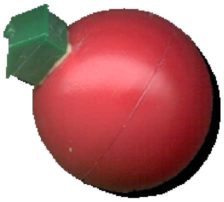
MarsPort 2002:
An Evolutionary Deployable Greenhouse for Mars



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1 Abstract

Future long-term manned spaceflight will rely on the ability to produce food onboard the spacecraft, reducing the payload that must be launched into orbit and significantly increasing the quality of life for the crews.

For the first manned missions to Mars, the duration is short enough that launching a full amount of rations for the crew is not prohibitive. However, the extent to which a Martian greenhouse would contribute to the diet of the astronauts and the overall mission represents a good opportunity for an initial extraterrestrial greenhouse. This greenhouse is not designed as an alternative to pre-packed rations; instead it augments the diet and improves the quality of life for the human explorers.

The Franklin W. Olin College of Engineering MarsPort Team has created a preliminary design for an autonomous Mars Deployable Greenhouse that supplements, by up to 25%, the diet for a crew of six astronauts and contributes to the scientific value of the Mars mission, consuming no other mission resources, including the valuable resource of crew time, under ideal operating conditions.

Crops are seeded, grown in a hypobaric environment using the highly effective hydroponic Nutrient Flow Technique, and then harvested by robots. Harvested crops are automatically processed in the MDG and loaded into a rover for delivery to the astronauts in their habitat.

The solution proposed is a two-level cylinder. The upper level features a transparent exterior that allows natural light to reach the plants. This transparent exterior is exposed by the deployment of two solar arrays. The upper level houses the plant growth structures, water and nutrient delivery systems, supplemental lighting, and autonomous harvesting systems. The upper level is subdivided by a vertical partition that would help control a pathogenic outbreak and can facilitate MDG operations at one-half capacity.

The lower level is essentially an “equipment room” that houses power generation equipment (Radioisotope Thermoelectric Generators (RTGs) and fuel cells), a Sabatier electrolyzer for water production, computing and communication equipment, crop processors, and additional water and nutrient delivery equipment. Environmental sensors and controls will be distributed between the two levels.

Additionally, a small, deployable experimental section contributes scientifically to the mission. This system will attempt to grow crops in Martian soil in a near-Martian environment.

The MDG is designed with the primary crops as the priority. After a tentative crop selection was made, the MDG was designed to create an environment ideal for these crops. Redundancy for reliability and safety over the 20 year lifespan of the greenhouse are present in the design.

2 Mission Overview

Most current mission outlines for human exploration of Mars call for a series of launches, due to the large payload requirements, and a long crew stay (500 days), to make the transit time (130-180 days each way) worthwhile[68]. The Mars Design Reference Mission (DRM) 3.0 is one outline for the first human mission to Mars. The DRM requires several launches over a period of two years to establish a base for a crew of six on the Martian surface.

In the first launch, an Earth Return Vehicle (ERV) will be put into orbit around Mars, and a Mars Ascent Vehicle (MAV) / In-Situ Resource Utilization (ISRU) propellant and life-support production plant combination will be landed on the surface. Over the course of eighteen months, the ISRU plant will produce all the propellants required for the MAV as well as a large supply of crew consumables, such as water and oxygen. At the conclusion of the 18 months, the readiness of the ISRU products will be evaluated, and, if sufficient propellant and consumables have been produced, the launch of the first crew will be given the green-light.

The first crew will launch two years after first ERV, MAV, and ISRU launch. A second ISRU/MAV will be concurrently launched to serve as the primary hardware for the second crewed mission, as well as a back-up for the first crew.

The DRM includes elements that are essential to the initial deployment of long-lived outposts on Mars. The extent to which additional elements are included in early colonization activities will depend upon whether or not the value-added more than compensates for any risk or expense that may be entailed in their deployment. The Olin College MarsPort team has designed a Mars Deployable Greenhouse (MDG) that will provide this value.

Parameter	Condition
Temperature	10 to 30°C
Relative Humidity	40 to 90%
CO_2 Partial Pressure	0.1 to 3 kPa
O_2 Partial Pressure	> 5 kPa
Inert Gas Composition	Optional
Ethylene Gas	< 50 ppb equivalent at 100 kPa total pressure

Table 1: Specified Environmental Conditions[1]

3 Design Objectives

The MDG's primary objective is to supplement the diet (up to 25%) for the crew of six astronauts. Additionally, the MDG must:

- contribute to the scientific value of the mission as much as possible without adding significant additional costs or risk
- land within ±15° of the equator [1]
- have a design life of 20 years [1]
- have a leakage rate of $< 1\%$ of the volume per day at normal operating pressure [1]
- light crops using incident solar radiation, with or without supplemental electric lighting [1]
- communicate its status to controllers on Earth
- maintain environmental conditions within specified ranges (Table 1)
- be self-sufficient under normal operating conditions such that the MDG will not consume other mission element resources, including the valuable resource of crew time
- either recover or dispose all waste associated with the functioning of the MDG

4 Mars Deployable Greenhouse Overview

The MDG houses 11 main subsystems: water and nutrient delivery, plant growth structures, harvesting, crop processing, environmental controls, waste management, crop delivery, experimental section, computing and communication, and power. These systems work together to satisfy the design objectives, completely autonomously. The astronauts' only responsibility related to the MDG under normal operating conditions is removal of the crops from the delivery rover and eating them. Should something break, they may also be called upon to serve as a repair team.

Diet Augmentation & Crop Growth is the primary function of the Greenhouse, and all subsystems either actively participate in this MDG activity or are designed to support the subsystems that do. Plant growth trays are complex and designed for facilitate growth and easy harvesting. These trays primarily use the Nutrient Flow hydroponic Technique (NFT), except for small aeroponic sections designed to start plants that reproduce from tubers.

A battery of harvesting robots, mobile and stationary, tend the plants from seeding to harvesting to removal. Harvested crops are then either processed in equipment located near the MDG's airlock, or, in the case of crops that do not need harvesting, delivered directly to the crop delivery rover.

The crop delivery rover is garaged in the airlock and is used for semiweekly crop deliveries.

Scientific Contribution is made by the experimental section, which is deployed external to the MDG by the crop delivery rover. This section seeks to develop plants that are better suited for a near-

MDG Subsystem	Diet Aug. Crop Grth	Sci. Cont.	Light Crops	Comun-icate	Env. Cond.	Self-Sufficient	Waste Rec/Disp
H_2O & Nutrient Delivery	√						
Plant Growth Structures	√		√			√	
Harvesters	√					√	√
Crop Processors	√					√	
Environmental Controls					√		√
Waste Management							√
Crop Delivery	√					√	
Experimental Section		√					
Computing & Communication				√		√	
Power	√		√	√	√	√	√

Table 2: Subsystems achieve Design Objectives. "Self Sufficient" indicates that the design of this subsystem was chosen to eliminate reliance on another DRM resource or human interaction

Martian environment through simple natural selection. It has a design life of five years.

Crop lighting is achieved primarily through ambient lighting, as the upper hull of the MDG is transparent. Research has found that the ambient Martian lighting is sufficient for crop growth in unshadowed plants. However, to increase growing space, several plant growth trays will be located in shadowed areas. To light these crops, and to artificially extend the photoperiod for all crops that would benefit from increased daylight hours, LEDs have been selected as supplemental lighting.

Communication is handled through a transmitter that communicates with an assumed communication satellite constellation that provides global coverage. This solution requires little power and will not be obscured during nighttime hours.

Environmental controls will maintain an internal hypobaric environment with a pressure of 200-210 millibars, with partial pressures of O_2 at 50-60 millibars and CO_2 at 1 about one millibar (equivalent to 5000ppm). Average temperature will be $22.75°C$ and average relative humidity will be held around 70% (19.48 millibars H_2O).

Waste Recovery / Disposal proved to be a challenge. While recycling or composting dead plant matter seemed to both be technically unchallenging and more in the spirit of the mission, it was unclear what value it would provide. After trading the additional mass and volume required for waste recovery equipment, it was determined that it was actually more efficient to bring more nutrients and dispose of waste.

Self Sufficiency was seen as a key way to decrease the cost of the mission. While the MDG is more expensive as a result of the level of automation included, and the number of systems required to operate independent of other mission elements, it saves the cost of astronaut time. The crew will be able to focus on their scientific mission rather than with the chores associated with tending a greenhouse.

5 Concept of Operations

5.1 MDG Delivery

5.1.1 Launch

The selection of a launch vehicle for the MDG is one of the driving forces in the design; both the volume available for the payload and the maximum mass are determined by the fairing dimensions of the selected launch vehicle. Because the design guidelines allow the design a 30 ton vehicle, this figure was used as a guideline for launch vehicle selection. Although the greenhouse may end up being much lighter (the desired outcome), a vehicle capable of lifting the maximum mass was baselined.

Except for the Energia rocket, no current heavy launch vehicle allows 30 tons to be delivered to Mars. The Energia rocket alone claims able to deliver up to 100 tons to LEO; however, this project has been mothballed since 1993 and does not appear to be viable at this point. The next largest vehicles are the Titan IV and the Space Shuttle, which can carry 24 tons to LEO; however this translates to only approximately 15 tons to Mars orbit. Based on this data, the team concluded that no existing launch vehicle meets our requirements, so we then looked at launch vehicles currently under development.

The most promising of these proposals is the Magnum launch vehicle. Although it is not yet developed and tested, the team feels it is reasonable to assume that it will be available at the time of the mission, given that all other Reference Mission elements depend on the existence of a vehicle capable of delivering 30 tons of payload to Mars. If the heavy launcher ultimately used is not the Magnum, the MDG can be delivered in any vehicle of comparable payload size and mass.

As with all other Magnum launches described in the reference mission, the MDG and "other significant payload" assumed to be included will be delivered to LEO, where they will rendezvous with the Nuclear Thermal Rocket (NTR) stage that has been launched by another Magnum. For the purpose of planning and payload packaging, it was assumed that the "other significant payload" is also Mars-destined.

Using a common launch vehicle as all other DRM elements, there should be a savings in mission economics. Additional savings on a per kilogram basis, as the Magnum will benefit from RLV and ELV technology advances, with an expected launch cost of approximately $2,200/kg [68].

5.1.2 Trans-Mars Injection

Because the MDG is not carrying any time-sensitive payload (plant seedlings, astronauts) the time spent in transit is not a crucial variable. Instead, given our tight mass budget and cost per pound of launched payload, the mass of propellant needed to launch the spacecraft on a given trajectory is the critical variable. While theoretically, the most energy-efficient trajectory is a Hohmann transfer, the fact that the orbital planes of Earth and Mars are inclined at 1.85° to each other forces the trajectory to deviate somewhat from this ideal. With these criteria in mind, we looked at the trajectories NASA has already developed for he Reference Mission, because our intention is to coordinate the launch of our MDG with the other components of the Reference Mission. Of the trajectories that were presented, the long-stay, minimum energy trajectory fits our criteria the best. It is the most energy-efficient of the three, being the closest to a Hohmann transfer, and allows the MDG to arrive at Mars at the same time as the other Reference Mission components, regardless of the trajectory they follow.

As with the launch vehicle selection, here the team again relies on technology yet to be developed by NASA for the Reference Mission. The TMI stage will be powered by Nuclear Thermal Rocket (NTR) engines as specified by the Reference Mission Addendum. The reason for this choice is that an investigation into current methods of propulsion has shown that no technology available today can deliver 30 tons into Mars orbit. In order to accommodate the various systems the MDG requires for plant production, the payload mass must necessarily exceed the capabilities of current technology. We feel that it is safe to assume that NTR technology will become a viable option, given the tests that have already been conducted, and especially because it is a mission critical technology. As with the launch vehicle, if NTR does not turn out to be usable, the team will rely on the method that the other Reference Mission components use.

The NTR engines will be used for the initial burn from LEO, as well as subsequent course adjustments on the way to Mars. Once the MDG enters orbit around Mars, it will begin aerobraking, using the NTR engine to initiate the deorbit burn and help separate the cruise stage aeroshell before entry.

During TMI, attitude will be controlled with 3-axis control. This system is the standard proven on past Mars missions, versatile and reliable.

It should be noted that the Reference Mission Addendum 3.0 discusses the potential of Solar Electric Propulsion (SEP), particularly as it would allow a "Three Magnum Mission." If the mission architecture is adjusted to use SEP instead of NTR, the MDG's TMI stage will switch to use the SEP stage as well, in order to reduce the number of launch vehicles required. This also has the benefit of launching less fissionable material into space, which will benefit the public perception of the mission.

5.1.3 Entry, Decent, and Landing

The team's approach to landing and deployment was to combine technology proven on Mars with small payloads and experience gained landing large payloads on the moon. The goal is to use proven methods in a novel application, minimizing the risk to the mission and reducing development time and cost.

The first EDL stage will be an aerobraking maneuver around Mars, starting with a very elliptical orbit and using friction with the Mars atmosphere to slow the spacecraft and circularize the orbit. This approach is a somewhat risky maneuver, given that an error in the spacecraft's velocity and/or trajectory can send it to burn up in the atmosphere or become lost in deep space. However, this method has been successful in Mars missions in the past and it is a very good means of slowing the spacecraft down, requiring no additional mass and fuel volume. Because the MDG is not carrying any time-sensitive payload (the plants are all transported as seeds), the aerobraking procedure can be lengthy, allowing for a more gradual process. This will in turn reduce the thermal stresses on the spacecraft, protecting the more fragile subsystems.

EDL processes will be controlled by the onboard computer. Radar and various accelerometers will be used to guide the MDG to its landing location and provide input to the guidance systems. Upon completing the aerobraking maneuver, the mission managers will evaluate Martian weather and determine if it is suitable to initiate atmospheric entry. If the landing site is currently engulfed in a dust storm, atmospheric entry will be delayed until more amenable conditions are present. There were several options reviewed for the thermal protection system during atmospheric entry:

Radiative cooling: in this system, the spacecraft is covered with an excellent insulator. During entry, this insulator is allowed to become red-hot and thus dissipate heat to protect the spacecraft. This is the system employed on the Space Shuttle, and has the advantage of allowing for a reusable entry vehicle and considerable mass savings over other methods. However, this cooling method is only suited to lengthy, gliding descent, where the rate of surface heating is equal to the rate of heat dissipated through the insulating layer. The other complication with this system is that during a lengthy descent, some heat will reach the inside of the spacecraft, no matter how effective the insulator. This can be a very serious problem on Mars, if no other method exists to dissipate the heat.

Heat sinking technique: this method employs a large mass of material with a high melting point to absorb the heat of entry. While this method allows for a reusable entry vehicle, it requires a fairly high amount of mass and because of this becomes wholly impractical for missions with significant entry heat loads.

Ablative cooling: this is so far the most common method of heat protection. Instead of providing a mass of material to absorb the heat of entry, this method uses a shield that sublimes away and thus cools the spacecraft. While this has the disadvantage of preventing entry vehicle reusability, the cooling effect is significantly better than with heat sinking (on the order of 107 J/kg) and allows for a very flexible descent trajectory. Because of the high-energy dissipation, this method provides the most cooling per kg of heatshield.

Based on a review of the above cooling methods, ablative cooling is the best choice. Entry vehicle reusability is not a consideration in this case and the ballistic entry trajectory precludes the use of radiative cooling.

Once the MDG has slowed down to 350-450m/s, the heatshield and outer shell will separate from the spacecraft and the parachutes will deploy. Based on the successful Mars Pathfinder mission, these parachutes will slow down the MDG to the terminal velocity 63 m/s. Because the atmosphere on Mars is only about $\frac{1}{10}$ of Earth's, the size of parachutes needed to completely slow down the MDG would be prohibitive in terms of both mass and stowed volume. Instead, the parachutes will be used in conjunction with retro rockets to reduce the size of each.

After considering the various types of parachutes available, the design chosen is a disk-gap-band parachute. This was the type of parachute used in the *Viking* mission. It was developed specially for high-altitude, supersonic speed, and low dynamic pressure applications, like the very sparse Mars atmosphere, still allowing for high drag and ease of construction. The parachutes will be made of Dacron, which is strong enough to withstand the force of descent and also sterilization and stowage.

The overall parachute system will include the three main parachutes, which will be extracted by three smaller pilot parachutes, in turn ejected by a mortar. Two smaller parachutes will also be deployed to help separate the outer shell and heatshield following atmospheric entry, before the main parachutes are deployed. This system is intended to have several layers of redundancy to ensure reliability; the rationale for the excess weight and complication of several deployed parachutes is ensuring that in case of a single parachute failure, the mission can still go forward.

Once the spacecraft reaches terminal velocity, the retro rockets will fire and the main parachutes will separate from the spacecraft. The MDG will include four Pratt & Whitney RL-10 engines, burning LOX/CH$_4$. These engines will be used not only for the descent stage, but also for the de-orbit burn and any course changes during TMI. The descent engines are gimballed and throttleable to give control over the landing and correct for off vertical entry. In addition to these, small rockets will be mounted on the sides of the greenhouse to control the vertical lean.

The greenhouse will land vertically, retro engines down. In order to function, it must be lying on its side, such that as much surface area is perpendicular to the sun as possible. In order to change the orientation, in effect to tip the greenhouse over, a safe and controlled mechanism is needed. Because of the emphasis on low mass and volume of mission components and the similarity of function, the team decided to use the same mechanisms for both landing and tipping the greenhouse. Both during landing and during final positioning the MDG will encounter impact stresses, so the mechanisms for reducing the resulting loads on the structure can be the same.

In designing the landing mechanisms, the team investigated both traditional means used on many prior missions (compressible lander legs) and relatively new, but proven technologies (airbags.) In the end, it was decided to use both systems. The airbags are inflated using retro rocket exhaust when the MDG is about 300m above the Martian surface. The bags are arranged to form a ring around the upper part of the structure, and to form a cushion at the bottom of the spacecraft. Those on the bottom absorb the shock of landing, while those at the top protect the MDG from impact during the tipping stage. The deflation of each set of airbags is controlled by the onboard processor; each small airbag can be individually deflated to assist in moving the MDG to a horizontal position. In addition to the airbags, compressible landing legs will be deployed. These provide an extra measure of redundancy, and allow the greenhouse to land perpendicular to the surface, preventing premature falling of the greenhouse. Because they can be controlled with more precision, they will be also used to slowly lower the greenhouse to its lying position, again preventing it from falling. Four landing legs will be arranged at the base of the spacecraft, and two will extend out of the top, such that when lying on it side, the greenhouse will rest on two top and two bottom legs. All six legs will be retractable and will feature a crushable core to aid in cushioning impact.

All of the EDL systems are mounted independently of the main MDG systems. This is to simplify construction and reduce the volume needing to be pressurized inside the greenhouse. An outer shell will cover the entire outside of the greenhouse, connected to the heatshield, protecting the airbags and lander legs. This outer shell will be separated from the spacecraft upon the deployment of the parachutes. While it adds mass and some complexity, it is necessary to protect the components that will need to be on the outside of the greenhouse during landing. The parachutes are housed in the nosecone, which opens and separates from the main body at the appropriate time. The top ring of airbags and landing legs will be stored in the top part of the structure, inside the outer shell. Also inside the outer shell will be the small tilt-correction rockets used during descent to keep the MDG perpendicular to the Martian surface. The retro rockets, fuel tanks, airbags, and bottom landing legs will be stowed on the underside of the MDG, outside the pressurized volume of the greenhouse. The heatshield will cover these components during entry, and will be ejected, along with the outer shell once the parachutes have deployed.

5.2 Pre-Crew Arrival Operations

5.2.1 Deployment

The greenhouse will be tipped on its side using the landing legs, in a process similar to cutting down a tree. Depending on how it lands, two bottom legs will extend while the other two retract and rotate, slowly causing the greenhouse to fall over. These will also be assisted by deflating all the airbags on the same side as the retracting legs. On top, the extra two legs and airbags will cushion the impact. The entire process will be executed several hours after landing, giving the spacecraft time to cool and perform systems checks.

All systems will be checked to ensure that they arrived on Mars in working order between the conclusion of the deployment phase and the launch of the first crew. With this strategy, it may be possible for astronauts to bring a replacement if a piece of equipment has been damaged, as their payload capacity permits.

The MDG will then activate its Sabatier Electrolyzer to begin in-situ production of water for the fuel cells and crops.

5.2.2 Startup

The MDG startup process will begin 130 days before the astronauts arrive (A-130). At this point, the airlock will be cycled once to verify its functionality. Following the test of the airlock, atmospheric controls (temperature, pressure, humidity, and composition) will be activated to gradually achieve the target environment for the greenhouse. 128 days before the arrival of the astronauts, the LEDs and their sensors will be be checked and cycled.

The biology water and nutrient delivery systems will be activated on A-125. This includes pumps, nutrient control, and filtration/purification. The moving systems of the plant trays will also be activated and tested. The MDG will then be ready for planting, as scheduled by the average time-until-harvest of each plant.

On A-120 days before the astronauts are scheduled to arrive, the MDG will automatically plant the first potatoes, which have an expected time until harvest of 132 days. Other plantings continue on the schedule shown in Table 3, with their first harvests scheduled twelve days after the scheduled arrival of the astronauts.

Day	Crop
A-120	Potato
A-108	Strawberry
A-107	Sweet Potato
A-100	Peanuts
A-85	Soybeans
A-68	Rice
A-67	Wheat
A-33	Tomato
A-12	Lettuce

Table 3: Initial Crop Planting Schedule

During the time between planting and harvesting, the MDG will continue to maintain a proper environment and monitor the growth of the plants. Should any plants mature faster than expected, they will be harvested, processed, and stored until the astronauts arrive. Tomatoes and lettuce are an exception and would have to be discarded if premature, as they do not store well.

5.3 Post-Crew Arrival Operations

The MDG is designed to be as autonomous as possible, as astronaut time is dedicated to exploration, sample collection, and analysis[16] and the MDG should not interfere with their scientific objectives. Under ideal conditions, the MDG design is completely self-sufficient, requiring no crew interaction, save to eat the food that the greenhouse produces and delivers . Even under non-ideal conditions, however, the need for human intervention has been minimized.

5.3.1 Daily Operations

Daily operations include harvesting crops that are mature, removal of non-producing plants, reseeding, and crop delivery as necessary. This will be accomplished autonomously.

5.3.2 Harvesting

Harvesting will be accomplished autonomously by a variety of harvesters, some of which are built into the growth tray while others are mobile. CCD cameras will monitor the growth trays, and the computing systems will select plants for harvesting at the appropriate time.

Harvested plants will be transported to a section near the airlock for processing, storage, and delivery. Delivery will be accomplished by a rover that will make a trip to the habitat on command from the astronauts (if they are running low on fresh produce) or when it is fully loaded. It is anticipated that these trips will occur roughly twice a week.

5.3.3 Replanting

Of the crops in the MDG, potatoes and sweet potatoes can be cloned from tubers, tomatoes can be cloned using cuttings, and strawberries use vegetative propagation. By aeroponically growing tomatoes from cuttings instead of seeds, the germination time, normally longer than most of the other greenhouse crops', is eliminated. Though cloning is a convenient method of reproduction for both types of potatoes and quick method for starting tomatoes, there are advantages to occasionally starting plants from seed. Clones are generally not desirable in that a disease would more easily be able to wipe out the entire crop[57]. Since the interior of our greenhouse will have been sterilized, disease is a smaller factor than it would be in a terrestrial garden.

More than enough seeds for the first three years can easily be brought in the MDG. Lettuce seeds are about 881 seeds per gram and have a typical life of five years in storage. Only about 80-90% of all seeds actually germinate, and that number decreases with time. If the MDG is dormant for two years, the seeds will retain virtually the same germination rate. To maximize storage life, seeds will be stored in airtight, lightproof containers at temperatures between 2°C and 10°C[43].

5.3.4 Maintenance

The MDG is designed to operate with minimal maintenance requirements and no scheduled human maintenance. Waste processing is completely automated, from collection of dead plants by the harvester robot to storage.

Dust-removal, a concern in the Martian environment, is accomplished with electrostatic repulsion. Dust should never build up on the surface of the greenhouse.

In the event that human access is required, it is possible to use the airlock and two walkways in the upper level. The lower level is accessible by lift-out flooring. In general, astronauts will need to wear their EVA for any unexpected maintenance. However, if the maintenance requires more dexterity than the EVA suits offer, and the alternative is a non-functioning greenhouse, the greenhouse environment can be brought up to a human-suitable environment for maintenance activities, so long as the failure is not in the environmental system.

5.3.5 Shutdown

The shutdown procedure is timed such that astronauts will receive their last food delivery four to six days before they leave the Martian surface.

The first step in the shutdown procedure is to stop planting. The time for this varies for each plant, and will be date of departure minus one week, minus the growth period of the plant in question.

Crops will then be harvested as usual until the conclusion of the final crop. However, because the seeds will eventually become "stale," a small percentage of the last harvest will be collected for subsequent restarting of the MDG. Any plants still alive six days before astronaut departure will be removed by the harvester and destroyed as waste.

Once the last plants have been terminated, all supplemental LED lighting will be turned off. Concurrently, the final food processing cycle will occur, and once complete, the final crops will be delivered to the MDG not less than four days prior to MAV liftoff. At this point, the biology portion of the water system will be shutdown as well as the nutrient delivery system (though the system will have already stopped adding nutrients to the solution two days before the last harvest).

The atmosphere control system will then be reduced to the minimum levels needed to keep the MDG structures in good condition. Atmospheric composition will no longer be regulated, but temperature, humidity, and pressure will still be controlled.

Some fuel cells will also be turned off to conserve fuel. RTGs cannot be turned off and will be used to provide the primary power necessary for systems that remain powered during hibernation.

5.3.6 Hibernation

While in hibernation, the only systems running will be the experimental section, communication at reduced capacity (beacon-monitoring using four signals to communicate the state of the greenhouse), data processing at reduced capacity, temperature control, and the condenser.

Leaving the condenser on to reclaim water during hibernation will keep the inside of the MDG as dry as possible. Excessive humidity can lead to corrosion of materials, degradation of electronics, and growth of harmful organisms (mold, evil microbes).

Pressure is controlled minimally to limit outgassing from materials. Aside from this limiting factor, reduced pressure on the inside is beneficial, as it reduces structural stress and leakage. The pressure will lessen slightly on its own due to leakage, anyway. While it is possible to actively reduce internal pressure as part of the shutdown procedure, separating and storing the gases would use more power and equipment, which is not worth the few benefits.

6 MDG Design Methodology

A philosophy that emphasized the simplest solution possible was utilized in designing the MDG. Whenever possible, all MDG-critical systems are redundant, and if not possible, designed to fail gracefully (with adequate safety margins). However, in order to push the cutting edge, it was decided that not all risks could be eliminated. This decision is valid as it allows for a more capable greenhouse and does not endanger the astronauts, as the MDG is not critical to the overall mission.

