M.A.G.I.C.

Mars Advanced Greenhouse Integrated Complex

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ABSTRACT

Human Exploration and Development of Space (HEDS) is a strategic enterprise of the National Aeronautics and Space Administration (NASA). One of the many goals of this initiative is the exploration and colonization of the planet Mars. One approach to this ambitious undertaking is to transport a minimum of resources and utilize as many Martian resources as possible, reducing the overall cost of the mission.

A long duration mission, which utilizes in-situ plant growth-facilities, reduces the dependence on consumable supplies from earth. The reduced number of cargo launches required lowers the cost of the project. Additional equipment may then be shipped in place of consumables. Data obtained from growing food on Mars can be used in planning for permanent habitation of the planet.

A team of undergraduate students and professors at the University of Texas at San Antonio (UTSA) has developed the Mars Advanced Greenhouse Integrated Complex (MAGIC). The project is designed to meet the requirements of the NASA reference mission. A two-phase approach is used. Phase I utilizes resources previously expended by NASA. Phase II is a conceptual design for large-scale growth of food on Mars. [1a, 1b]

1. INTRODUCTION

The project was divided into six teams; Systems Integration; Crop Requirements and Mission Plan; Greenhouse Layout and Structure; Atmosphere Supply and Control; Hydroponic Fluid Supply and Control; and Data Acquisition and Control. A sub-team developed a conceptual design of a robotic harvester. The teams were comprised of a mixture of biology students and civil, electrical, and mechanical engineering students.

A crop list was generated using a variety of parameters. Among these parameters are human nutritional requirements, menu versatility, harvest methods, gas exchange characteristics, Hydroponic nutrient requirements and dimensional restrictions. The technical details supporting the content of this paper are available in our reference report [1a].

The crop size and weight specifications were then established to help choose a greenhouse configuration. Analyses were performed comparing structural configurations (horizontal vs. vertical), and structural designs (rigid vs. inflatable). The vertical configuration provides the most crop space. The inflatable structure provides greater volume for plant growth. To stay within reference mission guidelines, a rigid structure was chosen as the baseline. Four vertical rigid structures provide redundancy, adequate crop space and harvesting area. One structure is modular for plant growth height. [1a, 1b]

Maintaining an atmosphere conducive to productive crop growth requires monitoring and controlling gas concentration, pressure, temperature, and humidity. The systems required to perform these operations involve the use or adaptation of existing atmospheric controls systems. For operations that could not be performed by existing or adapted equipment, new equipment was defined for future development.

The Hydroponic fluid supply and control system involves the design and synthesis of several subsystems. These include a nutrient production system, solution circulation system, water purification system, condensation system, and a sensing system.

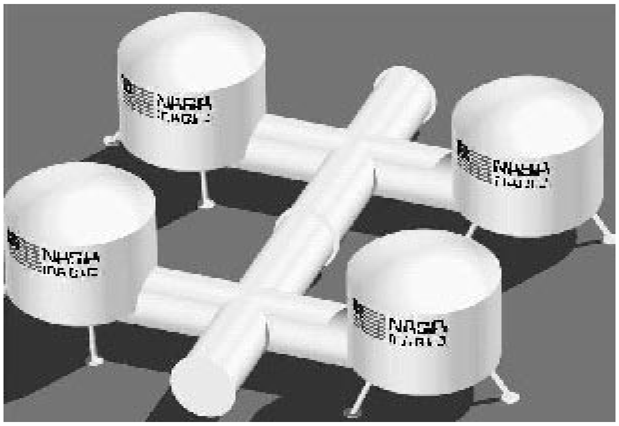
Control systems, power, and data acquisition systems were developed. Computer stations, fiber optics, electrical cable, video cameras, intercom stations, controllers, sensors, communication systems, voice recognition systems, airlock controls, and lighting systems were parameterized and discussed.

Finally, the need for an autonomous robotic harvester was identified with specific tasks for future development. Implementation of a robotic farmer would enable astronauts to utilize their time more productively. Basic requirements for the robot and future technological challenges were addressed.

PHASE I

Phase I of MAGIC was designed to meet the criteria described in NASA's Mars Reference Mission [1b]. The design makes use of four rigid cylinders and an interconnecting tunnel system. Sections two through six describe the design parameters and the atmosphere, hydroponic, and control subsystems. A robotic harvesting concept was then proposed.

Figure 1-1: Phase I Greenhouse Concept



2. LIFE SUPPORT REQUIREMENT

***Human Consumption Requirements*:** The daily needs for a human, based on an average metabolic rate of 4898 calories per person per day are: oxygen, 0.84 kg; food solids, 0.62 kg; and water, 57.28 kg. The effluents per person per day are carbon dioxide, 1.00 kg; water, 29.487 kg; and 0.109 kg. [1a]

***Human Nutrient Requirements*:** Human Nutrient requirements will be met by a combination of plant growth on Mars, and dietary supplements. The crops were chosen to meet U.S. RDA (Recommended Daily Allowance) and NASA Space Requirements for nutrition. The long-term effects on plant and human physiology have not been analyzed under Martian gravitational conditions. Dietary supplements allow NASA doctors to respond to potential physiological changes in the crews due to the diet. [2]

***Human Atmosphere Requirements*:** Life exists in a narrow range of atmospheric oxygen and carbon dioxide pressure. At sea level the partial pressure of oxygen is 21.21 kPa, and carbon dioxide partial pressure is 0.0318 kPa. The minimum partial pressure of oxygen (ppO_2) which a human can tolerate for extended periods is 19 kPa. Lower partial pressure of oxygen (ppO_2) can be tolerated for a short duration. However, there are side effects to lower pressure. Altitude sickness occurs after 8 to 10 hours of ppO_2 at 13.75 kPa. The maximum ppO_2 humans can withstand is 32.4 kPa, however lung irritation occurs after 12 to 72 hours at this level. Humans can tolerate $ppCO_2$ levels as high as 1.01 kPa for short periods (several days), and $ppCO_2$ levels of 1.59 kPa for very short periods under emergency conditions. A $ppCO_2$ of 0.40 kPa can be tolerated for long periods. The atmosphere control systems were designed to maintain the greenhouse within acceptable oxygen and carbon dioxide ranges for human and plant life. [3]

***Plant Productivity*:** The crops chosen and their required daily harvest volume are listed in Table 2-1. These volumes are designed to meet the needs of a six-person crew for two-year period (avg. 4898 cal/person/day). The starter solution will be given to the plants at the beginning of their growth. Plants will initially take up nutrients and store them within their tissues. The nutrient concentration will drop significantly at this time. It is not necessary to add nutrients until the vegetative growth stage. At that point, vegetative growth solution will be added to provide the plants with the nutrients needed at this stage. Nutrient content will be monitored and maintained by the hydroponics subsystems.

TABLE 2-1: Plant Growth Facility Crops

Average harvest requirement, per day, for each greenhouse crop is provided

Crop	**Soybean**	**Wheat**	**White Potato**	**Carrot**	**Spinach**	**Cabbage**	**Lettuce**
kg/day	0.60	1.89	0.77	0.28	0.35	0.08	0.27
Crop	**Tomato**	**Peanut**	**Dry Bean**	**Sweet Potato**	**Celery**	**Green Onion**	**Strawberry**
kg/day	1.52	0.22	0.08	0.67	0.08	0.27	0.26
Crop	**Peppers**	**Rice**	**Pea**	**Snap Bean**	**Beat**	**Radish**	**Broccoli**
kg/day	0.32	0.17	0.17	0.04	0.30	0.17	0.14

Each plant species has unique atmospheric temperature and humidity requirements. Two separate growing environments are required. One environment will be maintained in a temperature range of 16-20 EC and a relative humidity range of 65%. This environment will grow the following crops: wheat, white potato, dry bean, celery, peas, lettuce, spinach, broccoli, green onion, cabbage, strawberry, sugar beet, carrot, and radish. The second environment will be maintained in a temperature range of 22-26 EC and a relative humidity range of 65%. This environment will grow the following crops: rice, soybean, sweet potato, peanut, tomato, peppers, and snap bean. Warm temperature crops can be grown in cooler temperatures with a loss of yield. However, growing cool temperature crops under warm temperatures will lead to little or no edible biomass. The photoperiod for both environments will be 12 hours of light and 12 hours of dark. *Wheat yield is higher when grown with a 24-hour photoperiod. This extended photoperiod adversely affects other crops in the same environment. The lower yield in wheat will be offset by increased yields for other crops.* It is possible, and recommended to provide a greenhouse dedicated to growing wheat. This would allow for the 24-hour photoperiod and increase the yield. Due to flexibility of design as further research is completed, or at the astronauts request additional plants may be added to the menu.

