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RedThumb: A Mars Greenhouse design for the 2002 MarsPort Engineering Design Student Competition

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ABSTRACT

The MarsPort competition, sponsored by the Florida and Texas Space Grant Consortiums, was established to elicit student involvement in the manned exploration of Mars. The RedThumb team, comprised of students from the Aerospace Engineering Sciences Department at the University of Colorado, designed a greenhouse to be deployed on the Martian surface and meet the requirements put out by the 2002 MarsPort competition. This paper addresses the difficulties of engineering systems to operate in the Martian environment including radiation, micrometeorites, and dust storms. Diet requirements and the selection of crops are also discussed. The final greenhouse system includes seven, unmanned inflatable greenhouse modules called AGPods. There is also a manned facility called PlantHAB where AGPods are maintained and harvested and includes and additional 30 m^2 for salad type crops.

INTRODUCTION

Within 20 years, the first humans could land on the planet Mars. They will work, explore, and conduct science experiments on the surface of Mars before climbing back into the Mars Ascent Vehicle (MAV) for rendezvous with the Earth Return Vehicle (ERV) and the return trip home. They and subsequent spacefarers will require a dependable infrastructure from which to sustain life and launch spacecraft from the Martian surface. The NASA MarsPort Engineering Design Student Competition 2002 sought to enable up to six teams of students to conduct engineering trade and design studies in support of a MarsPort Deployable Greenhouse (MDG) for operation on the surface of Mars. One of the six teams accepting this challenging engineering problem was RedThumb, a team comprised of students from Aerospace Engineering Sciences department at the University of Colorado.

MISSION ARCHITECTURE

The teams were instructed to work within the framework of the Mars Design Reference Mission (DRM) 3.0. (http://spaceflight.nasa.gov/mars/reference/hem/hem1.html) The DRM outlines several launches over a period of two years to establish a Base Camp for the crew on the Martian surface. The Earth Return Vehicle (ERV) will be put into orbit around Mars and the Mars Ascent Vehicle (MAV) along with its In-Situ Resource Utilization (ISRU) propellant and life-support production plant will be staged on the surface eighteen months prior to the crew lifting off from Earth. In those eighteen months the ISRU plant will produce all the propellants required for the MAV to lift the crew off the surface as well as a large cache of crew consumables, such as water and oxygen. Two years later a second ISRU and MAV will be launched in conjunction with the first crew. This hardware will serve as the primary hardware for the second crewed mission, as well as a back-up system for the crew on the first mission.

To enable affordable human missions to Mars, producing crew consumables, utilizing Martian resources, and recycling waste products may be advantageous in reducing mission costs. Because of the transit time to Mars and limited launch window, resupply is not a good option, so crew self sustainability is critical. The MDG will aid in accomplishing these goals, but is not considered as part of the DRM 3.0. For the MarsPort competition the MDG was considered as a change to the architecture. The MDG can either be predeployed 2 years earlier than crew arrival or sent during the launch window when the crew departs. The MDG can be launched in a Magnum Launch Vehicle, as described in the DRM 3.0, or in another projected/existing launch vehicle. However, if the Magnum is used, another major payload should be assumed to accompany it. The amended architecture may take advantage of or augment the existing ISRU capability, if practical.

MARSPORT ASSUMPTIONS

The MarsPort competition also included the following six additional assumptions/requirements:

1. The design life of the MDG shall be 20 years.
2. Crew size is 6.

3. Leakage rate of the MDG should be less than 1% of the volume per day at the target internal pressure.
4. MDG crops will provide diet augmentation (i.e., will not be used to supply more than ~25% of the crew food).
5. Crop lighting will be provided using incident solar radiation with or without supplemental electric lighting.
6. Crew ingress/egress is not a requirement.

The MarsPort adopted several additional references as supplemental requirements that addressed the Mars environment, man-systems integration, and landing site selection. To meet the objectives, the MarsPort competition tasked the teams to address the greenhouse structure, light collection, water and nutrient delivery, atmospheric controls, crop selection, harvesting and materials handling, and thermal management. A minimal mass and lift-off volume approach was to be employed and, in addition, deployment options from the spacecraft and on the surface were to be analyzed.

MARS ENVIRONMENT

Understanding the Mars surface environment is important to determine appropriate design approaches, for the selection of suitable materials, and to establish bounds for engineering analyses.

