

MARTIAN GREENHOUSE DESIGN FOR THE NASA EXPLORATION HABITAT PROGRAM

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ABSTRACT

Long duration, manned space missions to Mars create many technical challenges and logistics of sustainability present some of the most significant questions. Mars' pattern of orbit brings it closest to Earth once every two years, and this is the optimal time to send payload on the two to three hundred day journey. Because of the lengthy gap between optimal launching times, designs for terrestrial missions to Mars must provide storage capable of holding two years' worth of supplies or include the ability for self-sustainment. Regular frequent shipping is implausible for replenishing supplies on Mars; even the amount of fuel required to send this large payload during the optimal time poses a problem. This cost alone raises questions about the feasibility of such missions. In order to successfully place a station on the Martian surface, the mission design must include a means for producing food, thereby creating some degree of self-sustainability. Fresh grown foods are essential for long-term sustainability, without which manned missions to Mars will continue to be limited in scope. Oklahoma State University is investigating various methods for producing food on the Martian surface as part of the 2015 eXploration Habitat (X-Hab) Academic Innovation Challenge sponsored by NASA and the National Space Grant Foundation. Previous OSU X-Hab missions developed Earth analogs for Martian transit and surface habitation, and the greenhouse complements the mission analogs. Our team is analyzing possible designs in search of the most feasible and useful concepts and will produce a full-scale model to prove their viability. The present design incorporates a solid central structure that is integrated with inflatable growing modules to maximize the plant growth footprint while reducing total mass and packed volume. In the current approach, deployment and structural design are driven by plant growth requirements and minimal crew interaction.

INTRODUCTION

NASA continues to study Mars and has successfully carried out multiple satellite, lander, and rover missions to the *orange* planet, which have resulted in numerous findings pertaining to Martian atmosphere density and composition data¹, evidence to suggest the presence of ancient aqueous environments on the surface², and the presence of organic compounds³. However, each new discovery made on Mars, usually brings forth more questions and uncertainty, as with the recently discovered increased levels of methane, which suggests that methane is currently being produced from a still unknown source⁴. In order to solve mysteries such as these, new technologies are needed on the planet's surface, which requires space exploration entities to devote decades of time and billions⁵ of dollars toward developing specialized payloads.

Time is one of the major factors hindering space exploration. Space rated systems required to successfully complete these missions must go through specialized development, often using technologies at low readiness levels. Small-quantity manufacturing of unique parts and scientific cargo takes much longer than traditional mass production. All mission hardware undergoes rigorous certification testing to insure high probability of mission success. Then, the system must be transported to Mars, and economical interplanetary travel always costs in time what it saves in money. In fact, in many cases "...missions take years to develop and by the time they launch, their technology is already outdated".⁶

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Funding is the other, more obvious, factor impeding space exploration. NASA's budget has been consistently reduced since the Apollo missions, due the end of the *space race* and the lack of obvious and immediate benefits from the expenditures. However, space exploration and research from the Apollo missions alone have contributed to numerous modern technologies. Some advancements in the medical field alone are the now standard, such as the self-defibrillating pace maker which wirelessly communicates with physicians, the programmable and implantable medication system currently used in every modern medical facility to deliver medication to patients, and medical imaging systems which allow doctors to detect tumors, organ failures, bone fractures, or any otherwise undetectable internal medical irregularity.⁷ These are only a few examples of technological influences from the earliest space programs and are representative of only one industry. Consideration of all of the benefits of the United States' space program validates the idea that "we are living off the investments made a generation ago".⁸ However, no matter how beneficial the space program has proven to be, or how important it could be to our future, the industry must adapt to mandated funding cuts and press forward under these new circumstances.

A solution to the funding and time constraints associated with seeking answers to questions surrounding Mars, is to place scientists on its surface. This would expedite the research process and allow scientists to adapt with the results of their studies, something that robots cannot do. The large initial investment of time and money required to land humans on Mars would produce greater scientific results, while in the long term saving time, and ultimately money, that is currently used to design small-scale exploratory robotic missions. However, putting humans on Mars presents its own set of obstacles. The feasibility of a mission to Mars has been in question for many years. Research suggests that a manned "Free-Return" mission to Mars could be accomplished as soon as January 2018.⁹ However, a manned mission to the surface is further away. The ambitious Martian colonization effort, Mars One, plans to launch their first crew members to the surface of Mars in 2024.¹⁰ NASA's more traditional approach, of multiple small-scale missions leading up to a manned mission to the surface, is tentatively set for the 2030's. Regardless of when each space exploration entity plans to land humans on Mars, their missions have one thing in common; all require more research and technological advances in order to become a reality. Food for astronauts on Mars is one of the most significant factors affecting long duration Martian mission feasibility. The cost associated with transporting all the food necessary to maintain a prolonged outpost on Mars is too large to be a viable option. Therefore, the only realistic option is it to produce a large portion, if not all, of the food required for maintaining life on Mars. In order to further our exploration and understanding of Mars, development of a practical method and system capable of producing large quantities of food on the surface of the planet is necessary.

BACKGROUND

NASA is currently focusing efforts on Deep Space Habitat (DSH) studies. Most notably on the Habitat Demonstration Unit (HDU) Project (Figure 1), which tests possible habitat concepts, modules, and configurations for multiple mission destinations, one of which is Mars. The HDU-DSH system is being studied at the D-RATS (Desert Research and Terrestrial Studies) center in Arizona to test and identify the optimum design and crew size for various mission requirements.¹¹ The eXploration Habitat (X-Hab) Academic Innovation Challenge, sponsored by NASA and the National Space Grant Foundation, allows universities to contribute to the development of DSH systems. Each university team accepted into the X-Hab program works to design a system that fulfills the requests for a mission proposed by NASA, and then each team constructs an analog prototype to demonstrate and test its design. The X-Hab Program benefits NASA by producing, demonstrating, and testing multiple design concepts and approaches to a single problem, which can then be modified, combined, or thrown-out, ultimately increasing the efficiency of NASA's design process. Since its inception in 2011, the X-Hab program has become an integral part of NASA's HDU-DSH research.