The minimum growth area required to meet mission requirements is 500 m^2. The area needed per crop per maturation period is listed in reference [1a]. However, this does not allow for emergency contingencies, such as a crop failure or a systems failure. Therefore, a minimum growth area of 600 m^2 should be constructed. Additional space provides for crop research, and a safety margin. It is possible to decrease the 600m^2 recommendation if wheat were grown in a separate greenhouse containing at least 200 m^2, and rice and soybeans are grown in a separate greenhouse containing at least 200 m^2. This reduced diet would provide the astronauts with sufficient caloric intake, however many necessary nutrients would be omitted from the diet. Dietary supplements would be required.

***Air and Water Revitalization via Bioregenerative Process*:** The requirement for O_2 per day is 0.84 kg/person. A safety margin should be incorporated. Research has shown that an active growing area of 25 m^2 will provide air revitalization for one moderately active person. This area can be in any configuration desired. In one study, potatoes were used to provide O_2. They were grown in a continuous production mode (the periodic harvesting and planting of crops at short intervals to maintain a steady state of life support). This implies various maturity rates of each crop. It is not known exactly how much O_2 each individual plant produced. Assuming 25 m^2 growing area of any crop produces 0.63 kg per day per person of O_2, at least 150 m^2 of plant growth is required. [5]

***Crop Mission Plan*:** Plants increase photosynthesis at elevated CO_2 levels. At sea level, the CO_2 partial pressure is 0.0318 kPa. Plants cannot survive in a partial pressure CO_2 level greater than 0.2 kPa [6]. Plants will tolerate much lower partial pressure O_2 levels than humans. O_2 levels must be high enough for germination and respiratory metabolism during dark hours, however this amount is quite small. The exact partial pressure of oxygen required by plants is specific to the individual species. The required germination oxygen level is lower than the necessary partial pressure of oxygen needed by humans. [7]

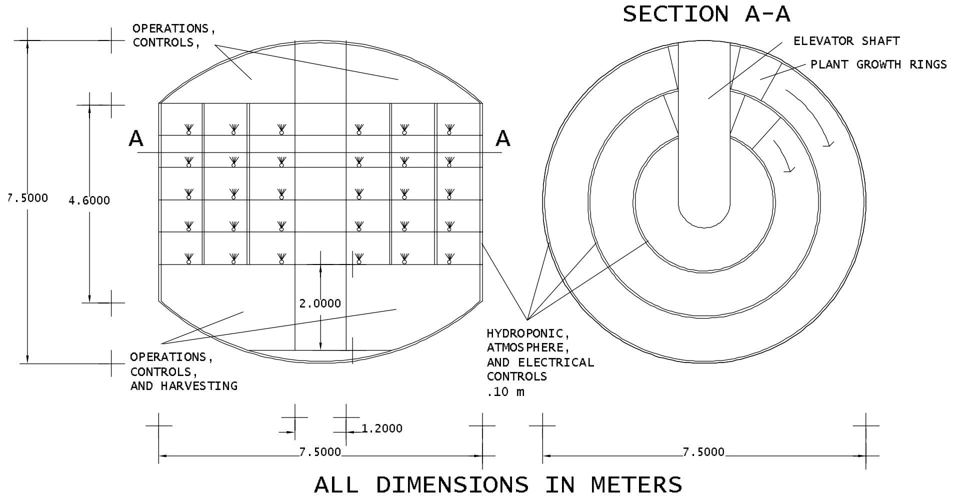
Plants grown at pressures as low as 14 kPa have only slightly lower germination percentages and stem lengths. Plants grown at 33 kPa do not show any significant changes in germination percentages and stem lengths as those grown at 101 kPa. [8]

Phase I of the plant growth facility will have an atmospheric pressure of 101 kPa, with a partial pressure of CO_2 of between 0.10% and 0.15% and a partial pressure of O_2 of between 15% to 18%. The airflow will be 1 meter per second at the top of each plant canopy. In Phase II, minimum atmospheric pressure will be 25 kPa. This will ensure maintaining partial pressures of CO_2 and O_2 within the required levels.

3. GREENHOUSE ARCHITECTURAL LAYOUT

***General Approach*:** The primary function of the Mars greenhouse structure is to provide an adequate environment to grow and process food. The structure should be pressurized, be easily constructed, and be easily maintained. The challenges that need to be addressed are maximizing the use of available space, providing a simple, modular construction scheme, and providing access for automated systems. The structural layout is provided in figure 3-1. A three dimensional cross-section is shown in figure 3-3.

Figure 3-1: Architectural Layout



***Space Requirements*:** A study of plant growth area in horizontal versus vertical configurations revealed the superiority in the vertical configuration's use of space. Vertical configuration utilizes available volume better than the horizontal configuration. The horizontal configuration presented hindrances to a modular shelving system because of the dimensional layout of the structure. The floor area of each level in the vertical configuration is identical therefore simplifying the use of a modular shelving system. In order to meet a crop requirement of 600 square meters [1a] five horizontal configurations would be needed whereas the vertical configuration would fulfill this requirement with four structures. The need to maximize plant growth area within a limited space makes the vertical configuration the logical choice. As indicated in Table 3-1, the better solution would be to choose the vertical inflatable cylinder. A single vertical inflatable cylinder provides $544m^2$ of growth area. This would meet mission requirements. However, for the purposes of this study we used a baseline vertical rigid cylinder per the reference mission.

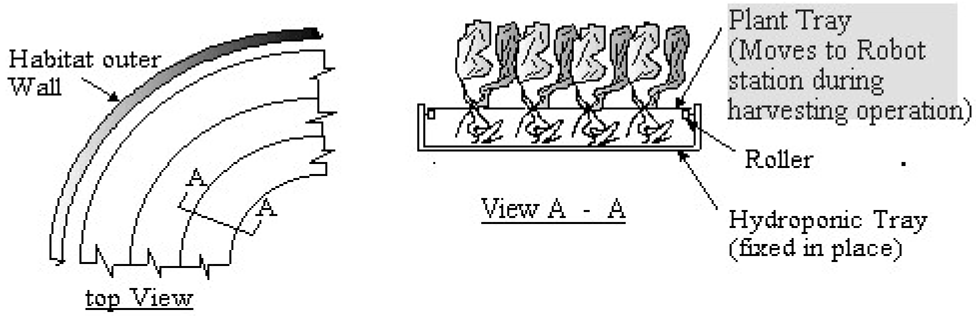
Table 3-1 Greenhouse Dimensional Analysis

Orientation	Vertical (Rigid)	Horizontal	Vertical (Inflatable)
Overall Dimensions (m)	7.5 ϕ x 7.5 L	7.5 ϕ x 7.5 L	9.5 ϕ x 9.5 L
Length Of Cylinder (m)	4.6	4.6	7.5
Plant Growth Capacity (m^2) 0.5m / 0.75 m shelf spacing	259 / 185	205 / 143	715 / 455

Two evolutionary phases are envisioned for the Mars greenhouse. Phase I utilizes structures currently identified by the Mars Reference Mission [1b]. Figure 3-1 shows a single unit from the selected Phase I layout based on the use of rigid cylinders.

Modular Shelf System**:** The vertical configuration uses a modular shelving system. The shelving systems consist of lighting, air circulation, hydroponics and plant trays. As indicated in Figure 3-1, the modular shelving system is arranged into four concentric circular segments with plant trays that can be moved into the elevator opening for harvesting, cleaning and reseeding.

Figure 3-2: Modular Shelf System



Space Allocation**:** Four vertical structures are required to obtain 600 m^2 of growth area. [1a] Each crop growth level will accommodate 37 m^2 of crops. Two structures will contain five levels with 0.75 m of vertical spacing. The remaining two structures will contain six levels with 0.50 m of vertical spacing. Each structure uses approximately 65% of the total 250 m^3 of volume for crop growth. The remaining 35% (87 m^3) is allocated for the following:

- Hydroponic fluid storage
- Automated controls
- Useable plant material
- Harvesting Equipment
- Atmospheric Controls

The structure provides compact and efficient use of space while maintaining sufficient space for both automated and human operations.