RADIATION

There are a number of forms of radiation that need to be quantified in order to complete a conceptual greenhouse design. Central to the design of the MDG is the visible portion of the spectrum ranging from 400nm to 700nm. This is the portion of the spectrum where plants photosynthesize. The visible spectrum varies with Mars orbital distance, eccentricity, and the change in the dust level in the atmosphere. Figure 1 shows the maximum, minimum, and mean power spectrum at Mars' orbital distance above the atmosphere and compares them to the spectrum at Earth's orbital distance above the atmosphere.

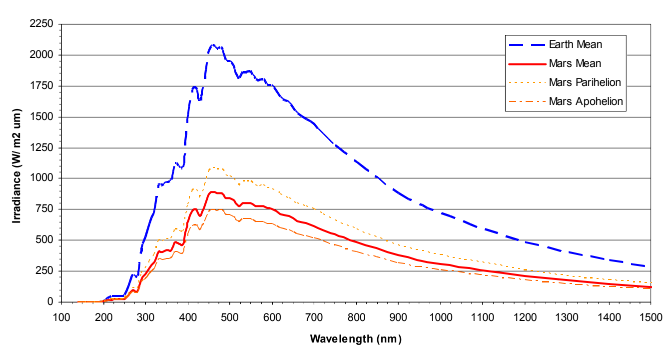

Figure 1 A comparison of the spectral power distributions at the top of the atmospheres of Earth and Mars. Mars' orbital ecentricity produces a variation in the spectral power between perihelion and apohelion (2000).

DUST DEPOSITION/ACCUMULATION

Measurements taken during the Materials Adherence Experiment (MAE) on Pathfinder indicate steady dust accumulation on the Martian surface at a rate of about 0.28% of the surface area per day (Landis and Jenkins 1997). The Mars Exploration Rover (MER) program has extended this analysis to account for variations in the atmospheric columnar dust amount. According to MER requirements, deposition rates increase with increased dust loading according to:

$$deposition = \frac{0.0018\tau}{0.5}$$

where τ is the vertical dust optical depth and complete coverage is when deposition equals 1.00. Therefore, methods of dust removal must be considered.

The ultraviolet and x-ray portions of the spectrum pose a hazard to plants, humans, and equipment and must be quantified to determine their threat. Figure 2 shows Mars' atmosphere provides some protection by absorbing energy below ~190nm wavelength. The resulting dose of UV radiation is much less than would be experienced in orbit, but more (and at higher energy wavelengths) than what would be experienced on Earth's surface.

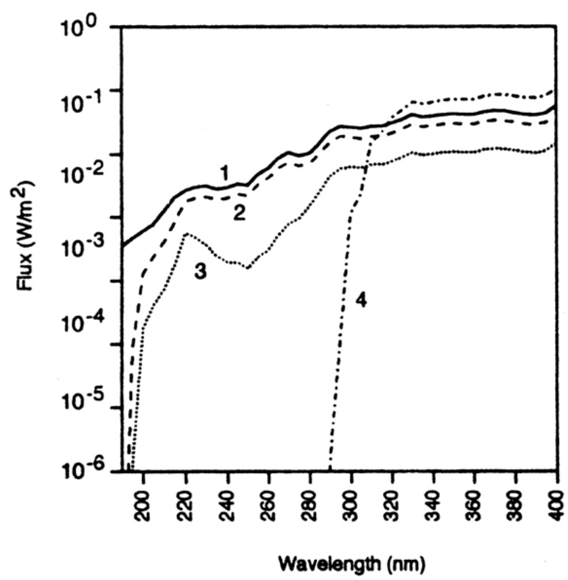

Figure 2 Solar UV radiation at the top of the Martian atmosphere (1), at the surface with zero zenith angle (2), at the surface 60N during spring (3), and on the Earth's surface at zero zenith angle (4) (Cockell and Andrady, 1999)

High-energy particle events include solar flares, Galactic Cosmic Rays (GCR), solar particle events (SPE), and the solar wind. Despite the lack of an intrinsic planetary geomagnetic field, the Mars surface is relatively well protected. Electrons from the solar wind are shielded from the surface due to interaction with the outer atmosphere. The atmosphere also attenuates both SPE and GCR. Figure 3 shows the surface dose versus carbon dioxide absorber amount for GCR (top) and SPE (bottom). The Mars surface carbon dioxide absorber amount is generally between 10 and 20 g/cm^2 depending on altitude and atmospheric density.