Figure 1: NASA's Habitat Demonstration Unit¹²

The X-Hab Academic Innovation Challenge is in its fifth consecutive year. The 2011 challenge was to design an inflatable loft to be added to the top of the HDU-DSH system in order to provide habitation functions (Figure 2).¹³ In the following four competition years, NASA offered multiple projects for which universities could write proposals.¹⁴ These topics ranged from vertical habitat layout, horizontal habitat layout, deployable airlock systems, robotic systems, various plant growth studies, storage systems, and expandable habitats. In the last five years, the X-Hab program has produced twenty-four separate university DSH studies, and Oklahoma State University's proposals have been selected to participate in the program every year. This year's design competition is to develop a method and create a facility for growing food on Mars, which will be a supplemental food source for four astronauts on a five-hundred-day surface mission. Oklahoma State University's Organics and Agricultural Sustainment Inflatable System (OASIS) meets these requirements and provides a realistic solution to the issues surrounding food production on the Martian surface.



Figure 2: 2011 Oklahoma State University's X-Hab Academic Innovation Challenge Inflatable Loft¹⁵

MISSION DESIGN

The OASIS greenhouse module (Figure 3) incorporates a solid central structure with four inflatable soft-good cylindrical tubes expanding outward. The solid central hub is a cylindrical pressure vessel design and shares similarities with NASA's HDU and International Space Station (ISS) Modules. The inflatable tube structures are *Greenwings* and contain the plant growth systems. The Greenwings use a spacesuit-like design combining multiple layers of various flexible materials. The entire module will operate at an equalized internal pressure of 60 kpa, to minimize the structural weight while still supplying appropriate breathable atmosphere composition. Total weight of the final landed model is approximately less than seven tons (Table 4).

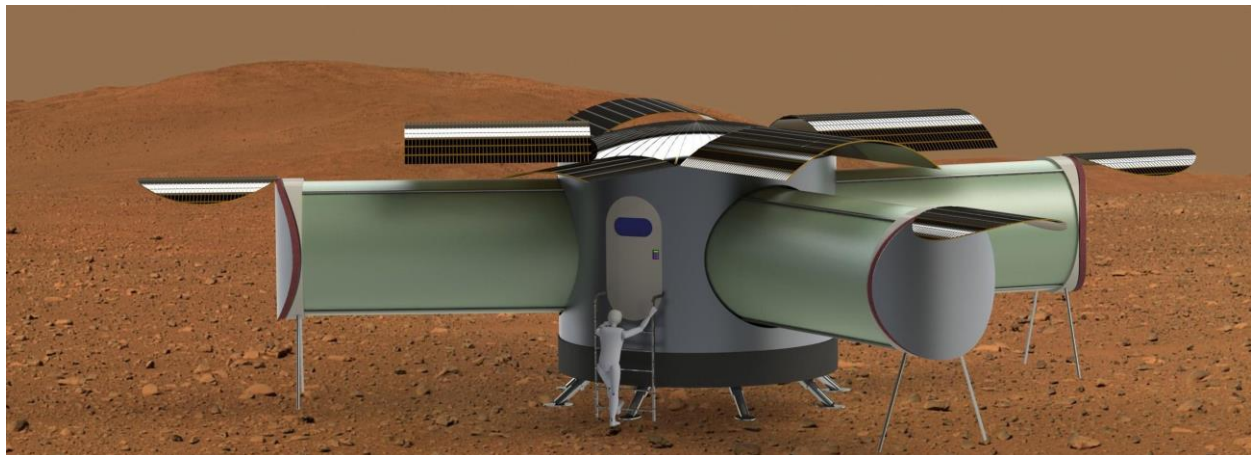


Figure 3: OASIS Greenhouse Concept

Section	Mass (kg)	Section	Mass (kg)
Ground Support Structures	1680	ECLSS	133
Bulkheads	1300	Plant Growth Equipment	120
Air Lock	800	Shielding	100
Outer Pressure Vessel (OPV)	700	Fire Detection System	80
Battery	600	Solar Panels	18
Inner Pressure Vessel (IPV)	450	Greenwing Soft Goods	370
Center Hub Ribbed Structure	300	Air Tank	110
Temp/Humidity Control	175	Total	6236

Table 1: Estimated Masses of OASIS Systems

Launch Platform and Interplanetary Transit

NASA’s Space Launch System (SLS), which is currently in development, will deliver OASIS to Low Earth Orbit (LEO). The SLS is the next generation heavy-lift vehicle that will efficiently put into orbit large-scale systems, which are needed for humans to accomplish interplanetary travel.¹⁶ The capabilities of the SLS are major design drivers, and the entire OASIS configuration conforms to the required mass and volume constraints. The OASIS stack has a maximum outer diameter of 4.6 meters and a maximum height of less than 13 meters (Figure 4). The interplanetary transit module easily fits within the cargo fairing of the SLS and is estimated to have a total mass of less than 100 Tons. Once the interplanetary transit module is in LEO, OASIS will make the initial delta v burn from a standard Hohmann transfer maneuver of less than 3 km/s.¹⁷ After this initial burn, the OASIS’s Interplanetary Module will be on a rendezvous trajectory to Mars for 8-9 months (Figure 5).