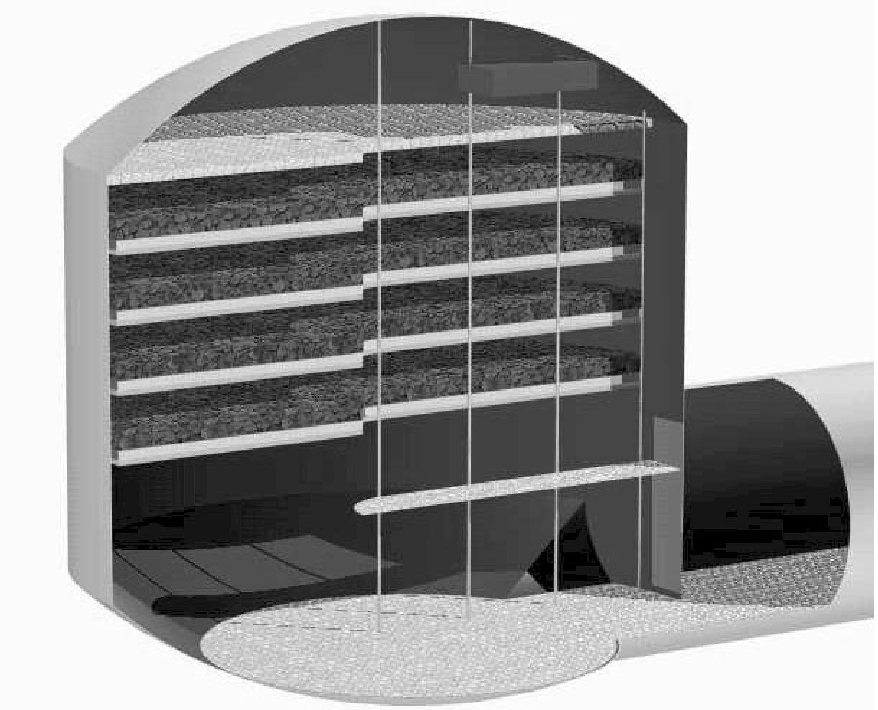
Support Overview**:** The exterior of the structure is an expended Mars cargo vessel. The framing will use a graphite-reinforced epoxy-material [11]. The supports for the shelving can be fixed to the sides of the structure before or after arriving on the Mars surface. Connections can be bolted pinned or welded as necessary. A rigid support frame for the structures should be used. The support frame would be assembled on the Martian surface. These frames will serve multiple purposes. First, the frame minimizes greenhouse heat loss by limiting direct contact with the Martian surface. Framing material will have low or nonconducting thermal properties to minimize heat transfer from the structure to the surface. A second purpose for the frames will be to maintain the greenhouse level. An auto-leveling system should be built into the frame. This is easily accomplished with electronic sensing devices and adjustable supports built into the frame itself.

The individual greenhouses will be connected together by tubular tunnels with airlocks at each entrance. These tunnels should be between two and three meters in diameter, allowing for equipment accessibility. These connecting tunnels will also be used to house control systems, and harvesting devices for the greenhouses.

***Inflatable Technology*:** Inflatable technology is currently under research for use on future NASA missions. An inflatable structure will provide significantly more space with only a minimal increase in dimensions. A 9.5-meter diameter structure, similar to the current TransHab module, would yield 570 cubic meters of volume [13]. This is a huge benefit in payload size and weight, which leads to an overall cost reduction.

The inflatable structure would use a similar support technology as the rigid structures. The frame could be stored in the "central structural core" removed, and setup prior to inflating the module [13]. This design requires longer setup times than its rigid counter part. However, the significant increase in growth space provides a more economical system than the rigid cylinders. Further research in this area should reveal this the better option for plant growth.

Fig. 3-3: Structural Cross-Section



4. ATMOSPHERE SUPPLY AND CONTROL SYSTEM

For ideal crop growth, the ranges shown in Table 4-1 must be maintained. Heat transfer analysis was conducted for the greenhouse structure. Detailed calculations and methods are available in the reference report [1a]. Air circulation requires two 125 W and two 150 W blowers. Polyurethane Foam insulation will be used on the greenhouse walls. The walls of the greenhouse will serve as heat exchangers. The blower capacity is based on 246 m² of plant shelving. The air-handling system provides from 3 to 4 air exchanges per minute, with air velocities ranging from .1 to 1.0 m/s. Chilled water coils at each of the blower's exits provide heat rejection and humidity control. Condensate, which forms on the coils, will be collected and measured in order to monitor evaporation rates. Atomized streams of water injected directly in the air stream provide supplemental humidification. [14]

Table 4-1: Atmosphere Supply and Control Requirements

Subsystem	Range Of Operation	
Air Revitalization System		
Oxygen	18.5 -23.45	%
Carbon Dioxide	300 -5000	µL / L
Chamber Pressure	101	kPa
Ventilation and Thermal Control		
Air Temperature	15 - 35	ºC
Relative Humidity	70 - 85	%
Air Velocity	.1 - 1.0	m / s
Leak Detection and Control Leakage Rate	1	% of the chamber volume/day

The pathogen filtering system will consist of two parts, coarse filters and electrostatic precipitators. The coarse filters will remove large particulate to prevent fouling of the air ducts. The electrostatic precipitators will remove the smaller particulate. A parts list can be found in Table 4-2.

Table 4-2: Parts list

Component	Characteristic
4 Blowers	(2) 125 W and (2) 250 W return blowers
Duct , Fibrous glass liner	Rectangular H=4” W= 5.5” Length = 1139.6’
Pathogen Filters, electrostatic precipitators	4 Area =0.5 m^2
Insulation	Polyurethane Foam 0.006m thick total area 48.5 m^2
2 Condensers	
2 Heat pump	100 W

Atmosphere Controls Analysis**:** Adequate supplies of oxygen are required for unsuited human entry into the greenhouse. Controlling levels of oxygen, carbon dioxide and other gases is a major concern for proper plant production and processing of plant waste. Maintaining a suitable atmosphere requires the regulation of oxygen, nitrogen, carbon dioxide, and other trace gasses. A system that can generate oxygen on demand, filter out carbon dioxide and replace or remove nitrogen is required. Oxygen and nitrogen separators are commercially available and are easy to integrate into an atmospheric control system.

Oxygen and the other atmospheric gasses will be lost to the Martian atmosphere through inevitable leakage at an assumed rate of 1% of the chamber volume each day. A self-sustained system minimizes the necessity for transport from earth. This loss comes to 0.013 kg of oxygen, 0.011 kg of carbon dioxide and 0.011 kg of nitrogen each day. Replacement oxygen can be provided from two sources. First, oxygen is a byproduct of photosynthesis. Previously, we have determined that 0.63 kg/day of oxygen can be obtained from 25 m^2 of plant area. If there are 300 m^2 in production at any given time, then 7.56 kg of oxygen will be produced each day. If the attendants collectively use 5.04 kg/day the greenhouse will experience a net oxygen production of 2.51 kg/day. Excess gas can then be separated using a commercial separator and stored for future use. The second method of obtaining oxygen involves separating elemental oxygen from bearing gasses in the Martian atmosphere. The Mars Surveyor 2001 lander, scheduled for launch on April 10, 2001, will demonstrate the viability of an oxygen generation system. The Space Technology Laboratory (STL) of Arizona State University has developed an Oxygen Generator System (OGS).

Table 4-3: OGS specifications

Parameter	Value
T{INCLUDEPICTURE \d "ballblau.gif"}otal system mass:	1000g
{INCLUDEPICTURE \d "ballblau.gif"}Start up power:	15W
{INCLUDEPICTURE \d "ballblau.gif"}Steady state power:	9.5W
{INCLUDEPICTURE \d "ballblau.gif"}Oxygen flow rate:	>0.5sccm
{INCLUDEPICTURE \d "ballblau.gif"}CO2 supply:	>2.5sccm
{INCLUDEPICTURE \d "ballblau.gif"}cell operating temp.:	750C
{INCLUDEPICTURE \d "ballblau.gif"}envelope:	8” x 6” x 5” (h,l,w)

If the OGS test is a success, then oxygen will be available for life support usage. Carbon dioxide is readily available from the Martian atmosphere and may need only some filtration to remove harmful elements. Nitrogen or some other carrier gas must be transported from earth or generated from some other means. Filtration of unwanted greenhouse gases is an easy task. Separation of oxygen, nitrogen, carbon dioxide, and volatile trace gasses can be accomplished using commercially available separators such as those available from On Site Gas Systems. These separators are available in many configurations and can satisfy almost any specification.

