

Mars Greenhouse Design: Development of biological life support systems for long-duration space missions

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Abstract

Biological life support systems based on plant growth offer the advantage of producing fresh food for the crew during a long surface stay on Mars. Greenhouses on Mars are also used for air and water regeneration and waste treatment. Operating a greenhouse at reduced internal pressure leads to mass and therefore cost savings. A major challenge in developing a Mars greenhouse is its interaction with the thin and cold Mars environment. This paper gives an overview of research at University of Florida's Agricultural and Biological Engineering Department in cooperation with NASA's Kennedy Space Center, to perform engineering analysis of design factors for low-pressure Mars greenhouses. Ongoing experiments focus on the heat and mass transfer at reduced pressure as well as on a water cycle analysis of closed ecological systems. The results of this study will improve the design of the environmental control system leading to an optimization of plant growth conditions.

Keywords: *Mars greenhouse; Mars environment simulation; Biological life support systems; Controlled environment; Space life science*

Introduction

Mars greenhouses are important components of the human Mars mission infrastructure as plant-based life support systems offer self-sufficiency and possibly cost reduction. Resupply is prohibitive for long duration Mars missions as it increases the launch mass and consequently the launch costs. Relying on frequent resupply from Earth



Figure 1: An artist's view of future manned missions to Mars involving greenhouses.

also increases risk to the astronauts. Greenhouses produce edible biomass as well as regenerate the air and water through photosynthesis.

The atmospheric surface pressure on Mars is on average 0.61 kPa, i.e. below 1% of Earth's standard atmospheric pressure (NASA, 2004). Operating a greenhouse at low interior pressure reduces the pressure differential across the structure and therefore, saves structural mass as well as reduces leakage. Studies have shown that plant growth is feasible at pressures as low as 20 kPa; plants even survive short-term exposure to pressures as low as 10 kPa (Wheeler, 2000; Fowler et al., 2002).

Rationale of Biological Life Support Systems

Consumables for human space missions amount to approximately 31 kg of oxygen, water and food per astronaut and per day as listed in Table 1. Simultaneously, the same amount of waste is created. Physico-chemical life support systems can provide oxygen, reduce carbon dioxide and recycle water, whereas biological life support systems can fulfill all these functions and additionally produce food (Eckart, 1996).

Table 1: Human metabolism values per crew member and per day (CM-d) for average activity level (Hanford 2004).

CONSUMABLE	UNITS	NEEDS	EFFLUENTS
Air			
Carbon Dioxide Load	kg/CM-d		1.00
Oxygen Consumed	kg/CM-d	0.84	
Food			
Mass of Consumed Food (dry basis)	kg/CM-d	0.62	
Energy of Consumed Food	MJ/CM-d	11.82	
Potable Water Consumed (incl. water in food)	kg/CM-d	3.91	
Thermal			
Sensible Metabolic Heat Load	MJ/CM-d		6.31
Latent Metabolic Heat Load	MJ/CM-d		5.51
Waste			
Fecal Solid Waste (dry basis)	kg/CM-d		0.03
Perspiration Solid Waste (dry basis)	kg/CM-d		0.02
Urine Solid Waste (dry basis)	kg/CM-d		0.06
Water			
Fecal Water	kg/CM-d		0.09
Respiration and Perspiration Water	kg/CM-d		2.28
Urine Water	kg/CM-d		1.89
Hygiene Water			
Hygiene Water (Flush, Hand Wash, Shower, Laundry, Dish Wash)	kg/CM-d	25.58	
Greywater	kg/CM-d		25.58
Total Mass	kg/CM-d	30.95	30.95
Total Energy	MJ/CM-d	11.82	11.82

The size of the Mars greenhouse depends on the number of astronauts and the desired amount of food grown locally vs. shipped from Earth. The required plant-growth area per person can be estimated at 50 m² to fulfill 100% of the food requirements. Food, if grown on-site, can regenerate some or all of the crew's air and water. If more than about 25% of the food, by dry mass, is produced locally, all the required water can be regenerated by the same process. If approximately 50% or more of the food, by dry mass, is produced on site, all the required air can be regenerated by the same process depending on the crop and growth conditions (Hanford, 2004).