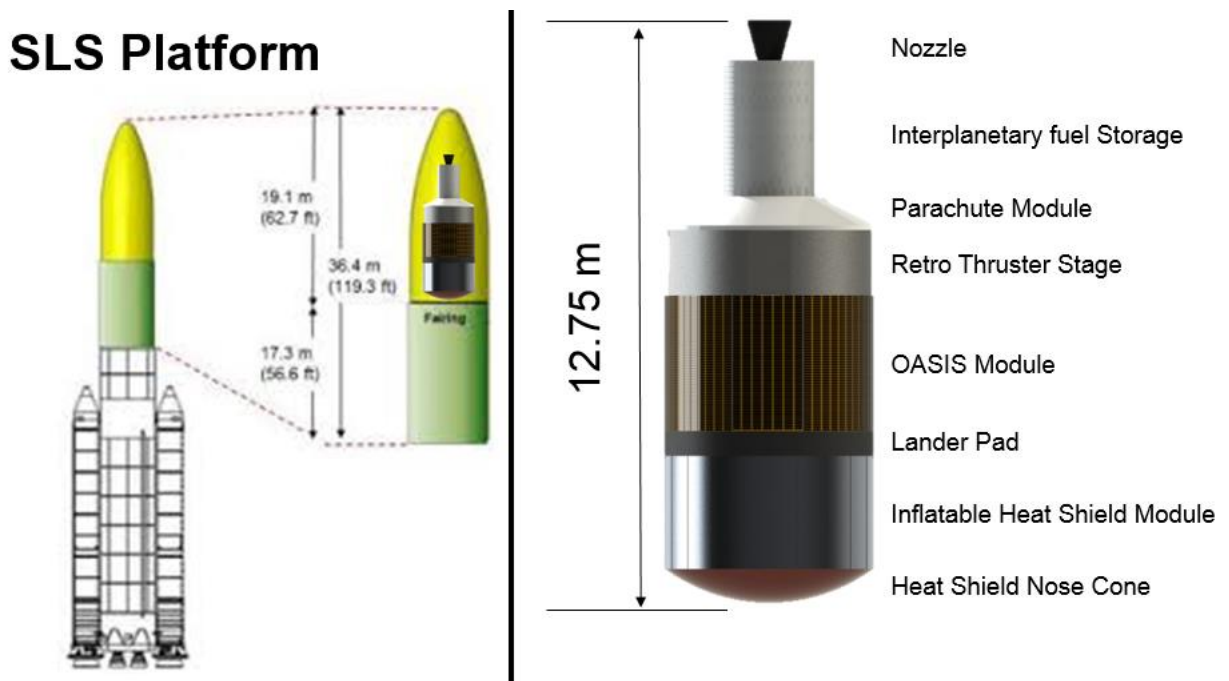


Figure 4: OASIS Interplanetary Transit Module Size and Visualization of System within the SLS Payload Fairing

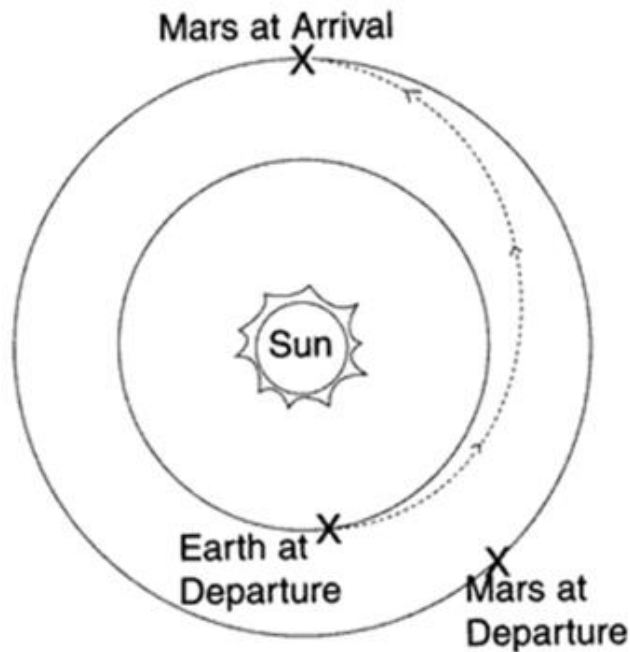


Figure 5: Interplanetary Transit Rendezvous Trajectory from Earth to Mars

Aerobraking, Entry, and Landing

Upon OASIS's rendezvous with Mars the interplanetary transit module booster stage detaches and the inflatable heat shield, roughly 15 meters in diameter, will deploy, and an initial aerobraking maneuver will put the module into a highly elliptical orbit around Mars. Multiple aerobraking passes will reduce orbital velocity and eventually drop the craft into a suborbital ballistic trajectory at roughly 3.5 km/s.¹⁸ Large-scale inflatable heat shields are currently in development for the purpose of enabling heavier payloads to achieve safer velocities in low density atmospheres.¹⁹ After burning through the thin atmosphere and reducing speed to close to Mach 2, a supersonic parachute will deploy to slow the craft further.²⁰ Once past the supersonic region, the inflatable heat shield and supersonic parachutes detach, and the subsonic parachute deploys. At an altitude below 5 km, the retro-thrusters engage, and the subsonic parachute detaches. The vehicle then uses the retro-thrust to slow to near zero velocity above the landing zone, while landing struts deploy, and the vehicle makes small adjustments to the final landing location based on the terrain. Once OASIS has successfully landed, the retro-thrusters detach from the top of the module and eject themselves from the area. The landing struts then level the module in preparation for deployment (Figure 6).