Temperature**:** Temperature will be measured by Resistance Temperature Detector (RTD). The range of this type of sensor is -40°C to 150°C. A sensor will be installed on every third crop tray to monitor ambient temperatures. This will ensure adequate plant growth requirements.

Pressure**:** Pressure will be measured by a Sputtered Thin Film pressure sensor. This sensor remains stable in extreme operating conditions. This high performance transducer incorporates a thin film sensor reducing the need for routine maintenance. These sensors will be mounted on the ceiling of the greenhouse. The sensor will be used to determine if a filter requires cleaning.

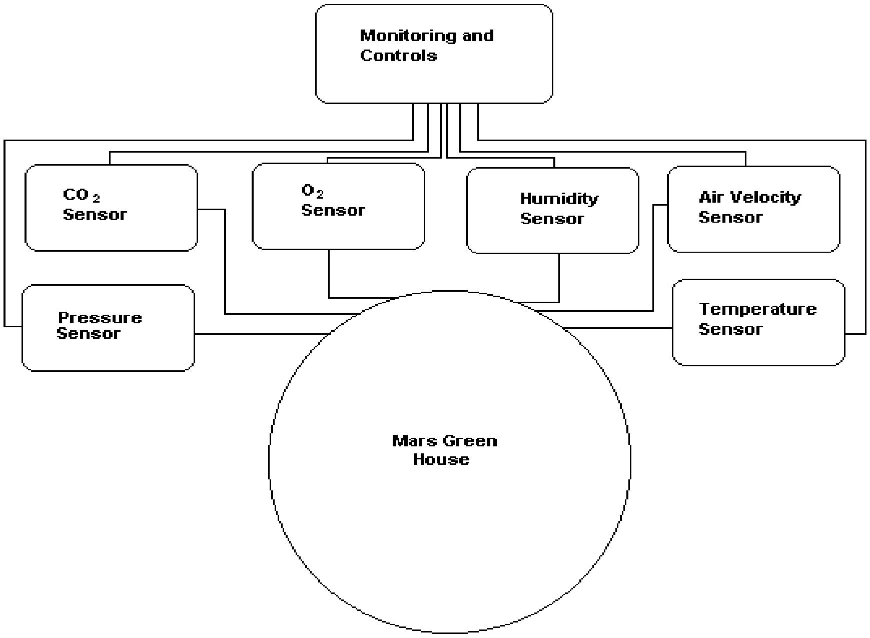
Humidity**:** Humidity will be monitored by a Relative Humidity sensor, which is configured with integrated circuitry to provide on-chip signal conditioning. These sensors contain a capacitive sensing die set in thermoset polymers that interacts with platinum electrodes. The laser trimmed sensors have an interchangeability of + 5%RH, with stable, low drift performance. The sensor will be placed in the greenhouse ceiling. This type of sensor can be operated in temperatures that range from $^-$40°C to $^+$85°C.

Sensors**:** Oxygen sensors will be installed at various locations within the greenhouse. The sensor external materials are entirely inert (Teflon and ceramic). The sensor can be used in biological applications or in harsh chemical environments. The sensor can also be operated in either liquids or gases, from vacuum to high pressure. The sensor can resist temperatures from -85°C to 135°C. The dual-chamber oxygen cell design requires biannual calibration. Air circulation will be monitored by a Gas Ultrasonic Flowmeter. This sensor has a wide operating range without pressure drop and does not require routine maintenance. Analog and digital outputs in velocity and actual volumetric flow rate are standard. The meter has a velocity range of 0.1 to 150 ft/s and it has no moving parts. The meter can measure gas flow in pipe or a duct ranging from ½-inch tubing to flue stacks over 25 feet in diameter with appropriate transducers. The meter can resist temperatures from $^-$20°C to $^+$140°C. The metering device will be mounted either in the ducts or next to the ducts. CO_2 and N_2 measurements will be made using a sensor that will be placed in the ceiling in the green house.

Velocity**:** In order to dissipate the heat generated by the lighting system an adequate air velocity had to be achieved. The surface temperature of the bulb were assumed to be 400 K and temperature of the air stream to be 293 K. Nusselts number was evaluated for the velocities ranging from 0.10 m/s to 5.00 m/s. Once Nusselts equation was evaluated corresponding average coefficients of convection were calculated. A direct correlation between average coefficient of convection and velocity is now known. Knowing the total amount of heat generated by the bulbs an average convection coefficient can be calculated. This is then cross-referenced with the range of convection coefficients tabulated, yielding an approximate velocity of 3.3 m/s

Figure 4-1 illustrates an overview of the atmosphere supply and control system.

Fig. 4-1: Atmosphere Supply and Control System Layout



5. HYDROPONIC FLUID SUPPLY AND CONTROL SYSTEM

Overall System**:** The hydroponic fluid supply and control system will produce the hydroponic solution that will be used by the crops. The hydroponic solution will contain the nutrients that the crops need in order to grow in the Mars greenhouse. This control system is broken into five subsystems.

- Nutrient Production System
- Solution Circulation System
- Water Purification System
- Condensation System
- Sensing System

Individual subsystem diagrams are available in the reference report [1a].

Nutrient Production System**:** The hydroponic solution will consist of a mixture of water and nutrients. The nutrients will be made up of decomposed plants and minerals. A storage tank is provided for the nutrient supply. The system mixes the nutrients with the water that will be flowing to the growing area trays through a system of pipes. A nutrient controller will control the amount of nutrients that are mixed with the water, and a pH controller will control the pH of the hydroponic solution. Once the fluid is produced, it will then go to the fluid circulation system.

An aerobic bioreactor produces the nutrients. Plant biomass will be finely ground and fed into the bioreactor (120-liter volume) at a rate of 0.2 kg per day. The bioreactor contains water at a pH of 6.5, a temperature of 35° C, and dissolved oxygen that is supplied by airflow through the bioreactor. The mixture will remain inside the bioreactor for 21 days. The reactor contents will be removed in batches of 40 liters every following week after the starting period of 21 days. The contents will then be filtered to remove solids. The extracted solution will then be analyzed to determine the type, and amounts of nutrients and chemicals present and add any if necessary.

***Solution Circulation System*:** This system takes in the processed hydroponic solution and distributes it into the growing area trays. The fluid is pumped through a pipe that leads into a row of trays. All of the trays are interconnected by pipes. As fluid begins to fill the first tray, it then will flow to the next tray, until all of the other trays are full of hydroponic solution. A sensor at the beginning and end of the last tray will measure the nutrient concentration of the solution and direct the flow accordingly. If the solution has enough nutrients, the solution will be directed back to the growing area trays through feedback valves and a pump. Otherwise, the solution will be directed to the water purification system. It is assumed that each of the growing area trays require the same amount of solution.

Water Purification System: The water purification system is comprised of a water recovery system, and a condensation system. The water recovery system is based on a diluted plant solution. This source ensures that water can be recovered, and filtered to be reused again. It will supplement the main storage tank that the habitat uses. This recovery system will allow maximized use of the available resources.