Mission economics were regarded as important, though they were not treated as a bottom line, but instead as a tradeoff. The question "is this extra mass/cost/volume important to the success of the mission and/or does it add something of value?" was frequently asked. The team believes that this method encourages the design of a greenhouse that is both more functional and less costly than might otherwise be achieved. One such example is in the automation of the greenhouse. While automated harvesting, planting, and crop processing, and the associated power supplies do add to the mission cost, this cost is less than what it would cost in astronaut time if greenhouse operations were added to their duties.

Reviews of major subsystems or subsystem groups (example: environmental control - biology) were conducted frequently to ensure sufficient communication, though the the team found that the complexity of the problem made higher amounts of communication necessary. Additional reviews within entire design team were conducted approximately every month. The team has learned that more frequent, brief reviews, on the order of once every two weeks would have been more appropriate and this method will be used in the period between the PDR and DDR.

Near the conclusion of the preliminary design process, two other review teams were brought in. The first was a Blue Team which included members of the Outreach team and the project's co-investigators. The Blue Team's review was primarily to ensure that the design was properly described so that those unfamiliar with the project could understand it.

The second review team, the Red Team, was chaired by Dr. Daniel Frey. It also includes Dr. Pete Young of MIT and Dr. Jeff Hoffman, a former astronaut. This team was charged with reviewing the PDR with a slant towards being as critical is necessary.

6.1 Functions of the MDG

The MDG's primary function is to provide diet augmentation, up to 25% for a crew of six astronauts during their stay on Mars. The crew will, however, bring enough food to ensure their survival should the MDG fail, and therefore it is not seen as mission critical but instead as an additional, beneficial mission element.

Additional functions required to accomplish the primary function include crop planting, crop harvesting, crop delivery, waste management, environmental control, and power generation. After reviewing the greenhouse elements, the Olin team also decided to add the functions of emergency crew shelter and scientific research to the MDG's capabilities.

6.2 Method of Design

Any system designed to support life requires solving many problems, often in parallel. To reduce the complexity of this highly parallel design challenge, the team chose to first select the planned crops and the estimated quantity required to achieve the caloric requirements. After the crops were known, the team developed the simplest greenhouse that would both support them and achieve the team's other design goals. This ensured that the greenhouse would achieve its design objectives with a solution that would not include costly and unnecessary features. The method of design is outlined in Figure 1.

7 Greenhouse Design

During preparation of the Conceptual Design Report, the team drew heavily upon the model outlined by Jenkins, Khanna, and Roylance in *Linking Design with Structural Mechanics and Materials*, a selection guide in which structure was driven to a greater deal by availability of materials than in most other models. In the design's continuation for this second phase, the selection of a reliable "tin can" model has allowed structural decisions to be made more independently of materials selection than was previously possible.

The structure of the greenhouse is the overall support system for all the different subsystems of the greenhouse, affording protection from shocks and stresses, the environments of Mars and space, and providing mounts for each component. In addition, the structure must provide for redundancy and protection in case of a system failure or crop disease. The structure determines the configuration of the various components both inside and outside the greenhouse. Because of this, the structure is both dependent upon and determines the placement and maximum size, shape, and mass of each individual component.

7.1 Structure Criteria

Launch Vehicle Volume: The first criterion of the structure is the volume enclosed within it; we plan to fully utilize all the payload volume we are afforded by the launch vehicle. Therefore, the outside shell has to be as large and thin as possible, taking away the least space from the crop growing areas and support systems.

Location of Center of Mass: In addition to the volume specification, the MDG structure and layout must also satisfy the center of mass constraint of the launch vehicle. The MDG must be arranged to have the center of mass as close to the center of the spacecraft as possible. This is given by the need to reduce the moment on the payload adapter and fairing during launch, and for attitude control during TMI.

Structural Loads and Stresses:

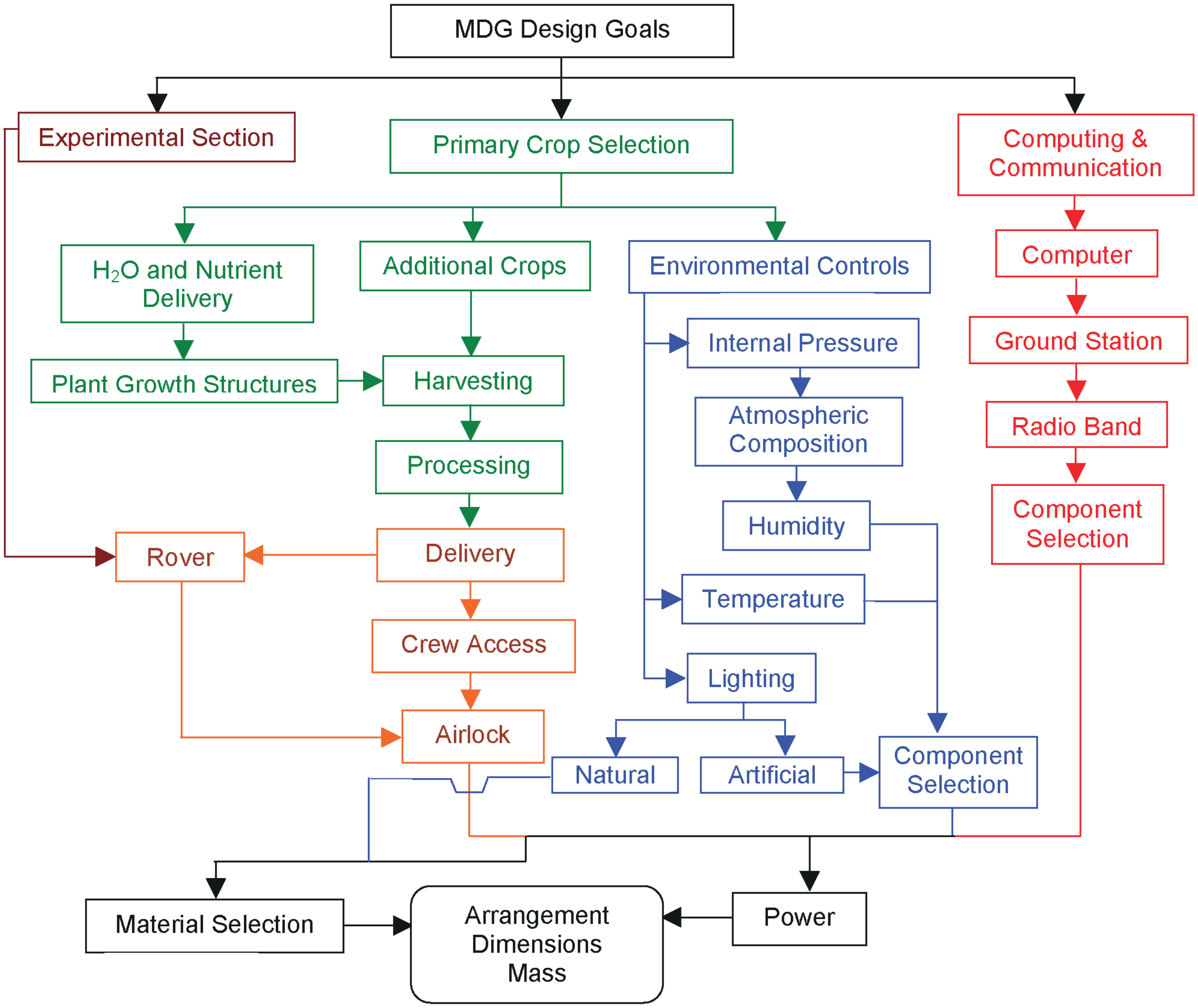


Figure 1: MDG Design Methodology

- *Pre-launch Activities:* Though the MDG will be designed to function for the majority of its lifespan in a Martian environment of low gravity and pressure, the design need also take into account the duration of its stay upon earth. Examples of non-service "function" include its handling, protracted subjection to terrestrial gravity and pressure during construction, and pre-launch treatments such as baking/thermal sterilization, in addition, incidental jerking and other stresses during pre-launch operations need also be assumed.

- *Launch:* During launch, the MDG will be exposed to high levels of structural vibration and shock from the firing and cutoff of the main engines. Especially during the first few seconds of launch, the MDG must also contend with auditory vibration due to the reflection of the rocket engine noise off the launch platform.

- *Interplanetary Transit:* During transport to Mars, stiffness is required to aid in maintaining the attitude and control of the spacecraft. The reduced need for corrective maneuvers will improve both fuel economy and the simplicity of navigation. All loads during this phase will be due to acceleration, and should be negligible in relation to those experienced during liftoff and descent.

  Thermal stresses must also be taken into consideration. One side of the MDG will always face the sun, and will thus become much hotter than the side facing deep space, straining and distorting the outer structure. Mechanisms must be developed to prevent this problem.

- *Planetary Deployment Operations:* Upon planetary landing, the performance characteristics demanded of the MDG undergo a dramatic shift. Assuming that the payload is delivered intact and without significant structural damage, the chief design parameter is reliable performance. Key factors contributing to reliability that are influenced by materials selection include effective management of thermal, optical, mechanical, and all other types of materials performance degradation. Damage due to UV radiation and corrosion should be considered at all points in materials selection. A moderate degree of dimensional stability on interior structures is also requisite for effective automation of harvesting and other tasks.

General Design Conditions and Parameters: To accommodate and balance the requirements for various phases of the mission, a dichotomous approach to the design of the structure was chosen. The outer shell and the interior panel components serve to improve the stiffness of the MDG and maintain pressure differentials. A heavier frame skeleton will serve to absorb and distribute both static and dynamic loads from lift off, EDL, and mounting of equipment.

Due to the thin atmosphere in the Martian environment and almost complete lack of atmospheric shielding, the levels of UV radiation to which the MDG will be exposed are higher than those on earth. The exterior structure must therefore be designed for service at these levels, and adequate shielding will be incorporated into the transparent panes of the upper hemisphere to shield the materials and plants of the interior.

Resulting from the 20-year requisite service life of the greenhouse, it is necessary that all materials chosen for close tolerance applications have relatively low rates of creep. For this reason certain classes of materials, such as thermoplastics, may be less well suited for more dimensionally exacting applications.

Though only the exterior shell will be subjected to the hard vacuum conditions of space, the interior components of the greenhouse will also be subject to accelerated out-gassing due to the hypobaric atmosphere maintained in the interior of the MDG.

As in all space missions, mass is to be minimized when and wherever possible. For this mission, the estimated costs of \$2200 per kilogram for lifting a payload into orbit using the Magnum launch vehicle is more than doubled by the additional need for fuel in Martian landing and the cost of having put this fuel into orbit initially. This mandates the use of lightweight, high strength alloys, polymers, and composites whenever feasible.

Incorporating a ±10°C margin of error in peak, unsustained temperature, and a ±20°C margin for sustained service temperatures, a temperature range from -100°C to 100°C is anticipated for the exterior structure. For the interior of the MDG, the fluctuations will be less extreme-particularly in the lower range, where temperatures will not be allowed to fall much below 0°C, and a greater degree of freedom is allowed in materials selection. This broad temperature range requires effective management of stresses associated with thermal expansion and contraction.

Facilitation of MDG Functions: To accommodate and balance the requirements for various phases of the mission, a dichotomous approach to the design of the structure was chosen. The outer shell serves to contain and maintain the internal pressure during all phases of the mission and to create a torque box to assist in the resistance of torsional forces. During transport, all stresses and shocks associated with launch, landing, and general movement of the greenhouse are to be absorbed and distributed primarily by a skeleton that will also serve as the load bearing members in the deployed greenhouse; supporting lighting, shelving, the MDG hull and translucent panels, and as contact points for ground supports. This skeleton will also provide axial rigidity to the greenhouse.

Because hydroponics will be used, the structure must allow for easy mounting of and access to water/nutrient solution pipes, lighting systems, and some means to allow harvesting robots to move around the greenhouse. To ensure redundancy, the interior design must allow the greenhouse to be easily separated into isolated sections, so that a growing area where the plants have become diseased can be sealed away to prevent the spread of the disease. The greenhouse must be as airtight as possible, in order to minimize leakage to the Martian environment, but also provide for some way by which the harvested produce can exit the greenhouse and reach the astronauts on Mars.

7.2 MDG Geometry

Several options for the MDG's geometry were discussed in the CDR. At that time, the team had tentatively selected a hybrid rigid/inflatable structure for the additional volume it offered. However, after the crop research was completed, it was found that the design objectives could be met within the dimension constraints of a rigid, "tin-can" structure. After this discovery, the team chose to reconsider the MDG structure, and ultimately settled on the simpler "tin-can" structure. A re-cap of the options presented in the CDR and the factors that led to this decision follow.

At first, the team investigated the possibility of an inflatable greenhouse, this design would offer great mass and volume reductions, allowing us to use a smaller launch vehicle or grow more crops. However, this design proved to be impractical, due to the difficulty in designing a material that would fulfill all the functions we require: flexibility, UV protection, transparency, etc. A multi-layered material was also considered, but again, a suitable material could not be found. In addition to material concerns, an inflatable greenhouse also makes mounting the growth structures and other systems very difficult.

A hybrid rigid-inflatable was then considered. In theory, this combination of the two extremes would mitigate the shortcomings of each while taking at least partial advantage of the strengths of both, the primary advantage being increased volume available for plant growth and systems with a minimal commitment of available volume and weight in the mission payload. The union of this design with a rigid unit would alleviate many of the issues related to infrastructure and mounting of equipment created by pursuing a strictly inflatable platform for development. Thus, the stability and robustness required for more delicate and essential systems would, in theory, be achieved without wholly forgoing the potential offered by an inflatable. A more detailed study, however, revealed that the hybrid concept did more to unite the disadvantages of rigid and inflatable structures than it did to unite the advantages.

Wishing to retain the expanding feature of the inflatable section, with its associated payload volume savings, the team next considered an extendable greenhouse, where one section of the greenhouse would telescope out to provide extra growing space for the plants. This design, however, was abandoned because the costs did not outweigh the benefits. An extendable greenhouse would have significant additional mass, in requiring two exterior, rigid structures and the telescoping mechanism. By improving the volume estimates, the team found that there would be no significant advantage to telescoping the greenhouse, because the stowed volume of the plant growing structures is essentially the same as the deployed. Furthermore, the complexity involved in extending the various nutrient delivery pipes, lights, and other plant growth structures greatly reduces the reliability of the greenhouse.

The final design is a rigid "tin can" model. The greatest factor in selecting this model was that there is simply no need for an expandable greenhouse. The potential mass reduction and additional, unnecessary volume offered do not outweigh the risks and difficulties associated with the other geometries. Specific difficulties with the other models include: fabrication, testing, deployment, growth structures, leakage, durability in the Martian environment, and precedent. While the team agrees with that inflatable and expandable structures should be tested in space, a manned-mission is not a suitable venue for their first use. The "tin can" is a mature, proven design that has been used in decades of manned space flight. Perhaps the greatest advantage of the rigid platform design for the MDG is the inherent robustness of the module. The rigid platform derives its greatest strengths from a far more perfect isolation of the MDG's interior from the Martian environment. The lack of interaction with external elements allows a greater degree of internal control and reliability. Leakage, UV shielding, and infrastructure support issues associated with the other models are all but eliminated in the rigid module.

The selected concept can be described as a "tin can" with a nose cone covering the parachute system, and the retro rockets, fuel, airbags, and landing legs located on the bottom. The remainder of the volume will be the actual greenhouse, including power supply systems, water generation, and crop growing areas. Before entry, the MDG will have an outer shell, which will release as the parachutes are deployed, so the final landed structure will have a single thickness wall. The top section of the MDG wall will be made of transparent polycarbonate to allow light to illuminate the plants below, with hinged panels of PVC's covering it during flight. Inside, the greenhouse is divided into two hemispheres by a floor. The top hemisphere contains the plants and their associated growth structures, while the lower hemisphere contains the power, water and gas maintenance, and control systems. To ensure redundancy, the greenhouse is also divided into a right and left half, each of which will be sealed off in case of an outbreak of plant disease. he MDG is domed on both ends for strength and distribution of stress.

7.3 Launch

As has been mentioned above, the launch phase, while relatively short, puts a great deal of stress on the payload. The first step towards protecting the MDG is to use the fairing and the rocket itself to concentrate the stresses, and then attach the MDG in such a way as to isolate it from the fairing. This will be done by means of kinematic mounts. These attachments resist the movement of the payload in all six directions, while isolating it from the vibration due to the rocket. The MDG also has a resonant frequency different from the resonant frequency of the launch vehicle, again reducing the loads. The materials for the MDG structure are also chosen such that only a very minimal amount of galling can occur, and the structure itself is not overconstrained.

7.4 TMI

During TMI, the most significant loads on the structure will come from thermal stress due to the differences in surface temperature of the sunny and dark sides of the spacecraft. This problem will be alleviated by spinning the spacecraft, to expose both sides to sunlight. This will be further assisted by paint coatings to reflect sunlight, and by careful choice of materials to avoid high coefficients of thermal expansion.

7.5 Landing

To counteract the thermal loads imposed by entry, the greenhouse will be protected by the heatshield, as well as a second outer shell, which will be ejected once parachutes deploy. The components inside the greenhouse are mounted similarly to the way the MDG is mounted inside the launch vehicle. This is again to isolate them from vibration, especially in the case of precision equipment. The shock of landing will be absorbed by the landing legs and airbags, which will also cushion the MDG during deployment. In this way, the stresses are again minimized. In addition to these measures, the interior compartments are reinforced to further strengthen the structure and the materials are chosen to increase the strength and stiffness of the structure.

7.6 Solar Panels

The solar panels that will be used to protect the upper hemisphere of the MDG during transit to Mars and landing will be deployed to expose both solar panels and the upper hemisphere of the MDG to the sun after the greenhouse has cooled sufficiently to relieve residual thermal stresses from landing. One of the central questions to be addressed in the deployment of these panels is the decision to allow for the panels to be closed again as a protective measure. Therefore, an analysis of the costs and benefits of several operational scenarios was performed.

The first option considered was permanent deployment using high reliability pyrotechnic actuators. The primary advantage of this one time deployment is its high reliability. However, it leaves the upper half of the greenhouse exposed and is thermally inefficient compared to other options.

Deployment only during active growing phases was also evaluated. Under this method, the solar panels would be deployed by redundant, single-use actuators (electric motors, hydraulics, or pneumatics) approximately 130 days before each crew is scheduled to arrive and closed with their departure. Closed solar panels during hibernation prevents unnecessary wear and protracted environmental exposure and offers better thermal control during hibernation. However, it also requires larger space, mass, and power investment, a loss of solar power during hibernation, and is not as reliable as one-time deployment.

The third option studied was daily opening and nightly closing of the solar panels during MDG operation. This would be accomplished with pneumatics, electric motors, or hydraulics and is the least reliable option considered. It does aid in night/day thermal cycling and prevents unnecessary wear and thermal loss during hibernation. It is high complexity and risk, requires substantial and robust deployment mechanisms, and more power.

Upon the basis of this study, it was decided to incorporate into the design the ability to close the panels between periods of production. This will allow increased thermal efficiency and reduce wear and environmental exposure of components. Unnecessary UV degradation and abrasion will thus be avoided during hibernation. This will also forgo the power production of the solar panels, increase the mass of the deployment actuators, and compromise reliability slightly.

Explosive bolts will be used to secure the panels together during transit to Mars. After landing and provision of a sufficient cool-down time for the MDG, the bolts will fire, allowing the two halves to separate. Reusable actuators will then be used to deploy the panels. During the course of greenhouse operations, the panels will be exposed during all growing phases and closed during all non-productive phases of operations.

Pyrotechnic actuators will also be incorporated into the design as a precautionary measure against failure of the reusable actuators while the panels are stowed. Should the Remote Agent detect actuator failure, the pyrotechnic actuators will fire and the panels will remain deployed until an astronaut performs maintenance or replacement of the defective actuator.

7.7 Transparent Upper Hemisphere

No single material met or fulfilled the many specifications and requirements demanded of this portion of the structure. Therefore, a layering technique similar to those employed in the design of the walls of the

TransHab module was used. As with all space applications, the use of multiple panes for redundancy and strength was assumed. For the upper hemisphere, the following functions were identified as critical to the success of the mission:

Hardness/Abrasion Resistance and Durability: Necessary due to abrasion from dust storms and micrometeorites that could degrade optical quality of the windows. Ribbon grown sapphire, Zirconia, and Alumina were identified as candidate materials for this application. Further study is required, but dependent upon the availability of appropriate research facilities.

UV Absorption/Filtration: Protection must be sufficient to protect the interior and reduce usage constraints upon interior materials. This function may be fulfilled incidentally as a secondary effect of another material selection.

Structure and Strength: Protection must be sufficient to protect the interior and reduce usage constraints upon interior materials. This function may be fulfilled incidentally as a secondary effect of another material selection.

Dust Removal: The deposition of atmospheric dust on Mars, and the dust storms that periodically occur on the planet result in a .3% per day loss in solar array performance due to dust obscuration. This problem will affect both the solar arrays used in the MDG, and the solar flux through the transparent upper hemisphere. Previous studies have been performed at John Glenn Research Center upon the effectiveness of wind-cleaning and vertical orientation of solar panels in preventing dust accumulation. Wind cleaning has previously been demonstrated to be ineffective in experiments, while the geometry of the proposed MDG design prohibits dependence upon vertical orientation. Electrostatic dust removal techniques, which were to be tested on the cancelled 2001 *Mars Surveyor Lander* [102], should be suitable for use on both the solar arrays and upper hemisphere of the MDG. The incorporation of a conductive outer layer near the surface of the greenhouse will enable the use of electrostatic dust repulsion techniques, simplify maintenance, and minimize damage to the surface from cleaning via mechanical methods. Indium-Tin-Oxide (ITO) has been chosen for this application upon the basis of its extensive previous use in the space program in such applications as dissipation of static electricity in thermal blankets. Thinly layered noble metals sandwiched between dielectric layers were also considered as an alternative, but disqualified upon the basis of reduced light transmission.

Structure and Strength: This layer will serve as the substrate for other layers and bear the majority of the load from the pressure differential. Conventional glass, fused silica glass, and polymeric materials such as polycarbonate (PC), or acrylics were identified as candidates. The low temperatures of the service environment and the UV blocking effect of glasses suggest their use for the exterior pane, as do the thermal shock resistance of both 96% silica and fused silica glasses. Mass considerations and the reduced thermal fluctuation suggest the use of polycarbonate for the interior pane. A trade study will be performed.

Leakage Control: The overall design must be compatible with the $< 1\%$ per day atmospheric leakage guidelines stipulated by the mission. This will be dependent chiefly upon the composition and quality of the seals around the windows. The desired minimization of loading of windows however, dictates the use of flexible, imperfect seals.

The low surface temperature of Mars complicates the use of elastomers, a traditional material for such situations. Methyl phenyl silicone – a radiation resistant elastomer whose low temperature performance extends as low as $-93°$C – will be used for the outer gasket, where the impact of its poor tear resistance and high moisture permeability [103] will be minimized. For the inner, higher temperature and moisture seals, fluorosilicone rubber was selected in the trade study due to its excellent gas and moisture permeability characteristics, low temperature properties, and moderate radiation resistance.

Due to the general brittle nature of candidate materials at service temperatures, and the vulnerability of layered materials in shear, the translucent panels will bear minimal loads within the greenhouse. The panels will be secured using flexible rubber gaskets affixed to the "ribs" of the MDG skeleton. Small compression pumps whose only function is the reclamation of leaked gasses will be incorporated into the gap between the first and second pane.

7.8 Exterior Hull

The hull/skin of the MDG will consist of two wholly independent walls, the space between which will be compartmented by the skeleton to isolate hull integrity failure and leakage. Each wall will therefore be required to independently fulfill the mechanical needs of the overall structure.

This portion of the MDG's construction is derived from the design of a basic pressure vessel. Upon the basis of this model and the available payload, the theoretical optimal design for dispersion of hoop and axial pressure is cylindrical with semi spherical end caps. The low pressures involved and the need for maximal utilization of available volume has led to the decision to pursue limited doming of the ends, while compensating for additional stress with reinforcement at the angular joins.

It is assumed that any material capable of providing the required stiffness will also be capable of supplying the necessary strength to contain the minor pressure differential needed. A composite core material will be used for this application due to the high elastic modulus to density ratio achieved by this class of materials.

7.9 Skeleton

The length of the cylindrical portion of the greenhouse will be divided into four equally spaced spans of approximately a meter in length by five circumferential ribs positioned between hulls of the module. These will be used for the mounting of shelving and infrastructure equipment, and will bear both natural and manufactured hoop loads.

Axial compressive and tensile stresses will be borne by a system of criss-crossing trusses contained within the XY plane of the floor and dividing the upper and lower hemispheres of the greenhouse. Compressive forces such as those during the shock loading of planetary landing shall thus be dissipated radially as hoop stresses to the circular ribs described above. Such a configuration is weak, however, in that it lacks the strength to resist significant flexure in the YZ plane. The high elastic modulus panels of the shell and the interior partitions will provide structural rigidity. A smaller number of supports oriented in whole and in part in the YZ plane will also help provide strength to the structure in this scenario.

As one of the larger elements in the mass budget, the structure is one in which reductions from marginally increased efficiencies represent potentially significant savings. Asymmetric structural construction techniques are one such opportunity for drastic reductions in weight. As the loading during certain phases of the mission – specifically that of landing and entry – is experienced primarily from the aft (thruster) end of the module, this is the region where skeletal strength is of greatest import. At the more lightly loaded fore end significant reductions in the weight and strength of the skeleton may be accommodated without reducing the performance of the MDG.

Material Choice Given the high-strength and low mass design objectives for the skeleton, early materials selection efforts focused primarily upon composite materials based upon fiber reinforced polymer and resin matrices with high strength and low density. Graphite-epoxy and other similar composites proved, however, to be unsuitable due to their poor performance and rapid mechanical degradation after sustaining "barely visible impact damage" and in shear. Their water absorption and accompanying degradation of mechanical properties in the event of interior hull failure also contributed to their disqualification for this application [104].

Traditional aerospace alloys of aluminum and titanium were considered subsequently for their past successful use in aerospace applications and widespread availability. Aluminum generally offers a lower manufacturing cost index, a higher elastic modulus for its density, and better wear characteristics. Titanium offers greater yield strength by density, greater impact strength, reduced thermal conductivity, and greater corrosion resistance.

To achieve the strength and impact toughness requirements necessitated by this application, the materials selection process focused upon identification of specific alloys and series of alloys possessing a majority of the desired characteristics. As neither aluminum nor titanium are particularly noted for their low temperature and impact applications, it was deemed advisable to focus particularly upon annealed alloys not fully hardened. For aluminum alloys, the 2000 and 7000 series were both identified as strong candidates upon the basis of their engineering for and extensive use in aerospace applications. Alcoa's recommendations were heeded in consideration of Alloys 2024 and 7075 for their use in "highly stressed structural parts" [100]. Among Titanium alloys, Ti-5Al-2.5Sn ELI Annealed, a high purity annealed alpha alloy was particularly noted for retaining "ductility and toughness at cryogenic temperatures... 5Al-2.5Sn-ELI has been used extensively in such applications" [105].

