

Design Parameters for Mars Deployable Greenhouses

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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.

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 CO₂, reduced light level and very cold ambient conditions.

Greenhouses designed for Martian conditions must satisfy several fundamental requirements such as being structurally sound and maintaining the desired interior climate when the exterior climate consists of very low pressures and temperatures. The overall greenhouse system must also be designed so that the interactions of plants with greenhouse systems such as ventilation and the overall water cycle function properly and so that basic physiological requirements for plant growth such as light, temperature and humidity are within desired limits.

GREENHOUSE STRUCTURES

The types of structures that might be used for plant production on Mars vary from small automatically deployed structures serving to house a small number of plants 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 the 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 and will deal primarily with inflatable structures. Structural requirements will be discussed first and then the relationships between the structure and the functional needs of the plants will be discussed from the point of view of experiences with terrestrial greenhouse engineering.

The first step in structural design is to determine loads. Martian gravity is 0.38 of Earth gravity (3.73 m/s²) so the dead loads will be considerably less than on Earth. The Martian atmosphere has a density of about 0.01 that of Earth. Wind loads on structures are calculated from:

$$q = (1/2\rho V^2)C_D \quad (1)$$

Where:

q = pressure on vertical flat plate, Pa

ρ = air density, kg/m³

V = air velocity, m/s

C_D = drag coefficient

For Earth, ρ of 1.2 kg/m³ is used and dividing by 1000 to give kPa:

$$q = (6 \times 10^{-4} V^2) C_D \quad (2)$$

Assuming 0.01 Earth density or 0.01 kg/m³ for the Martian atmosphere, gives

$$q = (6 \times 10^{-6} V^2) C_D \quad (3)$$

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, 1998). The wind forces on a Deployable Martian Greenhouse would be expected to be small because of the low atmospheric density. However, in a major storm, the squared velocity term in equation 3 combined with the low Martian gravity could produce a risk of uplift or overturning of a very light structure. Problems with distortion or fluttering of the wall could also occur if the velocity pressure is a significant fraction of the internal pressure. Even for an extremely high velocity of 100 m/s, equation 3 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)

$$\sigma_t = pr/t \quad (4)$$

Where:

- σ_t = tensile stress in shell, kPa
- p = internal pressure, kPa
- t = shell thickness, m
- r = radius of curvature, m

Bending stresses in a rectangular flat plate carrying a pressure load are calculated from (Timoshenko and Woinowsky-Krieger, 1959):

$$\sigma_b = KpL^2/t^2 \quad (5)$$

Where:

- σ_b = bending stress in a square plate, kPa
- p = pressure, kPa
- L = length of a side, m
- t = shell thickness, m

K = Constant determined by length to width ratio and edge conditions. For a square plate with clamped edges, $K = 0.0513$

Inflatable structures with curved geometry have been studied for Lunar and Martian use (Abarbanel and

Criswell, 1997; Nowak, Sadeh and Morroni, 1992; 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 (Irvine, 1981; Leonard, 1988; National Research Council, 1985; Otto, 1973; Shaeffer, 1996). 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.

GREENHOUSE DESIGN FACTORS

A complex set of design parameters must be determined for a Mars greenhouse. The Martian gravity, length of year and length of day are well known, but other factors have varying degrees of uncertainty or are unknown. 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 plant to be grown and the plant's pressure, temperature, humidity and lighting requirements.

AMBIENT CONDITIONS

ATMOSPHERIC PRESSURE

Atmospheric pressure varies widely with location and season on Mars. NASA (2000) 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.

WIND AND DUST

Because of the low atmospheric density, the loads produced by wind velocities will be low enough to neglect. However, the dust carried by windstorms 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. The 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.

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 2000). Temperatures may rise

above freezing during the summer at the equator. 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. Any plant growth on Mars must take place in heated environments.

LIGHT LEVELS

Estimates of light levels vary and it is often difficult to determine whether the tabulated values are for the Martian surface or for the Martian orbit. The distribution of direct and diffuse light is needed. Plant photosynthesis does not respond to the entire spectrum of light. Values of Photosynthetically Active Radiation (PAR) levels are needed for Mars.

