in the crew's mission. One limitation of early Mars missions is volume, and MarsGarden does not have sufficient empty volume to store this biomass for chemical extraction. Instead, the authors propose an Isolated Composting Bin (ICB) located outside of the main habitat. After harvesting, the crew will periodically load biowaste into vacuum sealed bags and store them outside of the habitat in the ICB. This allows for a quick way to dispose of the biomass each day while meeting planetary protection requirements. It also creates a stored supply of packaged and preserved compost material that can be used if desired.

5.3. Water Management

The indoor ecosystem created by the Mars Ice Home and the MarsGarden requires another key natural element: water. We considered ISRU technologies for the extraction of water from the Martian environment. Ongoing research is showing evidence of the presence of subsurface ice in the Northern Hemisphere of Mars [34]. In particular, we chose the Arcadia Planitia region [35] as the ideal location for MarsGarden and the coupled Mars Ice Home to access the Martian water resources with minimal impact to the Red Planet. The same drilling system used to fill up the ice layers of the shield can be used to harvest water for the crops' growth system. The water cycle is designed to be self-sufficient and minimize the water used in daily operations. However, water filtration and purification are essential, and we estimate that 0.125 m^3 of water will be consumed daily due to possible inefficiencies and losses in these processes.

5.4. Lighting System

The crops in MarsGarden will require a significant amount of light to grow. While a 10% transparency is expected of the ice walls that protect the greenhouse from radiation, the majority of light must be provided to the plants using Light-Emitting Diodes (LEDs). We calculated that only 58 W/m^2 of power from natural lighting would be available to the crops inside the greenhouse. Commercial practices typically require 345 W/m^2 of lighting flux for the light-intensive crops being proposed in this design (e.g. tomatoes) and 173 W/m^2 for the low-light crops (e.g. lettuce) [13]. Therefore, the majority of growth lighting must be supplied from LEDs. For this reason, a color-tunable LED system designed to replicate the color rendering index (CRI) of natural light was used in the greenhouse.

To minimize lighting losses, the LED lights are mounted on the underside of the spiral, shining directly onto the crops in the spiral. Additional LED lights are placed in the central core to grow vine crops. The lights are operated for approximately 18 hours per day to maximize growth while still allowing for several hours of lights-out respiration for the plants.

5.5. Power

Power is a critical resource in space missions, particularly those that are long in duration. Therefore, every effort was made to reduce power in this design through the use of innovative engineering. As an example, the trays that house the crops move through their entire lifecycle on the spiral using only gravity, requiring zero external power for movement. Other engineering designs contributed similar power savings, such as the effective use of waste heat, human waste, and nutrient recycling systems. The estimated peak power demand of MarsGarden is 53.5 kW, while the average power demand is 38.9 kW. Table 3 shows a breakdown of the estimated power demand for the greenhouse system. The majority of the power demand (over 90%) is from the LED lighting system. The remaining 10% of power is consumed by controls and computing, automation equipment, heaters, environmental controls, power conditioning, the tray lift system, water pumps, and a variety of valves and sensors. The lighting requirements were calculated by multiplying the average crop lighting requirement of 250 W/m^2 by the total growth area in the greenhouse and dividing by an LED efficiency. An efficiency of 95% was assumed for the LED lights.

Solar energy is a somewhat unreliable source of power for MarsGarden: sandstorms on the surface of the Red Planet may periodically reduce power to unacceptably low levels, and energy is needed during daytime and nighttime. Moreover, photovoltaic panels increase the total volume and mass to be launched from Earth. Therefore, energy production for MarsGarden will be handled by four main - and two backup - nuclear reactors producing 10 kW each [36]. NASA has analyzed the advantages of using nuclear power versus solar power for crewed Mars missions, and found many of the same disadvantages of using solar power. To ensure the safety and health of the crew regarding nuclear radiation concerns, the reactors will be located approximately 1 km from the greenhouse, per the same NASA study [37].