A materials selection trade study was then performed upon the identified alloys. The trade study suggested the selection of either Aluminum alloy 2048 or Ti-5Al-2.5Sn ELI Annealed, both of which offered similar modulus of elasticity and yield strength to density ratios. Aluminum 2048 was further recommended by its ease of fabrication and low cost. Better corrosion resistance, lower volume, and substantially higher impact strength favored the use of Ti-5Al-2.5Sn. Ultimately, it was the improved impact strength and known successful use in cryogenic conditions that resulted in the selection of Ti-5Al-2.5Sn for the skeleton of the greenhouse.

7.10 Interior Structural Materials

In the design of the MDG interior, countless material selection decisions need be made in each and every subsystem. Many of these, however, have already been made in the design of off-the-shelf technologies that have been identified for use, or have been inherent to the needs of other missions, and have already been addressed in the past. In the DDR, the space qualification of the materials utilized in off-the-shelf technologies will be investigated, but are currently assumed to be usable or easily adapted. Certain other decisions relating to the support structure and infrastructure must, however, be made independently. Major, system independent decisions are outlined here, while system-specific decisions will be covered in the appropriate section.

Table 5 shows a step-by-step breakdown of the volume of individual components and the amount of interior space remaining inside the greenhouse.

8 MDG Arrangement

The MDG will be primarily divided into two major sections: a plant growth section in the top half cylinder and an equipment/machinery section in the bottom half cylinder.

8.1 Upper Level

8.1.1 Greenhouse Access

The plant growth area in the MDG will be accessible by two walkways 0.75 meters wide by 2 meters tall that will run from the airlock in the forward end almost the entire distance to the rear end. The floor of the walkway will have hatches in it that will allow access into the lower service section. There will be no crew access into the central RTG area.

In order to preserve structural integrity and to simplify design, there shall be only one external access airlock. The airlock will be located in the center of the forward end of the greenhouse above the equator and will measure 1m square at the base and be 2m tall.

The airlock will be used in case crew access is required for repair purposes or for shelter in an emergency situation. The airlock will also be the area in which the produce delivery rover will dock to the greenhouse and the space in which the experimental greenhouse will be stowed on the voyage to Mars. Because the base of the door will be 3-5m above the ground (depending on the terrain of the landing site)

Alloy	Density g/cc	Strength MPa/g/cc	Stiffness GPa/g/cc	Impact Strength J	CTE $\mu/m-^{\circ}$C	Thermal Cond. W/m-K	Corrosion Resistance
Ti-5Al-2.5Sn ELI	4.48	160.7	24.6	44	9.4	7.8	high
Aluminum 7075-O	2.81	33.8	25.6		23.6	173	medium (C)
Aluminum 2048	2.75	150.9	25.5	10.3	23.5	159	low
Aluminum 2024-O	2.78	27.0	26.0		23.2	193	low (D)
Aluminum 2219-O	2.84	24.6	25.4		22.3	170	low

Table 4: Skeletal Material Options. “Strength” is effective tensile yield strength, “Stiffness”’ is the effective modulus of elasticity, and “Impact Strength” is Charpy impact strength

. [100],

Item	Dimensions (m)	Remaining Space (m^3)		Remaining
	diameter x length	Upper	Lower	Size (m)
Aeroshell	8.5 x 11	851.15		8.5 x 11
Nose Cone	8.5 x 1	567.43		8.5 x 10
Left Rocket & Airbag	0.5 x 10	502.64		8 x 10
Right Rocket & Airbag	0.5 x 10	441.77		7.5 x 10
Exterior Wall	0.250 thick	384.83		7 x 10
Floor	0.250 thick	192.42	174.92	
Solar Array	0.025 thick	177.14	174.92	
Window	0.250 thick	151.73	174.92	
Doming of Edges	0.750 thick	135.39	158.58	
Total:		293.97		

Table 5: Interior Space Breakdown

the airlock will be accessible to crew and the rover by a telescoping ramp that will be spring-loaded to extend to its full length. The ramp will be stowed beneath the nose cone and deployed by explosive bolts before the airlock is used for the first time.

The airlock will have three access hatches large enough for an astronaut to walk through with minimal ducking. One outward-opening hatch will be used to access the outside while the other two outward opening (from the airlock's perspective) will each open onto one of the walkways. Solenoid valves will open to allow pressure to flow from either compartment the greenhouse into the airlock and equalize the pressure. Two compressor pumps will allow the pressure from the airlock to be returned to the greenhouse. A minute amount of pressure will be left inside the airlock to blow out any foreign matter brought inside the greenhouse by the astronaut or rover. It will be unnecessary for the airlock to pressurize in order for the rover to dock. Every time the airlock is pressurized it will be bombarded by high intensity 1620 Watt UV lights to prevent the movement of pathogens from one side to the other or to eliminate any foreign pathogens that may otherwise enter the greenhouse with the astronaut. The airlock must also be sterilized before the external door is opened to reduce the risk of environmental contamination of the Martian environment. The astronaut will be protected by her space suit.

Seals used in the construction of the access hatch will have similar performance demands to those placed upon the window seals, and upon aircraft doors. For the outer of the two airlock doors, low service temperatures dictate the use phenyl methyl silicone, while fluorosilicone rubber will again be used for the interior seal.

Since the airlock will be very infrequently pressurized, depressurized, or sterilized, all airlock systems (compressor pumps, sterilization and illumination lights) will get their energy by diverting electricity from the growing LEDs for a short period of time.

8.1.2 Vertical Partition

The vertical partition between growing areas, which provides similar functionality to that of the floor plane partition, will be constructed of similar polycyanate honeycomb core material.

8.1.3 Plants, Processors, and Harvesters

The greenhouse must be divided by a vertical partition into two completely isolated sections, in order to protect one side from a potential problem in the other. Therefore, all biology systems must be duplicated on each side. This will also allow for MDG operations to easily be reduced to half-capacity, should a situation ever arise that would make this desirable. Also, the airlock will be centrally located at the front of the greenhouse, and will open to the exterior ramp that will be deployed upon landing, and will have two other doors, each opening to one side of the greenhouse.

The plant structures will be arranged in such a way to maximize growing area, while still providing enough room for other space-consuming necessities. Since it is important to have built-in space for astronauts to maneuver around the greenhouse in case of a problem, each half of the greenhouse will contain two plant growing structures, 1m wide each, with a 0.75m wide walkway between them. A harvester, programmed to collect the plants on the bottom shelf levels, will also inhabit this walkway. There will also be a harvesting system on the ceiling to gather plants from the top layers of the shelves. Both harvesters will deliver their goods to the food processing systems at the front. In the back of each section will be all necessary pumping, filtration, and delivery systems that are not located in the bottom hemisphere of the greenhouse. This layout will be identical on both sides, such that there will be two walkways and four plant structures (one on either end of the greenhouse, and two in the middle, separated by the air tight wall).

8.1.4 Communications System

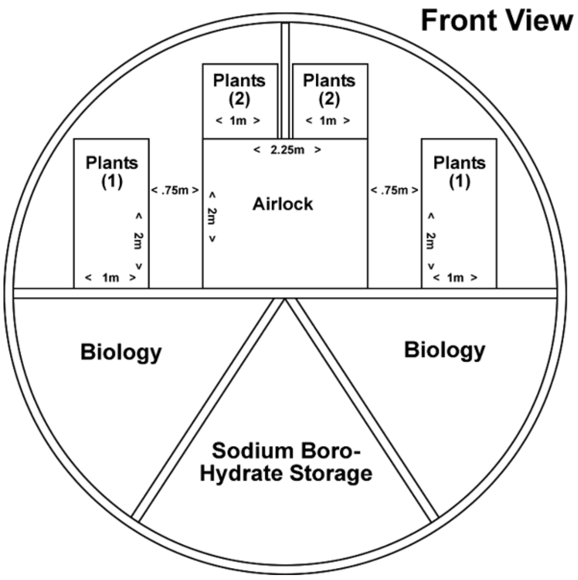
After landing on Mars, it is essential that the greenhouse have an exterior antenna system in order to communicate with Mission Control on Earth. A constellation of communication satellites with global coverage has been assumed to exist, and only a small antenna necessary to connect to these. Therefore, the communications system will be located underneath the solar panels during transit. Once the greenhouse has been deployed, and the solar panels open, the small, spring-loaded antenna will extend 180° and lock into position, enabling communication with the satellite constellation. This satellite constellation will relay communications traffic to Earth through a single, high-throughput satellite. Subsequent closings of the solar panels will not block the deployed antenna as it will extend past the end of the greenhouse.

8.1.5 Flooring

The division between the lower and upper hemispheres of the MDG will be marked in part by the network of trusses, an isolating floor between the two hemispheres is still needed to prevent disruptive intrusion of water and biological matter into the support systems, and to provide a usable walking surface for astronauts in the eventuality of needed maintenance. As sufficient and evenly distributed contact points with the underlying trusses may be incorporated into the design to account for the majority of the required strength, the chief demands placed upon this materials will be a high elastic modulus and low weight. A polycyanate ester core material has therefore been chosen for this application due to its high elastic modulus to density ratio. The lowered moisture absorption-as low as 0.3% at saturation versus that of 2.5% for traditional epoxies-allows fiber reinforced polymers to be used for this application [104].

8.2 Lower Level

8.2.1 Support Structures



In order to support the biology and plant systems in the top of the greenhouse, a sturdy support structure in the bottom hemisphere of the greenhouse is necessary. Although the primary purpose of the support structure is to support weight from the top hemisphere to the bottom hemisphere, the greenhouse will also undergo significant pressures from front to back, and from left to right, especially during takeoff, entry, and landing. Therefore, the primary support structure will be a floor, consisting of a flat panel that spans the diameter and length of the greenhouse, supported underneath by a honeycomb. This honeycomb is essential, as it will be able to absorb forces that may be incurred from all directions, especially during the three key times mentioned above. The floor will also have opening hatches or lift-out sections so that astronauts will be able to access the systems in the bottom half of the greenhouse. A supplemental support system will consist of honeycomb panels spanning the length of the greenhouse, attaching to the floor in the center of the greenhouse at a 60° angle. The angle measurement was chosen to provide maximum support strength, creating three equally sized compartments in the bottom hemisphere. Finally, a tertiary support system will be attached to the secondary support system. The tertiary system will consist of poles, extending at a 60° from the supplemental system, and attaching to the floor directly underneath the biology structures. Each side of the greenhouse will have four such poles, equally dispersed across the length of the structure. This system will serve as a means to provide lateral support underneath the floor not only helping to support the biology structures, but also providing extra support for the added weight of an emergency repair crew of astronauts and to absorb additional impact pressures incurred during takeoff, entry, and landing. The vertical wall in the top hemisphere will also serve as a tertiary support system.

8.2.2 Power

In order to prevent one side of the biology from being contaminated by the other side, the bottom section of the greenhouse must continue the isolation established in the upper level. Furthermore, if each half of the greenhouse needs to be self-sufficient, power must be divided in such a way that would allow one half to be shut down, while the other half is in full operation. In order to do this, the natural divisions created by the support structures will be utilized, dividing the bottom into three entirely secluded sections.

Although it is possible to access the bottom sections on the far left and right through the floor hatches, the center section must be entirely inaccessible to maintain seclusion. Therefore, it was determined that this section will be utilized almost entirely by storage of sodium borohydride for the fuel cells, but will also contain two RTGs. The two RTG stacks in the center section will be securely fastened to the support walls, one on either side, at the very bottom of the MDG such that the 1.14m end will be flush to the secondary supports, and the 0.41m end will be against the outer wall. The RTGs will also be positioned at the back of the MDG. The remainder of the center section, about 39.5m^3, will be used for sodium borohydride storage.

The other two bottom sections will be primarily filled with biology and storage systems in the front. However, each section will host one complete RTG stack, as well as the remainder of the necessary power systems in the back. This arrangement will allow the power sources in the side compartments to remain close to the power systems located in the center back of the greenhouse. Utilizing 0.75m of depth, about 162 fuel cells will be arranged around the RTG stack. Since both the left and right compartments will contain identical power systems for the purpose of redundancy, all 296 fuel cells can be accounted for with some extra for emergencies. Each side compartment will also contain a Sabatier electrolyzer for water creation, stored hydrogen, power distribution equipment, and an intake valve for CO_2 from the Martian atmosphere. These systems should not take more than 2.25m of depth, giving power a total of 3m of depth in each side compartment.

8.2.3 Biology

Most of the systems necessary for biology nutrient delivery and storage will be located in the bottom hemisphere at the front of the greenhouse. Five meters of depth (measured from the front of the MDG, towards the center) on each side have been allotted for systems such as: food processing, nutrient measurement instrumentation, nutrient storage systems, seed storage, a water reservoir, water purification, and water pumps. Since both sides of the greenhouse will be entirely self sufficient, each of these systems must be duplicated on both halves of the MDG. There is approximately 28.5m^3 of space for systems necessary for each of the two halves of the greenhouse, totaling 57m^3 of biology space in the bottom hemisphere. Part of this space will be consumed by the RTG located in each of the compartments, although this will probably only occupy 0.5m of depth (about 0.24m^3 per RTG). Also, the domed end of the greenhouse will eliminate a small portion of the allotted depth (up to 2.5m^3). Therefore, there will be approximately 25.5m^3 of space for biology systems on both sides of the greenhouse. Since it is assumed that not all of this space will be utilized, any remaining space may be used by backup storage or for extra fuel cells. Specific arrangement of biology structures is pending upon trade studies on the most efficient systems to use, as well as further research towards the dimensions of such systems.

8.2.4 Food Processing

Since the rover will never enter the biology section and will remain in the airlock when not delivering food, the harvested and processed plants must be delivered to the rover inside the airlock. In order to minimize food transportation systems, the processors will be located directly beneath the airlock in the front of the greenhouse. Food will enter the processors by a trapdoor activated by the harvester. Once the food is processed, it will be transported to the rover in the airlock. Immediately following food transportation, the airlock will be purified and decontaminated, before food from the other section is allowed to enter the airlock.

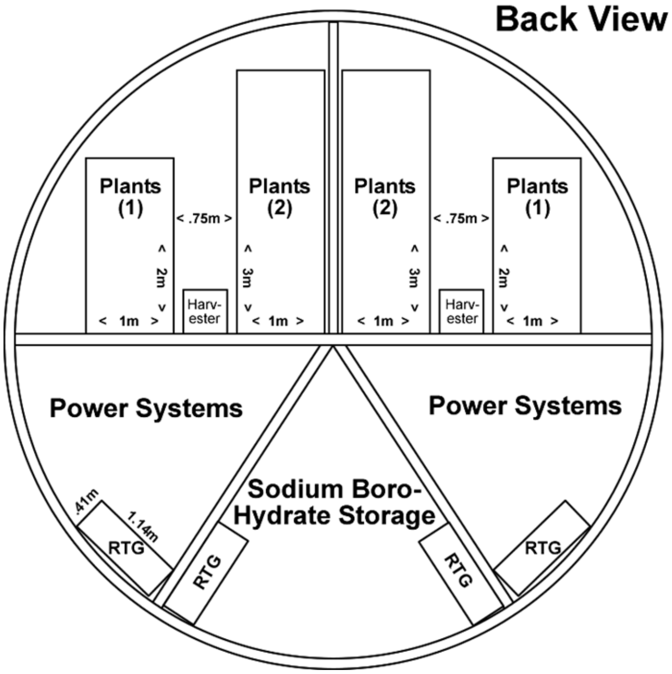
8.2.5 Computers and Backup Systems

Since the operating computers and interior communications systems will take up less than 2m^3 for each side, a minimal amount of space must be allotted to these systems. Therefore only 1m of depth in each of the two side compartments will be necessary for such systems. Consequently, since 1m of depth will provide 5.23m^3 of space (recall that there will be an RTG stack in this section), the remaining 4.75m^3 will be used for a backup pump system, and a backup water purifier (space and mass permitting).

8.2.6 Storage

The remaining 2m of depth in each side compartment will be used for storage of necessary and backup chemicals. This allows for 4.75m^3 of storage space per compartment. Currently, it is unclear how to best utilize such space, keeping in mind mass limitations. Potentially, the following chemicals can be stored: water, hydrogen, rocket fuel, and sodium borohydride. Also, it is possible that the hydrolysis system used for water creation will generate fuel, in the form of methane, as a waste product. This fuel could be stored in tanks that were initially empty at takeoff, and then potentially used by the side rockets in emergency situations.

Since the possibility exists that byproducts from some biology and power systems can be utilized elsewhere in the greenhouse or for other mission elements, a simple system can be used to store such substances. Substances brought to Mars to help start the MDG processes will be contained within an impermeable bladder in a storage tank. As these resources are exhausted, the byproducts will be stored in the area of the tank that is not enclosed in the bladder.



8.3 Mass Allocations

From the Mars Reference Mission, it was found that a total of 30 metric tons was allotted for the MDG. Furthermore, the engines, retrorockets and takeoff fuel do not count in this mass allowance. Although there has not been enough information gathered to have specific mass measurements, estimations have been calculated for each major system, and mass allotments have been made based on these estimations. The following chart shows such mass allotments. The allotments represent the maximum each set of systems could use, final numbers are still being refined.

Unfortunately, with the current arrangement, the bottom hemisphere will have about 1.5 times the mass of the top hemisphere. Further research must be conducted to determine if mass must be more balanced in order to decrease this ratio. If the mass balance must be changed, some massive systems in the bottom hemisphere, such as RTGs and water storage, can be moved to the top hemisphere.

System	Allotment (kg)
Structure & Support	14,000
Power	5,000
Biology & Envi Ctrl.	7,000
Computer & Comms	4,000
Total	**30,000**

Table 6: Mass Allocations

9 Biology Systems

9.1 Crop Selection

The well-developed crops of wheat, potatoes, sweet potatoes, soybeans, rice, tomatoes, and lettuce and the lesser-developed crops of peanuts and strawberries are planned as the MDG crops. Factors in selecting these crops included their appeal to many people, the variety of ways in which they may be prepared, their growth rate, and the feasibility of growth in the MDG.

9.1.1 Nutritional Analysis

Although the primary purpose of the greenhouse is to provide fresh food for the astronauts to enjoy, an additional benefit will be the calories it provides. The precise nutrient composition was considered secondary during crop choice because the greenhouse provides only a portion of the calories consumed by the astronauts and any essential nutrients may be provided by prepackaged meals. Still, when soybeans were evaluated, their abundance of amino acids was a decisive advantage. The team attempted to include crops that provide a range of nutrients so that the astronauts will not rely on the greenhouse for all of any particular nutrient. This assortment of crops will also be more relevant to future, longer-term, Mars missions that will have limited deliveries from Earth.

It is important to evaluate the nutritional value of the crops when including them in meals; a brief summary appears below each crop described.

9.1.2 Primary Crops

Brown Rice. Rice is also desirable for its ability to produce a high amount of energy within a small space. Since its roots do not require oxygen, rice might be grown separately from the oxygenation methods demanded by the other plants, and its production could be expanded temporarily if the oxygenator were to stop working. The Super Dwarf cultivar seems to be the best choice at the moment, but the team is still investigating options.

Current food preparation within the space program is limited to rehydration and heating to serving temperature; additional equipment would be needed to cook the rice[35]. Regardless of its disadvantages, its versatility is best of all the cereal grains[38].

Proximates	
Water	72.96g
Energy	112.00kcal
Protein	2.32g
Total Lipid	0.83g
Carbohydrate	23.51g
Fiber, total dietary	1.80g
Nutrients	
Calcium	10.00mg
Iron	0.53mg
Magnesium	44.00mg
Phosphorus	77.00mg
Potassium	79.00mg
Sodium	1.00mg
Zinc	0.62mg
Copper	0.08mg
Manganese	1.10mg
Selenium	0.00mcg

Table 7: Nutritional Value of Brown Rice (100g)

Sweet Potatoes. Despite requiring one of the longest growing periods, sweet potatoes have a high production rate and harvest index. In addition to the tubers, sweet potato leaves are edible. This is the only crop that does not have increased levels of protein when grown in controlled environments[39], and is an excellent source of vitamin A[40]. In CELSS - related tests at Tuskegee University, cultivars TI-155 and Georgia Jet were successfully grown in NFT hydroponic system[41]; TU-155 was selected.

Proximates	
Water	87.96g
Energy	35.00kcal
Protein	4.00 g
Total Lipid	0.30g
Carbohydrate	6.38g
Fiber, total dietary	2.00g
Nutrients	
Calcium	37.00mg
Iron	1.01mg
Magnesium	61.00mg
Phosphorus	94.00mg
Potassium	518.00mg
Sodium	9.00mg
Zinc	0.29mg
Copper	0.04mg
Manganese	0.26mg
Selenium	0.90mcg

Table 8: Nutritional Value of Sweet Potato Leaves (100g)

Strawberries. Fresh strawberries are desirable primarily for their psychological value, since they will significantly contribute to the variety of food in the greenhouse. An additional benefit is that their productive life is approximately twice as long as the time needed for them to grow to maturity, increasing their efficiency.

Strawberries have been targeted as a potential CELSS crop and grown hydroponically on a commercial scale. While they have not been used as extensively in CELSS testing as staple crops, the use of a sensitive harvester will greatly increase their suitability for inclusion in the MDG. Strawberries have been grown successfully in troughs with the berries hanging down in plain view, a layout that will be extremely accessible to the harvester during the lifespan of the plant.

Proximates	
Water	72.85g
Energy	103.00kcal
Protein	1.72g
Total Lipid	0.11g
Carbohydrate	24.27g
Fiber, total dietary	3.00g
Nutrients	
Calcium	28.00mg
Iron	0.45mg
Magnesium	20.00mg
Phosphorus	55.00mg
Potassium	348.00mg
Sodium	10.00mg
Zinc	0.29mg
Copper	0.21mg
Manganese	0.56mg
Selenium	0.70mcg

Table 9: Nutritional Value of Sweet Potato (100g)

120 days before astronaut arrival, strawberry seeds are moistened and germinate at a fairly stable 15-18°C. They then produce runners, some of which are trimmed off and some of which are allowed to root. Using runners instead of seeds for subsequent plantings saves approximately 1.5-2 months of each strawberry cycle. When the original plants are 9 months old, they are removed, and thereafter, plants will be removed after 7.5 months.

Peanuts Peanuts were chosen for their high caloric content and ability to provide variety. They may be pressed for oil, eaten as a snack with minimal preparation, or used to flavor a meal.

Peanuts have been grown experimentally at KSC, where a unique hydroponics system was used. Peanuts require a substrate above root level but below “ground” for the development of the nuts, which grow on pegs that grow down from the plant. The pegs need to be in complete darkness and surrounded by media, which will cause them to be a more challenging crop to maintain than most. Special attention is necessary to ensure proper positioning of the

Proximates	
Water	91.57g
Energy	30.00kcal
Protein	0.37g
Total Lipid	0.11g
Carbohydrate	7.02g
Fiber, total dietary	2.30g
Nutrients	
Calcium	14.00mg
Iron	0.38mg
Magnesium	10.00mg
Phosphorus	19.00mg
Potassium	166.00mg
Sodium	1.00mg
Zinc	0.13mg
Copper	0.05mg
Manganese	0.29mg
Selenium	0.70mcg

Table 10: Nutritional Value of Strawberry (100g)

Proximates	
Water	6.50g
Energy	567.00kcal
Protein	25.80g
Total Lipid	49.24g
Carbohydrate	16.14g
Fiber, total dietary	8.50g
Nutrients	
Calcium	92.00mg
Iron	4.58mg
Magnesium	168.00mg
Phosphorus	376.00mg
Potassium	705.00mg
Sodium	18.00mg
Zinc	3.27mg
Copper	1.14mg
Manganese	1.93mg
Selenium	7.20mcg

Table 11: Nutritional Value of Peanut (100g, raw)

substrate with respect to the plant in order to create a suitable environment for growth of the peanuts.

Wheat. A staple crop high in calories, wheat can utilize light 24 hours of the day and is not negatively affected by growth under low pressure conditions.[30] The crew is likely to feel more comfortable using a familiar food item, which may increase its positive psychological impact.

Varieties are available that make production in limited space more efficient. One of the first to be developed was Super Dwarf, which was only 30 cm tall but had low yields. The USU-Apogee cultivar has been selected, as it combines high production with full-dwarf height. While it is not as compact as Super Dwarf wheat, it has been specifically tailored to the conditions found in ALS systems. Other, more compact varieties are being produced as well, and some as short as 30-40cm may be available soon [31].

Tomatoes. Tomato is certainly one of the leading crops in CELSS research. Numerical optimization placed it in the top four crops for energy production; tomato would be one of the most versatile crops and simplest to prepare for consumption, but automated harvesting is more difficult to implement for this growth pattern than for that of crops such as wheat. Several miniaturized varieties are available, ranging in height from “Micro-Tom” (15 cm) and “Red Robin” (20 cm) to “Microtina” (20-25 cm).

Soy. While soybean has a lower harvest index, it is an essential component of an ALS because it contains all 20 amino acids and is high in calories, protein, and fat. A greater variety of products can be made from soy than most crops; soymilk could be a substitute for dairy products, and if soybeans are pressed for oil, the remaining soybean meal may be included in bread or used for texture. Processing will require additional equipment, which will be included as feasible.

Lettuce. Lettuce has been grown in ALS studies for decades[33]. Though it has few calories, it grows quickly and is a source of leafy greens. It can accept PPF levels ranging from 400 to 800[34] and can tolerate higher levels of sodium in the nutri-

Proximates	
Water	12.76g
Energy	329.00kcal
Protein	15.40g
Total Lipid	1.92g
Carbohydrate	68.03g
Fiber, total dietary	12.20g
Nutrients	
Calcium	25.00mg
Iron	3.60mg
Magnesium	124.00mg
Phosphorus	332.00mg
Potassium	340.00mg
Sodium	2.00mg
Zinc	2.78mg
Copper	0.41mg
Manganese	4.06mg
Selenium	70.70mcg

Table 12: Nutritional Value of Wheat (100g)

Proximates	
Water	93.76g
Energy	21.00kcal
Protein	4.00g
Total Lipid	0.33g
Carbohydrate	4.64g
Fiber, total dietary	1.10g
Nutrients	
Calcium	5.00mg
Iron	0.45mg
Magnesium	11.00mg
Phosphorus	24.00mg
Potassium	222.00mg
Sodium	9.00mg
Zinc	0.09mg
Copper	0.07mg
Manganese	0.11mg
Selenium	0.40mcg

Table 13: Nutritional Value of Tomato (100g)

ent solution[19]. In the team's literature searches, "Waldmann's Green" seemed to be the most commonly grown variety of lettuce, which outperformed "Grand Rapids," "Bibb," and "Buttercrunch" in productivity in a recent study. Consequently, this is the variety that will be grown in the MDG.

Potatoes. Potato has also been extensively studied because it is high in digestible starch and protein and has a high proportion of edible biomass. It is characterized by ease of preparation and propagation. Small tubers would be used to start the stock, but once grown, plants could provide leaves to start the next generation of crops[32].