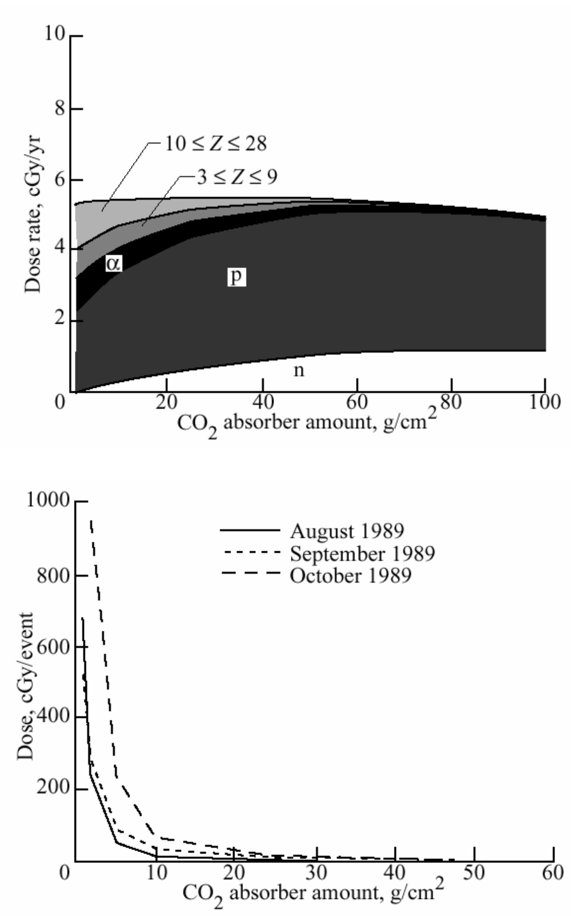

Figure 3 The skin dose for both GCR (top) and SPE (bottom) versus carbon dioxide absorber amount (Simonsen and Nealy 1993).

RADIATION EFFECTS ON PLANTS

Plants grown in a greenhouse on the Mars surface will be exposed to an increased ionizing radiation environment. The effects of this type of radiation on certain plants, and possibly humans, depending on the design configuration chosen, must be examined. In tests conducted on this subject, plants have shown greater resilience to radiation than humans do (Clawson, Hoehn et al. 1999). This evidence suggests that radiation-shielding requirements of non-human-tended greenhouses would be much easier to meet than human-tended greenhouses. Table 1 lists the effects and lethal doses of radiation in Sieverts (Sv) on selected organisms.

Table 1 Effects if Ionizing Radiation on Selected Plants (Clawson, Hoehn et al. 1999).

Organism	Observable Effects (Sv)	Lethal Dose (Sv)
Human (Annual Limit < 5 REM)	0.25	4.50
Onion	3.77	14.91
Wheat	10.17	40.22
Corn	10.61	41.97
Potato	31.87	126.08
Rice	49.74	19677
Kidney Beans	91.37	361.49
Potential Dose:	Solar Minimum: 0.40 Sv Solar Maximum: 1.20 Sv Proton Flare: 5.0 Sv	

MICROMETEORITES

Even though the thin Martian atmosphere provides some protection, micrometeorites pose a moderate threat to equipment and personnel on the surface of Mars that should be quantified. The influx of meteorites entering Mar's atmosphere can be estimated as

$$\log N = -0.689 \log m + 4.17$$

where N is the number of meteorites per year having masses greater than m grams incident on an area of 10^6 km^2 (Bland and Smith 2000). Atmospheric entry simulations indicate that particles from 10 to 1000 μm in diameter are slowed below 1 km/s before impacting the surface of the planet (Flynn and McKay 1990).

DIET AUGMENTATION / CROP SELECTION

The MarsPort requirements stipulated that the MDG should augment the crews' diet by producing 25% of their needs. The RedThumb team chose to use caloric intake as the measure of compliance. Table 2 shows the individual crew daily caloric requirements calculated two different ways compared to the average intake of crews of previous space missions. Data for older 5th percentile Japanese females were used to calculate the caloric intake for women while data for younger 95th percentile American males were used to determine caloric intake for men (NASA-STD-3000 1995). The resultant averages for the two calculation techniques show the wide variation in caloric needs depending on crew gender, age, and size. The average calculated intake for men agrees well with past mission intakes particularly when activity levels are taken into account (e.g. Apollo – sedentary; Skylab – highly active, heavy exercise; Shuttle – medium activity). Although conservative, the average calculated caloric intake for men was chosen as the target for RedThumb. In addition to normal daily activities, the reference mission specifies that 2 crew per day would perform EVAs with an average caloric need of 500kcal per crew per EVA. The 1000kcal need for EVAs were added to six times the individual crew requirement resulting in a total crew requirement of 17286 kcal per day of which 25% or 4321 kcal per day are to be produced by the MDG.