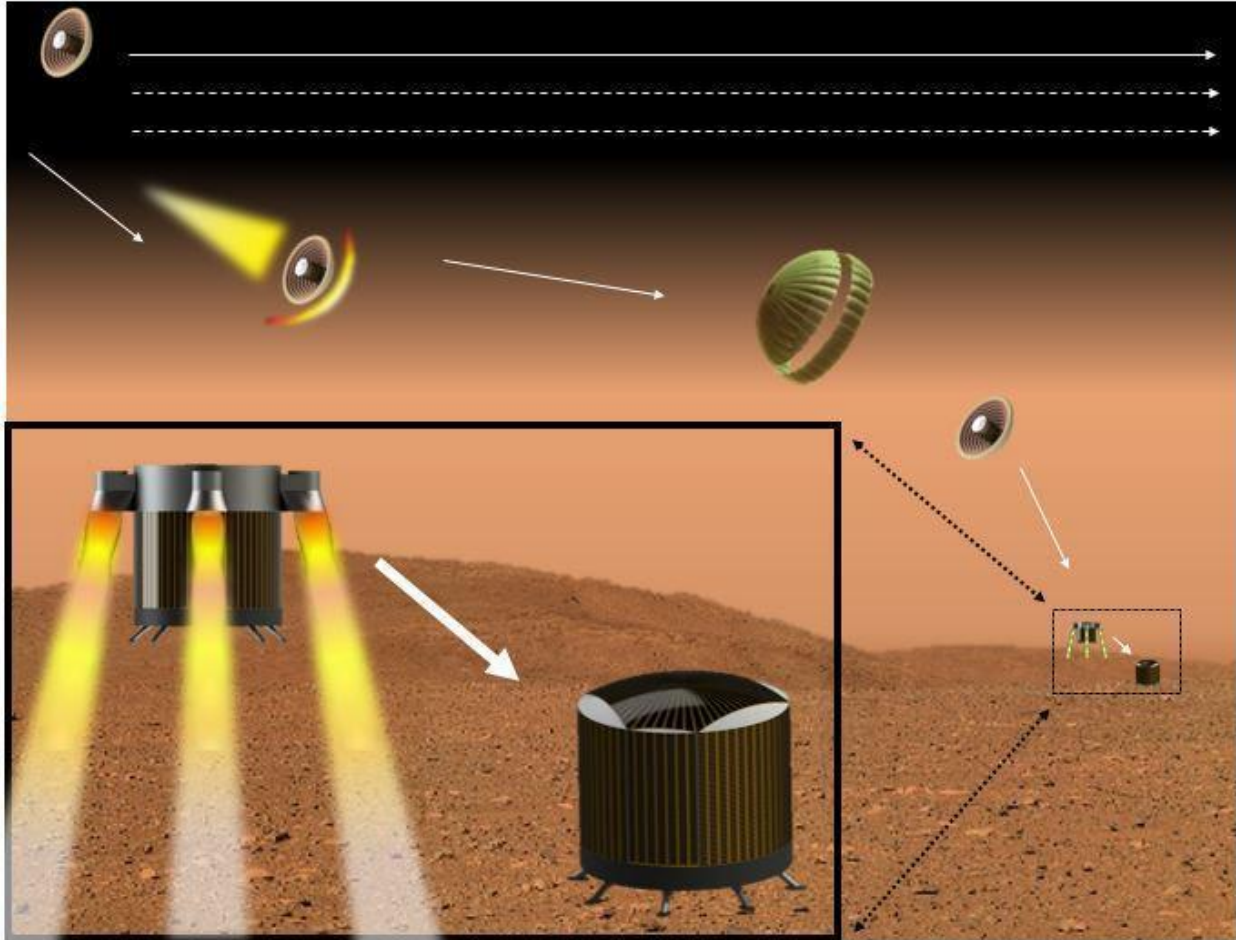


Figure 6: OASIS Entry and Landing Configuration

SYSTEM DESIGN

The design focuses on automation and redundancy, which allows astronauts to devote more mission time to other research obligations. The OASIS greenhouse module is intended to be a hands-free greenhouse system that requires only minimal attention. The inflation procedure occurs autonomously, and the entire system activates prior to astronaut arrival. This will insure that astronauts will have an operating food source when they arrive, and if a failure does occur, they will have enough advanced warning to decide how to proceed. When the deployment sequence is activated, OASIS will spring open five garage-door-like solar panel arrays (Figure 7). Then the Greenwing deployment system utilizes a constant pressure deployment method by integrating four wench controlled tension cables to stabilize the inflation procedure, by slowly and steadily allowing the volume to increase until the Greenwings are fully deployed. This cable system will force the endcap to maintain a perpendicular configuration and a uniform internal pressure, avoiding chaotic uncontrollable inflation that could result in rupture.²¹ In consideration of the low outer pressures on the Martian surface and the large diameter of the inflatable structures, each Greenwing will be extremely stiff. However, for added stability to the entire OASIS module and the ability to adjust the incline of the Greenwings for water return purposes, the end caps contain micro-castpiles that anchor into the ground upon deployment (Figure 8). After the green wings are fully deployed, additional garage-door-like solar panel arrays spring open from the endcaps, which completes the OASIS's deployment sequence (Figure 9). Once fully deployed OASIS's widest span is 18 m, maximum height is 5 m, useful interior volume is 51 m³, and total solar panel area is 97 m².