9.1.3 Algae

Algae was the earliest form of life support, studied in the 1950s for its ability to replenish oxygen[19]. It will be included in an exploratory role for food production, since it can offer lipids, protein, all essential amino acids, and nearly all essential vitamins. The vitamin B12 is not produced by plants, but many types of cyanobacteria can make it[38]. Harvesting methods could use simple machinery, and algae may be produced rapidly, making it useful in an emergency[38]. Though not appealing in its current form, advances in processing could make it more acceptable for consumption.

Algae will not be considered a food product of the greenhouse under normal conditions; current processing methods fail to make it palatable in large quantities. It is used as an additive in some items, but it is unlikely that it may be used in combination with the other greenhouse crops, and the remainder of the food will be pre-prepared. As an experimental crop, it will be present in small quantities in sections of the greenhouse that do not have the correct dimensions to be used for other plants. Flexible mats or tubes of algae could be hung in these areas. If other crops fail or more calories are desired, the algae would be used to start additional mats.

Multiple varieties of algae will be cultivated in order to maintain a variety of characteristics. New ways of using algae may come into being during the lifespan of the greenhouse.

Proximates	
Water	68.60g
Energy	141.00kcal
Protein	12.35g
Total Lipid	6.40g
Carbohydrate	11.05g
Fiber, total dietary	4.20g
Nutrients	
Calcium	145.00mg
Iron	2.50mg
Magnesium	60.00mg
Phosphorus	1.58mg
Potassium	539.00mg
Sodium	14.00mg
Zinc	0.91mg
Copper	0.12mg
Manganese	0.50mg
Selenium	1.40mcg

Table 14: Nutritional Value of Soy (100g)

Proximates	
Water	94.00g
Energy	18.00kcal
Protein	1.30g
Total Lipid	0.30g
Carbohydrate	3.50g
Fiber, total dietary	1.90g
Nutrients	
Calcium	68.00mg
Iron	1.40mg
Magnesium	11.00mg
Phosphorus	25.00mg
Potassium	264.00mg
Sodium	9.00mg
Zinc	0.29mg
Copper	0.04mg
Manganese	0.75mg
Selenium	0.20mcg

Table 15: Nutritional Value of Lettuce (100g)

9.2 Plant Growth Structures

All crops in the MDG will be supported in growth structures consisting of shelves with supports that will connect to the structural skeleton above the plants and extend down through the floor to either the central A-frame supports or the lower outside wall itself. The lighting system will share these supports.

All growth structures will be able to support up to 40kg per square meter and consist of a lower, stationary tray for the water to flow through and an upper support lid with multiple holes for plants to grow in. The upper lid will be a mobile continuous loop that will slowly move plants from one end where they are planted toward the harvesters at the other end with an electric motor. After the plants have been harvested, the lid will eventually circulate back to the top where another plant may be planted.

All shelves will be angled 15° from normal to the Martian gravitational field in order to facilitate water movement. The landing legs must stabilize the greenhouse so that this angle is not more than 5° above or below the intended 10°.

Crops will be started at the top of the slope where they may benefit from the light intensity near the LEDs. As the plants mature they will move down the slope where they will have more growth room.

The size and shape of any particular growth tray, and the amount of plants growing within any particular tray, depend on what kind of crop is being grown within the tray. There will be four tiers of shelves in the center of the greenhouse. This will decrease as the shelves approach the side walls.

The early growth of tomatoes will be in growth trays that feature aeroponic misting jets to facilitate quick early root growth.

The support frame for the hydroponics system demands balanced rigidity and strength. The length-oriented stresses associated with landing render terrestrial shelving structure models designed only for ”vertical” loading and compressive strength impractical. Attachment points with the skeleton of the MDG along the height of the units will assist in this task. In addition, dimensional stability for compatibility with automated harvesting and bio and operation in a moist environment are also required of the structures. Square Aluminum tubing has been chosen for this

Proximates	
Water	71.20g
Energy	109.00kcal
Protein	2.30g
Total Lipid	0.10g
Carbohydrate	25.23g
Fiber, total dietary	2.40g
Nutrients	
Calcium	10.00mg
Iron	1.36mg
Magnesium	27.00 mg
Phosphorus	57.00mg
Potassium	418.00mg
Sodium	8.00mg
Zinc	0.32mg
Copper	0.31mg
Manganese	0.23mg
Selenium	0.80mcg

Table 16: Nutritional Value of Potato (100g)

application due to its high strength, low weight, and ready machinability. Its tubular construction serves to increase rigidity and reduce weight.

9.3 Water & Nutrient Delivery System

Water is an essential element to plant growth, especially in hypobaric conditions. Water mixed with nutrients will make up the nutrient solution which will be the source of nutrition for the crops. A block diagram of the water flow in the greenhouse is shown in Figure 2.

De-ionized water will enter the nutrient solution system from the fuel cells and enter into the nutrient solution reservoir. Nutrient levels will be monitored electronically. When more nutrients of a given type are needed, de-ionized water will enter into the tank in which the nutrients were stored in dry form for the journey to Mars. A valve will open to allow the super-concentrated solution to flow into the reservoir until the correct amount has been added and nutrient levels are restored to nominal.

To reliably provide water to all of the plants, every growth tray will have a separate pump. The "mag-drive" pumps will have one moving part, a magnetized ceramic impeller, and will be immersed in the reservoir tank [91]. The water will flow down the angled growth trays, due to gravity, through the roots of the plants and be pumped into the sand filter to remove any large particles and to be the first screen for bacteria. A sand filtration system was chosen over other mechanical, ionic, or reverse osmosis filters because it does not require any additional electricity or replacement over the duration of the mission. From the sand filter, the water will pass under a UV lamp or high intensity light to remove any other bacteria in the water before it is returned to the reservoir. This system will be duplicated in both halves of the MDG.

For the sand filter, the water will return to the reservoir where a computer controlled UV lamp will act upon all bacteria in the water and either kill them or disrupt their DNA enough to render them sterile. The commercially available electronic control will be equipped with sensors to monitor bacteria levels in the water and optimize power use while ensuring the proper dose of radiation is delivered. Multiple lamps will serve as a redundancy mechanism in case a bulb malfunctions or burns out. The bulbs will be outside of the tank to allow them to operate at their highest efficiency temperature of 40°C without heating the water. Normal glass is opaque to UV radiation and therefore the window that allows light to flow into the reservoir will be made of quartz.

A number of hydroponic and aeroponic techniques, including the Static Aerated Technique (SAT), Ebb and Flow Technique (EFT), Nutrient Film Technique (NFT), Aerated Flow Technique (AFT), Root Mist Technique (RMT), and Fog Feed Technique (FFT) [23][24], were considered for the MDG. Hybrid aero-hydroponic systems were determined to be impractical and will not be discussed. The combined disadvantages of using the two systems together outweigh the advantages. Having two nutrient delivery systems where one would suffice would be unnecessarily expensive and complex. However, this does not rule out using both methods separately in the event that each is better suited to growing plants of different species or growth stages.

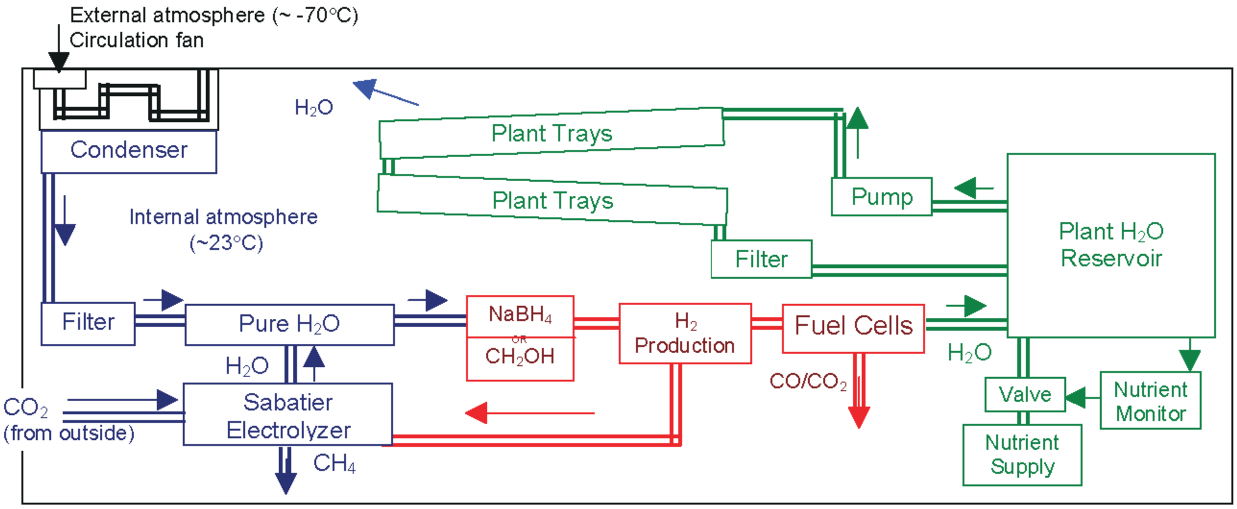


Figure 2: MDG Water Flow

Tomato Production Data	Hydroponics	Aeroponics
Days to germinate	14	immediate
Days to first flower	28	immediate
Days to first harvest	68-95	10-30
Last day of harvest	105-120	47
Crops/year	3.4	7.7

Table 17: Comparison of hydroponics and aeroponics. Hydroponics from seed, aeroponics from cuttings. Data from Colorado Power Partners, Denver, CO.

In order to quickly produce crops of high quality, the rootzone needs adequate aeration. Hydroponics allow for this by pumping air into the water (SAT and AFT), periodically draining the water (EFT), or exposing a section of the roots to air (NFT) [24]. The Static Aerated Technique seems to be the least advantageous because of the static water, which needs to be changed every two weeks. For some plants, such as tomatoes, having the roots constantly submerged can be detrimental. One of the most common causes of houseplant death is overwatering [25]. Periodic drainage of water is not as effective a method of aerating roots because the oxygen is provided at a different time from the nutrient solution. Continuously circulating systems provide more benefit for the plants while being more efficient in water usage. The aeroponic methods RMT and FFT provide oxygen to the roots by growing the plants in the air and spraying a water/nutrient solution over them at regular intervals. The two techniques differ by the size of the droplets sprayed – RMT uses water droplets from 30 to 100 microns in diameter, while FFT droplets are less than 30 microns. Since vegetables more readily absorb larger droplets, RMT would be a better choice than FFT[27]. The above conclusions show RMT and NFT to be the most viable growing methods. Of all these options, the RMT has the best potential production rates because it uses the least water, more than an order of magnitude less water and nutrients than hydroponic systems, and causes plants to grow faster[28].

Accordingly, aeroponics also uses more than an order of magnitude less fertilizer and nutrients than NFT. Although seeds and equipment will have been sterilized, any diseases will be less likely to spread because the plants are individually sprayed instead of sharing a common trough of water. However, the necessary mechanical equipment is a disadvantage for aeroponics. In NFT, one pump could be used to circulate water for an entire tray of plants, but one spray nozzle for an RMT system could only service a few plants. This translates to higher costs for AFT, which is reflected by the lower number of commercial aeroponic farms[55].

Recommended especially for growing fruits and vegetables, NFT is the best hydroponic technique available[29]. The great advantage it has over other hydroponic methods is that a depth of as little as two millimeters of solution can be used.

With the exception of the early tomato growth, all other plants in the MDG will get their water and nutrients through NFT or nutrient film technology where the roots are immersed in a few millimeters of water. The close proximity of the roots to the surface and the flow of the water allows the roots to get an ample amount of oxygen. This system was chosen over a conventional hydroponics system because of its lower water volume requirements and superior oxygenation abilities. It was also chosen over conventional soil because it is significantly more productive with far less mass.

System Failure. A system failure could be the most damaging to plants grown without the benefit of a water trough. In aeroponics, clogged nozzles or a power outage would leave the plants with no water source. A complete loss of the crop can be avoided, but the plants would still need to recover. As long as sprayings are spaced at intervals rather than continuous, the plants will not be as dependent upon a continual water supply. Experiments by Aeroponics International have shown that plants can survive without being sprayed for a week or more under special low-temperature, low-light, and high-humidity conditions. [28]. Plants in a gravity-drained NFT system are acclimated to the continual water supply. A lower water level due to a pump failure could have dramatic effects, especially because the roots are only partially immersed. A lack of regulation could cause a water level that is too high and would decrease the benefit of exposure to oxygen.[26]

Hypogravity. Testing of aeroponic systems under hypogravity conditions has uncovered possible problems. The lessened effect of gravity increased the effect of other forces such as surface tension on the behavior of water droplets. As a result, the droplets tended to hang onto the roots and apparatus, forming suspended bubbles of water. This phenomenon poses potential problems in regards to aeration of the roots and circulation of the nutrient solution. A possible solution is to spray air through the nozzles after spraying water. Experimentation with droplet sizes and speeds under simulated Martian gravity could improve results[28].

9.3.1 Nutrient Control

A computer will monitor the concentrations of at least the following nutrients: NO_3, K, Mg, SO_4, NH_4, PO_4, SO_4, Ca, Mn, Fe, Zn, Cu, Mo, C, B, and Cl. The macro elements, those required in high concentrations, are C, H, O, N, P, K, Ca, S, and Mg. Micro elements, found in lower concentrations but still thought to be essential, include Fe, Cl, Mn, B, Zn, Cu, and Mo. Special nutrients for certain species outside of what most plants need include Si, Al, Co, V, and Se [25].

Various parts of a plant, such as the stem, leaves, seeds, and roots, have different proportions of each element (Table 18). Because of this uneven distribution, different types of crops require different proportions of nutrients. In general, leafy crops, for example, need more N[25]. A plant's needs also vary as it goes through each of three main growth stages. Early vegetative growth mostly consists of leaf tissue. During this stage the nutrient solution is more concentrated because leaves have higher percentages of marcro elements and younger plants tend more towards nutrient deficiency than toxicity. During late vegetative growth, leaf and stem tissue grow about evenly. In the reproductive growth stage, nutrients are redirected to fruit and seed formation while other growth slows down[50]. Tailoring the solution for each plant and stage would be ideal but much more complicated than having a single nutrient system.

Plants take in NO_3, NH_4, P, K, and Mn relatively quickly; Mg, S, Fe, Zn, Cu, Mo, and C at a medium rate; and Ca and B more slowly. Contrary to what would seem to be a good way to provide the right amount of nutrients, many nutrients should not remain at a constant concentration with the initial levels by continuously replenishing the same amount absorbed. Those taken in more quickly could be high in the starter solution and soon drop to near zero. In the case of phosphorus, feeding in more as a plant absorbs it could allow the amount in the plant to rise as high as three times more than the optimal level. Excessive intake of one element leads to deficiencies in others. Instead, those nutrients likely to accumulate in excess should be kept at very low concentrations. Frequent "topping off" in small quantities keeps the levels much more even and stable[50].

%	Leaves	Stem	Seeds	Roots
N	5.00	2.00	3.00	3.00
P	0.30	0.20	0.50	0.20
K	2.50	2.30	0.70	2.00
Ca	1.20	0.30	0.10	0.20
Mg	0.50	0.05	0.20	0.05
S	0.50	0.30	0.20	0.20
mg/kg	**Leaves**	**Stem**	**Seeds**	**Roots**
Fe	100.00	40.00	100.00	800
Mn	75.00	20.00	50.00	25.00
B	5.00	3.00	0.50	5.00
Zn	50.00	20.00	50.00	30.00
Cu	10.00	1.00	5.00	10.00
Mo	2.00	1.00	1.00	1.00
Cl	1.00	1.00	1.00	1.00

Table 18: Approximate Nutrient Concentrations in various Parts of Wheat Plant[50]

Concentrated solution will be stored in a small tank. Macronutrients will each be stored individually, and micronutrients will be stored in one container in pre-measured proportions. Each of the two water systems in the warm and cold section will have a separate nutrient/water supply. A stretch no longer than 10-15 meters can be adequately supplied by one feed point[51]. Either way, the solution flowing out will be recirculated by a pump.

A possible alternative or supplement to monitoring nutrient concentrations in the water is monitoring nutrient concentrations in the plants. The concentrations in the plant are what really matters, and a tissue sampling give more accurate results. ICP-emission spectrophotometry, nitrate-N analysis, Kjeldahl or LECO Total Nitrogen analysis[50], and electrical conductivity are other methods to help determine if plant uptake of nutrients are at optimal levels[25].

9.4 Experimental Section

The experimental section will be a 0.75 meter cube with a clear top panel and a operational life of up to five years that will conduct an experiment to see if the simple addition of water can change Martian soil to be less hostile to life. When deployed from the rover with a spring-loaded mechanism triggered by an electric servo, a clamshell door at the bottom of the experimental section will spring, scooping up Martian soil and sealing the experimental section shut to avoid contamination. A box filled with seeds from multiple plant species will be dumped onto the soil and a canister filled with water and compressed gas will be mechanically opened when the clamshell door on the bottom is shut to provide water to the soil.

A simple atmospheric composition sensor will check at intervals of one day for changes in composition from the previous day. If any changes are recorded it will transmit its findings to the greenhouse to be transmitted back to Earth. Dust and other debris will be cleared from the window by a simple electric windshield wiper once every 5 days. All instrumentation systems in the greenhouse will only be turned on once a day and therefore will be powered by battery.

10 Environmental Controls

10.1 Internal Pressure

A hypobaric environment is one in which the pressure is lower than the standard condition; the MDG will have an interior pressure in the range of 200-210 millibars, significantly less than standard Earth pressure.

The primary advantages of a non-hypobaric greenhouse would be the ability to give the crew full access, without requiring them to wear EVA suits, and the ability to provide a measure of redundancy in case the life support systems fail in the laboratory/habitat modules. While requiring the crew to wear an EVA suit inside the greenhouse is a disadvantage of a hypobaric environment, it is not as severe as it would appear; modern technology has made significant improvements in the thinness and flexibility of suits. In addition, the crew does not need to withstand conditions as extreme as floating freely in space, meaning that their Mars EVA suits can be thinner and lighter than even modern spacesuits. The energy required to power six EVA suits (assuming all the crew work in the greenhouse simultaneously) for eight hours a day is much less than the amount needed to keep the entire greenhouse constantly at Earth pressure. If there were to be a failure of life support systems in the habitat module, the interior pressure of the greenhouse could be rapidly increased to allow the astronauts to temporarily seek refuge.

A lower pressure also requires less energy to maintain, and reduces the rate of leakage to the atmosphere. Lower pressure in a constant volume requires fewer moles of a gas, which is especially significant in terms of water vapor. Fewer moles will saturate the air to the proper relative humidity. Given that there exists need to manufacture water in-situ from hydrogen brought from Earth, any savings that can be made in terms of water usage will reduce overall launch weight and the energy needed to produce water for the greenhouse.

There are also great advantages to growing plants under hypobaric conditions. Research on the growth of plants in hypobaric conditions shows that yield can increase by as much as 76% at lower pressures and high humidity [30]. As pressure decreases, the rates of transpiration and photosynthesis increase, so plants are able to mature and produce faster[20].

The specific conditions for the greenhouse will depend largely on the final crop selection. From the perspective of plant growth, a pressure of 100 millibars is the most promising. The goal is to reduce the pressure as much as possible while still retaining robustness in the system. Were the pressure to be much lower, crop failure becomes a much greater risk; at 25 millibars, interrupting the water supply for more than several minutes can result in complete crop failure[20]. The increased rate of transpiration associated with lower atmospheric pressures causes a greater dependence upon a constant supply of water.

To meet atmospheric composition and safety requirements, however, the initial target pressure will be 200 millibars. The minimum O_2 partial pressure is 50 millibars (or 5 kPa)[1]. In order to maintain an environment with safe flammability levels, this pressure must constitute 30% or less of the total pressure[45]. Therefore, the total pressure must be a minimum of 167 millibars. The target pressure of 200 millibars gives an adequate cushion for the oxygen partial pressure, which can then be as high as 60 millibars without compromising flammability considerations.

10.2 Carbon Dioxide Enrichment

A common practice in commercial greenhouses is elevating the carbon dioxide concentration to many times the Earth's normal level of 300ppm [47], effectively increasing the rate of photosynthesis. Carbon dioxide must be present in a range of 1 to 30 millibars (0.1 to 3 kPa)[1]. In a total pressure of 200 millibars, 1 millibar of carbon dioxide gives a concentration of 5000 parts per million (ppm). Many scientists and commercial growers have noted increased photosynthetic rates and crop yields in experiments where greenhouses have achieved concentrations of 5000ppm[49].

A very high concentration of carbon dioxide will also make the plants more water-efficient; when carbon dioxide is so readily available, the plants' stomata can shrink, allowing less water out, and still capture the same amount of carbon dioxide[48]. Therefore, the elevated transpiration rate caused by the low pressure will be counteracted by the carbon dioxide enrichment. Although 5000ppm is a bit on the high side, some studies suggest that the ratio between oxygen and carbon dioxide is more important than the actual concentration of carbon dioxide alone. Because the MDG will have a greater concentration of oxygen as compared to Earth, any disadvantage created by an abundance of CO_2 will be counteracted.

10.3 Other Atmospheric Components

The other important constituents of the MDG's atmosphere are water vapor and an inert gas. The relative humidity will be regulated at about 70%. Under a pressure of 200 millibars and an average temperature of 22.75°C, a relative humidity of 70% would be achieved with 19.48 millibars of water vapor[16].

When the greenhouse is initially filled on Earth, it will have the aforementioned amounts of oxygen, carbon dioxide, water vapor, and an inert gas. The gas used here would be nitrogen because of its abundance on Earth.

10.4 Atmospheric Revitalization

To make up for lost gas due to airlock usage and leakage, gas will have to either be brought from Earth or taken in-situ from the Martian atmosphere. Using 1% of the internal volume per day as the maximum leakage rate, the MDG will lose its entire contents 73.05 times over 20 years. Although the estimated leakage will be significantly less, the following section will account for the maximum rate.

10.4.1 Oxygen

According to the chemical equation for photosynthesis, the amount (in moles) of oxygen produced by the plants is equal to the amount of carbon dioxide consumed.

$$6CO_2 + 12H_2O + \text{light} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$$

If a leakage rate of 1% per day were assumed, the rate of oxygen leakage would be less than the rate of production by the plants. Since the leakage rate is less than 1% per day, it can be assumed that under normal operation of the greenhouse, no oxygen will need to be resupplied. When oxygen levels rise past 27%, the computer will start the oxygen removal process. Oxygen will be stored in tanks until they reach maximum capacity. Oxygen produced after storage tanks are filled will be vented to the atmosphere. When the percentage reaches 24.4% (50 millibars), oxygen removal will stop.

10.4.2 Carbon Dioxide

With 95% carbon dioxide, the atmosphere on Mars can more than adequately supply enough carbon dioxide for the plants. The power system and atmosphere revitalization system can share equipment for capturing purified carbon dioxide from the environment. Because carbon dioxide has the narrowest margin, it will be the most carefully monitored and controlled.

10.4.3 Ethylene

Ethylene is a naturally occurring plant product that affects the rate of ripening in fruits. Too much ethylene causes fruits to rot. To control the amount of Ethylene in the greenhouse a product known as bioKES will be utilized[92]. Within the assembly, titanium dioxide composes a photocatylitic coating on borasilica glass beads that remove ethylene from the system when exposed to UV light.

10.4.4 Other Gases

Enough water will be brought to account for leakage of water vapor. In-situ collection of water vapor would not yield much, since water vapor is available at a mere 0.03% of the surrounding atmosphere. Humidity will be kept near 70% by the condenser and the computer-controlled humidifier.

The remainder of the internal pressure will be refilled with inert gases. To refill a volume of 60 m^3 at 200 millibars and 22.75°C 73.05 times would require 23071 moles of inert gas. Compressed to 3000 psi, this amount translates to 189.2 m^3 and a mass of 646.0 kg. Liquid nitrogen would take up only 0.8 m^3, but it would need to be cooled to -196°C. Given that carbon dioxide already needs to be extracted from the Martian atmosphere, the less costly (and voluminous) answer would be to also collect nitrogen and argon from the Martian atmosphere, these gases exist at levels 2.7% and 1.6%, respectively (see Table 19). The external atmosphere can be processed to remove other gases and leave behind nitrogen and argon in that ratio to make up the remaining internal pressure. As a backup measure, enough pressurized nitrogen and argon to fill the greenhouse once will be brought from Earth.

Gas	Percent
Carbon dioxide	95.32%
Nitrogen	2.7%
Argon	1.6%
Oxygen	0.13%
Water vapor	0.03%
Neon	0.00025%
Krypton	0.00003%
Xenon	0.000008%
Ozone	0.000004%

Table 19: Main component gases of Martian atmosphere[46]

10.4.5 ISRU Process

One of the greatest limitations on a 20-year manned mission to Mars is the capacity to bring an adequate supply of consumables. To account for worst-case scenarios and functionality over 6 years, the MDG will require at least 602 L of H_2O, 7556 kg of CO_2, and 46141.5 moles of inert gas.

Options for supplying consumables can be categorized by level of reliance upon Mars. The option requiring least reliance is to bring a 20-year supply of water, or the necessary components, and all other gases entirely from Earth. The sheer amount of mass and volume required immediately eliminates this option. Therefore, at least partial reliance is essential to the mission.

The opposite extreme would be to gather all water and gases in-situ. This would be possible for the gases, but water poses a problem. Two possible sources are vapor in the atmosphere or frozen water in the permafrost. Using water vapor as the sole source is not at all feasible because water vapor is only 0.3% of the atmosphere. Since oxygen is readily available by breaking down the carbon dioxide, the best option is to bring the hydrogen from Earth and extract oxygen from the air on Mars.

Enormous mass savings are gained through ISRU. The MDG's ISRU equipment utilizes the local atmospheric gases CO_2, N, and Ar. Since ISRU equipment has never been run in outer space, no truly proven technologies exist. Such technology has, however, been successfully tested under simulated Martian conditions in NASA laboratories, and the cancelled *Mars 2001 Surveyor Lander* was to carry the Mars ISPP Precursor (MIP) to be tested on the surface. It is assumed that since the DRM uses ISRU technology, the technology will have developed to a high level of reliability by the time of the MDG's launch.

The MIP has the ability to adsorb carbon dioxide, compress it, and convert it into oxygen. However, the oxygen generation system uses zirconia based solid oxide electrolyzer instead of the more efficient Sabatier process. The would like to use the MIP's reliable carbon dioxide adsorption process and temperature swing utilization and incorporate that with the Sabatier process for oxygen production. Not all of the carbon dioxide captured would be processed to make oxygen. As needed, a portion of the carbon dioxide will pass through a 30-micron filter and replenish the internal atmosphere of the greenhouse. Nitrogen and argon will be separated using similar absorption technology from the Mars In-situ Carrier Gas Generator (MICAGG) developed at NASA Ames Research Center. This device is also unique for its independence of power systems; it relies upon the diurnal energy cycles of Mars for all power [108].