Table 2 Caloric requirements (crewperson/day) calculated using two different methods (M, H and A are the mass, height and age of each astronaut in kg, cm and yrs, respectively) and the average caloric intake for past space missions. (Lane and Schoeller, 2000; Anon., 2001).

	Iowa State	**JSC**	**Average**
Men	1.7*(11.6*M+879)	[66+(13.7*M)+(5*H)-(6.8*A)]	2714.34
	=3436.72	=1991.95	
Women	1.6*(8.7*M+829)	[655+(9.6*M)+(1.7*H)-(4.7*A)]	1505.43
	=1897.12	=1113.73	
Apollo			1880.20
Skylab			2832.20
Shuttle			2118.20
Average			2276.87

In addition to providing the needed caloric intake, the total food systems must provide a balanced diet. Astronaut consumption of protein is essential to offset the reduction in muscle mass that occurs in the microgravity environment and should be maintained at 12-15% of the total calories. Approximately 50% of a crew's diet should be carbohydrates of which less than 10% should be sucrose and simple sugar. Approximately 30-35% of the total should be lipids, or fats (Lane and Schoeller 2000).

SYSTEM ARCHITECTURE

During our proposal effort, research into various greenhouse technologies enabled us to develop various configurations that we could analyze. We diluted the characteristics of a number of designs into three primary configurations. These configurations were traded with consideration given to driving system parameters that included structural mass, lighting mass and power, and additional crew time requirements. Our trade study assumed that many of the components and systems would be similar across configurations; therefore, we concentrated primarily on those aspects that would be unique to each configuration.

The three primary configurations were based from various concepts proposed in the life support literature. (Hublitz 2000) proposed a large transparent greenhouse that could utilize artificial as well as natural lighting and is similar in concept proposed by Gertner and also Sadler (Gertner 1999; Sadler 1999). The DRM 3.0 uses inflatable technologies, similar to the Transhab developed at JSC, for the construction of a science lab. Our second configuration is based on this technology and assumes that solar irradiance collectors provide natural lighting. Our final configuration was proposed by Clawson, Hoehn et al. (1999) called the Autonomous Garden Pod (AGPod). It is a transparent membrane structure that is smaller in comparison to Hublitz and is non-human rated and is intended to be part of a modular system where the plant growth units are brought inside the habitat for harvest, planting, and maintenance. Each of the three configurations was evaluated at three different operating irradiance levels. Setting the required irradiance at the plant level drives the size of the resulting system and the breakdown of natural versus supplemental lighting.

Our final system architecture selection was a hybrid design combining the elements of the small modular transparent greenhouse (AGPod) with that of the larger opaque inflatable volume. The AGPod has superior mass and natural light transmittance, but limits access to the crops and requires a pressurized volume to harvest, plant, and maintain. There is no allowance in the DRM or MarsPort requirements to bring the AGPods into the habitat, so we must provide that volume as part of our system. The larger opaque volume structure, called PlantHab, provides workstations to process the modules in a 'shirt sleeve' pressurized environment. Additionally, the PlantHab offers space to grow short cycled crops that benefit from more regular access. The AGPods will focus on staple crops, such as potato, that have a long growth cycle, is amenable to the ~12 hour lighting environment at our mission locations, and does not require regular access from the crew. The PlantHab systems will focus mainly on leafy salad greens that would be accessed regularly and are amenable to lower light values that are expected with the lower efficiency of the solar collectors and/or artificial supplemental lighting. Development of automated systems will first focus on the retrieval and delivery of the modular units by remote controlled rover, which reduces crew time during EVAs.

AGPOD

Figure 4 The AGPod

The AGPod, depicted in Figure 4, is a modular unit that resides external to the crew habitat pressurized volume to make use of natural direct solar illumination through transparent structures for all or part of the lighting needed for plant growth. This reduces the equivalent system mass (ESM) of crop production systems by eliminating the use of spacecraft internal pressurized volume and by reducing power and heat rejection resources that would otherwise be needed for total artificial lighting. By placing these structures in the surface environment, a natural difference in pressure that allows the use of mass-saving inflatable structure technology is produced. A plant-only rating on the structure and internal environment permits the use of lower pressures; further reducing mass and also leakage rates and it also lowers the required safety factors, which even further reduces mass. Additionally, mechanical failures as well as microorganism infections can sometimes pose a threat to an advanced life support system (Schuerger 1998) Dividing the total plant production capability into separate modules will reduce the risk of mechanical failure and crop loss due to pathogen infections. A modular system also allows for customization of atmosphere, nutrient delivery, etc. for specific crops.