Ambient light levels on Mars are high enough to sustain plant growth. However, because of the extremely low temperatures and pressures, any plant production must be conducted inside an enclosure. Even the best clear wall material for an enclosure will reduce light levels. The ideal wall material would allow transmittance into the structure 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; Evans, 1963; Hanan, 1998; Robbins and Spillman, 1980).

Another problem is that the wall materials with the highest light transmissivity 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 for a Martian greenhouse.

STRUCTURAL NEEDS

The main structural load on any configuration of a domed shaped Martian greenhouse will be imposed by the internal pressure. Gravity loads and wind loads will be much smaller. As discussed earlier, 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 and bending stresses in flat sheets also increase as sheet thickness decreases. A greenhouse wall must be as transparent as possible, which typically means the wall should be as thin as possible. Most greenhouse films are less than 1 mm thick, so stresses can rapidly approach the failure strength of the film. Reinforcing material can be added to films and sheets, but reinforcing material blocks or reduces light levels.

It is possible that the first greenhouses will be deployed from unmanned landers. An effective deployable greenhouse design must use a structure that is

lightweight. In addition, the design must lend itself to being stored in a folded configuration and then automatically deployed into its functional configuration. The wall material must also be capable of being folded and be able to be automatically unfolded into the functional configuration. 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 structures fabricated with flat sides. The 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 increases and wrinkles can appear when the temperature drops. Cycles of expansion and contraction can also produce stresses at joints that can lead to leakage problems. Many clear materials are sensitive to ultraviolet radiation and become brittle and discolor over time.

ENVIRONMENTAL CONTROL

The dominant environmental parameter in a Mars deployable greenhouse will be temperature. A heating system will be a necessity at night. There may be times during daylight hours that enough solar energy is available to maintain desired temperatures. 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 for a large portion of daylight hours. 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, the 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.

The greenhouse effect occurs in an enclosed volume with clear walls when visible light is transmitted through the clear wall material and a portion of the light is absorbed by objects inside the enclosure. As objects inside the enclosure absorb light, their temperature increases and the objects emit infrared radiation. If the wall material is transparent to visible light and opaque to

infrared radiation, then the infrared energy is trapped inside the enclosure, and the air temperature in the enclosure increases. Glass is transparent to visible wavelengths of light and opaque to infrared wavelength and is an ideal wall material for greenhouses. Unfortunately, many plastic films such as the common greenhouse film polyethylene are transparent to infrared radiation. The radiation characteristics of wall materials must be carefully selected to optimize transmission of Photosynthetically Active Radiation and block as much radiation in the infrared range as possible.

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. Replacement gases will have to be heated, adding to the energy load on 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. The 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 will need to be removed from the system and carbon dioxide will need to be added.

Temperature and relative humidity will need to 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 (Fowler et al, 2000a).

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.

T, (°C)	RH, (%)	Vapor Pressure, (kPa)
20	50	1.2
25	50	1.6
30	50	2.1
35	50	2.8
20	80	1.9
25	80	2.5
30	80	3.4
35	80	4.5

Table 1. Partial Pressure of Water Vapor in Earth's Atmosphere for Example Temperatures and Relative Humidities.

The values of vapor pressure in Table 1 vary by a factor of close to four. 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 (Fowler et al, 2000b) indicate that plants tolerate pressures down to 0.2 atmosphere or about 20 kPa without problem, but begin to wilt below this value. In other tests at KSC, plants survived below 10 kPa. 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 totally 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 hydroponic system's water. Water vapor pressure will fluctuate by several kilopascals as relative humidity varies (Table 1). 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

and total pressure. So for a given temperature and total pressure, relative humidity is a function of ambient water vapor pressure. The vapor pressure increases as moisture is added to the air through transpiration or evaporation from leaks in the hydroponic 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 have a significant influence on total pressure.