5.6. Mass

The total mass of MarsGarden is approximately 6,600 kg, which includes the outer structure, inner spiral structures, central core, upper and lower floors, plant trays, LED fixtures, water and air circulation systems, life support systems, furniture, batteries, plant nutrients, and command and control systems. A detailed breakdown of the system mass is shown in Table 4.

Structural mass, LED arrays, and piping were calculated based on material density and design dimensions. Nutrients, harvesting equipment, and seeds were calculated based on the expected quantity of crops planted and harvested each mission. The rest of the mass values were taken from NASA's Mars Ice Home estimate (as MarsGarden will share or duplicate certain equipment with the Ice Home).

The structural components account for over 60% of the overall mass. This motivates structural design and optimization: improvements in the use of materials and in the design of structural components pays significant dividends in minimizing the total mass of MarsGarden

Subsystem	Average power (W)	Peak power (W)
LED lighting	35,520	48,355
Controls	1,000	1,000
Automation equipment	800	1,350
ECLSS	400	800
Power system	400	500
Water circulation	325	325
Heaters	200	800
Mars Ice Home exchange	200	200
Miscellanoeus (sensors, valves, etc.)	50	200

Table 3: Estimated power budget for the Greenhouse system

Component	Mass [Kg]
Spiral structure	1,140
Inflatable structure	1,000
Structural core	830
Bottom floor	603
Top floor	340
Other structural components	47
LED Arrays	906
Nutrients	450
Piping	370
Command and Control	300
Air Distribution	200
Harvesting Equipment	100
Sensors	92
Pumps	45
Batteries	20
Furniture	10
Valves	5
Miscellaneous	142
Total	6,600

Table 4: Mass breakdowns of the components of MarsGarden

at launch. The mass breakdown of the structural elements is: 1,140 kg for the plant spiral structure (28%), 1,000 kg for the inflatable structure (24%), 830 kg for the carbon fiber inner core (20%), 603 kg for the bottom floor (15%), and 340 kg for the top floor (8%). The remaining structural mass comprises plant trays (3%) and support columns (1%).

5.7. Safety by Design

The feasibility of the entire mission infrastructure we developed relies on the capability of the system to survive unexpected failures and malfunctions in a context where no help could come from Earth in a timely manner. Our approach to risk mitigation is based on functional redundancy and multi-functionality of the systems in the greenhouse.

Functional redundancy is aimed at minimizing the risk of power or water shortages, which could compromise the operability of the growing system. A representative example of this is the implementation of two backup nuclear reactors, two water reservoirs and two water pumps in the design of MarsGarden. At the same time, this allows systems to be kept functioning even during periodical maintenance, with secondary systems brought online before the main systems are stopped.

The design of multifunctional systems simplifies the design solution by reducing the number of systems and subsystems implemented in the greenhouse module. It also provides sensible savings in the energy consumption and the total mass of MarsGarden, and grants safety and feasibility to the mission. The definition of multifunctional systems is obtained through a holistic approach to Ecology, Architecture and Systems design. Technology solutions are conceived to impact multiple design objectives inside the mission architecture, rather than satisfying single purposes. The selection and integration of technology solutions is therefore driven by their relevance to meet primary specifications, together with their impact on multiple design objectives and cross-related functionalities [38, 39].

An explicit instantiation of this principle is provided by the role we assigned to crops inside the mission infrastructure. Crops are introduced in the mission design primarily to provide food for the crew members. However, plants are also the main source of psychological benefit for the astronauts, and they are used to recycle CO_2 and human waste. According to the same principle, the spiral track connecting the two floors of the greenhouse can also be used as a running track for ex-

System	Function #1	Function #2
Plant harvesting	Provide food	Provide psychological benefits
Spiral track	Access for operations	Physical excercise
Plants	Recycle CO_2	Recycle human waste
LEDs	Provide light to plants	Provide extra heat
Kilopower reactors	Provide power	Provide extra heat
Human relaxation area	Mental well-being	Location to load trays into spiral
Waterfall	Aesthetically pleasant	Feeds hydroponics system
Water tank	Provides gravity-fed water	Adds extra radiation shielding

Table 5: Description of the main multifunctional features of the Greenhouse system

ercise. LED lighting and nuclear reactors provide extra heat to be used for conditioning of the inner space of the module. The water reservoir placed at the top of MarsGarden provides water for the growing system, but also adds extra radiation shielding to the most exposed portion of the shell [40]. Table 5 describes the main multifunctional features of MarsGarden.