Each AGPod module must provide a suitable environment in which to grow the plants, i.e. each module must execute all the life support functions. For each of the functions we evaluated whether or not to include hardware in each unit to accomplish these functions or to centrally handle the function and connect each module via an umbilical. For many functions there is an economy of scale (Clawson 2000). Therefore, the solution approach was to connect the AGPods via an umbilical to allow centralization of certain services while still maintaining a capability to run autonomously for short periods to facilitate deployment and retrieval operations. The umbilical is used to supply CO2 rich atmosphere, collect O2 rich atmosphere, and provides a pathway for communications to the main control computers in the PlantHAB. Supply and collection of photosynthetic gases requires a relatively low flow rate through the umbilical and short disconnections will not adversely impact the AGPod's performance. The hardware for both thermal and humidity control are located within the module. Both utilize the entire internal recirculating flow as well as interface with the local module environment making it somewhat impractical to accomplish via an umbilical.

Structure

The stress of flexible membrane materials under an internal pressure load is directly proportional to the radius of curvature and pressure while inversely proportional to the thickness of the material. Optical transmittance is directly proportional to thickness and also related to the geometry (radius of curvature). Therefore, there is a trade-off between increasing the thickness of the material and decreasing the radius of curvature when optimizing the structure for both transmittance and stress or lower mass.

Achieving higher-pressure capable transparent flexible structures involves an inflatable structure phenomenon known as pillowing, illustrated in Figure 5. When spaces exist between restraints, the underlying bladder bulges outward in an attempt to form a spherical radius, decreasing its local radius of curvature, which decreases stress. The challenge in exploiting this phenomenon is to the proper type of restraint system and to pay close attention to the interaction of the bladder with the restraint at the edges of the "pillow."

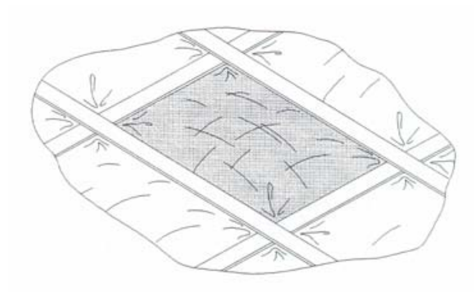

Figure 5 Pillowing of underlying fabric between spaces in the restraint (Stein, Cadogan et al. 1997).

Even though the thin Martian atmosphere provides some protection, micrometeorites pose a moderate threat to equipment and personnel on the surface of Mars. The influx of meteorites entering Mar's atmosphere can be estimated as

$$\log N = -0.689 \log m + 4.17$$

where N is the number of meteorites per year having masses greater than m grams incident on an area of 106 km2 (Bland and Smith, 2000).

The approximate wall thickness for inflatable structures is 0.001 inches. For a micrometeorite traveling at 19 km/s, the critical particle diameter that would puncture the structure is one sixth of the wall thickness [Hyde, J., 2001, personal communication]. This results in a particle diameter of approximately 4 μm. Assuming a spherical shape, the volume of the particle can be estimated. The particles are assumed to have a density of 1 g/cm^3, which is consistent with the range of 0.7 – 2.2 g/cm^3 measured for micrometeorites recovered from the Earth's stratosphere (Flynn and McKay 1990). The volume and density can then be used to estimate the mass of the meteorite particle. According to the mass distribution presented in Bland and Smith (2000), 2.2 x 10^{11} particles per year greater than 4 μm can be expected to impact an area of 10^6 km^2, or 0.22 particles per m^2 per year. The probability of x particle impacts in t years can be estimated as

$$P = \frac{(vx)^x}{x!} e^{-vt}$$

where v is the rate of impacts in one year. If x is taken to be zero, in order to determine the probability that the structure would not be hit, and t is one year, the probability of no punctures is 0.805. Over a 20-year period, the probability of no punctures becomes 0.013. This is extraordinarily conservative because the protection of the atmosphere is not considered. Atmospheric entry simulations indicate that particles from 10 to 1000 μm in diameter are slowed below 1 km/s before impacting the surface of the planet (Flynn and McKay 1990). In this case, the critical particle diameter for impacts normal to the surface of the structure is 16 μm [Hyde, J., 2001, personal communication]. Using the same method as described above, the probability of zero impacts capable of puncturing the structure over a one-year period is 0.986 and over a 20-year period is only 0.757.