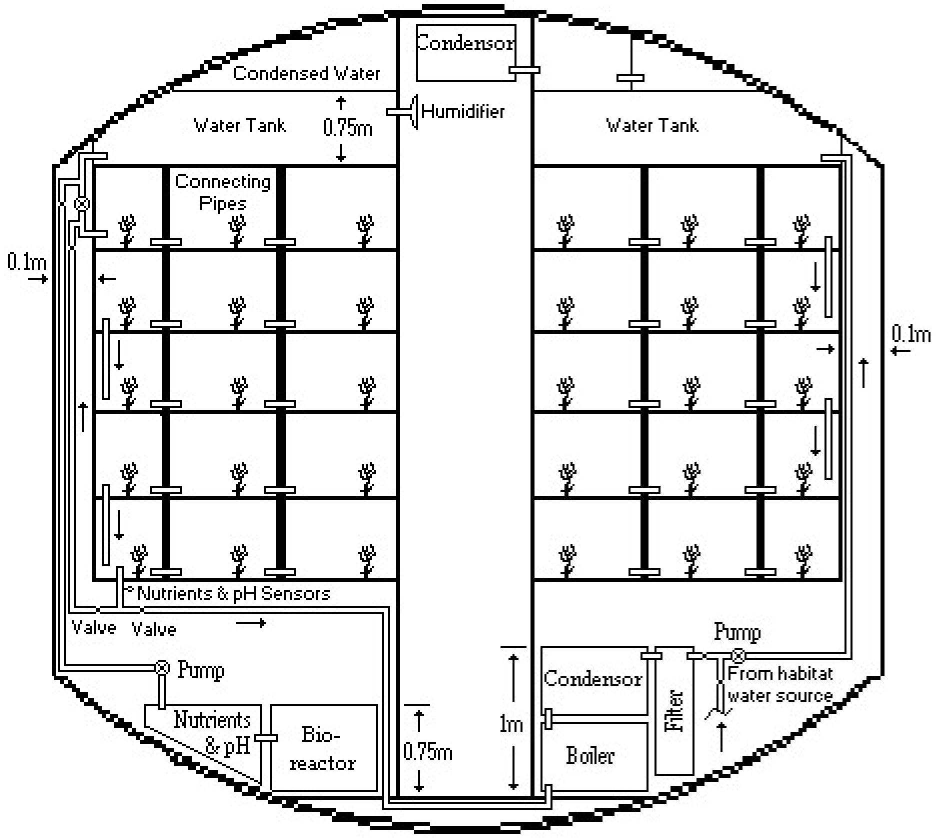
Water will come from any unused solution. This diluted solution must be purified before it returns to the main water tank. The process begins with nutrient sensors indicating to a microcontroller that the concentration of the nutrients in the solution is either within specified parameters, or not. When the concentration falls below acceptable values, the old solution would be removed; while at the same time fresh solution will be provided from the nutrient production system. The removed solution would then go through the purification process. It would start with a boiler that would heat the solution. The heated solution would then be collected in a condenser. Finally, it would be filtered to the proper safety levels and sent to the storage tank. The choice to utilize a boiler-condenser system was based on its ability to disinfect the water as well as purify it.

***Condensation System*:** Condensers will be used to collect any extra humidity inside the greenhouse. The condensers will convert the humidity to water. The water will then go to a storage tank. This system would ensure a maximum use of resources. The storage tank would be tied into the drinking water supply of the habitat. Since plants need a specific percentage of humidity in the air, a humidifier will be used to add humidity to the greenhouse in case the humidity falls to a low percentage. Both of the condenser and humidifier are controlled by a sensor to prevent them from working at the same time, which would defeat the purpose of this system.

***Sensing System*:** The sensing system is responsible for making all of the other systems work properly. This system utilizes a series of sensors that control the functions of each component in each of the subsystems. Most of the nutrient sensors must be custom designed because they are detecting specific chemical compounds, which are not commonly used. All of the sensors will feedback an electrical output to a microprocessor, which will regulate the functions of the hydroponic system according to the requirements.

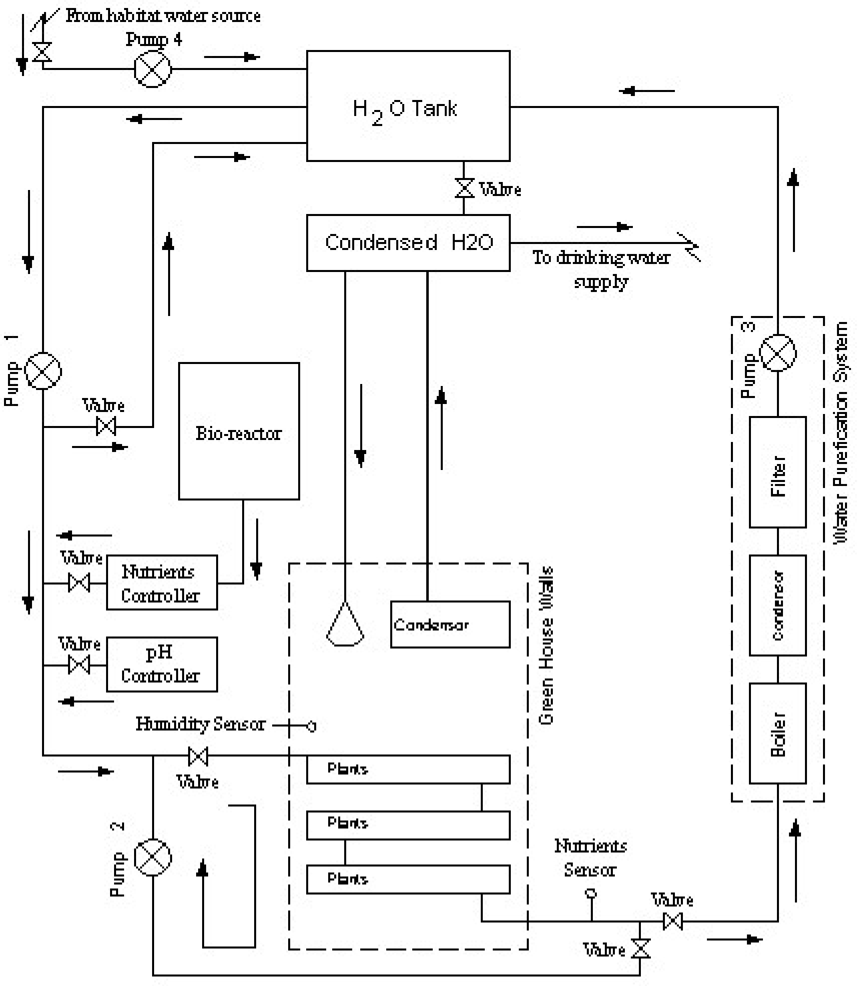
***Phase I - Vertical Rigid Structure*:** It will take the system 50 minutes to fill the trays with hydroponic solution. Each tray will be filled with solution up to 5 cm high [1a]. A view of hydroponic system arrangement within the greenhouse structure is provided in figure 5-1.

Fig. 5-1: Phase I Design Requirements



***Safety Measures*:** There are some safety devices installed throughout the system. The first device is a pressure safety valve. This valve is located on the main water pipe. It will redirect the water flow back to the main tank in case of an unexpected pressure increase. The second safety measure is a flow control valve between the main water tank and the condensed water tank. This valve will open to supply the main water tank with water in case of any shortage. Another safety measure is a flow rate gage located at the water exit. This gage will provide a flow rate reading, which would help in regulating the flow. In addition, fluid level sensors are located in each tank to provide fluid volume measurements. Finally, a valve located on the main pipe feeding water to the hydroponics system will enable the operator to shut down the system incase of emergencies. Figure 5-2 is an overview of the complete configuration of the hydroponic system.

Fig. 5-2: The Hydroponic Fluid System



6. DATA ACQUISITION AND CONTROL SYSTEM

***Master Control Center (*MCC*)*:** The master control center will be the main point of control for the facility. An overall schematic is provided in figure 6-1. The data line layout is illustrated in figure 6-2. Electrical elements in the greenhouse areas will send signals to, or receive signals from control systems maintained by the central computer system in the MCC. Additionally, the controllers will be able to interface with laptops or portable handheld computers in each area. The local interface with the master control center will be made using fiber optic cable. From the master control center, the astronauts will be able to control and monitor atmospheric sensors, heating systems, atmospheric gas supply system, hydroponic systems, potable water supply system, communications, radar, power control systems, airlock operation and robotics

***Computer Stations*:** The elements in each of the greenhouse areas will either send a voltage to a controller in that particular section or it will receive an operating voltage from a master controller. The controller is capable of handling 0-125 V input. It will then feed its output into a laptop that will be stationed in each area. The laptop computer can used to input data or observe data in that section or in any area throughout the complex. The laptop will be linked to the network via a fiber optic cable. Three servers in the master control center will provide redundancy. The monitors will be flat screens to conserve space. The capabilities of each PC are as such, 50 GB hard drive memory (master control center), 3 GB hard drive (area laptops), 1GHz speed and 128 MB RAM. The PCs in each area may be laptops.

***Fiber Optics*:** The computer network will be linked to the areas in the greenhouse with fiber optic cable. It will take approximately 10 meters of fiber optic cable. We are assuming an operational fiber optic PC. Digital to fiber optic converters will be needed for each PC output/input.

