Greenhouse Design for the Mars Environment: Development of a Prototype, Deployable Dome

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Abstract

Concepts for landing missions on Mars often include greenhouse structures for plant production. The types of structures proposed vary from small automatically deployed structures for research purposes to larger structures that would be used for food production. Present plans are that greenhouses on Mars will be operated at internal pressures as low as 0.1 to 0.2 Earth atmospheres. Low internal pressures permit the use of structures with lower mass, but complicate the heat and mass transfer processes involved in maintaining a suitable environment for plant growth and raise questions about the requirements of plants for growth at low pressures. Results are given from preliminary tests of lettuce growth at 25 kPa.

Keywords: Mars, Greenhouse, Low Pressure, Lettuce

INTRODUCTION

The purpose of a greenhouse used on Earth is to provide a confined space maintained at desirable environmental conditions for plant growth (Aldrich R. A. et al., 1994). This concept can be extended to applications on the surface of other planets such as Mars. The Martian environment differs from that of Earth in several important ways including lower gravity, very low density atmosphere rich in CO_2, reduced light level and very cold ambient conditions.

GREENHOUSE STRUCTURES

The types of structures that might be used for plant production on Mars vary from small automatically deployed structures for research purposes to larger structures that would be used to grow plants as part of a manned expedition. The structural requirements will vary depending on the size and purpose of greenhouses, but the functions necessary for successful plant growth will be similar regardless of size. This paper will focus on design concepts for small automatically deployed structures.

The first step in structural design is to determine loads. Martian gravity is 0.38 of Earth gravity (3.73 m/s^2) so the dead loads will be less than on Earth. The Martian atmosphere has a density of about 0.01 that of Earth. Wind loads on structures are calculated from:

$$q = (\tfrac{1}{2}\rho V^2)C_D \qquad (1)$$

Where, q is pressure on vertical flat plate, Pa; ρ is air density, kg/m^3; V is air velocity, m/s; and C_D is drag coefficient. The drag coefficient for a dome or half cylinder resting on the ground varies from +1.4 positive pressure to -0.5 suction across the structure (ASCE, 2002). The wind forces on a Deployable Martian Greenhouse would be expected to be small because of the low atmospheric density. Even for an extremely high velocity of 100 m/s, equation 1 gives a pressure of 0.06 kPa on a vertical flat plate.

Stresses in a curved shell loaded by internal pressure are calculated from (Timoshenko and Woinowsky-Krieger, 1959):

$$\sigma_t = pr/t \qquad (2)$$

Where σ_t is tensile stress in shell, kPa; p is internal pressure, kPa; t is shell thickness, m; and r is radius of curvature, m. Bending stresses in a rectangular flat plate carrying a pressure load are calculated from (Timoshenko and Woinowsky-Krieger, 1959):

$$\sigma_b = KpL^2/t^2 \qquad (3)$$

Where σ_b is bending stress in a square plate, kPa; p is pressure, kPa; L is length of a side, m; t is shell thickness, m; and K is a constant determined by length to width ratio and edge conditions.

Inflatable structures with curved geometry have been studied for Lunar and Martian use (Sadeh and Criswell, 1995; Schroeder and Richter, 1994). The structures in these studies have been large enough for human occupancy, but many of the same principles will apply to the smaller structures being considered for a deployable greenhouse. Inflatable structures are a type of tensile structure (Leonard, 1988; Otto, 1973). Tensile structures include tents and other structures fabricated using membranes as structural elements. Membranes only carry tensile loads in the plane of the shell or fabric and can not carry compressive or bending loads. Hublitz (2000) evaluated design parameters for inflatable Mars Greenhouses.

GREENHOUSE DESIGN FACTORS

The Martian gravity, length of year and length of day are known, but other factors have varying degrees of uncertainty. As a starting spot, as much information as possible about the location, size, shape, maximum allowable weight and required lifetime of the structure is needed. In addition, as much information as possible is also needed about the type of plants to be grown and the plants' pressure, temperature, humidity and lighting requirements.

Ambient conditions

1. Atmospheric Pressure. Atmospheric pressure varies widely with location and season on Mars. NASA (2004) gives the surface pressure as about 0.61 kPa and lists observed values from 0.69 kPa to 0.9 kPa at the Viking 1 Lander site. Atmospheric pressure is always extremely low compared to Earth and from a structural analysis viewpoint is effectively zero.