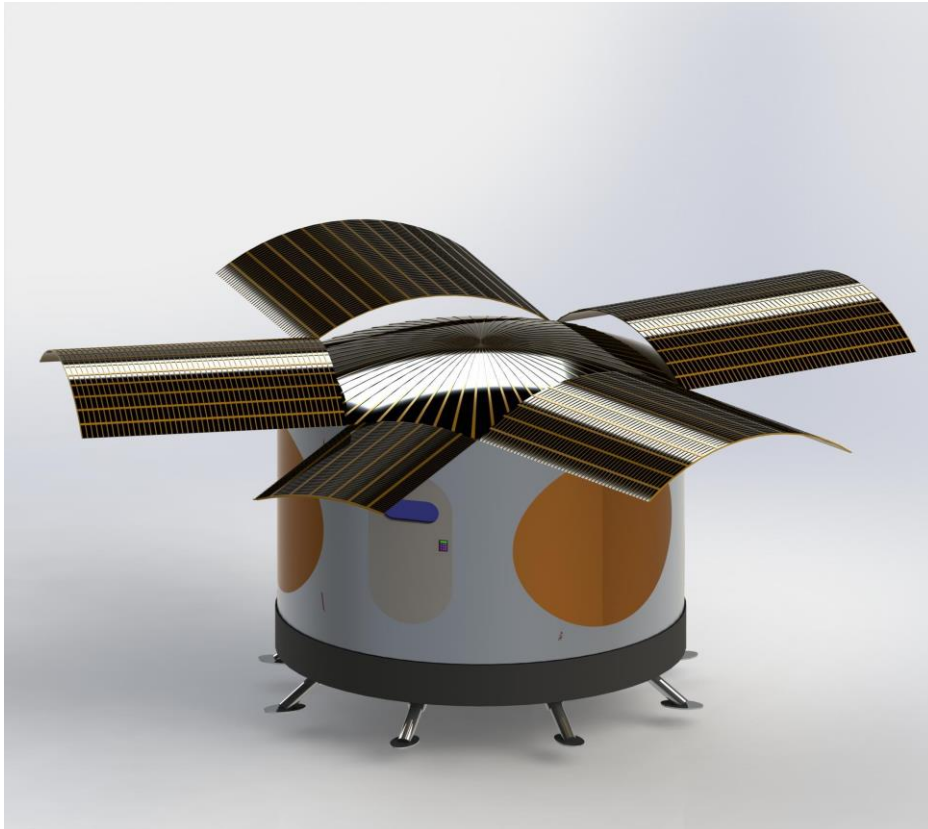


Figure 7: OASIS After Initial deployment of Central Solar Arrays

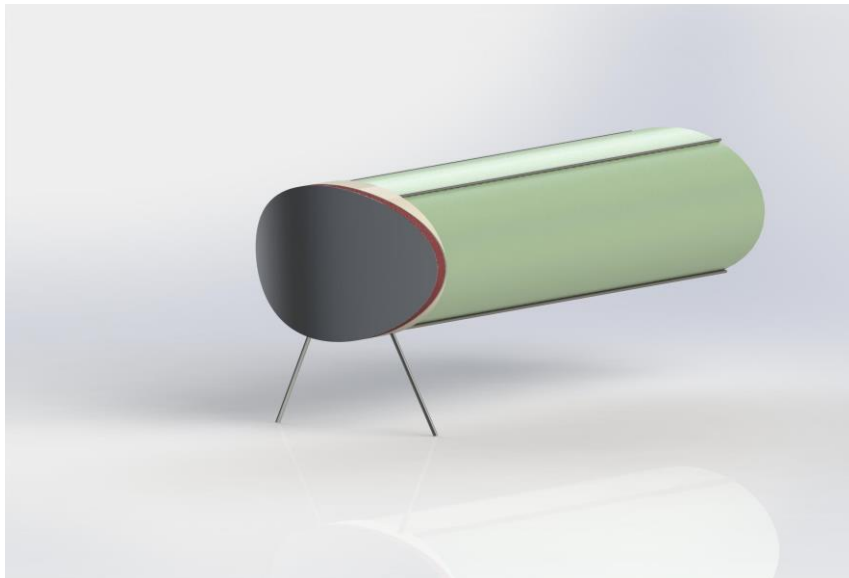


Figure 8: Greenwing Exterior with Endcap, Axial Deployment Tension Cables, and Micro-Castpiles at the Endcap

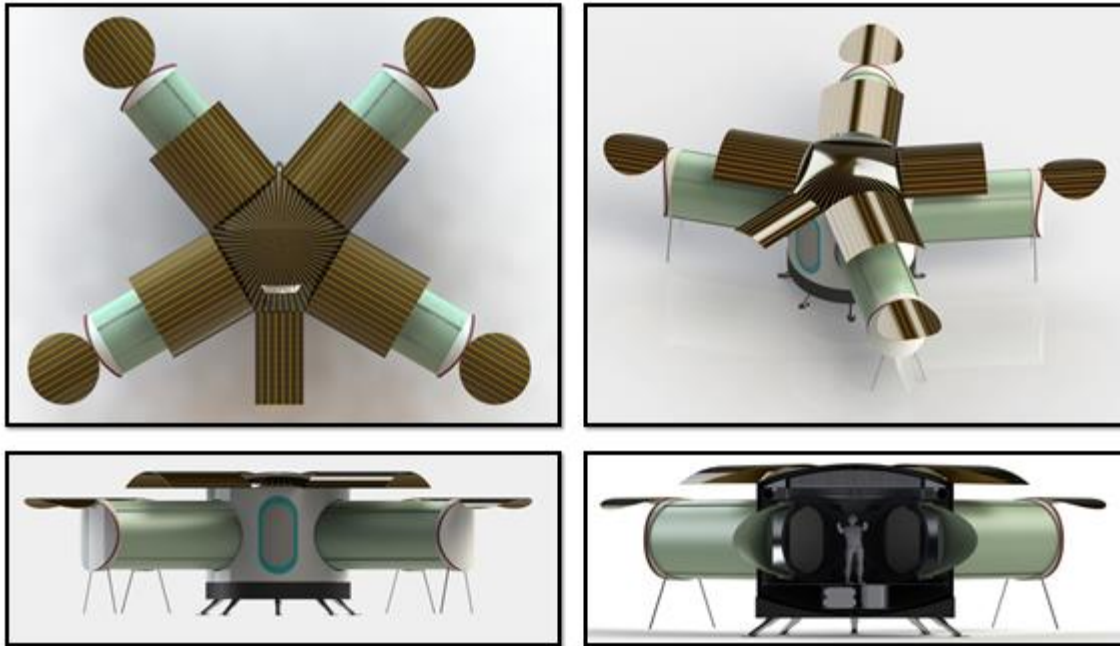


Figure 9: Multiple views of the fully deployed OASIS Module

Central Structure Design

The central hub's overall parameters are similar to NASA's HDU. The exterior diameter of the cylindrical pressure vessel design is 4.6 m, with a flat height of 3 m, and a 0.5 m dome on the top and bottom for a total height of 4 meters. The wall thickness is a little less than 13 centimeters and contains a basic I-beam rib structure, inner pressure vessel, outer pressure vessel, honeycomb stiffener, and an insulation-shielding layer, which is similar to the ISS's structural configuration without the micro-meteoroid protective layer.²² The inner and outer pressure vessels are aluminum alloy with wall thicknesses of 2 mm and 3 mm, respectively. Within the central structure are all of the plant growth systems, HVAC systems, fire suppression systems, power storage systems, carbon dioxide collection systems, water tanks, and atmosphere tanks. The fire suppression system, Carbon dioxide collection system, and HVAC systems are in the upper pressure vessel dome. The HVAC systems consist of a boiler, condenser, pump, fans, humidity control, and ducting. The plant growth systems are located in an easily accessible system bay beneath the floor in the lower pressure vessel dome, which contains all the control units, pumps, nutrients, and water systems necessary to sustain plant growth. The atmosphere tanks, water tanks, and batteries are stored in the remaining volume of the lower pressure dome. (Figure 10). The central hub is the common access point between the four Greenwings. Each Greenwing is isolated from the central hub and from the other Greenwings with pressure bulkheads and pressure doors. These are not airlocks, so when astronauts enter a Greenwing, the atmosphere composition will be equalized with the central hub. However, the pressure door allows for specialized atmosphere composition and humidity for each of the four independent Greenwings, which can be optimized for the specific plants present, as long as the pressure door is open for only a limited amount of time. The module also has a traditional airlock located in the central hub for entering and exiting the greenhouse structure. (Figure 11).

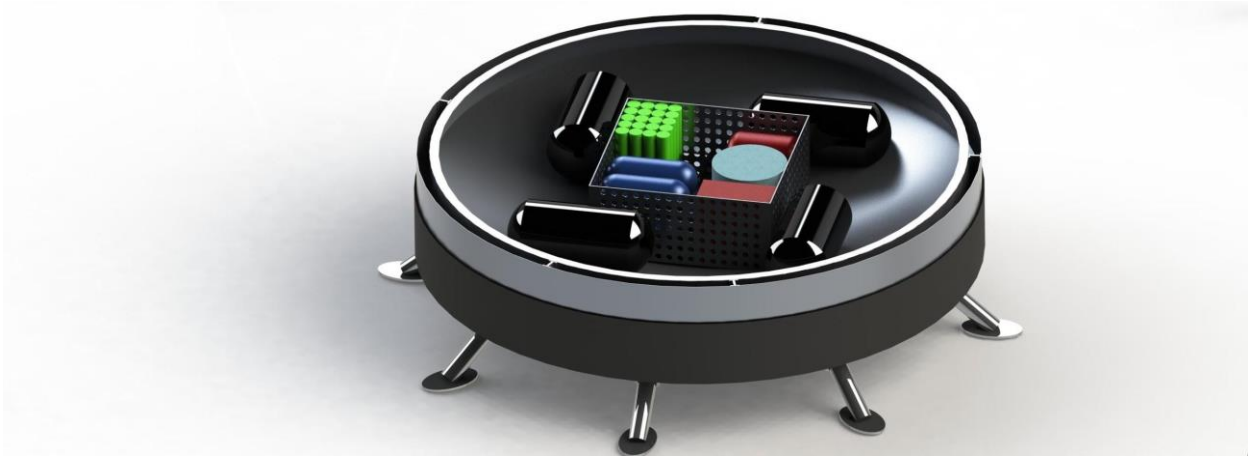


Figure 10: Lower Pressure Vessel containing Plant Growth Systems Bay and Atmosphere Tanks