While a full risk analysis was beyond the scope of this work, additional safety factors were considered. As mentioned previously, the nuclear reactors that power MarsGarden are located 1 km away to minimize radiation concerns. Additionally, systems were designed with two or three-fault redundancy. As an example, every valve that is used has a backup valve piped in parallel with it so that the system can function even with one of the valves failing. Similarly, two backup pumps support pumping water to the top of the greenhouse and battery packs are included to allow up to 3 hours of continuous operation in the event of a power outage. Minimization of risk to the crew and the crops was a primary design driver and is managed through use of multifunctionality and redundancy.

5.8. Prototyping

To demonstrate the overall architecture and to assess its assembly feasibility, the design process included the development of a small prototyping model, shown in Figure 12. The model is a 3-D printed representation of half of MarsGreenhouse. It shows its main components: the inner structural core, with the relaxation space on top and the helical track around it; the inner thermal shield and the outer radiation shield. Each of the elements can be removed from the model and studied separately. Mock-up models are widely used in the architectural context to review the internal and external architectural space. The use of mock-up models in the design process of MarsGreenhouse once again highlights the will to integrate scientific reliability and human-oriented aspects in the final design solution.

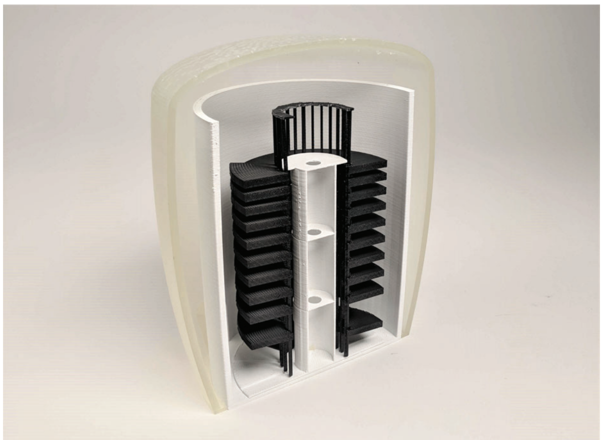

Figure 12: 3D printed model of the Greenhouse

6. Concluding Remarks: Envisioning Resiliency and Sustainability on Mars and on Earth

With the MarsGarden concept, this paper introduces a new paradigm for architecture for human exploration of space and extraterrestrial residency. Our approach integrates physical and mental wellness of the astronauts among the primary drivers of the design, complementing functional, safety and feasibility issues. The natural environment of Mars and the artificial ecosystem of the space modules provide on-site resources for the self-sufficiency of the mission. The introduction of the innovative spiral design of the growing system optimizes internal space in terms of volume, mass, efficiency, functionality and ergonomics. This opens up a new spectrum of possibilities in the design of human-oriented spaces for habitation, where spaces for work and well-being, systems, and ecology interact and produce mutual benefits.

The concept indicates avenues for research and development of advanced technology solutions to support human residency on Mars. Future developments will focus on further optimization of the piping and wiring systems for energy and water distribution across the greenhouse facilities. Detailed design studies will be extended to the optimization of the deployment system to minimize its complexity and reduce the associated risk of malfunctioning. In addition, the partial automation of cultivation and maintenance routines will be investigated further, accounting for safety measures and routines of the astronauts in more detail.

MarsGarden is designed for the Martian environment. However, the self-sufficiency of MarsGarden makes it adaptable for different environments with minor changes to its overall concept. Future developments could therefore include the adaptation of our module to different settings. The module could be conceived and adapted for other extreme environments, such as in lunar or seabed exploration, but it could also contribute to sustainable development of agriculture on Earth wherever access to growing land is restricted. Vertical hydroponic farming systems like MarsGarden are becoming an innovative alternative to traditional extensive agriculture.

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