***Electrical Cable*:** If nuclear power option is used, the unit power supply will have to be located a safe distance from the greenhouse. A transmission line will be used to bring electricity into the structure. The line should be protected from the adverse temperature. There will be several electrical distribution points in the greenhouse. Not all the motors, pumps and sensors will use the same D.C. input voltage, so several different regulated power supplies will also be required. Some effort should be made to standardize DC inputs and regulation so less power shifting is required. [25]

***Video Cameras*:** Small digital video cameras will be positioned throughout the greenhouse. They will send microwave transmission to a video network that will be setup in the master control room. The number of cameras needed is estimated at 30. Ten of these will be used as spares. Video compression will be used. Using Image Compression places an extra burden of computation time upon the processing of compressed images. This is because the images must first be decompressed before being processed. When the images are large, as in the case of many photogrammetric images, which are typically over 100 Mbytes for gray scale digitized aerial photographs, the time taken to decompress the image can add significantly to the processing time. Algorithms could be designed so that video compression would not be required.

***Intercom Stations*:** Each area in the greenhouse will contain intercom stations. They will be small in size and transmit their audio via microwaves. The number of intercom stations needed is estimated at 15. Seven of these will be used as spares. Station personnel will also be required to wear on person wireless communication modules at all times. The total number of modules required is 15.

***Controllers*:** Electrical elements, such as sensors will be fed into a controller. The sensor-input voltage will be from 0-10 volts. In response to commands from the PC stations, the controller will output the necessary control voltages to the pumps, filters, motors and blowers in the greenhouse. The controller will use two VMIC2700 data acquisition boards. The total number of inputs needed per controller will be 30.

***Sensors*:** The sensors that will be used will provide a 0-10 Volt signal to the controller in each area. [26]

***Communications Systems*:** The stations will posses several communication systems. One will be a microwave-based radio. The very long length of communication distance between Mars and Earth presents some problems. One is that, even at the speed of light, it will take 10 minutes for signals to reach the Earth from Mars and vice versa. This means that the mode of communication that will be used is on a one person sending only basis. They will have to wait 20 minutes minimum for a reply. [27]

***Voice Recognition Systems*:** To make the astronauts work involving computer stations easier and less time consuming, a voice recognition system should be used. Speech Recognition (SR) software is software that has the ability to audibly detect human speech and parse that speech in order to generate a string of words, sounds or phonemes to represent what the person said. Natural Language Processing (NLP) software has the ability to process the output from Speech Recognition software and understand what the user meant. The NLP software could then translate what it believes to be the user's command into an actual machine command announces it, acquire “OK” and execute it. A current problem with voice recognition software is that it is only good for one person. Current technology permits only one individual voice to be recognized per computer station. This is a major problem and does not appear solvable in the next 5 to 10 years. Voice recognition software requires greater than 100 MB of memory for use. Perhaps, a system will be developed where any user can interface audibly with any computer station one individual at a time.

***Airlock Controls*:** There will be one airlock connected to the greenhouse structure. An air pump will infuse O2 into the chamber until atmospheric sensors detect at least a 95/5 ratio of O2 to CO2. A pressure, O2 and CO2 sensors will be required. Motors will open the inside and outside hatches. The process will be able to be controlled from the master control center and set in motion in an automatic cycle. Alarms will actuate when the airlock is in use. The whole processed will be monitored at the master control center, with manual override commands available.

***Lighting Systems*:** The lighting system for the plant growth area will be provided by 400 W high pressure sodium lamps (6 per plant area) which yield an average photosynthetic photon flux of 1500 u mol m S/msqd s when operating at full power. The lamps are powered by dimming ballast (Zone Mate, Widelite Corp, San Marcos TX), which will allow variable light levels for each crop area, which are controlled by the chambers data acquisition recording and control system. The crop will be separated from the lamp bank by means of a polycarbonate plastic sheet barrier. To obtain better environmental conditions for the plants, porthole windows have been designed to let in sunlight. Because the sodium lamps are pressurized, there is a problem with transporting them in a cargo hold exposed to vacuum. Light emitting diode (LED) banks are unpressurized and can produce the necessary light for plant growth. Further study on using LED banks in necessary.

Fig. 6-1: Controls

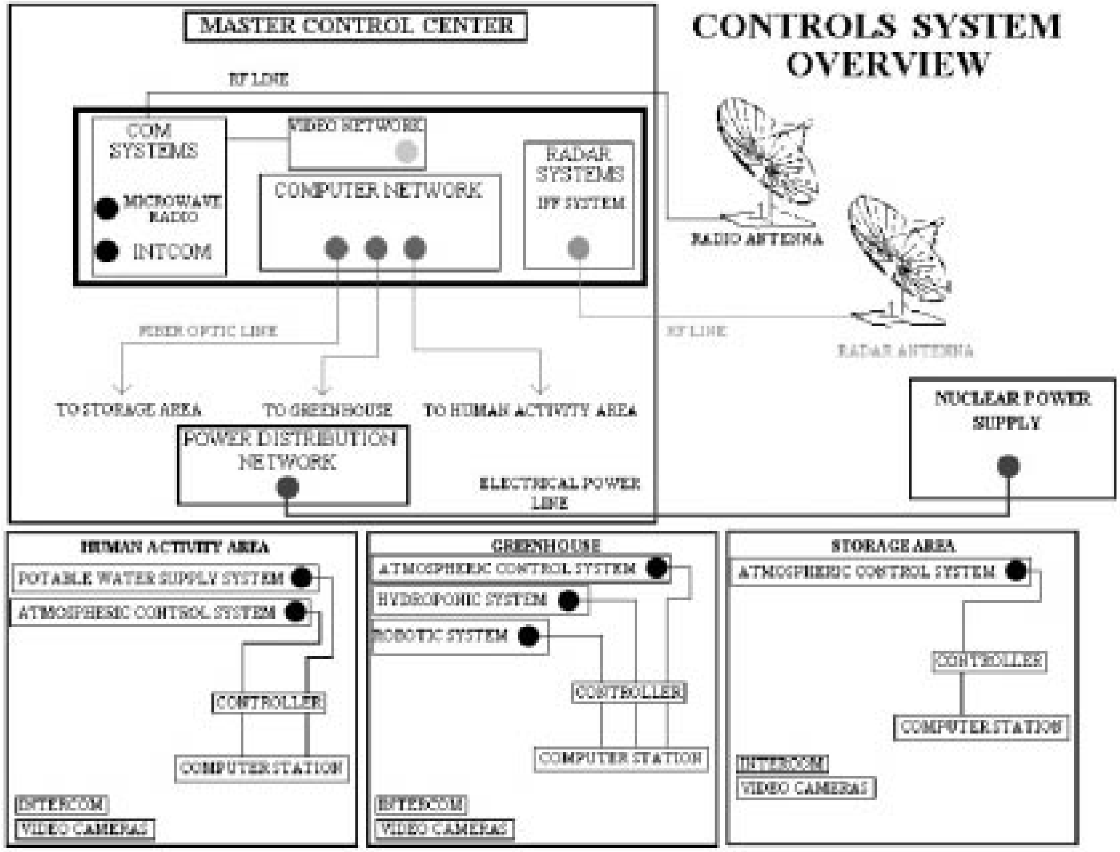
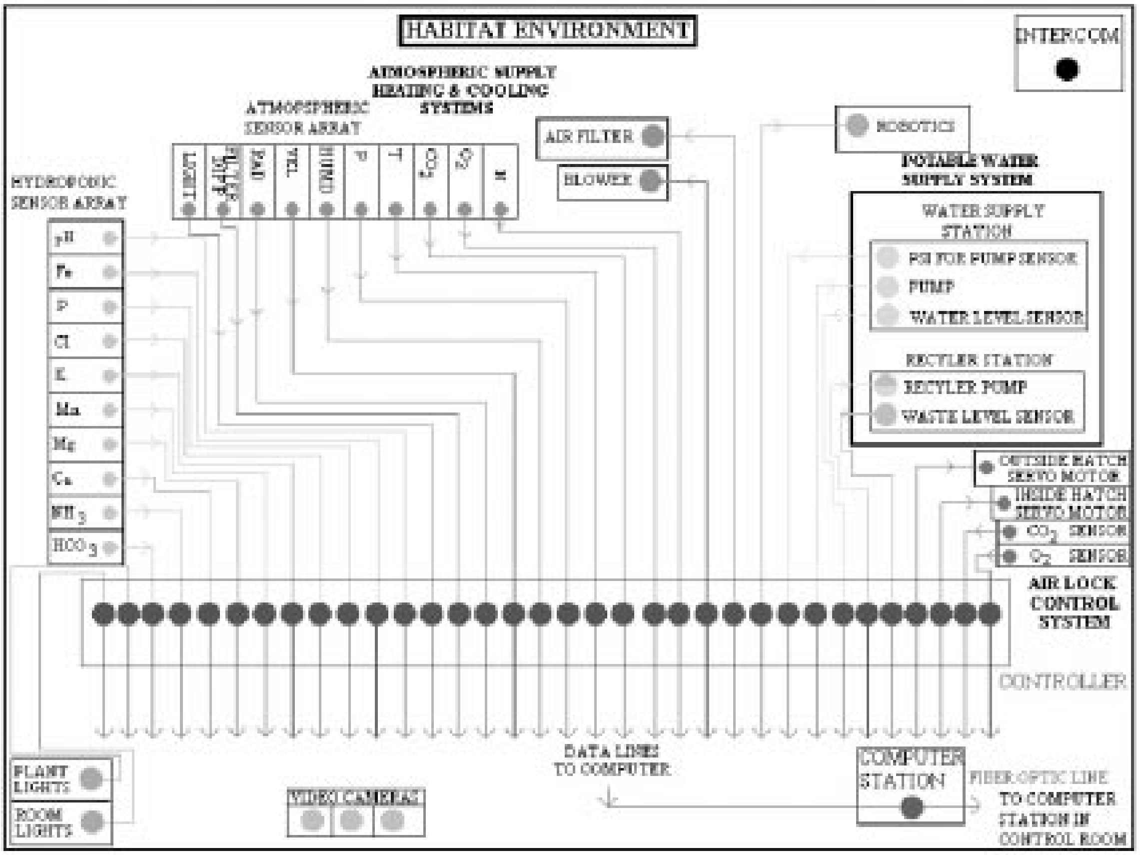