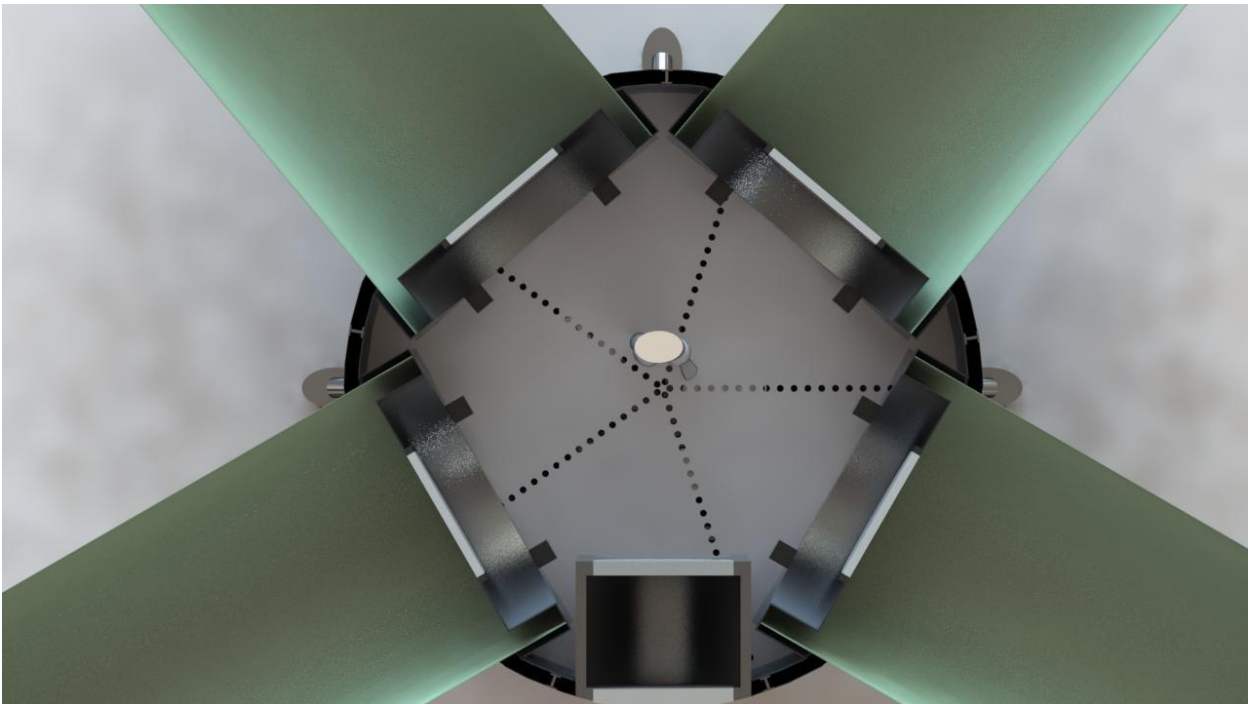


Figure 11: Downward Sectional View of Interior Hub, Showing All Four Pressure Doors and the Main Airlock

Inflatable Structure Design

Inflatable structures are quickly becoming a viable option for primary support structures in space mission designs. NASA is investigating the feasibility of using a three story inflatable system for interplanetary transportation of crew members on deep space missions, which is known as TransHab.²³ OASIS's four cylindrical Inflatable Greenwings are each 5 m in length, have an outer diameter of 2.2 m, and an internal pressure of 60 kpa. Each Greenwing has a solid endcap that makes up portions of the central hub prior to deployment. Greenwings have a wall thickness of less than 5 mm and are composed of two categories of material, structural and attenuation layers. The outermost materials compose the structural layers, consisting of (from the outside in) a restraint bladder, which is the gas retention layer, and a webbing layer. Next are the attenuation layers, which provide abrasion, radiation, and thermal protection.²⁴ The Greenwings, when not deployed, are packed into the volume surrounding the pressure door (Figure 12). ILC Dover, has studied similar cylindrical inflatable structures

under a NASA contract, which produced positive results and useful information regarding packing methods, inflatable restraint design, and manufacturing considerations.²⁵ Inside each Greenwing is a strap support system, much like the rack-based system in use on the ISS. The strap support system is integrated into the inflatable structure and is the attachment point for aeroponic plant growth systems and LED strip lighting (Figure 14). This design is beneficial because, as plants mature, the aeroponic lines and LED light source can be raised or lowered to the optimal height for ideal plant growth. The floor is also integrated into the inflatable structure and hardens after inflation.