10.5 Emergency Astronaut Environment

In the event of a catastrophic habitat module malfunction, the atmospheric pressure and composition would have another set of parameters for human life support (Table 20).

Parameter	Requirement
Total Pressure, kPa	97.9-102.7
O_2 Partial Pressure, kPa	19.5-23.1
CO_2 Partial Pressure, kPa	< 707
Oxygen	0.13%
Temperature, K	291.5-302.6
Relative Humidity, %	25-70

Table 20: Respirable Atmosphere Requirements (Operational) International Space Station, 1996[45]

In order to increase the oxygen pressure to the minimal amount required for humans, the greenhouse would need 144 more millibars of oxygen. To bring the overall pressure up to an acceptable level, an additional 635 millibars of other gas are needed. Since there is no lower limit on carbon dioxide, that partial pressure will not have to be increased, especially because the astronauts themselves will be slowly adding to the carbon dioxide as they respirate. The MDG plants will use only about half the carbon dioxide produced by the astronauts, so, if necessary, the carbon dioxide addition process can be reversed. The nitrogen-argon mixture will be used to pressurize the greenhouse in emergency mode because nitrogen and argon together can be added at a faster rate than nitrogen alone. The extra argon should have no effect on the astronauts; it is an inert gas ordinarily found in Earth's atmosphere. Enough compressed gas to bring the atmosphere up to livable levels will be stored on hand.

This emergency option is not meant for any significant duration. The MDG is designed to support this environment for only a period long enough for the astronauts to assess the situation and then either make brief repairs to the habitat or escape in the ascent vehicle.

10.5.1 Air Circulation

The greenhouse will require an air circulation system to ensure that gases are evenly distributed and to pollinate plants. The first reason, continuously mixing the air, serves many purposes. In stagnant air, an envelope of CO_2-depleted air would develop immediately around the leaves as they use the CO_2 directly in contact. Adequate air circulation will keep a fresh supply of CO_2 constantly available. One experiment in the Netherlands increased the photosynthesis rate up to 40% by increasing wind speed from 0.10 to 1.0 m/s. Since plants primarily take in air during the day, the fans will not need to serve that purpose at night[49]. Instead, the fans will operate infrequently during that period. The only purpose they will serve then is to make the gas composition and heat sensors' readings more accurate by mixing any areas of concentrated heat, cold, or component atmospheric gas.

Of the plants chosen for the MDG, strawberries, potatoes, and sweet potatoes can propagate through asexual reproduction. Lettuce, soybeans, and peanuts, have a high degree of self-pollination without external help[56]. Wheat, tomatoes, and rice need to an agent to help with pollination. These plants need gentle shaking or wind currents at 6-7m/s for an adequate rate of pollination. In addition, cross-pollination is desirable whenever possible so that not every plant will have the exact same genetic makeup and thus be susceptible to complete annihilation by a single disease[57]. The speed necessary is much higher than the speed needed for air circulation and is possibly harmful to the plants if applied continually. In the interest of energy conservation and the plants' well-being, only crops that need wind pollination will have a fan with a higher speed setting. The fans will switch between off, low speed, and high speed at preprogrammed intervals throughout the day and night. Conventionally, greenhouse circulation fans are rated by cubic feet per minute (CFM). The recommended CFM value is 0.75 times the volume[58].

10.6 Lighting

Lighting technology has made rapid advances in recent years. For example, Light Emitting Diodes (LEDs) have historically increased in performance by nearly 30 percent per decade since they were created in the 1960s [53]. This provides several options for the lighting of the MDG.

10.6.1 Ambient Lighting

To facilitate the use of natural lighting, the growth area of the greenhouse features a transparent exterior wall constructed of polycarbonate. On clear days, the incident radiation on Mars is sufficient to provide lighting for the plants [60], as polycarbonate has a hazing effect of only 1%, which is relatively low [100]. However, Mars receives only 50% of the solar radiation that is received on Earth. The Martian day is 24.62 Earth-hours long. In the equatorial latitudes, approximately 12 hours of daylight exists throughout the Martian year. However many of the plants that will be grown in the MDG would benefit from more than 12 hours of light [19]. In addition, dust storms, which block out much natural light (increasing optical depth to 6), are frequent and unavoidable[59]. This means that incident solar radiation cannot provide all the lighting that is required for the MDG to function optimally.

Therefore, it is necessary to include an artificial lighting system, despite any problems that might have to be overcome. Due to the power demands of artificial lighting, it is advisable to use natural lighting to the extent permitted by the optimal exterior structure. Electrical lighting will primarily be used to light shadowed growth areas, to artificially extend the daylight hours, and to supplement natural light during dust storms.

10.6.2 Efficiency

Given that electrical power on Mars will be a very precious commodity, efficiency is a primary factor in deciding which lighting system to use. Several options exist that may be applicable to the MDG; these include low-pressure sodium, metal halide, incandescent, fluorescent, mercury vapor, and high-pressure sodium lamps[54]. Recently, LEDs and microwave sulfur lamps have been developing into extremely competitive products[61]. Lighting efficiency is generally measured in lumens/watt. For the purposes of the MDG, it is assumed that efficient lighting is more desirable than lighting that generates excess heat and heating can be provided in a more efficient manner than by lights.

The majority of less modern lighting methods have maximum efficiencies that are significantly less than 100 lumens/watt[62]. In addition, such lights generally produce light at more wavelengths than just those necessary to grow plants. For plants to be healthy and grow, they require only the wavelengths of maximum chlorophyll and cartenoid absorption[66] and those at which the rate of photosynthesis is highest.

An additional measure of efficiency is the ratio of usable wavelengths to unusable wavelengths generated. For example, low-pressure sodium is very "efficient" at 150 lumens/watt, but the majority of the light it produces is in the yellow range, rendering it useless to plants, which primarily require wavelengths in the red and blue ranges[67]. High-pressure sodium undergoes spectral shift as the input wattage is changed[73]. LEDs can provide high efficiencies, around 100 lumens/watt in the red spectrum and around 25 lumens/watt in the blue[53]. The efficiency of microwave sulfur lighting ranges from 100-150 lumens/watt[70]. Microwave sulfur light provides roughly the spectrum of the sun, but concentrates more in the visible portion of the spectrum than the invisible portion.[70].

10.6.3 Lamp Life

Lamp life is a very important issue; frequent resupply will not be an option on the Martian surface. Many older lighting methods have lifetimes around 20,000 hours or less[54]. In contrast, LEDs can last around 100,000 hours, which translates into almost 11.5 years of continuous use[54]. As only four to six years of occupancy are planned, the lights will not need to be replaced. Microwave sulfur lamps have an unknown lifetime and as technological advances allow their efficiency to increase, it is possible that they will never need replacement[62]. This is drastically better than the 2.5 years that conventional lighting sources might last.

The efficiency of most lamps degrades throughout their lifetime. This can influence not only the straight lumens/watt efficiency, but also the light spectrum produced. Specifically, metal halide lamps have been known to undergo spectral shifts as they age [63]. In contrast, LEDs and microwave sulfur lights experience no degradation of either efficiency or light spectrum produced.

10.6.4 Reliability & Safety

Reliability is also a critical issue. The landing is not expected to be very soft and it is imperative that the lighting sources remain functional after landing. The bulbs used by most conventional lighting sources tend to be fragile. In contrast, LEDs are solid-state lighting devices, which makes them very shock and vibration resistant[72].

Safety to both the plants and astronauts is an important factor in deciding which lighting source to use. Mercury, an environmentally toxic substance, is used in most efficient conventional sources[71]. Neither sulfur lamps nor LEDs contain mercury. If damaged or broken, mercury vapor and metal halide lamps may also emit harmful ultraviolet radiation into the growing area[64]. Microwave sulfur lamps require a radio frequency screen to protect plants from the microwaves. However, it is unknown what the dangers would be if a microwave sulfur lamp were to be damaged[73].

All of these traits suggest that a successful MDG would require the usage of either LEDs or microwave lamps as the primary lighting source.

10.6.5 Primary Lighting

Microwave sulfur lighting is not practical for applications in the MDG as a primary lighting source. Though it has a very high efficiency, it is a point source which would kill any plant within a few feet and must be placed to allow for diffusion of both light and heat, unless light piping is used[73]. The disadvantage of current piping technology is that it causes the light to lose approximately 50% of its efficiency[70], eliminating the most significant advantage of this system. By the time the MDG launches, piping technology may have improved enough for microwave lighting to be a practical primary light source for the MDG, but at this point one cannot say for certain [73].

LEDs have been selected for the MDG's primary lighting system. LEDs are commonly used in arrays, which are placed above each growing area due to a very low level of heat produced. This conserves a great deal of space and maximizes growth area. Another advantage of LEDs over other lighting sources with comparable lumens/watt ratios is that all of the light produced is of the specific wavelength needed for the plant to use it. Unfortunately, blue LEDs do not have very substantial efficiency at this time, so it could be advisable to use an alternative lighting source to provide the blue light. Blue fluorescents are a more electrically efficient source for this supplementary light, though blue LEDs are still more practical for several reasons. Fluorescent lights will not last as long and emit significantly more heat in the direction of the plants as compared with LEDs. From a de-

		Incandescent		LED		Microwave Sulfur		Low Prs Sodium	
	Weight	Score	Wtd	Score	Wtd	Score	Wtd	Score	Wtd
Efficiency	0.35	0.5	0.2	4.3	1.5	2.5	0.9	5.0	1.8
Life time	0.20	0.5	0.1	4.5	0.9	5.0	1.0	3.0	0.6
Durability	0.10	1.0	0.1	5.0	0.5	3.5	0.4	2.5	0.3
Safety	0.25	2.0	0.5	5.0	1.3	4.5	1.1	2.0	0.5
Usable wavelengths	0.10	3.0	0.3	5.0	0.5	3.5	0.4	0.5	0.1
Total	1.00	7.0	1.2	23.8	4.6	19.0	3.7	13.0	3.2

		Metal Halide		Hg Vapor Lamps		High Prs. Sodium		Fluorescent	
Efficiency	0.35	3.3	1.1	2.0	0.7	4.3	1.5	2.5	0.9
Life time	0.20	2.5	0.5	2.8	0.6	2.5	0.5	1.5	0.3
Durability	0.10	2.5	0.3	2.5	0.3	2.5	0.3	2.5	0.3
Safety	0.25	2.0	0.5	2.0	0.5	2.0	0.5	2.0	0.5
Usable wavelengths	0.10	4.0	0.4	2.5	0.3	3.5	0.4	4.0	0.4
Total	1.00	14.3	2.8	11.8	2.3	14.8	3.1	12.5	2.3

Table 21: Lighting comparison matrix. Microwave sulfur listed is assumes light piping required. Scale: 1 - 5; 5 is best

sign perspective, it is more efficient to use blue LEDs because their use allows for the space management benefits of LEDs to be maximized, while supplemental fluorescent lighting would significantly limit these benefits. [67]. However, blue LEDs have only been around for a few years and their efficiency is skyrocketing. By the time of MDG launch, it is probable that the efficiency of blue LEDs will be high enough to use exclusively LEDs as the primary lighting source.

One common belief about LEDs is that they are not capable of producing adequate levels of light intensity. This is not accurate. The MDG guidelines require a midday light intensity of $500\mu\text{mol/m}^2\text{/sec}$, and a minimum of $200\mu\text{mol/m}^2\text{/sec}$ [1]. Quantum Devices Inc, which provides the majority of the LED lamps currently used by NASA[73], has two new commercial LED products that meet the light intensity requirements for plants. Their new SNAP-LITE LED lamp can produce an irradiance output of up to 400 $\mu\text{mol/m}^2$ /sec[65]. This directly corresponds to the light intensity that is needed for successful potato growth[54]. Quantum also manufactures the Q-Beam lamp, which has a maximum light intensity of at least 1500 $\mu\text{mol/m}^2$ /sec[65].

LEDs are generally more directional than other light sources[53], however use of reflective surfaces or another type of reflector would be a good way to maximize light usage. Porcelain-coated reflectors are excellent and require little maintenance[74]. It is very important to ensure that reflectors are kept free of any coating that obscures the light. Aluminum foil or white paint can be used beneath the growing area to help with the reflection of lighting.

10.6.6 Secondary Lighting

In order for astronauts to perform any necessary maintenance on the interior of the MDG, a secondary lighting system was considered. This light is necessary because humans operate best with white light, which is not generated by the primary LED lighting. After reviewing microwave sulfur, high-pressure sodium, fluorescent, and metal halide systems, it was decided that they posed too many additional design, power, and space requirements to be effective. Instead, astronauts will use portable lights that are brought to their work site.

10.7 Sensors

10.7.1 Atmospheric Composition

Concentrations of carbon dioxide, oxygen, nitrogen, argon, and ethylene will be monitored by two infrared gas analyzers.

10.7.2 Temperature/Humidity

The warm section and the cool section of greenhouse will each be equipped with a wet and dry bulb temperature/humidity sensor. The dry bulb will provide the computer with temperature readings and the wet bulb will provide the comparison temperature, allowing the main computer to calculate relative humidity. A humidity sensor with electrical parts directly exposed to the greenhouse environment will not be used due to possible increased degradation of the equipment over time[87]. Ideally, the temperature/humidity sensor will operate between the ranges of 5°C to 35°C and 40% to 80% relative humidity. The accuracy should be at most 2°C or 4-5 percentage points of relative humidity.

Environdata's WT20 wet and dry humidity sensor can measure temperatures to a calibration accuracy of plus or minus 0.2°C. It has an operational accuracy of plus or minus 0.3°C under operating conditions of -10°C to 50°C and 0% to 100% relative humidity, which completely covers the range of greenhouse conditions[88]. Backup sensors would be brought, as the average operational time is five years before a replacement or overhaul is needed. Four extra units for each side of the MDG will be brought. The running sensor will be deactivated and a new one activated at five-year intervals.

10.7.3 Pressure sensors

The MDG will utilize pressure sensors for both the purposes of measuring atmospheric pressure and "wind" pressure created by circulation fans. One type of sensor at vertical and horizontal orientations will be used for both applications because both have the same environmental constraints. Also, in the very extreme case of multiple sensor failures, the wind sensors can be turned horizontal for use as atmospheric pressure sensors. Silicon pressure sensors will be used for their proven dependability. These devices have been used successfully to detect changes of one millibar in airflow systems. Other common applications are in the harsh environment of an automobile as well as in the human heart[98].

Honeywell silicon pressure sensors have the operating range necessary for the MDG. The series 24PC sensors are used to measure absolute pressure from 138 millibars to 1034 millibars. They have the ruggedness to operate from -40°C to 85°C and have been shock tested to 150g. Small and lightweight, each has a mass of 2 grams[99]. A desirable characteristic this series does not include is temperature compensation. However, the temperature within the MDG will be carefully regulated, even during hibernation.

10.7.4 Light

Photosynthetically Active Radiation (PAR) will be measured throughout the growing area so that plants will be ensured adequate light and artificial lights will not be running needlessly. Readings from light sensors will allow a computer to calculate how much artificial lighting is necessary to reach the optimum amount of PAR. More or less artificial light will be automatically put out to account for seasonal changes or unexpected dust storms.

The light sensor will have a photodiode to change light energy into a small current and filters to block light outside of PAR range. One advantage to using a photodiode is that it does not consume any power.

LI-COR Biosensors produces the LI-190 Quantum Sensor, made specifically for measuring PAR and used in scientific photosynthesis studies. The operating temperature is from -40°C to 65°C at 0% to 100% relative humidity[89]. Atmospheric pressure does not affect the readings in any way. These sensors are made to last for decades, but it is possible that some factors could reduce accuracy over long periods of time unless the sensor is recalibrated. Causes such as high humidity and dust can give a measurement error of up to ±2% per year[90]. If general maintenance of the greenhouse is done, the sensors can easily be checked and recalibrated if necessary. Two sensors will be brought for each section of crops for a total of 24 sensors (3 wheat sections, 2 potato sections, 1 sweet potato section, 2 soy sections, 2 strawberry/tomato sections, 1 rice section, 1 peanut/lettuce section). With this arrangement, LED output can be tailored to the varying light needs of the different plant species. Each sensor will hang down near the leaves of the plants on levels one and two. Sensors on the highest level will be attached to the rim of the NFT trays. Sensors will have a slight tilt in the direction of circulation fans to prevent settling of excessive dust and pollen.

10.8 Ultraviolet Radiation

Although Mars is farther from the sun than Earth, its atmosphere is significantly less substantial, allowing UV radiation to sterilize the surface. Ozone in the Martian atmosphere is about 2% that of Earth's at best. As a result, Mars is subject to more radiation in the wavelengths from 300-360nm. However, carbon dioxide helps to absorb and scatter UV rays. For wavelengths shorter than 204nm, carbon dioxide absorbs a significant amount of UV light, and for wavelengths shorter than 190nm, it provides an effective shield. The effect of other gases in the critical wavelengths is negligible[36].

Another factor in the amount of surface UV radiation is dust, which also absorbs and scatters rays, mostly in the wavelengths between 200 and 220nm[37]. However, this effect is much more variable than the effect of atmospheric gases. While there is always some dust in the air, dust storms and weather phenomena cause unpredictable changes.

Ultraviolet wavelengths from 330nm and less can be potentially damaging to plants and humans. In general, plants have a higher tolerance to UV radiation than do humans. While a dose of 450 REM could be lethal for a human, a lethal dose for wheat is about nine times higher at 4022 REM. Potatoes, rice, and beans have even higher tolerances. Plant seeds have successfully been germinated and grown even after six years of exposure to cosmic radiation. There is no danger of plants becoming dangerous to the crew due to cosmic radiation; the FDA has approved the practice of irradiating foods[60]. Therefore, the restriction on UV dosages inside the greenhouse is that of crewmembers entering for maintenance purposes or a habitation module emergency.

The greatest amount of UV radiation not absorbed by atmospheric gases or dust is in the 300+ nm range, with less coming through between 200 and 300nm. The plants in the MDG can grow well with minimal filtration of UVC (200-280nm) and UVB (280-300 nm).

10.9 Redundancy

There will be two separate environments within the MDG divided by the airlock and a barrier wall that runs the length of the greenhouse.

The risk of pathogenic infection of the crops within the MDG will be minimized by chemical, radio, or thermal sterilization of the MDG prior to launch. Diversity of represented species will be the primary defense against the rare chance of pathogenic attack because few pathogens can destroy a wide variety of crops. In the event of a catastrophic pathogen, loss of pressure or other catastrophic failure of one half of the MDG, the barrier walls will protect the other half.

Systems for the circulation of water and nutrients, generation and circulation of atmosphere, harvesting and storage of the plants and even the valves that allow the flow of atmosphere from the growing area into the airlock will all be separate for each side of the greenhouse. In order to go from one side of the greenhouse to the other, the airlock must be depressurized of the atmosphere from one side, sterilized by high intensity light, and repressurized with the atmosphere from the other side.

11 Power System

Power for the Mars Deployable Greenhouse is based upon the following precepts:

- Power is mission critical
- Diversification and redundancy are a necessity
- Production of harmful byproducts should be avoided at all costs

- Heat production must be kept to a minimum to prevent the cooking of growing plants
- Integrating power systems with other systems to optimize resources would be ideal
- Power system should reflect the needs of the MDG and the philosophies of the team and NASA

With these precepts in mind, the power team undertook a case study to investigate the options for power production. The results are shown in Table 22.

Due to the conditions on Mars, the duration of the mission, and the needs of the team, it is likely that RTGs will be the primary power supply, with fuel and photovoltaic cells as auxiliary and backup power.

The needs of the team are essential in designing the power system for the MDG. Despite using the most efficient systems available, the greenhouse requires an enormous amount of power. This is mostly due to the lighting system necessary to provide plants with sufficient energy to carry out photosynthesis. The breakdown on energy needs for the greenhouse is shown in Table 23.

The total energy needs are, at maximum usage times, approximately 46kW. For guaranteed energy availability, however, power production of at least 50kW should be maintained at those peak times. Peak times of growth and harvesting directly precede and coincide with times of astronaut occupation, for a total intermittent time of six years of habitation.

11.1 Transport, Landing and Deployment

A one time power usage of 1kW is necessary for the launch, landing, and decent phase. Energy the begin production of water and communicate initially is also needed before full operation begins. Therefore, some source of energy must be available before the greenhouse has landed. Radioisotope Thermoelectric Generators produce a steady stream of energy from before the greenhouse leaves Earth, which can be used to meet this need. As part of deployment, the doors on the top hemisphere will be opened to reveal solar panels on their interior while at the same time exposing the windows to sunlight.

11.2 Initialization of Power Systems: Water Production

Water is essential to the function of the MDG. While the obvious necessity of providing water for plant growth is important, the power for all the systems of the MDG to run at full capacity are dependent upon H_2O.

Several options have been examined for the production of water in-situ. The two most promising are Zirconia electrolyzers (ZE) and Sabatier electrolyzers (SE). A trade study has been performed, and the results are shown in Table 24

	SE	ZE (kW)
O_2 production	0.48kg/day	0.15kg/day
CH_4 production	0.24kg/day	0.00kg/day
Power	0.12kW	0.25kW

Table 24: Water Production Options[97]

It is most likely that a Sabatier Electrolyzer will be used, as it is more energy efficient, produces more water per unit of energy, and does not require high temperatures as with ZE. The reaction to produce water is as follows:

$$4H_2 + CO_2 \underset{cat}{\longrightarrow} CH_4 + 2H_2O$$

Therefore, it is only necessary to bring hydrogen[97], because carbon dioxide is easily obtained from the Martian atmosphere. There are several ways in which this might be done. Hydrogen can either be brought in a liquid state, compressed gaseous state, or as a component of another compound, such as sodium borohydride. Case study appears in Table 25.

Therefore, it is most feasible to transport a large quantity of sodium borohydride to Mars, as it is an innocuous, unreactive powder. Once dissolved in water, it can be pumped over a catalyst to release pure hydrogen. The reaction is as follows:

$$NaBH_4 + 2H_2O \underset{cat}{\longrightarrow} 4H_2 + NaBO_2$$

	Historical Uses	**Watts/kg**	**Reliability**	**Weaknesses**	**Advantages**
Radioisotope Thermoelectric Generators (Plutonium 238)	23 space missions, including Mars landers	5 to 7	no moving parts	alpha particles expensive	extra heat
PEM Fuel Cells	prototype autos, home generators, hospitals backups, and other systems	5000[1]	degradation of membrane	bring fuel	clean
Photovoltaic Cells	Used terrestrially and in space	40	moving parts to deploy; dust storms and high OD[2] on Mars	requires energy storage for night period	inexpensive, no by-products
Scarlett Solar Arrays	Deep space probes	5 to 7	moving parts to deploy; dust storms and high OD on Mars	requires energy storage for night period	expensive
Nuclear Fission Reactors	On Earth and also a Reference Mission element	100-3000	moving parts	alpha particles expensive	extra heat

Table 22: Power Options

	Landing	Deployment	Hibernation	Growth	Harvesting
Landing	1.00	0.00	0.00	0.00	0.00
Nutrient Delivery	0.00	0.00	0.00	0.60	0.60
Waste	0.00	0.00	0.00	0.00	0.06
Harvesting	0.00	0.00	0.00	1.30	1.30
Misc. Bus	0.00	0.00	0.50	0.50	0.50
Water Production	0.00	0.00	0.12	0.12	0.12
Lighting	0.00	0.00	0.00	42.00	42.00
Comp/Comm	1.00	1.00	1.00	1.00	1.00
Total kW	**2.00**	**2.00**	**1.62**	**45.52**	**45.58**

Table 23: Power Needs

	Nuisance Factor	**Mission Danger**
Gaseous	High - large, highly compressed tanks	Medium: flammable
Liquid	High - coolant system required	Medium: flammable
Bonded	Medium - requires reaction to release H_2	Low: completely innocuous

Table 25: Hydrogen Storage Options[96]

The result is hydrogen and dissolved sodium borate. Water can be distilled from the sodium borate and re-fed through the system. The hydrogen, after being reacted with the CO_2, will release more water and CH_4. This water can be recycled back into the system to dissolve more $NaBH_4$. Once a critical mass of water has been produced, fuel cells may be brought online.

11.3 Strength in Diversity: The Power Triangle

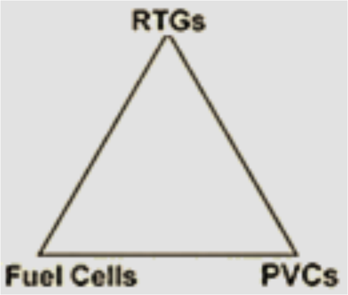


Figure 3: Power Triangle

11.3.1 Radioisotope Thermoelectric Generators

RTGs have powered every manned mission for NASA. As a passive way of harnessing the heat of atomic decay, they are incredibly reliable, generally all have an effective lifespan of 25 years. Most are powered by Plutonium 238 and rely upon the Seebek effect of non-uniform conductancies to produce electricity across a temperature differential. It is possible that a Stirling Engine Cycle could be used instead to harness this temperature differential, as it is two to three times more energy efficient.

Since NASA uses RTGs on such a regular basis, they have reached a point of modularization, where each system does not have to be individually designed for a mission. The standard stack of 18 RTGs produces 5.4 kW, measures 1.14m x .41m x 7.38m, and has a mass of 1.008 metric tons. The size significantly limits the number of stacks – four stacks will be used in the MDG. While this would not be sufficient energy to run the entire MDG in the case of a massive fuel cell failure, it is possible that using mini-Stirling engines would double the power output to approximately 44kW, nearly enough to run the entire greenhouse.

11.3.2 Fuel Cells

Fuel cells will comprise a great deal of supplementary and backup the power for the MDG. Their minimal size, lack of harmful byproducts, and ability to be linked with the biology system are great advantages. However, because significant quantities of fuel must be brought to run them for prolonged lengths of time, they do not make a good primary power source. Two types of fuel cells are currently under investigation.

Direct Methanol Liquid-Feed Fuel Cell: This cell uses the following reaction:

$$CH_3OH + H_2O \rightarrow 6H^+ + CO_2 + 6e^-$$
$$\frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_20$$
$$CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2 + 2H_2O$$

This produces six spare electrons which must complete the circuit of the greenhouse before being reunited with their hydrogen ions, which have jumped the membrane in the fuel cell[93].

The Direct Methanol Liquid-Feed Fuel Cell (DMLFFC) produces carbon dioxide, which is essential to plants and water production, and which is also very common in the Martian atmosphere. Venting it out of the greenhouse would pose no harm to the astronauts, greenhouse or planet. Water produced would be recycled through the plant nutrient delivery system, and much would be recaptured with a condenser in the humid greenhouse.

Each 5kW DMLFFC measures 131 cubic centimeters, and weighs less than 1kg. It has a lifespan of 2000 hours, which requires that they be changed at least four times per year[93]. Therefore, for six years of habitation, 240 fuel cell stacks must be brought to meet all the power needs with one method. For the minimal power needs of hibernation (the other 14 years), another 56 fuel cells must be brought. The total volume and mass is 4.625m^3 and approximately 296 kilograms. Of course, this does not include storage systems for bringing hydrogen, methanol and storing a constant supply of the 3% methanol solution.