Fig.6-2: Data Line Layout



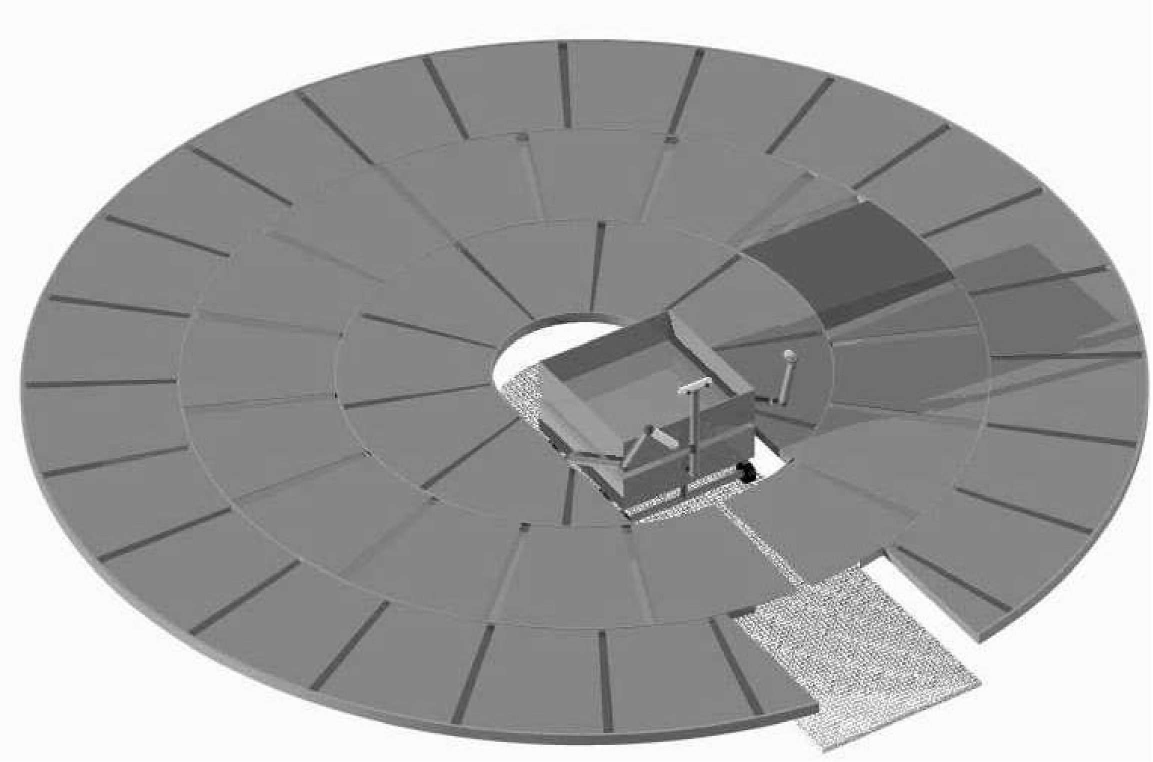
7. AUTONOMOUS ROBOTIC HARVESTER

The autonomous robotic harvester will perform farming duties in the MAGIC greenhouse. The goal is to have the robot monitor the crops and perform the harvesting with minimal human assistance. The robot will have a variety of programs depending on the task required. There will be a manual override, which can be remotely operated, both from Mars and on Earth.

The design of the robot was based on the vertical, rigid cylinder (Phase I) design. The robot will have the capability of elevating approximately 1.5 m. It should have four hydraulic actuators that will elevate and level the robot at all times. This allows the robot to travel in various terrain. The robot should elevate to the different levels of the greenhouse. This elevator can be operated by the robot. The aisles of the elevator will have a maximum width of 1.5 m. The robot will need this space for mobility and versatility. The crop area and the storage/processing area are separate, with storage and processing being done at the ground level. If necessary, the robot should be able to pick the trays up and transport them to the harvest area.

The robot will perform most of the operations at the crop level. Operations such as cutting, sorting, placement of crops, planting of new seeds and cleaning of the tray will be performed at the crop level. These operations will be accomplished by the use of two versatile mobile arms. The arm will have interchangeable tooling. The robot will be programmed to interchange the tools by itself. It will have the capability to remove the trays from its location if necessary. This task will be accomplished by using a lift mechanism, which will pick up the trays and then transport them to the harvest area. The robot should have a lift mechanism that will allow it to carry a load, for example a basket, so that it can place crops after it performs the desired operation.

Fig. 7-1: Rotating Trays and The Robotic 'Farmer'



PHASE II

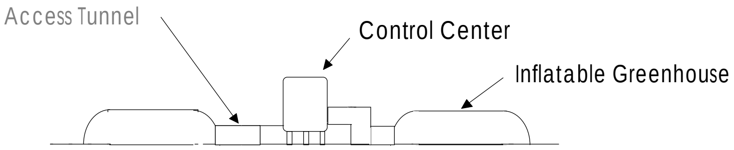
Phase II of MAGIC is a conceptual design for a future extension of the food production facility to support a growing population, beyond the constraints of the reference mission. Using a single rigid structure as a central control and harvesting center, large, tent-like greenhouses could be arranged in a spoked pattern, as seen figure 8-1.

8. PHASE II AND THE MARTIAN REGOLITH

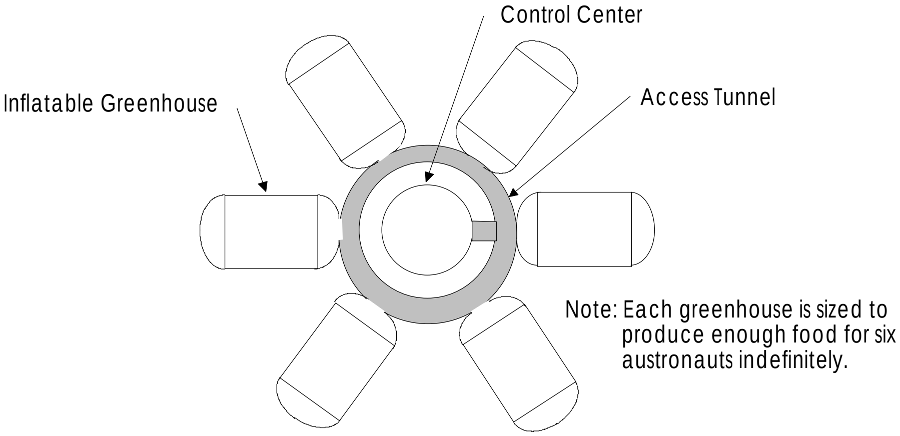
Some compounds found in Martian regolith are also found in Earth’s continental crust at comparable amounts. Martian regolith contains some compounds that are not found in Earth's continental crust. Some of these compounds include Na_2O, SO_3, and Cl. Reference [1a] outlines the composition of oxides in weight percent of several Martian sites. A comparison of the Earth’s continental crust is also listed. Use of Martian regolith in Phase II will require chemical fertilization.