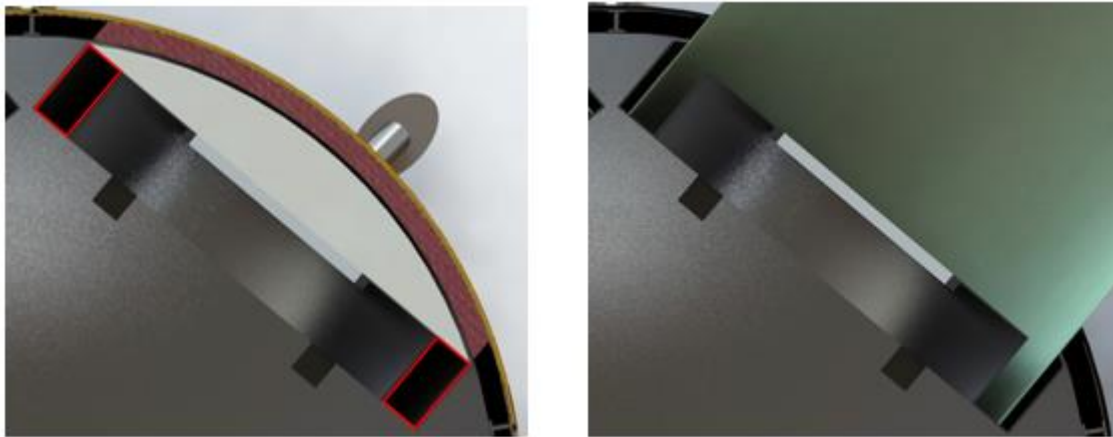


Figure 12: Sectional View of Pressure Bulkhead Before (Red Boxes are Packed Volume) & After Greenwings Deploy

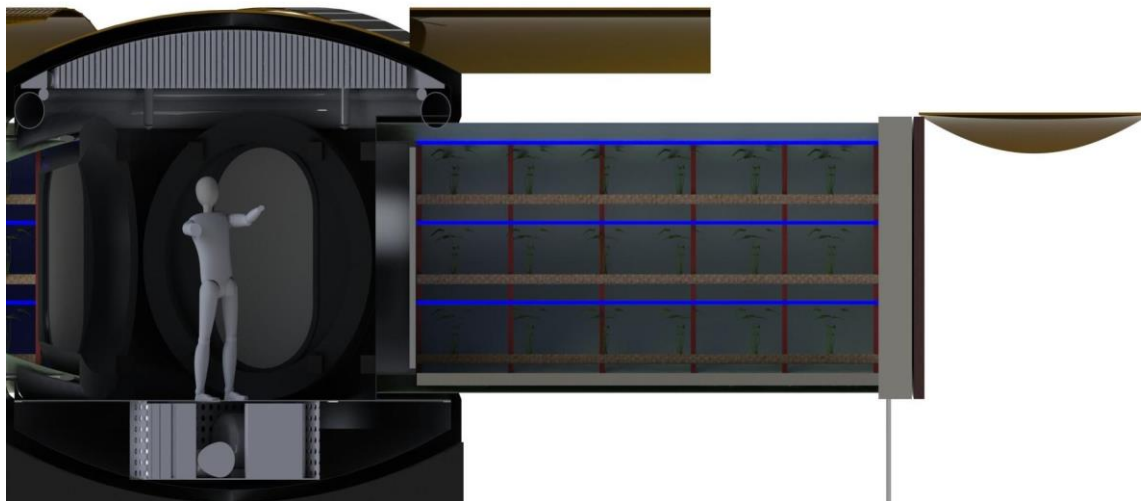


Figure 13: Greenwing Interior (LED Lighting seen in Blue, Aeroponic Lines in Brown, Support Straps in Red)

Plant Growth Systems

OASIS will utilize an aeroponic growth system (Figure 15), because they consume less nutrients, use non-organic nutrient supplements, increase gas transfer at roots, result in higher productivity, and have a reduced overall weight. The preliminary crops selected for growth are spinach, lettuce, carrots, onions, cucumbers, radishes, snap peas, strawberries, and blackberries. These crops were chosen for their nutritional value; plant yield; resilience; and light, nutrition, and environment requirements. The nutrient solution will use a 2-part fertilizer composed of cations and anions; pH levels will be monitored and will dictate fertilizer composition. The

nutrient solution will be distributed to the appropriate Greenwing using bladder tanks, which can be manually actuated in the case of a power outage. Water for the aeroponic system will be limited, and advanced reclamation systems will be necessary to ensure proper recycling. Currently the ISS restricts water usage to just under two liters per day.²⁶ OASIS's water cycle will use less water daily because it will not be consumed by astronauts and is only used to support plants. A reverse osmosis water reclamation system will be used and water condensed from the Greenwing atmosphere will also be recaptured. Each wing will operate at independent temperatures to optimize growth of the plants they support (Table 2). Planting times and crop spacing is crucial to mission success, as crops must consistently produce fruit to supplement astronauts, and overpopulation will result in yield reductions (Table 3). LED lighting systems provide the means for photosynthesis and are wavelength controllable (red, green, and blue light) to produce optimal conditions for the plants they are supporting.²⁷ The lighting control system will also maintain lighting schedules designed to provide the ideal duration of lighting for each individual crop, while also reducing the power usage at any given time.