Sodium Borohydride Fuel Cell: While relatively similar in use to the DMLFFC, the Sodium Borohydride Fuel Cell (SBFC) has some marked advantages. The reaction is as follows:

$$NaBH_4 + 2H_2O \rightarrow 4H_2 + NaBO_2$$

With the hydrogen separated from the rest of the compounds, it is passed through the fuel cell, which separates the positive hydrogen ions from their electrons, which must travel the MDG power grid before being reunited with the hydrogen and oxygen to produce an output of water. The only other results are heat and $NaBO_2$ (sodium borate), which is the harmless substance most commonly known as borax soap[95].

The advantage to using "Borax Cells" is the stability and storage properties of sodium borohydride. When bonded to borax, hydrogen produces a white powder which is generally non-reactive and easily maintained. Normal methods of transporting hydrogen require massive pressurizers and/or cooling mechanisms - sodium borohydride can be kept in a relatively simple storage unit. It is only in the presence of the catalyst that hydrogen is released, and when the catalyst is removed, the reaction ceases[96].

When in use, the sodium borohydride is dissolved in a water to a 44% solution. As such, it yields approximately 5kWh/liter (kWatt hours per liter). Since the majority of the water will be produced upon reaching Mars, the amount of sodium borohydride to bring on the mission must be calculated based upon undissolved powder. Each cubic meter of sodium borohydride powder stores 11,000kWh. Each kilogram of sodium borohydride powder stores 9300kWh. Therefore, each kWh of fuel brought will require 9.09×10^{-5} cubic meters and 1.08×10^{-4} kilograms. In order to provide the last required 6kW of power during peak times, 315,576kWh must be produced. Therefore, fuel cells will require another 28.7 cubic meters and 33.9kg [106].

Furthermore, the property of DMLFFC which causes them to degrade so quickly is linked to the corrosive properties of carbon monoxide on the platinum membrane. With no possibility of creation carbon monoxide in this reaction, it is surmised that the effective life span of the fuel cells would significantly increase, decreasing the number of cell stacks necessary to power the mission. This is an area which merits further investigation.

11.3.3 Solar Array

Of all options considered, a solar array takes best advantage of natural resources afforded us. However, with the significant disadvantages inherent in solar energy on Mars, the mission should not depend upon them, nor should too much be invested in making them work.

Factors working against solar cells are significant. There is approximately half the ambient light on Mars as there is on Earth. In general, solar panels work best when angled towards the sun. The Martian environment, however, mitigates the importance of this: on clear days (OD of 0.4), indirect sunlight constitutes 30% of the total light reaching Mars's surface; in a dust storm (OD of 6.0), 99% of the sunlight reaching the Martian surface is indirect[59]. This means that a large, planar array is better than a small array with a sophisticated light focussing or sun tracking system. Severe dust storms and nighttime make power production unpredictable. While they are very lightweight, expanding solar panels to cover sufficient surface area is difficult and not worth the effort.

However, advantage of spare surface area on the exterior of the MDG must be taken. When the hatch on the top of the MDG is opened to expose windows there to sunlight, the inside of those hatch doors are exposed skyward as well. There are 110 square meters available for the tiling of solar cells, which are approximately 25mm thick. PVCs will not make a huge impact on the power resources of the MDG – perhaps 1kW [68] with current technology – yet this could be critical in an unexpected situation.

12 Materials Handling

12.1 Harvesting Techniques

There will be two types of harvesters to handle the two crop types. Most of the greenhouse will consist of long trays of wheat, rice, and lettuce which start growing at one end and have matured by the time they reach the other end. The most difficult crops to harvest are the strawberries and tomatoes. Therefore, it was apparent that a minimum of two categories of harvesters was required for the greenhouse. The first would harvest the wheat, rice, and other crops whose fruiting bodies are located uniformly on the plant; the second would harvest tomatoes and strawberries.

One of the first designs considered for the harvester for the tomatoes and strawberries was a Stewart platform, a lightweight overhead structure on which an arm and manipulator could be mounted. This would free the aisles for human access, and while the six-point suspension would require additional computing power to operate, it offered an enviable amount of freedom of movement. As the plans for the greenhouse changed, however, it became clear that the harvester would not have sufficient room to harvest, due to the placement of the LEDs.

Mounting the same arm and manipulator on a track instead would allow movement to be easily controlled, and the question was then whether it should be located on the floor, ceiling, or one of the shelves. A harvester attached to the sides of the shelves would most likely only be able to harvest one side of the aisle, so this was not seriously considered. While mounting it on the ceiling would have kept it out of the way, additional structural support would have been required, support that will be incorporated in the floor in any case for human access. Therefore, a floor-mounted track was chosen as the movement mechanism.

The robot will have a central body housing control systems. Located opposite the arm on the upper surface of this body will be a compartment that will provide space for harvested produce. The entire structure will rotate about the center, allowing the arm to reach farther to each side. The arm will have several degrees of freedom and support a Barrett hand, small camera, and additional light. This will allow it to recognize individual fruits. In the palm of the hand are controls that allow it to exert an extremely light force and avoid damage to the fruit.

It will harvest strawberries, tomatoes, both types of potatoes and possibly soybeans from the lowest two sets of shelves. With its hand, this harvester will be able to place items into the processors and rover. It will have such delicate control that it can pollinate the tomatoes by shaking them and place strawberry runners in the tray. It will also transport bins of produce from the other harvesters. When it is not in use, the rover will stay near the food processing section. At that time, its processing power may be used to evaluate images from cameras above and determine the readiness of other trays for harvesting.

It would be preferable for this robot to harvest some of the soybeans green so that they may be eaten as edamame. Soybean pods, however, are extremely similar in appearance to the leaves and may be too difficult to distinguish without genetic engineering to change the color of the leaves or pods. Whether this is possible or not, mechanisms will be in place to harvest the entire bush when it reaches maturity.

A similar automated harvesting system consisting of a 2 axis transporter and 5 axis manipulator and gripper has been developed by Metrica for use in space facilities. Some of their advances may be used, such as the sheathing for the robot arm. The robots in the MDG, however, will not be needed for heavy lifting and should be considerably smaller.

Since potatoes are the only crops that will grow stationary, they will have the most unique harvesting system. The trays will be one meter wide, so the harvester arm will not be capable of reaching that distance. Instead, trays will tilt toward the aisle, allowing the potatoes to slide within easy reach of the harvester. The trays and their covers will be attached independently so that blades spanning the trays will sever the roots of the plants when the drawer-like trays are pulled out. When the trays have been pulled to the halfway point, the rover will pull down lightly on the handle, tilting the tray. This will cause the entire contents of the tray to slide downward. Guards will mechanically restrain the drawer from proceeding beyond a certain angle, and when it is empty, it will take little effort for the robot to return it to a horizontal position. The plants will also be removed down by the arm, and while they should be intertwined enough that most are pulled out together, the remainder may be dislodged by pulling out and tilting the drawer again; this will cause the cover to tilt as well. This system will require additional support in the corner of the structure, which will become a pivot point for the tray.

The other harvesters will be located at the end of each tray. They will run along horizontal tracks perpendicular to the trays and continuously remove the plants at the end of the tray. The harvesters themselves will not be large, but since they are on tracks, they will be capable of reaching all the plants on the meter-wide trays. It would have been possible to design harvesters that also moved up and down between trays, but that would have introduced another direction of motion.

Each harvester will be specifically designed for the crop that will grow in that tray. The wheat and rice harvesters will be very similar, but since the wheat is a different height, it will be adjusted accordingly. Both crops will be monitored for greenness in the heads, and when the crop is ready, stalks will be sheared off at the base and sheaves taken to the processor. The upper 4cm will be cut and stored in a bin and the remaining stalks taken to the inedible biomass storage unit. Lettuce harvesting will be far simpler, with a simple prong pushing the disc on which the lettuce was grown up out of the tray. The head of lettuce will then slide down within reach of the other harvester below. Peanuts will be the most challenging to harvest, as the peanuts themselves grow between two layers of the tray in a light-shielded zone. The plants themselves will be sliced off at the base by a simple moving blade, and a bar mounted on a second track will scoop them toward a place where they can be collected.

There will be similar mechanisms to clear roots and stalks from each growth tray. The plants should not adhere to the belt, and any remaining particles would be dried by the lights below before they reached the other end, making them even easier to dislodge. As an accumulation of this type of debris in the hot area above the lights would pose a fire hazard, it will be important to remove all debris with regular cleaning.

12.2 Crop Processing

All produce will be taken to the processing section at the end of each aisle next to the airlock. Some of the crops will merely be stored there in a refrigerated section, but there will also be machinery to grind the grain and other capabilities as determined by the menu that is planned.

None of the produce will be washed at this point. While the crew will wish to rinse them in a hydrogen peroxide solution, this will be most effective directly prior to consumption.

Some of the space will be used to sprout soy and wheat in order to increase the amount of fresh vegetables the crew will receive. Two trays will be located on the top of this section as close to the end as possible in order to benefit from natural light, and a small amount of supplemental lighting will be provided as well. As they take a very short time period to grow, the sprouts will be one of the most flexible crops in the greenhouse.

Storage space will certainly have to be reserved for the potatoes, since they constitute the largest crop volume that will be harvested at once. Otherwise, as much of the produce as possible will be placed directly into the rover.

This section will have stored containers for shipping grain and small food items to the habitat. With the risk of contamination, none of these will be returned for reuse, so a very large number will be needed. These will not need to be insulated in any way since the temperature of the interior of the rover will be controlled.

A grain dryer could be useful to extend the storage life of grain or prepare it for grinding. It is unlikely that one will be needed, since plans currently entail multiple shipments each week and the grain will be sent to the crew fresh. It is inefficient to reserve space for a grain bin for the possibility that it will be necessary to have a reserve. If delivery cannot proceed normally for any reason, wheat can stay at moisture content levels of as much as 22% for 3-5 days. There is the possibility that a grain dryer would make grinding proceed more smoothly. A bin dryer would best suit the small amounts and strict energy use requirements faced in the MDG. Another alternative is aeration within the grain bin.

12.3 Crop Delivery Rover

The rover will have a major role both in deployment and the daily operation of the greenhouse. The team's model calls for the rover to be stored in the airlock during transit and deploy the experimental section and location markers. It will dock in the airlock whenever it is not in transit so that it can be loaded when produce is harvested. From there it will make 2-3 trips weekly to deliver the load. This rover will need to be specially equipped to deal with the severe conditions it will encounter on Mars.

12.3.1 Power

For simplicity's sake, the rover will be powered by a fuel cell. The 8000 hours at 5kW a fuel cell provides will allow it to operate on a single fuel cell for the entire length of the mission, although the amount used will be highly dependent on the distance the habitat is located from the greenhouse. For redundancy, another cell will be included as well. The water to power the cells will be supplied when the rover docks with the greenhouse.

While it is travelling, the rover will use over an order of magnitude less than the power that is available, but this will allow the addition of features that may make the rover more versatile. It will also allow the rover to maintain greater speeds and have additional power for computing and signal transmission. In the event it is needed to operate at night or is exposed to extreme cold, some of the excess power can be used for heat production. Martian temperatures fall to as low at -110°C at night.

12.3.2 Navigation and Control

While much will be known about the landing site, the robot will need to be able to move independently in order to place the experimental section and find its way to the habitat. It will be travelling relatively long distances over uneven terrain whenever the greenhouse is in operation. It is also reasonable to assume that its path will not be direct.

As much of the software and navigation controls as possible will be derived from the *Sojourner* and the 2003 rovers to lower development costs. This rover will be equipped with the same combination of 5 laser stripe projectors and 2 CCD cameras. They will be mounted on the front of the vehicle at the upper edge of the cargo container. The abundance of power, however, allows the use of a real-time, multitasking system architecture, and these cameras will be monitored constantly so that the rover can maintain a reasonable speed. The array will be mounted on a platform that tilts, allowing the rover to survey the foreground when it is moving slowly and look farther ahead when it is moving more rapidly. Other obstacle detection mechanisms will include potentiometers and a sensitive bumper.

Once the optimal route has been found, the rover will deposit transmitters to be used as waypoints, reducing the amount of computing power needed for navigation and increasing the speed it is able to travel at. The rover will use dead reckoning as a redundancy measure, and to recall and identify areas that are extremely rough so that it can slow down.

In order to reduce the possibility of contamination and prevent the loss of air into the non-pressurized airlock, a close match with the hatches is needed, and the rover will need to be able to find its precise location within the airlock. While most of this can be done with locators implanted in the walls, the rover may also need to make use of its camera.

12.3.3 Telecommunications

This will use the same radio modem and radio whip antenna as the Sojourner. The primary advantage of this choice is that it is a proven technology on the surface of Mars, but it also consumes low amounts of power and required a small amount of volume and mass. The primary disadvantage is that it has a limited transmission range (approximately 500 m), but continuous contact is not necessary. This system will be used to alert both the greenhouse and the habitat of its approach, and possibly to transmit data from the cameras. If a more powerful communication system is desired, other systems exist which have been designed for relay communication across many kilometers in space.

If the rover is not operating on its usual schedule, which may occur if crops fail to ripen on schedule or the astronauts are too busy to unload the rover when it arrives, the habitat or MDG can send a message to the other when the rover departs. If the rover malfunctions out of the range of both and does not arrive when expected, the astronauts can be notified in a timely manner so that it may be retrieved.

12.3.4 Mechanics

The rover will derive some features of the *Sojourner* rover from the *Pathfinder* mission to streamline production efforts. It will use the same rocker-bogie system to maximize its mobility in uneven terrain. Each of its six wheels will be independently powered, and four will be independently controlled. With this arrangement, the rover will be able to turn in place and surmount obstacles larger than its wheels.

On the platform, there will be the box in which the food will be placed during transit, fuel cells, and sensing equipment. This box will be shielded from radiation and insulated so that it stays between 4 and 10°C. A few removable compartments will be available to hold containers of flour, other processed foods, and small items such as tomatoes. This compartment will be insulated with aerogel and have an interior volume of 0.15 cubic meters. It will actually be divided into two sections corresponding with the two sections in the greenhouse, and each of these will open independently to prevent contamination. As an additional measure to prevent microorganisms from travelling from the habitat to the greenhouse, the interior will be sterilized with UV light each time it is used.

The upper surface of the food compartment will be flat, allowing the experimental section to be stored there in transit. Springs to push the experimental section clear of the rover will be placed toward the front.

12.4 Resource Recovery

With all of the nutrients necessary for the mission easily stored within a few square meters, there is very little reason to implement resource recycling. Because of contamination issues and the goal that the MDG be as self-sufficient as possible, neither liquid or solid astronaut waste will be used in the MDG.

Unused biomass cannot simply be tossed out of the greenhouse because of the risk of environmental contamination. The use of a bioreactor in the MDG is also improbable due to the high energy demands of current technology bioreactors and other abundant sources of CO_2. Large-scale composting is impractical in the MDG because it requires the addition of several different kinds of bacteria which may escape into the greenhouse and may not survive the trip to Mars. The concept of a small experimental compost system in the MDG was also discarded because of the relatively large critical mass necessary to initiate composting.

Most unused biomass from the crops, such as roots, will be put into a chamber along the outside wall of the MDG. Once sealed inside, a compressor pump will remove all of the pressure to reclaim as much moisture as possible. The chamber will then be cooled by a piece of metal that will conduct heat from the chamber out to the Martian environment. The cold temperature and near 0 pressure inside the chamber will prevent bacteria from forming on the biomass.

13 Communication Systems

In the design of the radio communications system that will link the MDG to targets both as near as its own rover and other elements of the reference mission, to communication with the ground team via NASA's Deep Space Network, the fundamental goals of simplicity and reliability were established in the design of the CCDHS. Therefore, particularly in view of the strong selection of commercial off-the-shelf (COTS) technologies available, it was decided that this subsystem would rely solely upon such less expensive and proven COTS technologies. This affects cost savings in design, development, and testing of new technologies and mission-specific support systems, as well as assuring the pre-qualification and proof-of-technology of the components for space use.

13.1 Command and Data Subsystem

This consists of the central processing unit that receives data from various external sources (i.e. subsystems, earth command, etc.) and controls all aspects of greenhouse operations upon the basis of this information. It also formats data for downlink and processes digital uplink data. This subsystem contains two primary components:

13.1.1 Data Logging

A solid-state data recorder developed and qualified for space use will be used to eliminate the need for continuous real time communications. By storing and processing data internally during radio blackout periods and between downlinks it is possible for the mission to utilize the beacon-monitoring technology demonstrated on *Deep Space 1*. Thus communications expenses and load placed upon the DSN system will be minimized.

Three solid-state recorders were evaluated for compatibility with the mission (Table 26). As it is desired to minimize the number of telemetry sessions with DSN as much as possible, and as a large number of complex sensors will be used in conjunction with a high degree of system automation, substantial storage capacity upon which to store the sensor data upon which the automation will depend is required. BAE Systems' SU-214G was selected upon the basis of its large storage capacity, internal redundancy, error correction, and reliability.

13.1.2 Computer

Due to the degree of automation desired in operation of the MDG a fundamental goal of scalability and performance was established for this subsystem. Therefore, to accommodate proven automated control technologies and such as Remote Agent and future iterations of this and similar software, it is advised that only flight computers based upon chips operating at speeds over 100MHz be considered candidates for the mission. The current primary drawback of these chips is their unproven track record. However, further testing and proof-of-technology should be completed well in advance of the reference mission launch date, and allow the resolution of all issues with their use.

The harsh conditions of space require use of a radiation hardened (RH) processor qualified for and proven in space. Unfortunately, original development and adaptation of such processors from commercial production lines is slow, and radiation hardened processor speeds currently lag several years behind their commercial counterparts. Other key factors in the selection of the flight computer are ease and diversity of interfacing for the acquisition of data from the large number and variety of sensors necessitated by the target degree of automation. Software compatibility with the Flight Linux project is also considered to be desirable.

Several flight computers, some existing-others still under development based upon either the RAD750, Sandia Pentium, or PowerPC 603e were considered for use in the design of the MDG. The X2000 Mission Data System (X2000 MDS) based upon the RAD750 and currently under development at JPL, was ultimately selected. It was selected on the basis that the X2000 design goals of modular, powerful, and versatile space computing coincided with the needs and goals of the Olin Marsport Team, and the perceived high reliability of its development and delivery in time for launch of the MDG. The X2000 MDS was

Manufacturer	BAE Systems	Alcatel	CSE
Model	SU-214G	SSR 120	EOS-AM SSR
Capacity	214Gbits	120Gbits	160Gbits
Life	5 yrs	7 yrs	5 yrs
Reliability	.99	.98	.92
Error Correction	Yes	No	Yes
Power (W)	110/75/40/15	160/80/30/NA	N/A
Mass	36Kg	25Kg	
Volume	.052m^3	.22x.223	
Redundancy	Full	Hot/cold interface & control	No single point failures

Table 26: Data Logging Systems

contracted for use in 5 missions, including the *Solar Probe*, *Mars Sample Return*, *Europa Orbiter*, and *Pluto/Kuiper Express*. As all missions were scheduled for launch prior to the earliest possible Reference Mission launch (2011), the full development of the technology in time has been deemed low-risk by the team.

13.1.3 Software

To achieve the desired degree of automation in the MDG, and to most effectively exploit the advantages of beacon-monitoring technology, highly sophisticated automation software is required. The Remote Agent software tested on *Deep Space 1* is a prototype of the sort of technology that is envisioned. Environmental controls, and day-to-day operation of all subsystems will be entrusted to software controls. Unique emergency situations and initial deployment will reside in the hands of ground control.

Funding from the MDG mission should be used to finance additional research into the area of automated control systems and into the development and testing of the specific software needed for the mission.

One of the primary issues in the design of the CCDHS was the relatively short service life of available components. For solid-state data recorders, the proscribed service life ranged from 5 to 7 years. During the course of a 20 plus year mission throughout which parallel operation of a backup system must be assumed, this would necessitate the incorporation of as many as 12 data recorders with 5 year operating lives. This statement assumes negligible degradation in life expectancy in non-operating systems upon the basis of the majority of degradation being linked to power and thermal cycling during use [101].

As the issue of component service life is of great import in all aspects of the reference mission, and to prevent unnecessary mass and fuel expenditures, it is advised that research into the development of highly durable CCDHS components be sponsored and budgeted into the cost of the Reference Mission. Due to the universality of the issue, the costs of this development will be distributed appropriately among the various mission elements, and should not constitute a great portion of the MDG budget.

13.2 Telecommunications Subsystem

In the design of the TCSS, the availability of a Comsat constellation providing global coverage of Mars, which will in turn interface with an aerostationary, high data rate communications satellite that will relay data to Earth was assumed [101]. This greatly simplifies the design of the TCSS in relation to the previously assumed in need for independent communication capacity.

As the operating frequencies and other specifications of the Comsat constellation are currently unknown, an optimal configuration for the TCSS may not be determined at this point. For the purposes of mass, power, and space estimates, certain assumptions were, however, made. The system required is assumed to be comparable to other high-reliability, high data rate satellite communications systems on earth, such as that aboard Air Force One.

Due to the criticality of the communications subsystem, all components will be cross-linked and fully redundant. Should the issue of technological service life arise, it will be addressed in an identical manner to that used in the data handling system.

13.2.1 Beacon Monitoring

Reliance upon the beacon monitoring technology demonstrated on *Deep Space 1* will be used to minimize the load placed upon the Deep Space Network (DSN) while retaining a measure of safety comparable to that of more constant radio contact or lock. Its use is particularly well suited to the MDG during the extended periods of hibernation in the MDG's operation. With the cost of a 1-hour telemetry session with the DSN peaking at over $1,000 per hour, the ability to fully monitor the craft using smaller dishes at a cost of only $100 per day contributes substantially to the economy of long-term missions such as this [107]. The signal protocol to be used in the beacon monitoring of the MDG is described in Table 27.

Subcarrier Signal	**Message Conveyed**
1	All systems healthy
2	Contact for data downlink or minor error within 2-4 weeks
3	Minor error-establish 2-way within 1-2 weeks
4	Critical error-establish 2-way communication ASAP

Table 27: Beacon-Monitoring Protocol

14 Conclusion

The first generation Mars Deployable Greenhouse presented in this Preliminary Design Review is a key step towards a Martian future. Technologically "simple" and highly automated, the MDG augments the diet of the first crew to set foot on Mars with fresh, healthy produce while using no additional mission elements and requiring no crew time.

The team recognizes that there are technologically more advanced ways to solve the MDG problem, which may require reduced launch mass and volume. However, these solutions are all dependent on experimental technologies that are not ready for use in a manned mission with a requisite life span of 20 years. Consequently, the MDG proposed is the best, most reliable system for a first generation greenhouse.

The MDG will play a valuable role in the daily lives of the first crew. These six astronauts will benefit psychologically from fresh produce in their diet. Technologies used in this greenhouse will also be of use to future long-term space missions, as astronauts may one day venture out on missions of durations that make bringing all the necessary rations impractical.

In addition, the results of the experimental greenhouse will help pave the way for the next generation of Martian greenhouses. These will be essential for larger-scale and longer-term Mars missions. Until such a time as these next generation greenhouses are ready, for at least 20 years, the MDG will continue providing Martian explorers with fresh produce.

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A Mission Timeline

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
2011	●							
2012	●							
	●							
			●					
			●					
2013								●
								●
								●
								●
2014				●	●			
		●			●	●		
		●			●	●		
		●			●	●		
2015		●			●	●		
		●				●	●	
								●
								●

1. MDG Transit
2. Crew Presence
3. Initial Water Production
4. System Startup
5. Planting / Growth
6. Harvesting
7. Shutdown
8. Hibernation

B Landing Sites

The team recognizes that considerations other than those most advantageous to the successful operation of a greenhouse will determine the location of early Mars outposts. Nevertheless, in the spirit of total optimization, the team has devoted some attention to site selection because some of the advantages for a greenhouse may also pertain to the program as a whole. A number of sites were considered for the MarsPort base, with three studied in detail. Factors of the greatest weight were feasibility of landing, scientific interest in the site, and, unique to a greenhouse, the availability of ambient light (i.e. no mountains that would obstruct sunlight). Sites with relatively smooth terrain also were important, so that a sizeable base could be established without requiring significant levelling or grading of the surface. The three candidate sites are Gusev Crater, the Valles Marineris, and the Elysium Paleolake Basin.

B.1 Gusev Crater

The first potential landing site studied was Gusev Crater, 13° S, 183° W (Figure 4), at the mouth of the Ma'adim Valis. The light here should be more than adequate for plant growth due to its equatorial proximity; the crater walls should not cause any significant additional shading of the greenhouse, as the site would be a few kilometers from them. Since the Gusev Crater was formed from the impact of a meteorite, it can be safely assumed that the ground will not collapse from under it. The crater's 150 kilometer diameter allows for a great deal of error room in landing, as just about anywhere within the crater is a safe place to touch down, though maintaining a safe distance from crater walls is important. The crater has a depth of 1600 meters[7], which offers some shelter from weather occurrences outside of its bounds. The ground is, however, slightly inclined, which could prove to be a difficulty in landing [5]. The walls, though themselves of interest, also limit the mission. Expeditions outside the crater (well within the range of the rovers described in the Reference Mission) would be hindered by this formidable obstacle. This crater is not yet an official landing site for any future Mars mission.

Researchers have created a theory of the history of the Gusev Crater, suggesting that its location at the mouth of the Ma'Adim Valley would have caused it to become the basin for many floods. From preliminary observations, scientists have also found indication that there exists sedimentation in the area. Scientists, intrigued by this evidence, are trying to further research it. Other research potentials at this site include prospects in exobiology – if there was once life on Mars, it is a strong possibility that the sediments in Gusev Crater contain fossils. In 1995, NASA named Gusev Crater a high priority for biological exploration [8].

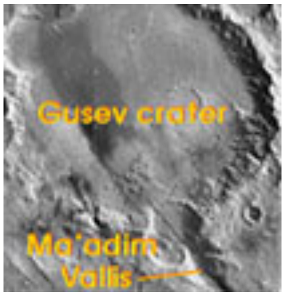

Figure 4: NASA photo showing Gusev Crater and the Ma'Adim Vallis

B.2 Candor Mensa / Vallis Marineris

The second outpost location studied was Candor Mensa / Vallis Marineris, 5.5°S; 74.5°W (Figure 5). Again, due to equatorial proximity, lighting would be excellent, but shadows from cliffs near the landing zone might cause shading of the greenhouse.

Although there exist some flat areas on which to land, there would be little room for error, as steep cliffs and dropoffs await. However, if landing were successful, this site would provide the best protection from dust storms as well as the greatest scientific value among sites considered.