2. Wind And Dust. Because of the low atmospheric density, the loads produced by wind will be low. However, the dust carried by wind is important, Dust suspended in the air changes the overall quantity of light and the distribution of direct and diffuse radiation. Information on the rate of deposition of dust on the surface of a greenhouse is needed. Power produced by the solar cells on Mars Pathfinder dropped by 0.33% per day (Muser and Alpert, 2000). It will be necessary to develop a method of dust removal from the exterior of the greenhouse.

3. Temperature. The average surface temperature on Mars is approximately –63°C with an average diurnal range of around –103°C to –5°C (Hiscox, 2000). The diurnal temperature range observed by the Viking 1 Lander was –89° C to –32°C (NASA 2004). Daytime temperatures in the summer at the equator may be suitable for plant growth, but nighttime temperatures are far below the temperature range where plants can survive.

4. Light Levels. Estimates of light levels vary and it is difficult to determine whether values are for the Martian surface or for the Martian orbit. The distribution of direct and diffuse light is needed. Values of Photo synthetically Active Radiation (PAR) levels are needed.

Ambient light levels on Mars are high enough to sustain plant growth. However, because of extremely low temperatures and pressures, any plant production must be conducted inside an enclosure. Even the best clear wall materials reduce light levels. An ideal wall material would allow transmittance of the wavelengths above 400 nm at angles of incidence from zero to 90° and zero transmittance out of the structure for all thermal wavelengths beyond 3000 nm (Aldrich and Bartok, 1994; Robbins and Spillman, 1980).

The wall materials with the highest light transmisivity are thin films that have low thermal resistance and low mechanical strength. Thin films can be reinforced by straps or frames, but these reinforcing elements reduce the amount of light. It may be necessary to supplement ambient light with artificial lighting to achieve satisfactory plant growth. The power requirements of artificial lighting are very high; however, in contrast to most situations on Earth, the waste heat from artificial lights would be very useful on Mars.

Structural Needs

The main structural load on any configuration of Martian greenhouse will be imposed by internal pressure. Gravity loads and wind loads will be much smaller. The stresses in a curved shell are directly related to the internal pressure and the shell radius and are inversely related to the wall thickness. Stresses in flat sheets increase with pressure and sheet width. Bending stresses in flat sheets also increase as sheet thickness decreases. Walls must be as transparent as possible, which means walls should be as thin as possible. Most greenhouse films are less than 1 mm thick, so stresses can rapidly approach the film's failure strength. Reinforcing material can be added to films and sheets, but reinforcing material blocks or reduces light levels.

A spherical shape gives the best strength to weight ratio for carrying pressure loads and curved shapes such as hemispherical domes or half cylinders have better strength to weight ratios than shapes with flat sides. Curved shapes also have lower surface area to volume ratios, which is an advantage when considering heat loss through the wall surfaces. However, the lower surface area to volume ratio can be a disadvantage when light collection is considered.

Many film materials exhibit large thermal expansion and contraction. Large stresses are produced if the film is restrained from changing length as the temperature decreases and wrinkles can appear when the temperature increases. Cycles of expansion and contraction can also produce stresses at joints. Many clear materials are sensitive to ultraviolet radiation.

ENVIRONMENTAL CONTROL

The dominant environmental parameter in a Mars deployable greenhouse will be temperature. A heating system will be a necessity at night. Solar collectors can be used to increase the amount of energy, but collectors will not be effective during times when light is diffuse because of dusty conditions or clouds. Even on the best days, supplemental heating will be required. If a transparent film is used for wall material, the heating system will consume major quantities of energy, so utilizing as much solar energy as possible will be critical. Significant quantities of solar energy are available on the Martian surface, but as on Earth, solar energy on Mars is not always available when required and is never available at night. If supplemental lighting is used, cooling may be necessary because electrical lights produce very large quantities of waste heat. Because of the cold surroundings, cooling should consume much less energy than heating. The quantity of solar energy available to heat a greenhouse can be increased by the use of solar collectors and concentrators when direct sunlight is available. Thermal storage is necessary when using solar systems in order to provide a steady supply of energy throughout the day and night.

Glass is transparent to visible wavelengths of light and opaque to infrared wavelength and is an ideal wall material for the greenhouse effect. Unfortunately, many plastic films are relatively transparent to infrared radiation. The radiation characteristics of wall materials must be carefully selected to optimize transmission of PAR and block as much radiation in the infrared range as possible.