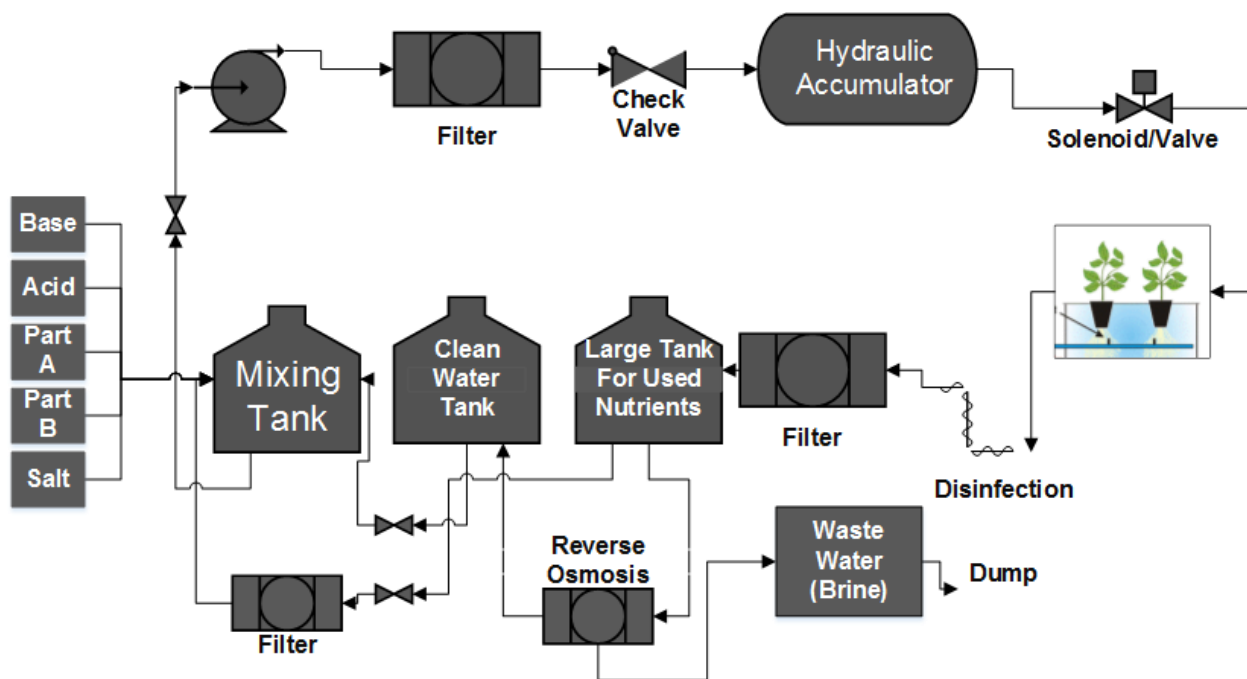


Figure 14: Aeroponic Plant Growth System Configuration

	Wing 1	Wing 2	Wing 3	Wing 4
Temperature	20 – 22°C	16 -18°C	11-12°C	15.5-21°F
Plants	Onion	Lettuce`	Spinach	Strawberry
	Cucumber	Carrot	Radish	Blackberry
	Peas			

Table 2: Greenwing Temperatures and Planting Plan

Plant	Greenwing Number	Required (cm)	Spacing	Time to maturity (Days)	Planting (Days)	Interval
Snap Peas	1	15.24	15.24	60	2	2
Cucumber	1	30.5	30.5	70	2	2
Onion	1	15.24	15.24	120	4	4
Lettuce	2	15.24	15.24	60	1	1
Carrots	2	7.62	7.62	70	1	1
Spinach	3	10.16	10.16	60	3	3
Radish	3	15.24	15.24	35	2	2
Strawberry	4	91.4	91.4	-	-	-
Blackberry	4	121.9	121.9	-	-	-

Table 3: Greenwing Planting Plan with Plant Spacing, Time to Maturity, and Planting Intervals for Each Crop

Power Collection Systems

The solar power collection system incorporates large rigid solar panel arrays, flexible solar panels integrated into the top sun exposed portions of the inflatable Greenwings, and battery systems to store the collected power. Flexible solar panels have been tested in previous Oklahoma State University projects and have been successfully demonstrated in inflatable configurations (Figure 15). Initial calculations of average solar power collection show, with OASIS's 97 m² of solar panel area, solar panel efficiencies of 40%, and average solar irradiances of 590 W/m² could provide as much as 25 kW of power.²⁸ However, this number is calculated using ideal conditions and should be taken as a maximum; during sand storms, this value could be reduced by as much as 95%. A rough estimate of OASIS's power consumption budget totals over 22 kw of power. This is below the Ideal maximum power collection; however, the power consumption value is estimated as a constant. Therefore, unless more solar panel area is added, solar panel efficiency is increased, or power consumption is reduced, the module will most likely run into power management issues. Adding more solar panel surface area is a feasible option and rough calculations show that simple folding solar arrays, like those used on the Curiosity Rover mission, could increase maximum solar power collection by 10 kW, which is more reasonable.

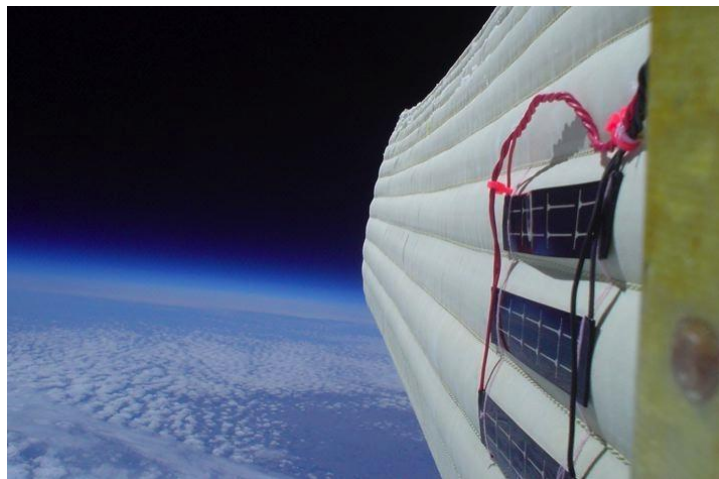


Figure 15: Flexible Solar Panels Successfully Incorporated with an Inflatable Design in a High Altitude Test³⁰

TESTING METHODOLOGY

In order to demonstrate and test the methods used by the OASIS design, full-scale analog and multiple small-scale experiments are being conducted. A full-scale analog of a Greenwing will be constructed of wood, and will contain a functioning aeroponic, lighting, HVAC, and environmental monitoring system (Figure 19). This model will then test overall power consumption from lighting, aeroponic, and ventilation systems. Additionally, the full-scale analog will model and allow testing of the strap support system within each Greenwing as well as answer many questions regarding operating space ergonomics and provide full-scale visualizations of the design's capabilities. The aeroponic system within the full-scale model will grow carrots and lettuce, which will facilitate testing of the water reclamation system, nutrient dispersion system, and the amount of light needed for successful growth. A 1/5th scale inflatable Greenwing constructed from urethane coated nylon will demonstrate the inflation process from the initial packed state to the fully deployed state (Figure 16) using previously developed test and evaluation techniques³¹. This will facilitate testing of the tension cable controlled pressurization technique proposed. There is also an architectural model in development that will accurately depict the stages of Greenwing deployment and the overall design of the OASIS System on a 1/20th scale. With these analogs and models, meaningful test results will be obtained, and useful demonstrations will provide information about the OASIS design that could not be obtained from solely conceptual methods.



Figure 16: OSU's X-Hab team in the process of building a full-scale analog of an OASIS Greenwing



Figure 17: OSU X-Hab team members considering different methods to build a 1/5th scale inflatable model

FUTURE STUDY

Moving forward, the Oklahoma State University Space Cowboy's would like to further investigate methods to reduce power consumption of the OASIS module. One option is to use natural light collection and transportation for all or partial plant photosynthesis. One study suggests that a natural light collection system is capable of providing nearly an additional kilowatt of effective lighting power for a lunar application.²⁹ This could reduce power requirements substantially. Additionally, the largest consumer of power within the OASIS greenhouse are the HVAC systems which accounted for more than half the overall power consumption. Newer technology could result in slightly more efficient systems, which could be the difference between missions to Mars becoming feasible or remaining science fiction.

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