Mars Environment

The Mars environment differs from that on Earth in several significant ways including lower gravity, very low density atmosphere rich in carbon dioxide, reduced light levels and very cold ambient temperatures.

The average atmospheric pressure of Mars is 0.61 kPa. Pressure varies with season and location, e.g. a pressure variation of 0.69 to 0.9 kPa has been observed at the Viking 1 lander site at 22° North latitude (NASA, 2004). The average surface temperature on Mars is -63° C with an average diurnal range of -103° C to -5° C (Hiscox, 2000). The thinness of the Mars atmosphere and the low solar irradiance guarantees a large daily temperature range at the surface under clear conditions.

Transparent Mars greenhouses can take advantage of the available solar light as the day length of Mars is 24.6 hours and thus, the plants experience a photoperiod similar to Earth. The ambient light levels on Mars are high enough to sustain plant growth. However, plants must be grown in a total enclosure due to the low ambient temperature and pressure. The transparent greenhouse wall material reduces the available light needed for photosynthesis. Frequent dust storms on Mars result in a deposition of dust on the greenhouse leading to a further reduction of the light levels. Methods for removing dust from the surface have to be developed.

Experimental Setup

A large stainless steel vacuum chamber (1.2 m x 1.2 m x 1 m) is used to simulate the Mars environment. The vacuum chamber is filled with 100% carbon dioxide. The chamber wall temperature will be kept as low as -30° C by placing it inside an industrial walk-in freezer. A transparent lexan dome (semi-sphere with a diameter of 1 m) and an aluminum base serve as the greenhouse model. High pressure sodium growth lamps are mounted above the chamber window to provide photosynthetically active radiation for the plants. Table 2 compares the simulated environmental conditions that a greenhouse experiences during the experiments to the actual conditions on Mars.

Table 2: Environmental conditions for Mars (NASA, 2004; Hiscox, 2000) vs. vacuum chamber.

ENVIRONMENTAL PROPERTY	MARS	EXPERIMENT
Rotation Period (Day Length)	24.62 hours	24.62 hours
Gravity	3.69 m/s ²	9.81 m/s ² (Earth)
Surface Pressure	~0.61 kPa (variable, depending on season & location)	0.61 kPa
Average Temperature	-63° C	-30° C
Diurnal Temperature Range	-103° C to -5° C	-30° C
Solar Irradiance	589 W/m ²	600 W/m ²
Atmospheric Composition	95.5% CO ₂ , 2.7% N ₂ , 1.6% Ar, 0.15% O ₂	100% CO ₂



Figure 2: A greenhouse dome is installed into a vacuum chamber that simulates the low pressure and low temperature of the Mars environment.



Figure 3: Waldmann's Green Lettuce grown at 25 kPa, 27° C, 75 % relative humidity and a light level of 200 $\mu\text{mol}/\text{m}^2\text{-s}$.

Figure 2 shows the dome and the vacuum chamber that are placed in the walk-in freezer.

A dome similar to the one that serves as a greenhouse model for this study has been used by the Kennedy Space Center as an autonomous low pressure growth chamber. In a preliminary test lettuce had been grown at a pressure of 25 kPa for 45 days (Bucklin et al. 2004). However, during this lettuce growth experiment the dome was not exposed to simulated Mars conditions as the focus of the study was the plant response to low pressure. Figure 3 depicts the greenhouse dome during the test.

Greenhouse Environmental Control

The environmental control system is responsible for maintaining the environmental parameters within appropriate boundaries to optimize plant growth. It

manages the interactions between lighting, temperature, relative humidity, total pressure, oxygen concentration and carbon dioxide concentration. The set points for the environmental parameters depend on the requirements of the selected crop.