Gas leakage will occur from the greenhouse. All practical closed systems holding gas under pressure leak because of the pressure differential across wall surfaces and the difficulties of maintaining tight seals of flexible materials. Heating of replacement gases will add to the energy load of the greenhouse. Carbon dioxide can be replaced from the Martian atmosphere, but water vapor and oxygen will be difficult to make up.

The greenhouse will require a ventilation system. Plants will require some minimum air velocity over leaves for gas exchange. Plants transpire and release oxygen as a byproduct of photosynthesis. Even if the overall system is closed, the plant growth volume must be maintained within a certain range of relative humidities and at some point, surplus oxygen must to be removed from the system and carbon dioxide will need to be added.

Temperature and relative humidity must be constantly controlled to maintain a satisfactory environment for plant growth. An overall environmental control system will be required to manage the interactions between lighting, temperature, relative humidity, oxygen level, carbon dioxide level, pressure, the hydroponics system and plant growth (Albright et al, 2001; Fowler et al, 2002).

PLANT CONSIDERATIONS

The plant consideration that has the largest impact on structural design is the internal pressure of the greenhouse. The absolute minimum internal pressure is the sum of the partial pressures of carbon dioxide, water vapor and oxygen inside the greenhouse. The partial pressure of carbon dioxide in Earth's atmosphere is 0.035 kPa. The partial pressure of carbon dioxide in the Martian atmosphere is about 0.57 kPa. The partial pressure of water vapor in Earth's atmosphere, referred to as the vapor pressure, varies with temperature and relative humidity. At comfortable room conditions of 25°C and 50% relative humidity, the vapor pressure for Earth's atmosphere is 1.6 kPa. Table 1 gives values of vapor pressure for several combinations of temperature and relative humidity. The values of vapor pressure in Table 1 vary by a factor of close to three. This variation can be neglected in open systems operating at Earth atmospheric pressure, but the variation is important in closed systems operating at reduced pressures. Tests in the vacuum test chamber at Kennedy Space Center (KSC) (Fowler et al, 2000) indicate that plants tolerate pressures down to 20 kPa without problem, but begin to wilt below this value. In other tests at KSC, plants survived below 10 kPa for short periods of time. Plants have a region of temperatures in which they function best and also upper and lower limits beyond which they display heat or cold damage. Temperature also has a major influence on transpiration rate and on dissolved oxygen levels in root moisture.

The internal gas mix must contain minimum levels of carbon dioxide, water vapor and oxygen. The maximum desirable levels of these components will not total 10 kPa so some inert gas will be required to supply the remainder of the desired pressure. The pressure and the gas mix in the greenhouse will require monitoring and control. In a closed system, the carbon dioxide partial pressure will drop as carbon dioxide is consumed by photosynthesis. At the same time, oxygen is released by the plants and the oxygen partial pressure will increase. Water vapor partial pressure will increase as the plants transpire and add water to the gas mix. Excess water vapor will have to be removed from the gas mix and recycled into the soil media or the hydroponics system's water. Water vapor pressure will fluctuate by several kilopascals as relative humidity varies. Carbon dioxide will have to be replaced as it is consumed by photosynthesis and oxygen will have to be harvested and stored or discharged before it reaches undesirable levels.

Just as with temperature, plants require a certain range of relative humidity to function. Relative humidity is the ratio of the ambient water vapor pressure to the water vapor pressure at saturation for the same temperature. For a given temperature, relative humidity is a function of ambient water vapor pressure. Vapor pressure increases as moisture is added to the air through transpiration or evaporation from leaks in the hydroponics system. Under Earth atmospheric pressure in an open system, the change in vapor pressure is not important, but in a totally closed system at low pressure, fluctuations in vapor pressure will significantly influence total pressure.

Hydroponics systems will need to be as tight as possible to reduce the quantity of water that evaporates from leaks. At high relative humidities, condensation on interior wall surfaces will occur. Condensation by itself will reduce light levels and over time will promote dirt and mineral collection on wall surfaces that will further reduce light levels.

A minimum internal air velocity is needed for the gas exchanges required for photosynthesis to occur. Velocities in excess of this minimum should be produced by the ventilation system operating to remove moisture from the system, so maintaining the minimum required velocity is not expected to be a problem. The plant will also require some minimum volume for its canopy.