Lighting and Insulation system

A transparent structure on the Martian surface is susceptible to dramatic heat loss especially at night. To counter this heat loss, Figure 6 shows flexible insulation blankets that will cover the structure at night and double as reflectors during the day to increase the amount of light available for plant growth.

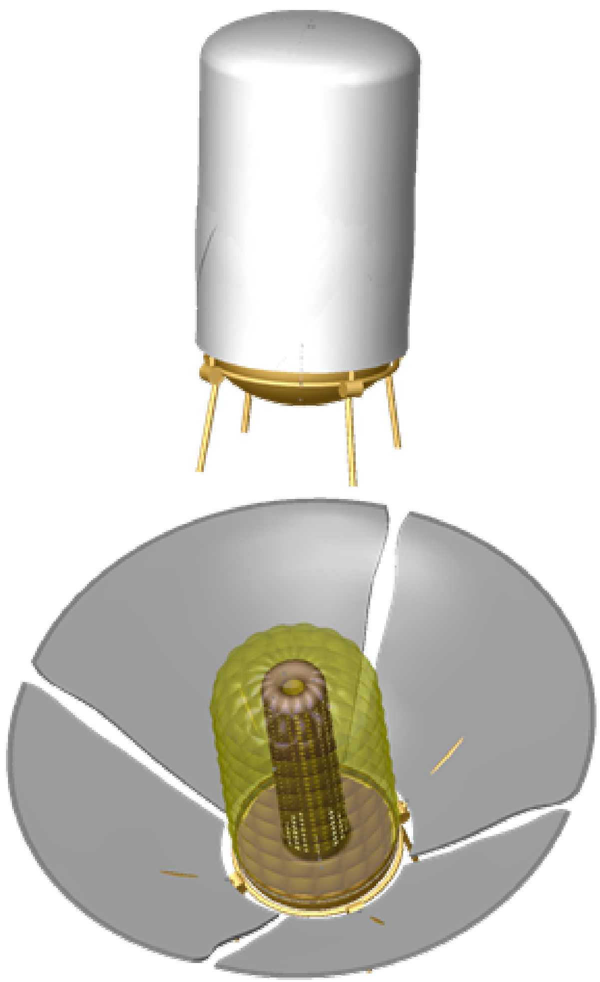

Figure 6 The insulation blankets to reduce nighttime heat loss double as solar reflectors during the day to increase light to the plants.

PLANTHAB

The PlantHab structure must be lightweight to reduce launch mass and have sufficient volume to accommodate the internal systems while using the lowest possible payload volume on the launch vehicle. The PlantHab, shown in Figure 7, provides both an area for growing salad type crops (Upper PlantHab Level) and an area for maintaining the AGPods (Lower PlantHab Level). There is also sufficient area for the storage of plant growth supplies such as lighting, atmospheric control, computers, nutrient delivery systems, and waste processing systems.

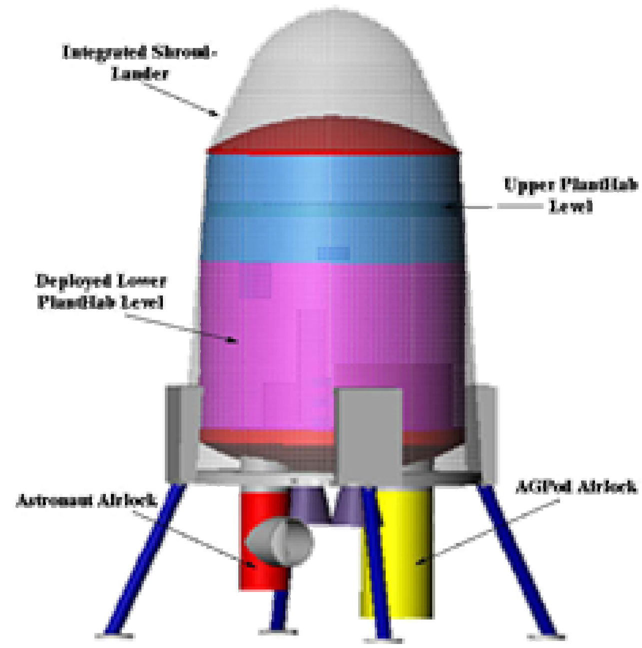

Figure 7 The PlantHab in the deployed configuration with two levels and two airlocks, one for crew ingress/egress and one for AGPod deployment and retrieval.