The large chasms in Valles Marineris may be of great scientific value. Since the walls of some of the troughs reach as high as seven kilometers, a great deal of Martian history can be learned from studying the different layers of rocks[6]. Specifically, the rocks in and near Candor Mensa are particularly young (most likely from the Late Amazonian age [9]), and probably came from local volcanoes. Attaining samples of these volcanic rocks, and studying their makeup and origins, may lead to the discovery of the thermal history of Mars. Furthermore, material from nearby dunes could verify the existence of volcanic vents Mars. The extremely convenient location of Candor Mensa would also allow most of these samples to be obtained through the use of rovers and balloons, and would not require extensive resource-consuming treks. The greatest disadvantage to Candor Mensa (and the rest of Valles Marineris) is clearly the dangers in landing a craft in or near the chasms. Any small mistake could translate to the crashing of a vehicle, and a devastating failure of the mission. Also, there is the slight possibility that a nearby volcano could erupt, as recent studies indicate that Mars may still be geologically active[13].

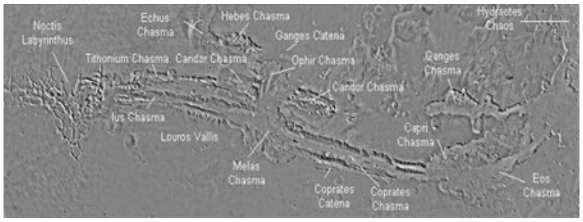

Figure 5: Map of the Valles Marineris

B.3 Elysium Paleolake Basin

The third and final site considered to date is the Elysium Paleolake Basin, 5°N and 197°W (Figure 6). Ambient lighting is adequate.

The basin is a moderately safe place to land, but probably not a good location for a large building. Although it looks flat, the ground is most likely fairly rough, and may include "platey" and flow-like textures[11]. Since the area is relatively flat, complications with hills should not be a problem. However, being in such an open location also leaves any vehicle or building in the basin fully open to any wrath the weather can unleash upon it.

The Elysium basin is the only place on Mars where there is clear evidence that an outflow of water existed. Although the basin is one of the most recently formed on Mars, there is also evidence that shows that this basin's existence on Mars was intermittent. Such intermittency could lead to a great deal of discoveries about Martian climate and biology. It is possible that this basin, and its neighboring lake system, could have been the ideal location for life on Mars[12]. Also, since the basin was formed from volcanic activity, some studies on Martian volcanoes can take place. Treks of distances greater than 100 kilometers would be required to fully explore the basin.

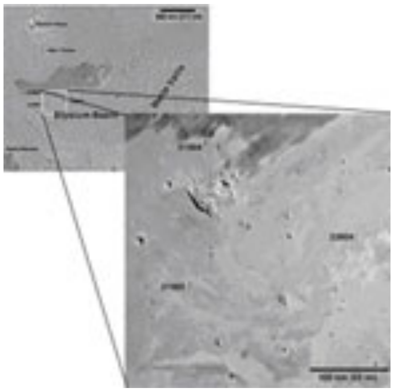

Figure 6: A picture of the general area around the Elysium Basin and a blowup of the potential landing area.

B.4 Role of Future Data

Information gathered by upcoming missions will contribute to the selection of a landing site for manned missions. The *Mars Odyssey*, currently in its aerobraking phase, carries a high resolution thermal emission imagining system (THEMIS) capable of identifying previously undetectable Martian features. These include hydrothermal vents and hot spots, buried ice, and carbonate deposits. If located, these features are likely be of high scientific priority for detailed exploration, as they are more likely to hold evidence of life than other areas may be. The *Odyssey* will also utilize a gamma ray spectrometer to measure distribution and quantity of 20 elements [10]. One example of the benefits of this study is that measuring hydrogen in the upper meter of regolith will assist in estimating the amount of water available to future missions.

In 2003, the *Mars Express* and its lander, the *Beagle 2*, as well as two Mars Exploration Rovers will be launched. The *Mars Express* mission includes an instrument called Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS), a ground-sounding radar used to locate subsurface water reservoirs [14]. The 2005 *Mars Reconnaissance Orbiter* can be expected to contribute even further to landing site selection with its 20-30 centimeter main camera [10]. The 2005 mission will be especially important in helping to select as level a landing site as possible for the MDG. A level, smooth landing site helps reduce complexity of the landing system and supports that are required.

C Compilation of Assumptions

There are a variety of assumptions that have been made in order to prepare this preliminary design review

1. The safety of the astronauts cannot be compromised.
2. Planetary protection is a high priority.
3. The primary contribution that an early greenhouse can make to the Mars program is to increase the quality of life of the colonists with fresh produce. The large fraction of their nutrition will be provided by pre-packaged rations.
4. Only proven technologies will be used in the early greenhouse. The exception to this assumption is that any technology required for the Reference Mission, developed or otherwise, is usable for the MDG.
5. Opportunities for new technologies and agronomy research that may provide more effective nutritional delivery to colonists should be accommodated in the evolutionary greenhouse.
6. Compatibility and interoperability with other Reference Mission elements is essential.
7. Systems should be multifunctional and of value to other mission components whenever possible.
8. Failure should be graceful.
9. Everything is a potential resource.
10. A global communication satellite constellation will be in place around Mars[101].
11. The "other significant payload" required if the Magnum launch vehicle is used[1] is also Mars-destined.

D Lighting Program

Potatoes, having the lowest light requirements, can be very productive on ambient light alone, even during a mild storm. During a large storm, they will not receive the optimal amount of light, but will have more than the minimum amount. No power is allotted for potatoes.

Tomatoes have the second lowest light requirement, but they have an extended 16-hour photoperiod, so they will only consume power at night or during a large storm. The nighttime allotment for tomatoes is four hours after sundown at 400 μmol/m^2/s, which consumes 6.56 kW. Like tomatoes, lettuce has an extended photoperiod. Their nighttime allotment is for 400 μmol/m^2/s for six hours before sunrise. During the day, the peak intensity for lettuce will be a total of 800 μmol/m^2/s. Wheat is a special case; it will ideally be exposed to a constant supply of light. With both the largest growing area and the highest capability to utilize light, wheat will need by far the greatest amount of light. It is planned to have 1250 μmol/m^2/s for the twelve hours of daylight and 1200 μmol/m^2/s of artificial light at night.

Aside from the crops just mentioned, all other crops will use light during the day only. Throughout the approximate twelve hours of daylight on Mars, each will have six hours of "peak" LED output (with the exception of wheat). This six-hour period is the time during which the LEDs will have enough of a power budget to run at their specified maximums. The first six daylight hours will be the peak time for rice and peanuts. The second six hours will be the peak time for soy, sweet potatoes, strawberries, and lettuce. Staggering the peak times in such a way lowers the maximum amount of power necessary by 11.7 kW. Base values and peak values of photon flux density are broken down by crop in Table 28. LED power allotments are such that crops are somewhat dependent upon incident sunlight. However, in the case of a complete blockage of incident light, the LEDs alone will be able to meet minimum requirements.

Setting a maximum power limit on the LEDs and depending upon sunlight means that light deprivation could potentially occur if there is significant blockage of sunlight. The only plants completely dependent

Crop	Time (hours)	Area (m^2)	Needs μmol/m^2/s		Peak Photon Flux W/m^2	Daytime Power Watts		Nighttime Power Watts	
			Low	High		Min	Max	Min	Max
Potato	12	4.0	150	250	63	0	0	0	0
Soy	12	16.4	500	1000	250	656	8856	0	0
Rice	12	9.2	600	1800	450	1288	12328	0	0
Peanuts	12	8.0		900	225	3520	3520	0	0
Sweetpotato	12	6.0		1000	250	3240	3240	0	0
Strawberries	12	3.0	300	500	125	0	120	0	0
Tomato	16	16.4	400	45	113	0	0	0	6560
Lettuce	18	8.0	400	800	100	0	2720	0	3200
Wheat	24	30.0	1200	1250	312.5	23700	23700	36000	36000

Table 28: Clear Day, 195W/m^2 ambient light

Crop	Time (hours)	Area (m^2)	Needs μmol/m^2/s		Peak Photon Flux W/m^2	Daytime Power Watts		Nighttime Power Watts	
			Low	High		Min	Max	Min	Max
Potato	12	4.0	150	250	62.5	0	0	0	0
Soy	12	16.4	500	1000	250	656	8856	0	0
Rice	12	9.2	600	1800	450	1288	12328	0	0
Peanuts	12	8.0		900	225	3520	3520	0	0
Sweetpotato	12	6.0		1000	250	3240	3240	0	0
Strawberries	12	3.0	300	500	125	0	120	0	0
Tomato	16	16.4	400	450	112.5	0	0	0	6560
Lettuce	18	8.0	400	800	100	0	2720	0	3200
Wheat	24	30.0	1200	1250	312.5	23700	23700	36000	36000

Table 29: Dust Storm, 115W/m^2 ambient light

upon sunlight are potatoes, which, because of their extremely low light requirement, will still grow during a global dust storm. All other crops will have support by artificial lighting. Enough power will be available at all times of the production cycle to meet minimum light levels of 50 W/m^2 on LEDs alone.

E Outreach Status Report

E.1 Olin College Outreach

As a new college, Olin is pursuing an aggressive and expansive advertising campaign for its own purposes that are easily redirected to supporting the Outreach mission of Olin's MarsPort team. It is in Olin's best interests to advertise its successes in this type of national competition. That more than half Olin's student body is participating in the MarsPort Competition provides further incentive for Olin to support its MarsPort team with its own resources. This effort has already born fruit and will continue well past the end of this school year.

E.2 Community Outreach

Olin's MarsPort team understands the importance of outreach both to the competition and to the college as a whole, this is why roughly 7 of Olin's team is currently involved in the outreach component of the project. Olin's prospective and current students, faculty and staff are very connected to and interested in the space program. The external community is therefore the focus of Olin's outreach program. The goal of this program is to excite people, who currently hold limited interest in space, about the idea of space exploration. Community outreach can be broken down into two segments: youth-focused and at-large. The team's website will serve as the focal point of its outreach efforts, though it is not the only method of content delivery that will be used.

E.2.1 Youth Outreach

The youth component of Olin's outreach campaign will be lead by Erika Brown, a prior member of MIT's NASA Means Business Team and the educational coordinator for the New England Mars Society, and 5 members of Olin's team who have developed expertise in developing engineering education materials for the JASON foundation.

The Olin MarsPort team's website provides a means of reaching students worldwide (though, in practice, the team's efforts will be limited to English-speaking students). The website will soon include models of the greenhouse outer structure created with CAD modeling software by members of the team.

A Choose Your Own Adventure Story was added to the website materials in December. This story is oriented towards students in grades 6-8, and follows the model of the popular book serious by the same name. In this story, the reader discovers that he, or she, has awoken in a strange unfamiliar location. This location turns out to be the surface of Mars. The reader is compelled to choose the paths taken by the main character and determine whether he will be rescued from the barren surface.

The primary focus of Olin's youth outreach is an educational kit for use in grades 4-8. This kit will provide assistance to teachers of these grades in the instruction of their students in space. This kit will have two components: interactive in-class learning activities and an online educational resource nexus for teachers. The interactive activities are created by the team and are intended to be operable with low financial overhead. Currently these activities include a solar light demonstration as well as planetary size and distance comparison activities. These activities allow the students to learn through observation instead of lecture. Other activities are currently being developed including a bingo game that will test students' knowledge about space, the sun, and the planets in our solar system.

The educational resource network will be a multiphased project. It's purpose is to provide "one-stop shopping" to teachers interesting in teaching material relating to outer space. The first phase will involve locating a wealth of existing educational material online and adding links to this material on the team website (projects.olin.edu/marsport). Then the team will provide overview summaries of each source of online materials as well as critically evaluating the content for usefulness. This will allow teachers to visit our website and get direct access to quality materials to assist in their instruction. It will effectively eliminate their wasting time searching for quality materials and for materials relevant to their subject matter.

This kit will be refined throughout the duration of this project with regular checks on each set of online materials to note new additions or any change in quality. These kits will be refined based on feedback received from instructors at both Pollard Middle School in Needham, MA and Roosevelt Middle School in Eugene, OR. Once the team is satisfied with the nexus and other materials, it will publicize these materials to a much larger educational community. The team has received support for this from Dr. Ioannis Miaoulis, Dean of Engineering at Tufts University, who has championed the introduction of engineering standards into the Massachusetts K-12 Curriculum Frameworks Program. This support will be useful in publicizing the team's materials and resources to the larger educational community.

The team is exploring assisting the New England Mars society in its Boy Scout Space Merit Badge program. The Mars Society has already developed materials for this use, but with Olin's help the distribution of these badges and training sessions will be able to increase. Therefore the support Olin's team is providing will be logistical in nature.

E.2.2 At-Large Outreach

The year: 2009.
The place: Mars.
The plotline: outrageous.
This is The History and Mystery of Mars.
(cue music)

The History and Mystery of Mars is a monthly radio drama written, performed, directed, recorded, edited, produced, and broadcast by the Olin College Marsport Team. The idea is simple, the narrative verbose, and the plagiarism apparent. The series has many purposes. First and foremost its purpose is to inspire interest in the stars above and the unknown world still yearning to be explored. Second, and only slightly less foremost, it seeks to illustrate that Olin College is not just an engineering school; it is a school driven by creativity and innovative ways of approaching challenges. Third, it is meant to make people laugh. Fourth, the series is meant to document the personal peeves of the authors, as any good parody would. Fifth, and perhaps most shrewd, it was intended to add an extra incentive for the judges to choose Olin College as a finalist, knowing that if they didn't, they would never hear the climatic series finale that will be the topic of conversation for months to come.

The outrageous plot is as follows: it is assumed that NASA actually plans to launch a deployable greenhouse, based on designs submitted to them in a student competition, to the planet Mars. It is also assumed that the planet Mars is inhabited by green bug-eyed monsters with antennae who live below the surface, and who have been aware of the existence of Earthlings for some time. The Martians are a significantly advanced race, but highly xenophobic. However, once they learn of Earth's manned mission attempt to Mars, they overcome their timidity and develop Operation Greeting, the Martian Unified Government's plan of making first contact with the Earthlings. Of course, as in most stories, things are not always what they seem.

The History and Mystery of Mars draws it's inspiration from great classics such as Douglas Adam's The Hitchhiker's Guide to the Galaxy and Orson Welles' War of the Worlds, and draws its fans from exotic places like New Jersey. It is hoped that by listening to the series, interest in space projects and the Marsport competition specifically will be spawned. It is also hoped that a small glimpse into the world of Olin College might be gained from the experience.

Currently the first four installments of The History and Mystery of Mars are available from Olin's Marsport website at http://projects.olin.edu/marsport. The remaining two installments, including the shocking finale, will be produced in April and May respectively. Efforts will be made to get college and online radio stations to play History and Mystery to their audiences. Babson College's radio station should be especially accessible to Olin's students.

Flower Show A key component of Olin's outreach plan is to spread the benefits of space exploration to those groups who may not appreciate the opportunities presented by such exploration. The crux of this effort is the creation of a booth at the New England Flower show, which is attended by 150,000 visitors.

Exposing horticultural enthusiasts to the importance of Mars exploration is a very different approach to outreach. It is worthwhile and important to educate the average individual about the prospects of Mars exploration and how useful such missions can be. The connection between what these horticultural enthusiasts do on Earth and the MDG allows for access to this previously uninterested group of individuals.

As part of the outreach efforts, Olin's NASA design team is working with juniors and seniors from Needham High School to plan and create a display booth at the New England Flower Show, held at the Bayside Exposition Center in Boston during March 16^{th} - March 24^{th}. One of the main goals of this project is to help create enthusiasm for Mars exploration in high school students. Due to a high level of interest on the part of the students, they have also contributed their skills as research assistants to Olin's team. Their research has included background research on launch vehicle payload mass and volume. Their participation in actual research for the project will enable them to be better-informed managers of the booth for the Flower Show.

These students are responsible for designing and creating the booth under the guidance of Olin's MarsPort team. A true understanding of all the important design topics is expected from the high school students, as they will be the ones manning the booth during the Flower Show in March. This is because all of Olin's students will be in France for the duration of the Show.

The booth will incorporate a large variety of information in a visually pleasing format. It will include many informational posters, a computer slide show of the CAD models of the greenhouse, sample plants grown using a hydroponics system, and a sample of simulated Martian soil, along with some detail handouts about the design competition. The posters will include such information as crop selection, nurturing and maintenance, greenhouse design, Martian soil and atmosphere, and general information on the design competition. There will also be a computer at the display booth that allows show visitors to browse the Olin MarsPort website and listen to the *History and Mystery* radio series.

In terms of press coverage, both Chris McArdle and Olin Director of Communication Joseph Hunter will promote the MarsPort booth at the Show. Dr. McArdle's assistance will include the creation of press packets to be sent to the hometown newspapers of the MarsPort team members. From Olin's perspective this outreach program will assist in the formation of a stronger bond between Olin College and the Needham community at large. This provides further incentive for Olin to help publicize the event and virtually guarantees local press coverage.

After the Flower show, the booth created for it will be modified slightly and then used in other venues as appropriate. The team has reached an agreement with Anthony M. Schilling, Operations Director, Unicco Integrated Facilities Services, to promote and host this display in a mall. The Boston Museum of Science has also expressed some interest in a display from us. Similar agreements are being sought for additional public displays. For both technical assistance and a possible outreach venue, the team also contacted Disney Corporation, which operates The Land greenhouse project at Epcot Center. They provided useful information, but cannot make any commitment to display our exhibits at this time.

Culinary Schools Connections are being made with culinary schools in the vicinity of Olin for a Mars bake-off event. The goal of this activity is to create competition for chefs to generate recipes using only ingredients that would be available to the astronauts on Mars. The recipes concocted in such a bake-off could be used to further increase the quality of living for the astronauts on Mars through creative and appetizing preparation of the MDG's crops. This competition will have prizes that will at least in part be financed by the payments provided by NASA for Olin's participation in the competition.

Olin College Olin College publishes a newsletter, *Innovations*, that is distributed to thousands of individuals including perspective students and those in the corporate world. The most recent copy of *Innovations* included an article about the NASA MarsPort competition and Olin's participation. Similarly the tabloid-style *O.V.A.L.* is sent to all students who have expressed interest in Olin College, and its second installment also included an article on Olin's MarsPort effort.

Other Colleges An article on Olin's MarsPort participation has appeared in the *Babson Free Press*, the student newspaper of nearby Babson College, and the team's collaboration with Wellesley College greenhouse director, G. Duncan Himmelman, will virtually guarantee similar exposure of the team's activities at Wellesley College.

External Publications A key component of Olin's MarsPort team's outreach effort includes gaining professional external press coverage. Chris McArdle, who is serving as team reporter, is a professional freelance writer whose articles have appeared most recently in the *Boston Globe*. She is working to increase press coverage of Olin's team and the competition itself, in this effort she is working with Olin's Director of Communication Joseph Hunter. The *Needham Times* wrote an article on the 31^{st} of January covering the team's achievements in getting selected as finalists. The Boston Globe has also published a small brief on the team's accomplishments. In terms of national coverage, The *Christian Science Monitor* published a story about Olin on February 5, 2002 that included information on the MarsPort competition and Olin's participation in it.

F Nomenclature

A: Date of First Crew Arrival
ALS: Advanced Life Support
AFT: Aerated Flow Technique
CCD: Charged Coupled Device
CDHSS: Command and Data Handling Subsystem
CDR: Conceptual Design Review
CELSS: Controlled Environment Life Support System
COTS: Commercial, Off-the-Shelf
DDR: Detailed Design Review
DRM: Design Reference Mission
DSN: Deep Space Network
EDL: Entry, Descent, and Landing
EFT: Ebb and Flow Technique
ERV: Earth Return Vehicle
EVA: Extra Vehicular Activity
FFT: Fog Feed Technique
ITO: Indium-Tin-Oxide
ISRU: In-Situ Research Utilization
LED: Light Emitting Diode
LEO: Low Earth Orbit
MAV: Mars Ascent Vehicle
MDG: Mars Deployable Greenhouse
MICAGG: Mars In-situ Carrier Gas Generator
MIP: Mars In-Situ Propellant Production Precursor
NFT: Nutrient Film Technique
NTR: Nuclear Thermal Rocket
OD: Optical Depth
PAR: Photosynthetically Active Radiation
PC: Polycarbonate PDR: Preliminary Design Review
PPF: Peak Photon Flux
RH: Radiation Hardened
RMT: Root Mist Technique
SAT: Static Aerated Technique
SE: Sabatier Electrolyzer
TCSS: Telecommunications Subsystem
TMI: Trans-Mars Injection
TWTA: Traveling Wave Tube Amplifiers
UV: Ultraviolet
ZE: Zirconia Electrolyzer.

G Team Biographies

Sean Munson, Project Manager. Since submitting a crude battleship design to the Navy in kindergarten, Sean has had his sights set on engineering. Over time, he developed a strong interest in aerospace, and designed a replacement for the space shuttle in seventh grade, the result of which he was able to present to NASA engineers at Marshall Space Flight Center. Sean attended High Technology

High School in Lincroft, New Jersey. During his four years at High Tech, Sean participated in the FIRST robotics competition, completed a research project in magnetic levitation and linear induction, and was an active student leader. Also an accomplished web developer, Sean has worked both as a consultant and at a medium-size video conferencing company. Sean is also an Eagle Scout and active as a Section Officer in the Order of the Arrow, Boy Scouting's National Honor Society. At the present, Sean is one of 30 Olin Partners helping to develop the college's academic program and student life before becoming part of the class of 2006.

Joelle Arnold, Power Systems. Joelle comes to Olin College from Middletown Springs, Vermont. Cocaptain and founder of her policy debate team at Rutland Senior High School, she has trophied in several regional competitions. High school achievements also include Junior Engineers and Technicians Society President and lead trombonist in RHS' state recognized Jazz Band. She has also been employed by SSESCO/Sage Physics and Engineering of St. Paul, Minnesota, where she uses computational fluid dynamics to model diesel engines. In the summer of 2000, she researched for SSESCO investigating the state of Acoustical Modeling software, a project for which she was recognized as and Intel Science Talent Search Semi-Finalist and a Finalist at the Northern New England Junior Science and Humanities Symposium. A staunch advocate of a "renewable" future, free time finds her listening to her favorite folk artists of SolarFest, wrestling with her collies and playing bridge.

Jessica Anderson, Outreach. Jessica, a graduate of the Valley High School and Academy in Albuquerque, New Mexico, became interested in astronomy and space while taking a basic Astronomy course during her senior year of high school. A dancer since the age of three, her passion for life spans a plethora of areas. She is intrigued by knowledge and plans to fervently study all she is able to during her career at Olin. The opportunity to be an Olin Partner is one she will feel gratitude for and dismay at forever, while acknowledging that without the support of her family and her faith in God she would not have been able to achieve all she has.

Katerina Blazek, Engineering. Kate is a graduate of Henry M. Gunn High School, Palo Alto, California, who originally hails from the Czech Republic. She was a member of the nationally ranked Gunn FIRST Robotics Team, where her specialty was creating pneumatic vice grips and devices to move balls. Kate also led the community outreach part of the team and headed the video production group. She spent her summer at Xerox Palo Alto Research Center (PARC) making a documentary about interns, doing production support, and learning about the virtues of caffeine and Macintosh editing systems. In her spare time, she translated a textbook about the methods of coloring glass and volunteered at Recording for the Blind and Dyslexic. Since coming to Olin College, Kate has concentrated on fielding questions and comments about her dyed-red hair and not getting lost in Boston.

William Clayton, Outreach Coordinator. Will graduated from Henry D. Sheldon High School, Eugene, Oregon, at the top of his class with an International Baccalaureate Diploma as well as an Honors Diploma. Will enjoys travelling and participated in the People to People Student Ambassador program between his junior and senior year. He was Sheldon's Outstanding Chemistry Student and Outstanding Mathematics Student during his senior year. Will was selected as one of the Franklin W. Olin College of Engineering's first 30 students, the Olin Partners. Outside the classroom William is interested in creative writing, reading, philosophy and computers. William is currently a founding member of the Needham Olin Technology Exchange, which refurbishes computers and provides them to primary and secondary school students in need, and is a staff writer for the *Babson Free Press*. William's interest in engineering can be traced back to his childhood when he spent much time building with LEGOs. He has always been interested in space and the concept of space travel. William is very interested in robotics and hopes to work on cybernetics and robot/human interaction throughout his career.

Susan Fredholm, Materials Science. Susan has always enjoyed math and science but recently became interested in materials science after attending ASM International's first Materials Camp in August 2000. When not doing academic work, she purses her life long passion for dance by continuing to perform, study and teach. She graduated from Alvirne High School in Hudson, New Hampshire, in 2001 and is very excited to be an Olin Partner.

Matthew Hill, Materials Science & Structures. Matt is a graduate of Oak Park and River Forest High School, where he was academically active as a member of both the Scholastic Bowl and Math teams. Outside of the classroom, he has also played varsity volleyball and earned national recognition for his artistic abilities as a potter. Currently, Matthew is one of thirty student partners at F.W. Olin College of Engineering who is working with faculty to develop the curriculum and student life for the college's opening in fall 2002. He continues to pursue his interests in art and athletics, and is a founding member and co-director of the Needham Olin Technology Exchange, a volunteer student group that refurbishes computers for needy area children.

Nicole Hori, Botany. Nicole is a resident of Honolulu, Hawaii and a recent graduate of Upper Columbia Academy in Spangle, Washington, where she started a science club. Nicole is currently an Olin Partner. For Nicole, work on the MarsPort project has become a lifestyle, offering opportunities for inside jokes and satisfying pure intellectual curiosity. Nicole is also a vegetarian who understands the challenges in creating a nutritional and appealing diet from plants. Her other research interest is in cell and molecular biology, and she intends to eventually find a career in biotech. This summer she traveled through Lima, Peru and San Francisco to Seattle, where she began a cross-country road trip that eventually brought her to Needham, Massachusetts. In her spare time, Nicole plays the guitar and enjoys visual arts.

Adam Horton, Botany & Engineering. A graduate of Essex Junction High School from Westford, Vermont, Adam was fascinated with advanced Biology and Botanical Science in high school. Adam's desire to tinker, build, and create have led him to undertake such tasks as designing and building the Geodesic dome he lives in with his family and restore a 1972 VW Beetle. Adam is also interested in symbiotic relationships especially in biological systems. Outside interests include acting, singing and helping to create Olin College.

Grant Hutchins graduated from Santa Fe High School in Edmond, Oklahoma. His interests include writing electronic music and learning about anything he can, especially cryptography and the history of computing. He made his first "animated movies" with a friend on his V-TECH Video Painter that he received for Christmas in third grade. He also enjoys playing many different musical instruments (none very well), and was the captain of his school's nationally competitive academic team. Grant's favorite experience was spending a month in Japan with his best friend Souichirou. Grant enjoys working with the MarsPort team while producing *The History and Mystery of Mars.*

Cheryl Inouye, Botany. Cheryl recently graduated from Pearl City High School in her home state of Hawaii. Her interest in the NASA competition stems from early childhood books such as *The Magic Schoolbus: Lost in the Solar System.* Cheryl enjoys science and helped to start her high school's Science Bowl Team. One of her first projects at Olin College, Biodiversity, sparked Cheryl's devoted passion for plants and ecology. When not studying, she likes to play music and practice martial arts.