If a hydroponic system is used, it 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 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 the maximum light

Relative humidity, (%)	Temperature of environment, (°C)	Vacuum, (in Hg)	Temperature of coolant, (°C)
83.5	26.7	0.00	22.0
81.2	27.2	9.77	22.0
79.0	27.8	19.81	22.0
71.4	27.9	28.74	22.0
53.3	25.5	0.00	11.8
53.4	25.5	10.30	11.8
52.2	25.7	20.35	11.8
47.0	26.4	29.15	11.8
42.1	22.3	0.00	3.0
42.2	22.6	10.35	3.0
40.9	23.7	19.93	3.0
32.8	24.5	29.47	3.0

transmittance while keeping heat loss to acceptable levels. Radiation heat transfer should dominate for Martian conditions. The low density atmosphere will reduce conductive heat transfer through the atmosphere outside the greenhouse. Convection should also be small because of the low air density, but convection could be important at high wind velocities. Operating the greenhouse at internal pressures as low as 0.1 Earth atmosphere has been discussed, but it appears that plants may not tolerate 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 but will become more important if the pressure is increased.

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. Preliminary calculations indicate that in the middle of the day and in the middle of the summer, a greenhouse can operate on Mars if radiation losses are controlled, but a practical greenhouse design must be designed for conditions during the winter and at night year round.

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). Plants consume carbon dioxide and give off oxygen during photosynthesis, but they also respire and require a small level of oxygen. Plants also give off water vapor during transpiration. 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

Preliminary tests have been conducted to clarify air and moisture relationships at low pressure. The water cycle at low pressures was observed by measuring the rate of evaporation in a vacuum chamber. The vacuum chamber was equipped with a vacuum gage, humidity sensor, and thermometer. For cooling, a small copper cooling coil was mounted inside the chamber. An open petri-dish was placed in the chamber as a source of water. The amount of water that evaporated was calculated based on the difference in weight from the beginning to the end of the experiment. Afterwards the rate of the water cycle was calculated by dividing the change in weight of water by the duration of the test. The temperature of the chamber was maintained at approximately 25° C. The observed saturation relative humidities are shown in Table 2 at different vacuum levels.

Table. 2. Saturation relative humidity

WATER CYCLE AT LOW TOTAL PRESSURE

Saturation relative humidity and thus saturated vapor pressure did not show dependence on total pressure and was a function only of temperature (Fowler et al., 2000b). But the rate of evaporation increased with decreasing total pressure (Rygalov et al., 2000). The results of water cycle measurements are presented in Figure 1

Fig. 1. Effect of total pressure on water cycle intensity

Plant transpiration also increased with decreasing total pressure (Figure 2). Both the rate of plant transpiration and the rate of water evaporation increased with decreasing of total pressure. These rates affect both the water recirculation system and the ventilation system used to regulate relative humidity.

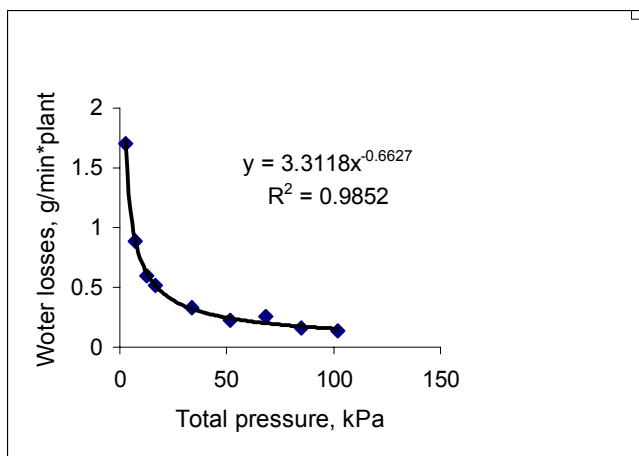
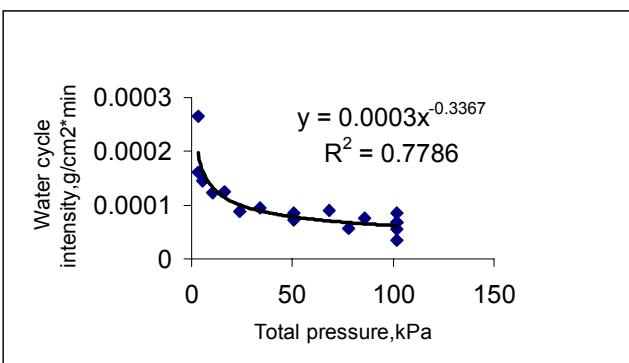


Fig. 2. Water loss of plants at different levels of total pressure.



CONCLUSIONS

Further tests of low pressure systems are being conducted (Fowler et al, 2001) 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 -32°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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