The structural design and the leakage rate are driven by the pressure differential across the greenhouse structure. In order to minimize the pressure differential the greenhouse will be operated at a reduced internal pressure. The reduced greenhouse pressure depends on the minimum level of oxygen, carbon dioxide, and water vapor pressure that the plant requires for photosynthesis, photo-respiration and evapo-transpiration. Nitrogen is inert and serves as pressurizing gas to achieve the desired total pressure. Over time plants take up carbon dioxide and release oxygen. Therefore, the environmental control system has to scrub excess oxygen and replenish the carbon dioxide. On Mars the carbon dioxide could be taken out of the planet's carbon dioxide rich atmosphere, in case of an autonomous plant growth facility that is pre-deployed before the first humans arrive. Once the greenhouse is interfaced with the human habitat the air loop between the humans and the plants will be closed. Additionally, gases lost due to leakage have to be replaced.

Water vapor pressure increases when the plants transpire and it has to be removed from the air in order to maintain a constant total pressure. The water vapor condensed out of the atmosphere will be recycled to the plants. Relative humidity is a function of water vapor pressure and temperature. Plant transpiration increases with decreasing pressure (Rygalov et al., 2004). The most limiting factor in determining the minimum internal pressure for the Mars greenhouse is likely to be the ability of plants to maintain their water status in spite of high transpiration rates.

A ventilation system ensures a homogenous gas mix in terms of gas composition, temperature and humidity inside of the greenhouse. Furthermore, ventilation leads to a minimum air velocity over the plants to facilitate gas exchange.

All environmental parameters have to be tightly controlled during the experiments. Low pressure influences sensor readings in some cases and therefore, the sensors have to be calibrated under low pressure prior to the experiments. Table 3 lists the greenhouse environmental set points that were chosen for the experiments.

Table 3: Properties of Mars greenhouse atmosphere.

ENVIRONMENTAL PROPERTY	MARS GREENHOUSE
Greenhouse Atmospheric Pressure	10/25 kPa
Greenhouse Atmospheric Composition	62% N ₂ , 25% O ₂ , 10% H ₂ O, 3% CO ₂
Temperature	+15 to +25° C
Relative Humidity	70 to 85%

Thermal Analysis

A challenge for the design of the temperature and humidity control system is to determine the effect of operating the greenhouse at low pressures on the heat and mass transfer. Radiation heat transfer will be the dominant mode of heat transfer inside the low pressure greenhouse as well as in the Mars environment. Conduction and convection are reduced due to the low pressure atmosphere. The reduced convection coefficient causes difficulties in heating up or cooling down equipment and material by convection. During the day cycle, when the growth lights are turned on, the greenhouse receives radiant energy. A heating system makes up the heat loss of the greenhouse atmosphere to the environment, especially during the night when the radiation from the light is not available. The presence of plants in closed systems complicates the heat and mass transfer analysis by adding latent heat transfer (evaporation and condensation) to sensible heat transfer (conduction, convection and radiation). Evapo-transpiration leads to increased humidity and water flux. If the humid air comes in contact with a surface at a temperature below the dew-point temperature, condensation will occur. Condensation on the transparent greenhouse shell leads to reduced light levels. Solutions are tested in order to avoid condensation/frost formation

inside of the greenhouse shell by maintaining a greenhouse wall temperature above the dew-point temperature. Changes in pressure affect also gas diffusion rates, surface boundary layers and water evaporation rates (Rygalov et al., 2004). Plants' evapo-transpiration rates increase with decreasing pressure, even at constant vapor pressure deficit.

Results of the thermal analysis and water cycle study will lead to a robust thermal control system that should:

- control the temperature and humidity within appropriate boundaries.
- achieve a uniform temperature and humidity distribution.
- prevent condensate/frost forming on greenhouse shell.
- minimize night time heat loss.

A schematic of the thermal analysis and water cycle study is depicted in Figure 4.