Steven Krumholz, Outreach & Engineering. Steven graduated from Monticello High School, Charlottesville, Virginia, where he was not only captain of the chess and academic teams, but also was the student ambassador to his school's improvement team, representing the student body to the faculty and county Board of Education. He was on a state-ranking Odyssey of the Mind team, and was named the school's most outstanding student in both math and science. As a senior, he started a card game company with a friend as an independent study, and donated all of the company's proceeds to his school as charity. This extroverted, playful dreamer is currently one of the 30 Olin Partners. When not in school, Steven is usually found playing games, admiring penguins, or watching sports (especially hockey).

Daniel Lindquist, Outreach / CAD. Dan is a graduate of the Porter-Gaud School in Charleston, South Carolina, where he was an active member of the Faraday's Candle Science Club, Scholastic Bowl, and National Ocean Science Bowl Team. He also began a computer club which focused on designing a student run webpage for the student body. Dan's love of engineering, entrepreneurship, and all things computer related made Olin College, his current place of study, a perfect fit, and he is excited about contributing to the NASA design project.

Que Anh Nguyen, Outreach. Que Anh graduated from Andrew P. Hill High School in San Jose, California, where she was the battalion commander of her high school JROTC unit. During her high school years, she also held the office of class president, as well as served as Supreme Court Chief Justice. Que Anh's interests, besides leading and coordinating, includes everything from robotics, astronomy to swimming, singing and tennis. Her primary interests however lies in Engineering and Research. She spent her summers doing thin film technology research at the Advance Materials Laboratory in Albuquerque, New Mexico and working as an intern at IBM's office in San Jose. Que Anh is involved in the outreach efforts, focusing on coordinating the Mars display booth at the New England Flower Show.

Joy Poisel, Outreach. Joy graduated from Bloomington High School in Bloomington, Illinois. There she was actively involved with the Environmental Club and Scholastic Bowl. She was a medallist in the annual World Wide Youth in Science and Engineering (WYSE) and won multiple state medals at Science Olympiad competitions. Joy's interest in the stars grew from her love of Science Fiction novels and TV shows. Joy is currently an Olin Partner.

Nicholas Zola, Outreach Nick has wanted to be an astronaut ever since he was a kid, although originally it was merely for the chance to float around in free fall. Since then, he has a developed a keen appreciation for the vastness and complexities of space. He hopes one day to work for NASA; until then, he is resigned to devoting his time to research projects like this one, including an astrophysics research project on supernovae centered at Harvard University. Although Nick often finds himself on other planets during design competition meeting, his ultimate goal is to actually land on Mars someday. Nick graduated from La Jolla High School in San Diego, California, before coming to Olin College.

H Co Investigators

Stephen S. Holt, Professor of Physics. Dr. Stephen Holt, an astrophysicist, was previously the Director of Space Sciences at the NASA-Goddard Space Flight Center in Greenbelt, Maryland.

Dr. Holt received a B.S. degree with honors in Engineering Physics and a Ph.D. in Physics from New York University before joining the staff of the Goddard Space Flight Center. His primary research discipline is high-energy astrophysics, the study of the universe via the detection and interpretation of celestial X-rays and gamma rays. He has been selected to be Principal Investigator and/or Project Scientist on eight NASA scientific spacecraft, including joint missions with Germany, Japan, Russia, and the United Kingdom. He has more than 200 refereed publications in technical journals and scholarly books, and has been awarded the NASA Distinguished Service Medal, the NASA Medal for Exceptional Scientific Achievement, and the John C. Lindsay Memorial Award for Outstanding Science. He is a Fellow of both the American Physical Society and the American Association for the Advancement of Science.

Dr. Holt has served on numerous national and international committees such as the National Academy of Sciences' Space Science Board Committee on Space Astronomy and Astrophysics, the National Academy of Sciences' Panel on Science Policy, and the Executive Committee of the American Physical Society. He has been elected Chair of a number of scientific society venues, including the High Energy Astrophysics Division of the American Astronomical Society and multi-national Joint Scientific Program Committee of the World Space Congress.

An outstanding teacher and a lecturer, Dr. Holt has taught in both the physics and astronomy departments at the University of Maryland, and has been invited to make more than 100 major presentations at scientific society meetings and international symposia. Dr. Holt also serves as Director of Sciences and Professor of Science at Babson College.

2001. "Young Supernova Remnants," S.S. Holt and U. Hwang (eds), AIP Conference Proceedings 565, American Institute of Physics (New York).

2000. "The Next Generation of High Energy Astrophysics Observatories," S.S. Holt, in "IAU Symposium 195, High Energetic Physical Porcesses and Mechanisms for Emission from Astrophysical Plasmas", P.C.H. Martens, S. Tsuruta and M.A. Weber (eds), Astronomical Society of the Pacific, pp.5-13.

2000. "The X-Ray Remnant of SN 1987A," D.N. Burrows, E. Michael, U. Hwang, R. McCray, R.A. Chevalier, R. Petre, G.P. Garmire, S.S. Holt, and J.A. Nousek, Astrophysical Journal (Letters) 543, L149.

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Erika Brown, Graduate Student, MIT. Erika Brown is a graduate of Vanderbilt, where she received a BS in biomedical engineering. Erika is also a graduate of the International Space University's Summer Session program. She has worked for both Lockheed-Martin in Houston and Boeing in Huntsville, Alabama. Last year, she was a member of MIT's NASA Means Business team, which produced a project titled "2020 Vision." At MIT, she works in the MIT manned-vehicle lab investigating adaptation to artificial gravity systems for long duration space flight. She is the led for the MIT TransLife biosatellite project. She is the educational coordinator for the New England Mars Society, where she organizes educational events. She is also the Outreach Coordinator for bioengineering education for the VaNTH consortium. As Outreach Coordinator, she works on national K-12 outreach for biomedical engineering, including the development of curriculum to be used in grades K-12.

Woodie Flowers, Pappalardo Professor of Mechanical Engineering, MIT. In addition to his MIT position, Dr. Woodie Flowers is also a Distinguished Olin Partner. He received a B.S. from Louisiana Tech University and S.M., M.E., and Ph.D. degrees from MIT. His current research includes work on the creative design process and product development systems. He helped create MIT's renowned course "Introduction to Design." Dr. Flowers has received national recognition in his role as host for the PBS television series *Scientific American Frontiers* from 1990 to 1993 and received a New England EMMY Award for a special PBS program on design.

He is a member of the National Academy of Engineering, a Fellow of the American Association for the Advancement of Science and recipient of an Honorary Doctor of Humane Letters from Daniel Webster College. He was recently selected to receive a Public Service Medal from NASA and the Tower Medallion from Louisiana Tech University. At MIT, he is a MacVicar Faculty Fellow, an honor bestowed for extraordinary contributions to undergraduate education. He was also the inaugural recipient of the Woodie Flowers Award by FIRST, a national organization that promotes youth involvement in science and technology.

Currently, Dr. Flowers is a director of four companies and is on the board of Technology Review magazine. He is a member of the Lemelson-MIT Prize Board Executive Committee, is National Advisor and Vice Chairman of the Executive Advisory Board for FIRST; and is a member of the Historical Commission in Weston, Massachusetts where he lives with his wife Margaret.

2000. "Promoting Leadership in Girls in an informal Education Environment: The FAIHM Program," C.E. Lathan, C. Abrhams, W. Flowers, T. Gray, D. Newman, D. Stolnitz and D. Soderholm.

1999. "Integrating Engineering Science and Design: A Definition and Discussion," B. Linder and W. Flowers. Proceeding of the Mudd Design Workshop II, Harvey Mudd College, Claremont, CA.

1997. "The Virtual Workshop: A Simulated Environment for Mechanical Design," J. Barrus and W. Flowers. Proceedings of the Symposium on Virtual Reality Manufacturing Research and Education.

1996. "Student Responses to Impromptu Estimation Questions," B. Linder and W.C. Flowers. Proceedings of the 1996 ASME Design Engineering Technical Conference and Computers in Engineering Conference, Irvine, CA.

G. Duncan Himmelman, Director of Wellesley College Botanical Gardens. Dr. G. Duncan Himmelman received a B.A. in Botany and History from Hobart and William Smith College. He received a M.Sc. in Ornamental Horticulture from the University of Guelph in Ontario, Canada. In 1990, he earned a Ph.D. in Ornamental horticulture with minors in plant ecology and landscape architecture from Cornell University.

For the previous 20 years, Dr. Himmelman has worked at Olds College in Olds, Alberta, Canada. He was Horticulture Program Coordinator from 1991-1994. He has been the Lead Instructor in the Horticulture Program from 1996-present. From 1978 to 1981, he was Assistant Nursery Manager for the Metropolitan Toronto and Region Conservation Authority in Ontario, Canada.

Dr. Himmelman is a member of several professional societies. Since 1977, he has been a member of the American Association of Botanical Gardens and Arboreta. In 1982, he became a member of the Landscape Alberta Nursery Trades Association. He is also a member of the International Society of Arboriculture, specifically the Prairie Chapter.

1999. *Plant Propagation*, 1999; Extension Services Department, Olds College, Olds, Alberta.

1998. *Botanica* [Canadian Edition]; Introduction; Raincoast Books, Vancouver, B.C.

1998. Hot New Trees and Shrubs for the Prairies, Summer 1998; *The Gardener for the Prairies*, The Saskatchewan Gardeners, Inc., Saskatoon, SK.

1997. *The Ultimate Plant and Garden Book; Contributions*; Crown Publishers, N.Y.

1995. *Landscape Design*, Extension Services Department, Olds College, Olds, Alberta.

Christine McArdle, Journalist Dr. McArdle holds B.A. (Hons) and Ph.D. (Medicine), Glasgow, Scotland. In 1972, she served as Publications Director for the City of Edinburgh, Scotland. Dr. McArdle has also worked as a medical researcher in Scotland and as the Publications Director, for Project Software and Development Inc.. Currently a freelance writer whose articles have appeared in *The Boston Globe* and *The TAB.*, Dr. McArdle is known for her articles on rail travel across America. She is also a guide at Arnold Arboretum in Boston and a naturalist for the Appalachian Mountain Club.

Jonathan Stolk, Assistant Professor of Mechanical Engineering and Materials Science. Dr. Jonathan Stolk joined Olin College from Bucknell University, where he served as a Visiting Assistant Professor.

Dr. Stolk holds M.S. and Ph.D. degrees in Materials Science and Engineering from the University of Texas at Austin and a B.S. in Mechanical Engineering from the University of Texas at Arlington. Before joining Bucknell, Dr. Stolk was an Assistant Instructor and Graduate Teaching Assistant in the Department of Mechanical Engineering at UT Austin, where he taught the Materials Engineering lecture and laboratory courses. He received several teaching awards at UT Austin, including the Materials Science Department Exemplary Teaching Award, the Lockheed Martin Teaching Excellence Award for Exemplary Performance in Engineering Teaching, and the H. Grady Rylander Award for Excellence in Engineering Teaching.

Dr. Stolk's Ph.D. research involved the development of new chemical synthesis techniques for nanocrystalline metallic and composite materials with low thermal expansion and high conductivity. Dr. Stolk has research experience in corrosion fatigue behavior of carbon fiber-epoxy composites in high-pressure seawater, and he has many years of industrial experience in the area of testing and failure analysis of materials and components. Dr. Stolk also worked as a Research Scientist at the Institute for Advanced Technology, where he evaluated the performance of materials for use in electromagnetic launcher rail conductor applications. His current research is focused on the synthesis, processing, and characterization of novel metal alloys and metal-polymer nanocomposites with specialized mechanical, electrical, and thermal properties.

Dr. Stolk is passionate about engineering teaching and the development of new laboratory experiments, and he greatly enjoys working with undergraduate students on independent or group research projects. In two years at Bucknell, Dr. Stolk supervised a dozen student projects. Several of his research students have presented their work at national conferences, and he recently published the results of one student research project in a leading materials science journal. Dr. Stolk developed and taught a new Advanced Materials lecture and laboratory course at Bucknell, and was recently voted "Bucknell's Favorite Professor" by first- and second-year students.

2001. "Synthesis and Processing of Nanocrystalline Ag-Fe-Ni for Low Thermal Expansion - High Conductivity Thermal Management Applications," J. Stolk, M. Gross, D. Stolk, and A. Manthiram, *Journal of Materials Research*, vol. 16 no. 2, pp. 340-343.

2000. "Chemical Synthesis and Characterization of Low Thermal Expansion - High Conductivity Cu-Mo and Ag-Mo Composites," J. Stolk and A. Manthiram, *Metallurgical and Materials Transactions A*, vol. 31A no. 9, pp. 2396-2398.

1999. "Chemical Synthesis and Properties of Nanocrystalline Cu-Fe-Ni Alloys," J. Stolk and A. Manthiram, *Materials Science and Engineering*, B60, pp. 112-117.

1998. "Synthesis, Processing and Microstructure of Aluminum Borate-M (M=Co, Ni, and Cu) Nanocomposites," J. Stolk and A. Manthiram, Presentation at the 127th TMS Annual Meeting, San Antonio, Texas.

1998. "Chemical Synthesis and Processing of Nanocrystalline Cu-Fe-Ni Alloys," J. Stolk and A. Manthiram, Presentation at the 127th TMS Annual Meeting, San Antonio, Texas.

Mark H. Somerville, Assistant Professor of Electrical Engineering and Physics . Dr. Mark Somerville joined Olin College from Vassar College, where he had been an Assistant Professor of Physics since 1998. He holds M.S. and Ph.D. degrees in electrical engineering from MIT, as well as an M.A. (first class honors) in physics from Oxford University. He did his undergraduate work at the University of Texas at Austin, where he earned a bachelor of science (highest honors) in electrical engineering as well as a bachelor of arts (special honors) in liberal arts (English concentration). His academic honors include the Joint Services Electronics Program Doctoral and Post Doctoral Fellowship, the Office of Naval Research Graduate Fellowship, and the Rhodes Scholarship.

Dr. Somerville's research focuses on the physics of semiconductor devices, with particular emphasis on high electron mobility transistors, which hold great promise for high-speed wireless and optical communications. He is currently examining the use of light emission to understand failure mechanisms in these devices; this work is supported by a Research at Undergraduate Institutions grant from the National Science Foundation.

2001. "Determining Dominant Breakdown Mechanisms in InP HEMTs," M.H. Somerville, C.S. Putnam, and J.A. del Alamo, accepted for publication in *IEEE Electron Device Letters*.

2000. "Physical Mechanisms limiting the manufacturing yield of mm-wave power InP HEMTs," S. Krupenin, R.R. Blanchard, M.H. Somerville, J.A. del Alamo, K.G. Duh, and P.C. Chao. *IEEE Transactions on Electron Devices*, vol. 47(8), pp. 1560-1565.

2000. "A physical model for the kink effect in InAlAs/InGaAs HEMTs," M.H. Somerville, A.N. Ernst, and J.A. del Alamo. *IEEE Transactions on Electron Devices*, vol. 47(5), pp. 922-930.

2000. "Visualization: Leading Students from the Classroom Towards Research," J. Lombardi and M.H. Somerville. 2000 AAPT Summer Meeting, Guelph, Ontario.

1999. "Breakdown in millimeter-wave power InP HEMTs: a comparison with GaAs PHEMTs," J.A. del Alamo and M.H. Somerville. *IEEE Journal of Solid State Circuits*, vol. 34(9), pp. 1204-1211.

Brian Storey, Assistant Professor of Mechanical Engineering. Before coming to the F.W. Olin College of Engineering, Dr. Storey was at the University of California at Berkeley, where he completed his Ph.D. in mechanical engineering in May 2000.

Dr. Storey holds an M.S. from the University of Illinois at Urbana-Champaign, where he worked in experimental heat and mass transfer, and a B.S. from the University of Texas at Austin. He has also worked in active sonar systems and underwater acoustics at University of Texas Applied Research Labs.

Dr. Storey's Ph.D. research involved detailed computational modelling of fluid dynamics, heat and mass transfer, and chemical kinetics in the study of sonochemistry, an ultrasound-based chemical processing technique. His current research interests are fluid mechanics, computational science and engineering, numerical methods, heat transfer, chemically reacting flows, biomedical ultrasound, and geophysical fluid dynamics. Dr. Storey is currently publishing in a leading journal the results of an undergraduate research project which he supervised at Berkeley.

"Shape stability of sonoluminescence bubbles: a comparison of theory to experiments," Storey, B.D. *Physical Review* E. 64, 017301.

2001. "A reduced model of cavitation physics for use in sonochemistry," Storey, B.D. and Szeri, A.J. *Proceedings of the Royal Society A*. 457 1685-1700.

2000. "Water vapour, sonoluminescence and sonochemistry," Storey, B.D. and Szeri, A.J., *Proceedings of the Royal Society A*. 456, 1685-1709.

1999. "Species segregation in sonoluminescence bubbles," Storey, B.D. and Szeri, A.J. *Journal of Fluid Mechanics*. 396. 203-221.

1999. "The effect of streamwise vortices on the frost growth rate in developing laminar channel flows," Storey, B.D. and Jacobi, A.M., *International Journal of Heat and Mass Transfer*, 42, pp. 3787-3802.

Gill Pratt, Associate Professor of Electrical and Computer Engineering Before coming to Olin, Dr. Pratt was Associate Professor of Electrical Engineering and Computer Science and a researcher in parallel computer hardware at the Massachusetts Institute of Technology, where he received his Bachelor's, Master's, and Doctorate degrees in Electrical Engineering and Computer Science. As a member of MIT's AI Lab, he directed the MIT Leg Laboratory, focusing on the development of robots with legs and devices for helping people walk. In his research Dr. Pratt and his students emphasized "series-elastic" actuators with more natural properties than industrial robots possess, and "virtual model" control languages that allow natural dynamics and active control to work synergistically. Dr. Pratt's two-legged "dinosaur" robot was featured in a recent *Scientific American* article.

Dr. Pratt received excellent reviews while teaching MIT's core subject in computer architecture and has served as both a member and a mentor to several extracurricular student project groups. He is an enthusiast of hands-on, "do-learn" education, and has a strong interest in the societal aspects of technology, including "green" technologies like electric cars and larger issues like the impact of robotics on the quality of life.

2001. "Pseudo-trajector Control Scheme for a 3-D Model of a Biped Robot," J. Kanniah, G.A. Pratt, J. Pratt, and A. Parsaghian. submitted to the Fourth Asian Conference on Robotics and its Applications.

2000. "A General Control Architecture for Dynamic Bipedal Walking," C.M. Chew and G.A. Pratt. *IEEE International Conference on Robotics and Automation*, San Francisco, California.

2000. "Force Controllable Hydro-Elastic Actuator," D.W. Robinson and G.A. Pratt. *IEEE International Conference on Robotics and Automation*, San Francisco, California.

1999. "A Minimum Model of Adaptive Control Approach for a Planar Biped," C.M. Chew and G.A. Pratt.
Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, Kyongju, Korea.

1998. "The Solar Vehicle Concept," G.A. Pratt and J. Worden. *American Solar Energy Society.*

I Consulting Members

Merle Jensen is the Assistant Dean of College of Agriculture at the University of Arizona in Tucson. Dean Jensen is an expert in hydroponics and is frequently consulted for that field.

Andy Sugar is a researcher for Dynamac Corporation, who works at Kennedy Space Center. His research focuses on growing plants in hypobaric conditions and the use of LED growth lights. He is primarily a consultant with regard to hypobaric plant growth.

Christopher D. Raleigh is a Microbial Mat researcher at NASA's Ames Research Center. He is a consultant in the usage of microbes within the greenhouse and is serving as a link to other research that is being done at Ames.

Hillary Thompson Berbeco is an Assistant Professor of Chemistry at Olin College. She received a National Science Foundation Graduate Research Fellowship. As a Director's Postdoctoral Fellow at Lost Alamos National Laboratory, Dr. Berbeco investigated the chemistry and thermodynamic properties of novel catalyst materials intended for fuel cell use. Dr. Berbeco is serving as a chemistry consultant, especially in the area of fuel for power systems.

George Fix is a Senior Principal Materials Engineer at Raytheon Electronic Systems. His areas of specialty include: failure analysis of polymers, structural adhesive bonding systems and dielectric materials for both microwave transmission and high voltage electronics. George has thirty years experience in electronic, optic and structural applications of materials science.

William H Fossey, Jr. is a Senior Principal Engineer with the Raytheon Mechanical & Materials Engineering Laboratory in Lexington Massachusetts. He has 30 years experience in the design, analysis and development of composite hardware for numerous applications including spacecraft, missiles, aircraft, and ground equipment. Components/assemblies include both primary and secondary structures, and radomes.

Daniel Frey is an Assistant Professor of Mechanical Engineering at Olin College. Professor Frey holds numerous patents, and has published extensively in peer-reviewed journals. He is a consultant in the area of structural design and analysis and coordinated the Red Team review of the PDR.

Joanne C. Pratt is an Assistant Professor of Biological Sciences at Olin College. Professor Pratt's research involves biochemistry, molecular biology, and DNA mutation. She is a consultant for radiation effects and concepts involving genetically modified plants or microbes.

James Philips is an Associate Professor of Science at Babson College. Professor Philips is a community ecologist and non-molecular biologist. He has provided information about existing ecosystem projects and will continue to serve as an advisor for this topic.

Gregory Goins is a research scientist for Dynamac Corporation in the Advanced Life Support/Space Biology laboratories at Kennedy Space Center. His research focuses on the testing of hardware to allow plants to grow in space. He is a consultant in the areas of lighting and nutrient delivery.

John Graff is a graduate student at Boston University. He worked on the development of a photon recycling semiconductor light-emitting diode (PRS-LED). He is serving as an LED consultant.

Neil Yorio is a Plant Physiologist for Dynamac Corporation, who works at Kennedy Space Center in the Advanced Life Support research group. His research focuses on plant physiology studies and he is being used as a consultant for the influence of various light spectrums on plant growth.

Richard K. Miller is the President of Olin College and a Professor of Mechanical Engineering. Dr. Miller has been a consultant to many companies including the Aerospace Corporation, NASA's Jet Propulsion Laboratory, Hughes Aircraft Company, and Astro Aerospace Corporation (TRW), where he made significant contributions to the Heliogyro, Solares, Mast Flight Experiment, Milstar, Mobile Transporter, and many other projects. His research interests revolve around structural dynamics and nonlinear mechanics with application to earthquake engineering and spacecraft structural design. He is serving as a consultant on external structure, atmospheric controls, and system dynamics and controls.

David Kerns is the Provost and Franklin and Mary Olin Distinguished Professor of Electrical Engineering at Olin College. Dr. Kerns was recently elected Vice-President of the IEEE Education Society and serves on its AdCom. His research interests include MEMS devices, analog circuit design, silicon-based optoelectronics, and radiation effects on microelectronics. He is primarily serving as a consultant on the effects of radiation on integrated circuits.

Sherra Kerns is the Vice President of Innovation and Research at Olin College and a Visiting Professor of Electrical Engineering and Computer Science at M.I.T. Dr. Kerns has received both the IEEE Millennium Medal and the 2000 ASEE ECE Distinguished Educator Award. Her research has focused on the reliability and information integrity of microelectronic circuits. She is a consultant on the effects of radiation on computer systems and the electrical environment of space.

Jill Crisman is a Senior Olin Partner for Electrical and Computer Engineering at Olin College. Dr. Crisman's research is focused in robotics, computer vision, and graphic simulation. She is a consultant for robotic systems, especially in reference to robotic vision.

John Bourne is a Professor of Electrical and Computer Engineering at Olin College, Professor of Technology Entrepreneurship at Babson College, and the Director for the Sloan Center for Online Education at Olin and Babson Colleges. Professor Bourne's research interests have included Quantitative Electroencephalography, Visual Evoked Response Studies, Syntactic Pattern Recognition, Applied Artificial Intelligence, and Quantitative Quality Methodologies. He has also built his own greenhouse and used hydroponics as a hobbyist. He is a consultant for hydroponics, greenhouse sensors, and online education modules.

Helen Donis-Keller is a Professor of Biology and Art at Olin College. Professor Donis-Keller served as Director of the Human Genetics Department at Collaborative Research, Inc. where she led the research group that developed the first genetic linkage map of the human genome during the 1980s. Her research has included mapping the human genome, identifying genes and mutations, which give rise to heritable disorders, bacterial genetics, nucleic acid chemistry, and analysis of viral genomes. She is primarily a consultant on bacterial genetics and contamination issues.

Jason Krumholz is a graduate of Lawrence University in Appleton, Wisconsin, with a bachelors degree in biology. Krumholz has a passion for space study and education, having taught space physics at a Center for Talented Youth (CTY) summer program. He provided information and ideas for outreach including suggestions for activities in the education kit.

Brian Sauser is the Senior Program Coordinator for the New Jersey NASA Specialized Center of Research and Training (NJ-NSCORT) and New Jersey EcoComplex. Dr. Sauser has agreed to work with Olin's design team. He has offered to pass questions on to whomever of his researchers would be the most appropriate.

Richard Stoner is the CEO and founder of Agri-House, Inc. Mr. Stoner is the inventor of the Method and Apparatus for Aeroponic Plant Growth (patent #4,514,930) and principal-inventor of the Method for Organic Disease Control (Patent Pending, 1994) and most recently a Tuber Planting System #6,193, 958. He has agreed to assist us in any ways he can. He is a consultant on aeroponics.

Lynn Andrea Stein is a Professor of Computer Science and Engineering at Olin College. Professor Stein has received both the General Electric Foundation Faculty for the Future Award and the National Science Foundation Young Investigator Award. Her research and interests focus on A.I., robot-human interaction, intelligent control, information management and computation. She also designed an intelligent room while a professor at MIT. She is a consultant for information management and robot/MDG control systems.

Burt Tilley is an Associate Professor of Mathematics at Olin College. Professor Tilleys research interests include the dynamics of fluid systems, heat transfer devices, and general applications of mathematical modeling. He is a consultant with regard to mathematical modeling of greenhouse systems and team management.

Randy Tustison is the manager of the Materials Engineering Department of Raytheon Electronic Systems. Materials Engineering addresses materials research and development as well as design and production support for all of Raytheon locations, with emphasis in the Northeast. He joined Raytheon Research Division in 1978. He is a member of the American Vacuum Society, where he was Chairman of the Vacuum Technology Division in 1990-91, a member of the American Physical Society and Sigma Pi Sigma, Physics Honor Society. He is a member of SPIE Executive Program Committee and Chairman of the SPIE Aerosense 2001 Window and Dome Technologies and Materials VII Conference. He also serves as the Chair of Raytheon's Materials and Processes Technology Network. Dr. Tustison graduated from Purdue University with a B.S. degree in Physics, and from the University of Illinois, receiving a M.S. and Ph.D. in Materials Science and Metallurgical Engineering. Prior to joining Raytheon, he was a Research Associate in Physics at the Massachusetts Institute of Technology.