Phase II of the plan incorporates one expended cargo vessel as the control center serving, and as many as six inflatable low-pressure greenhouses. Each of the inflatable units will have the capacity to serve six astronauts. Thirty-six crewmembers could be continuously served. Figure 8-1 is provided as an illustration of the Phase II concept.

Fig. 8-1: Phase II Concept



Side View



Top View

9. FUTURE STUDIES

Mars In-situ Manufacture Of Structural Materials**:** Over a long-term presence on Mars, it is expected that there will eventually exist many more plant waste parts (stems, leaves, and roots) than are needed for conversion to plant nutrients. There is a company in Amarillo, Texas that is currently producing wood-like structural materials out of the waste parts of wheat plants. The processing of plant waste into composite materials could have advantages to a Martian colony and should be investigated.

Inflatable Structures**:** Inflatable structures provide a greater volume for plant growth than the rigid cylinders selected for Phase I of MAGIC. The inflatable habitat concept (TransHab) currently under consideration for the International Space Station should be investigated further for use as a possible replacement for the rigid cylinders.

Use of Indigenous Martian CO_2 for Plant and Human Life**:** The concentration of CO_2 in the Martian atmosphere is too high to support plant life. Mars has a preponderance of $CO_{2,}$ and practically none of the carbon and oxygen necessary for life. A process or mechanism devoted to converting CO_2 into the basic elements of carbon and oxygen needs to be developed. [1a]

Greenhouse Thermal Protection**:** Thermal analysis should be done on the effects of the extremely low temperatures of Mars on the greenhouse facilities. Much can be done to optimize the maintenance of plants in a healthy thermal environment. Simple, reliable, and effective methods of achieving this should be pursued.

The Robotic Farmer**:** The autonomous robotic harvester has a mission to replace human activities for tending the greenhouse and processing plant food. The robot should ideally be able to seed and tend plants prior to the arrival of humans and have the facility in full production when humans arrive. It then should continue the harvesting and food processing duties during human presence. Trade-off analysis should be performed to weigh the cost of developing and maintaining the robot against the need for the inhabitants to devote their time to other duties. [1a]

Martian Crop Development**:** New breeds of plants need to be developed that have high productive capacities and minimal foliage. This development would be relevant for missions of long duration on Mars. Improvements in the productive capacity of wheat, with reduced foliage compared to typical wheat stocks, have been achieved on Earth. Such improvements may be attainable with other plants as well.

Further Development of MAGIC, Phase II**:** Phase II of our study calls for the use of the Martian soil in lieu of hydroponics, and a crop arrangement not much different than that used on Earth. This quasi-terraforming concept is a challenge in, among others, the issues of materials, heat transfer, gas leakage, and crop choice. Further information on the nature of the Martian soil will be instrumental in the development of this phase. [1a]

10. LESSONS

For many of the students participating in this project, MAGIC was the first opportunity to experience the design of a large scale, complex system. Working in small teams, as part of a larger team, with common goals requires an effective, reliable system of communication among the members and the individual teams. Ideally, this system should be in place before even the first design parameter is established. This reduces the number of redundant tasks being performed and ensures that everyone understands what is required of them. A constantly updated interactive web site can assist in this communication.

11. OUTREACH

Several actions were taken to ensure exposure of MAGIC to the community at large, so that others may learn from the challenges encountered during the project. Following the conference at the Lunar and Planetary Institute, a newsletter circulated at UTSA as well as the student newspaper will publish articles about MAGIC. In addition, a local television station may cover the project. The posters that were developed for the conference will be on display for high school students and parents during “Engineering Week”, hosted by engineering students at the university. Finally, the World Wide Web site, which was developed for intercommunication among the MAGIC design teams, will become a permanent part of the UTSA division of engineering web site. This will allow material to be accessed and referenced by those working on further aspects of the design, or on similar projects.

12. CONCLUSION

MAGIC addressed the prospect of developing a food production facility on Mars by implementing a two-phase, expanding approach. Each individual design challenge involved varying levels of trade off analyses, projections, and assumptions. As further information is gained on the nature of the Martian atmosphere, soil, and climate - designs can be refined and finalized. Furthermore, advances in gas production and water production technology, as well as advances in robotic autonomy, will improve the design of each individual subsystem. Like the original pioneers of the American frontier, future astronauts will need to learn how to "live off the land" as they venture further away from home. MAGIC is the first bold step in that direction.

REFERENCES

1a. Reference Report

1b. Mars Reference Mission. NASA.

2. Whitney, Eleanor Noss, et al. Understanding Normal and Clinical Nutrition (Minneapolis/St. Paul: West, 1994).

3. Designing For Human Presence in Space. http://augusta.msfc.nasa.gov/ed61/papers/rp1324.

4. Information provided by Terry Tri, NASA-Johnson Space Center.

5. http://science.nas.nasa.gov/services/Education/Settlement/Contest/Results/96/winner/seis.html.

6. Stern, Kingsley R. Introductory Plant Biology (Chicago: Wm. C. Brown, 1997.

7. Information provided by Keith Henderson, NASA-Johnson Space Center.

8. Walkinshaw, C. H and S.G. Galliano. New Corps for Space Bases. http://www.hort.purdue.edu/newcrop/proceedings1990/V1-532.html.

9. Rieder, R., et al. *The Chemical Composition of Martian Soil and Rocks Returned by the Mobile Alpha Proton X-ray Spectrometer: Preliminary Results from the X-ray Mode*. Science, 278: 1771-1774 AND *Mars Pathfinder-APXS Preliminary Results - Comparison @* http://mpfwww.jpl.nasa.gov/MPF/science/apxs_comparison.html. (site suggested by Keith Henderson).

10. Controlled Ecological Life Support Systems Human-Rated Test Facility: An Overview
Donald L. Hennington and Terry O. Tri, NASA Johnson Space Center

11. Analysis of Lunar Base Life Support Systems with Different Closure Levels
Dr. Peter Eckart, Institute of Astronautics, Technishe Universitat Munchen, 85747 Garching Germany

12. Johnson Space Center's Regenerative Life Support Systems Test Bed
D. J. Barta and D. L. Henninger, Lyndon B. Johnson Space Center, NASA, Houston, TX 77058

13. Brown, David. Launchspace. "Inflatable Accommodations on the ISS". Vol. 3, num.6. p. 32.

14. Subsytem and Parameters: Chamber fitting pg.3

15. Dr. Daniel Barta from HEDS-UP Program

16. Lunar Farming; Frank B. Salisbury; pg.82

17. Dr. Keith Henderson from HEDS-UP Program

18. Frank P. Incropera and David P. DeWitt, "Fundamentals of Heat and Mass Transfer," John Wiley & Sons, NY, 1996.

19. Robert W. Fox and Alan T. McDonald, "Introduction to Fluid Mechanics," John Wiley & Sons, NY, 1992.

20. Norman S. Nise, "Control Systems Engineering," Addison-Wesley Publising Company, CA, 1995.

21. Michael J. Moran and Howard N. Shapiro, "Fundamentals of Engineering Thermodynamics," John Wiley & Sons, NY, 1996.

22. A.F. Mills, "Basic Heat and Mass Transfer," Richard D. Irwin, Inc., 1995.

23. Lindon C. Thomas, "Heat Transfer," Prentice Hall, NJ, 1992.

24. Giorgio Rizzoni, "Principles and Applications of Electrical Engineering," Richard D. Irwin, Inc., 1996.

25. Dr. J.W. Frazer: Professor of Electrical Engineering at The University of Texas at San Antonio.

26. Omega Engineering Inc: Supplier of electronic sensors. **{** HYPERLINK http://www.omega.com/ **}**

27. Queensland University Of Technology: Australian University