Conclusion

A detailed understanding of the heat and mass transfer under low pressure conditions is necessary to improve the thermal control in order to optimize plant growth. The results of this study will influence the selection of material

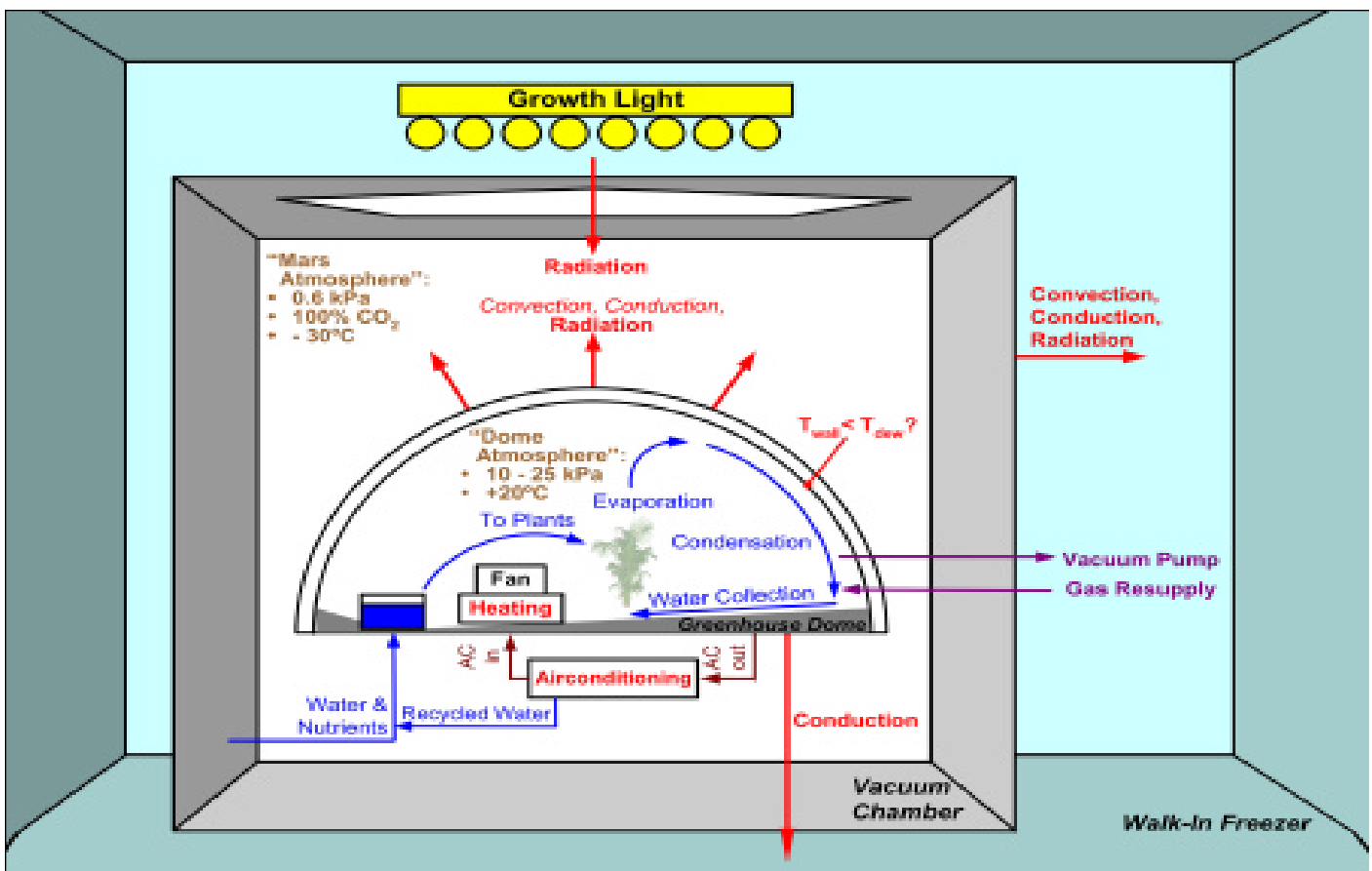


Figure 4: Experimental setup for the thermal analysis and water cycle study.

and equipment as well as the control algorithm. The next set of experiments should include diurnal variation of freezer temperature and light levels in order to simulate the Mars day-night cycle as closely as possible.

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Note

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