The biggest challenge for the design of a deployable Martian greenhouse is to achieve maximum light transmittance while keeping heat loss to acceptable levels. Radiation heat transfer will dominate for Martian conditions. The low density atmosphere will reduce conductive and convective heat transfer through the atmosphere outside the greenhouse. Operating greenhouses at internal pressures as low as 0.1 Earth atmosphere has been discussed, but it appears that plants may not be productive at pressures below 0.2 or 0.3 Earth atmospheric. Conduction and natural convection inside the structure will be greatly reduced at 0.1 Earth atmosphere and hence a higher pressure may be required to maintain a good thermal and mass transfer balance. During the day, the greenhouse will receive direct radiation from the sun and some diffuse radiation. The greenhouse will lose radiant energy to all of the very cold surrounding objects and depending on sky conditions; it will lose radiant energy to cold portions of the sky away from the sun. At night, the surrounding objects will be even colder and the greenhouse will lose radiant heat to the cold sky.

The presence of plants complicates the heat transfer analysis by adding latent heat transfer (evaporation and condensation) to sensible heat transfer (conduction, convection and radiation). The changing mix of carbon dioxide, oxygen and water vapor in the greenhouse must be accounted for in heat transfer analysis. Other factors of importance include leakage from the hydroponics plumbing and condensation on the inside of the greenhouse wall.

LABORATORY TESTS

Several research groups are developing facilities to study the behavior of plants at low pressure (Brown and Lacey, 2002; Chamberlian et al, 2003; Ferl et al, 2002; Goto et, 2002). The tests described here are from preliminary studies with a 1 meter diameter dome shaped low pressure growth chamber developed as a prototype of a Mars Greenhouse by the Advanced Life Support group at KSC and the University of Florida. Tests conducted to clarify air and moisture relationships at low pressure have been conducted in a large vacuum chamber used to test space suits and several small chambers (Fowler et al, 2000; Fowler et al, 2002; Rygalov et al, 2002).

An automated closed environmental growth chamber was developed at KSC that operates at pressures down to 25 kPa. This system called the Mars Dome Greenhouse is depicted in Figure 1 and Figure 2. The system is shown in Figure 3 as used in testing.

The base of the dome is stainless steel and the dome is made of clear Lexan. Internally, a monitoring and control system regulates the atmosphere to predetermined set points. The system is controlled electronically by a microcontroller which interacts with sensors and appropriate relays and solenoids to enact systems for each parameter. Algorithms were developed to control each parameter. The main component of the system is a central tower, the Automated Tower Management System (ATMS). The ATMS consists of a tube with a fan and heater at the top to create airflow in the system. Directly below the fan a cooling coil is used both for air temperature and humidity control. Underneath the cooling coil is a water collection pot that receives condensation from the cooling coil. This pot of water is then pumped back through a selective manifold that distributes the water back to the plants, thus completing the water cycle of the system. An outside PC is used to log data from the experiment. A regulated vacuum pump is used to maintain the desired pressure.

The ability of the system to grow a crop was tested by growing nine plants of Waldmann's Green Lettuce at 25 kPa pressure, 0.2 kPa carbon dioxide and 5 kPa oxygen. Plants grown in arcillite medium with Osmocote time release fertilizer. An automated watering system was used. The watering system was based on scales continuously weighing each plant. Water and CO_2 were the only two outside inputs to the system. The experiment lasted 45 days with the first week (germination) done at regular pressure and then the plants were trans-planted and put into a 25 kPa environment. At the end of the experiment, the plants were harvested (Figure 4) and analyzed.

. One plant died and was removed from statistics. The average plant weight was 237.4 g with SD of 57.3 g, average dry weight was 23.7 g with SD 4.5 g, average diameter was 26.1 cm with SD of 2.2 cm, average height from soil was 25.0 cm with SD of 2.6 cm and average light level was 314.3 µmol with SD of 65.3 µmol. Six plants displayed tip burn, four plants had rusty spots on older leaves and there was mold on the soil surface under dead leaves of one plant. Evapotranspiration rates of the lettuce are presented in Figure 5. Evapotranspiration rates were calculated from the continuous pot weights collected by the data acquisition system. Rates were calculated based on linear fits of short-term plant weight changes. The evapotranspiration curves are of sigmoid form similar to plant growth curves. The system successfully grew a crop of lettuce past the typical harvest date.

CONCLUSIONS

Further tests of low pressure systems are being conducted to provide information about methods needed to maintain conditions desirable for plant growth under Martian conditions. Plants will be grown in a model greenhouse with inside pressure in the range of 10 to 20 kPa and the environment outside at about 1 kPa and –20 °C. Optimal hardware and software for low pressure greenhouse control and regulation will be developed as part of the plant growth studies.