The structure must be able to survive the defined mission lifetime of 20 years. Since the PlantHab will be human-rated, the structure should provide sufficient protection for the crew and internal systems from radiation and micrometeorites. It must be able to maintain the necessary atmospheric pressure and constituents while reducing the system leakage. It must support the internal pressure loads as well as the equipment and crew weight. Permeability and flammability of candidate materials must be considered in the selection process. Leak-tight construction of the PlantHab is also needed to decrease system leakage. Crew ingress and egress will be necessary to maintain the plants, thus creating a requirement for an attachment to the crew habitat and/or an airlock.

Maintenance bay

The main purpose for the lower level of the PlantHab, shown in Figure 8, is to harvest the AGPods and store harvested crops. However, atmospheric control for the upper level of the PlantHab is also stored here. Furthermore, inedible biomass from harvested crops is also taken care of in the waste management leaching process. A hoist is used to raise and lower each AGPod from the surface through the airlock to the maintenance bay. The AGPod airlock is a flexible sleeve drawn down from the PlantHab over the AGPod. Once sealed at the bottom it is pressurized allowing access from the interior of the PlantHab.

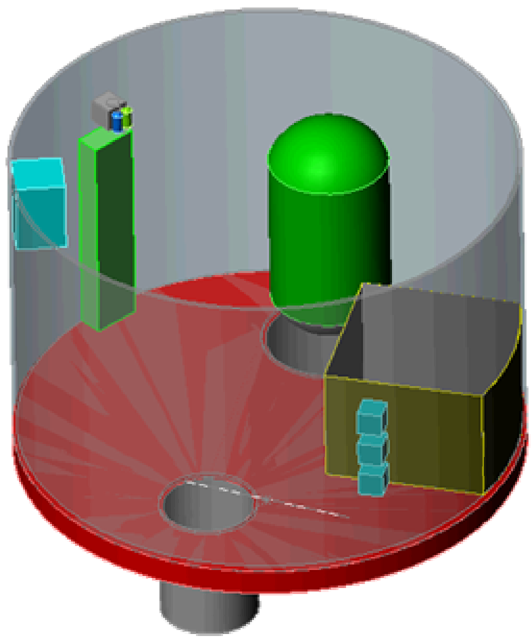

Figure 8 PlantHab lower level configuration

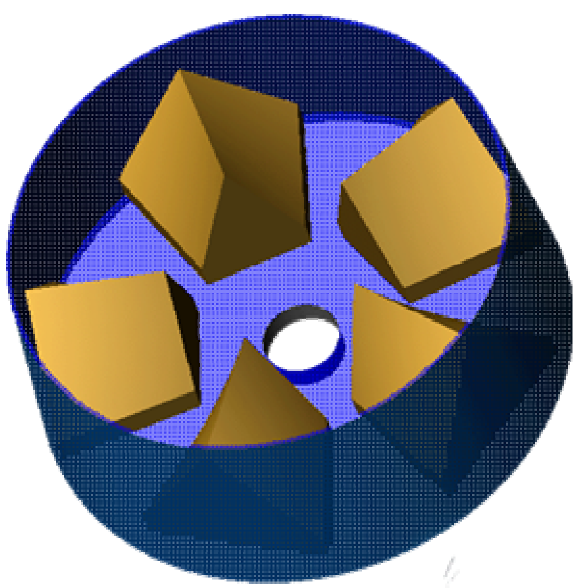

Figure 9 PlantHab Upper Level

Stairs or an elevator allow astronaut access to the upper level to tend to the salad crops grown on A-frame style aeroponic systems similar to those in

Figure 10 A-frame style aeroponic system (EPCOT)

OPERATIONS

The four main operations of the MDG system are crop collection, planting crops and maintenance of both the AGPods and PlantHab. Planting crops will be the first operation that occurs after deployment. The crops will be planted when the MDG arrives on Mars and the deployment process has been finished. The AGPods will have to be opened up to place seeds on the A-frame tower in the AGPods. The PlantHab trays will be planted when they are deployed. Once the system has started and the seeds planted, the next operation would be collecting the crops. Crop collection includes the actual picking of the crops, crop storage and then replanting or pruning for re-growth.

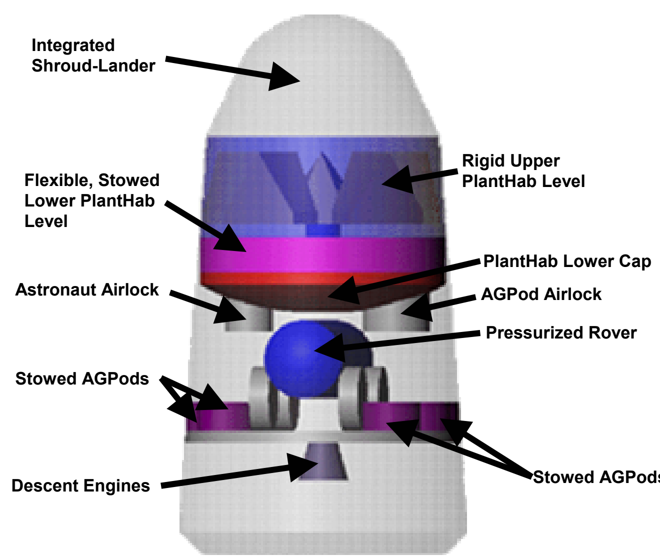

Figure 11 The RedThumb MDG system in the stowed configuration for Mars transit.

SYSTEM CAPABILITIES

CROP SELECTION

The final crop selection was made to meet the dietary requirements set by MarsPort. The selected crops were selected based on productivity, lighting and environmental requirements, harvesting and post-processing requirements, psychological and dietary concerns. The final crop selection is shown below in Table 3. A growing area of 100 m^2 is needed for this task. This was accomplished with a 30m^2 PlantHab and seven 9.9 m^2 AGPods.

Table 3 Final Crop Selection

Crop	Percentage of Total Growth (%)
PlantHAB	
Lettuce, raw	6
Red Tomatoes	4
Chard, Swiss	4
Cabbage	4
Carrots	2
Strawberries	2
Spinach	0
Peanuts	0
PlantHAB Total	32.21
AGPod	
White Rice	47.15
Brown Rice	23.61
Sweet Potatoes	7.24
Soybeans	0
Potatoes	0
Wheat	0
AGPod Total	67.25
Greenhouse Total	**99.46**

PHYSICAL SYSTEM MASS

The physical mass of the greenhouse is the mass of the greenhouse and its components. This does not include the mass of the power generation equipment required to provide the greenhouse with the enough power to run. Table 4 shows the breakdown of the physical mass of the greenhouse. This is the launch mass but does not include the equivalent system mass of power or crew time.

SYSTEM POWER CONSUMPTION

The greenhouse power is broken down and shown below in Table 5. This is the maximum amount of the power the greenhouse will need in order to run at full capacity at all times on the Martian surface. Power requirements will be reduced based on surface temperatures, plant maturity, etc.

Table 4 Physical Mass of Greenhouse

Component	Mass (kg)
PlantHAB	
Inflatable Structure	508
Composite Structure	276
Thermal Control	1931
Humidity Control	2012
Artificial Lighting System	2069
Waste Management	150
Airflow Fan	66
Nutrient Delivery System	650
Atmospheric Control	30
PlantHAB Total Physical Mass	7692
AGPod	
Humidity Control	50
Thermal Control	162
Airflow Fan	3
Transparent Membrane	5
Bottom Shell	25
Internal Air Duct	10
Nutrient Delivery	50
Atmospheric Control	10
Reflector System	50
AGPod Stand	10
AGPod Total Physical Mass	375
7 AGPods + PlantHab = 10316.68	

Table 5 Power Requirements for greenhouse system in kW

Component	Power (kW)
PlantHAB	
Thermal/Humidity System	23
Atmospheric Control	3.32
Lighting ESM Mass	18.6
PlantHAB Total Power	44.92
AGPod	
Thermal/Humidity System	1.4
Atmospheric Control	0.11
AGPod Total Power	1.51
7 AGPods + PlantHAB = 55.49	

CONCLUSION

The RedThumb design meets the requirements outlined by the MarsPort competition in a unique hybrid. The hybrid design maximizes mission adaptability and environmental customization. With the AGPod, a low power system utilizing natural lighting and a modular approach minimizes the impact of pathogen or mechanical failures. The plant rated, AGPod, structure minimizes structural mass. The PlantHab utilizes a man-rated structure for easy access by the crew to minimize the impact of short growth cycles and multiple harvests. The PlantHab adds safety to the mission by including another man-rated structure.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AGPod	Autonomous Garden Pod
ALS	Advanced Life Support
CO2	Carbon Dioxide
DRM	Design Reference Mission
ERV	Earth Return Vehicle
ESM	Equivalent System Mass
EVA	Extravehicular Activity
GCR	Galactic Cosmic Rays
IEEE	Institute of Electrical and Electronic Engineers
ISRU	In Situ Resource Utilization
MAE	Materials Adherence Experiment
MAV	Mars Ascent Vehicle
MDG	MarsPort Deployable Greenhouse
MER	Mars Exploration Rover
SPE	Solar Particle Events
UV	Ultraviolet