There is a great deal of uncertainty about most of these design factors except for outside temperature, and even this will vary with location on Mars. The first step is to decide on the best available values for external ambient conditions. The question of the internal pressure is critical for design of the components of the greenhouse. Once the outside design conditions have been established and the internal operating pressure has been selected, then the environmental control system must be designed with the needs of the plant in mind.

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Figures

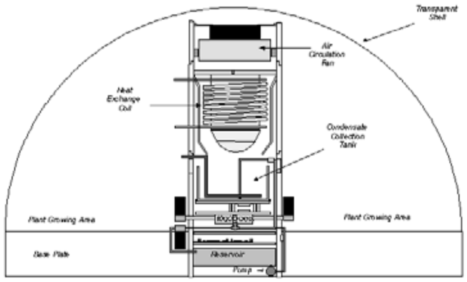

Figure 1 Mars Dome Schematic

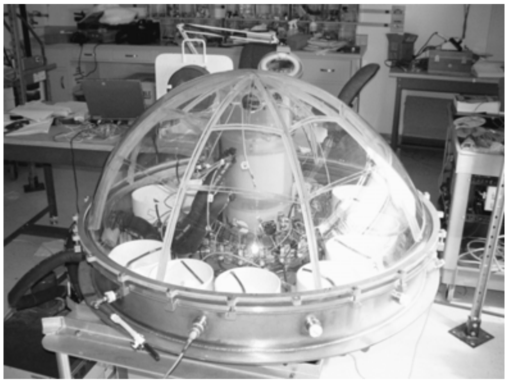

Figure 2. Mars Dome Details.

Figure 3. Mars Dome Production mode

Figure 4. Plants Ready for Harvest.

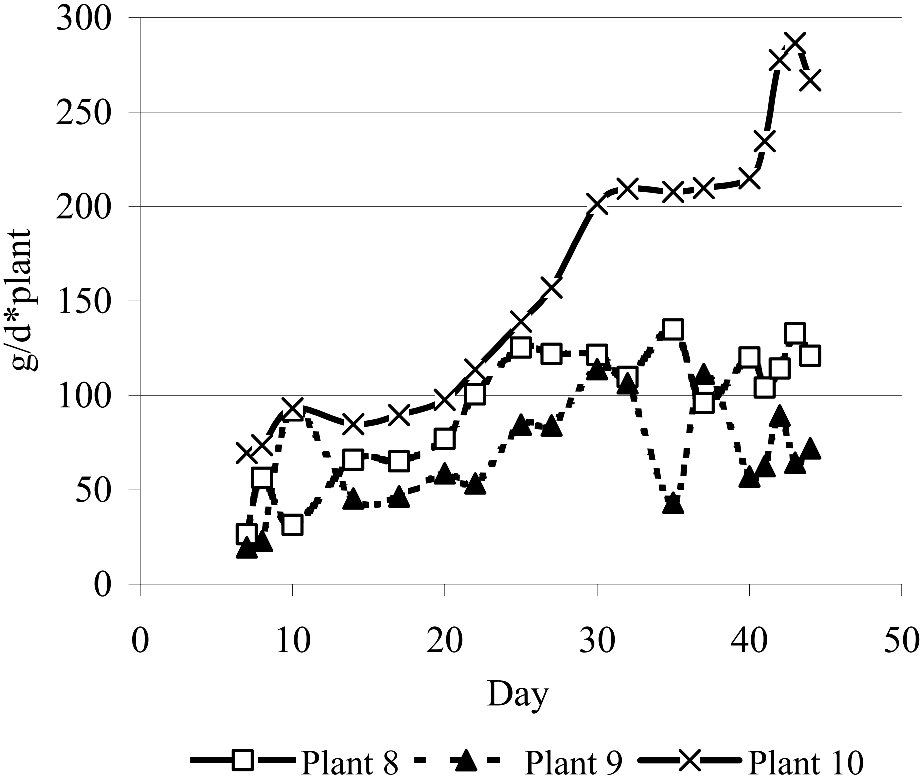

Figure 5 Evapotranspiration Rate of Lettuce Plants

Tables

Table 1. Partial Pressure of Water Vapor.

T, (°C)	RH, (%)	Vapor Pressure, (kPa)
25	50	1.6
30	50	2.1
35	50	2.8
25	80	2.5
30	80	3.4
35	80	4.5