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PRELIMINARY GREENHOUSE DESIGN FOR A MARTIAN COLONY: STRUCTURAL, SOLAR COLLECTION AND LIGHT DISTRIBUTION SYSTEMS

UNIVERSITY OF IDAHO

The design of a greenhouse that will be a component of a long-term habitat on Mars is presented. The greenhouse will be the primary food source for people stationed on Mars. The food will be grown in three identical underground modules, pressurized at 1 atm to allow a shirt-sleeve environment within the greenhouse. The underground location will support the structure, moderate the large environmental variations on the surface, and protect the crops from cosmic radiation. The design effort is concentrated on the outer structure and the lighting system for the greenhouse. The structure is inflatable and made of a Kevlar 49/Epoxy composite and a pipe-arched system that is corrugated to increase stiffness. This composite is pliable in an uncured state, which allows it to be efficiently packaged for transport. The lighting system consists of several flat-plate fiber optic solar collectors with dual-axis tracking systems that will continually track the sun. This design is modeled after the Himawari collector, which was designed by Dr. Kei Mori and is currently in use in Japan. The light will pass through Fresnel lenses that filter out undesirable wavelengths and send the light into the greenhouses by way of fiber optic cables. When the light arrives at the greenhouse, it is dispersed to the plants via a waveguide and diffuser system.

INTRODUCTION

The greenhouse is intended to be the primary food source for a Mars-based habitat. The food will be grown in three identical modules that are located underground. The design effort is concentrated on the outer structure and a lighting system for the greenhouse. The structure is inflatable, made of a Kevlar 49/Epoxy composite that is corrugated to increase stiffness. The lighting system consists of several flat plate fiber optic collectors with dual-axis tracking systems that continually follow the sun. The light passes through Fresnel lenses that filter out undesirable wavelengths and send the light into junction boxes in the top of the structures by way of fiber optic cables. The light is then taken from the junction boxes and dispersed to the plants by a waveguide and diffuser system.

STRUCTURAL DESIGN

The design of the outer structure of the food production system consists of three identical modules, each having the capability of producing 50% of the food required by the Mars colony. The modules will be located at a depth of 4 m below the martian surface. This underground location will shield the plants and colonists against harmful radiation, support the structure, and assist in moderating the extreme environmental variations that occur on the surface of Mars. The structure will be pressurized at 1 atm, or 101.3 kPa, in order to maintain a shirt-sleeve environment in which the colonists can work without requiring the use of a pressurized spacesuit.

The structure of the greenhouse is inflatable and is made of prepreg composite material that can be cured to a permanent, solid structure. An inflatable structure has several advantages over a rigid design including the ease with which it can be packaged and transported, as well as the reduction of workload associated with the construction of the greenhouse. Most importantly, however, is the fact that an inflatable structure made of a composite that is pliable in an uncured state can be inflated and tested on Earth, and then deflated and packaged for transport to Mars.

The composite chosen for the structure of the greenhouse is Kevlar 49/Epoxy. Kevlar 49/Epoxy has excellent material properties, including its specific tensile strength, specific stiffness, and impact strength. This composite also has a high potential for structural use as well as a high repairability rating(1). The structural properties of Kevlar 49/Epoxy compare well to other structural materials (see Table 1).

Table 1. Materials Comparison

Material	Density (lb/in^3)	Spec Tensile Strength ($\times 10^6$ in)	Spec Stiffness ($\times 10^8$ in)	Reparability	$/lb (88)
Stainless Steel	0.29	0.86	1.03	moderate	2.46
Al 2024-T6	0.10	0.57	1.05	moderate	1.87
Ti-6Al-4V	0.16	0.81	0.99	low	20
Graphite/Al	0.09	1.14	2.33	moderate	1000
Kevlar 49	0.05	5	2.2	high	15

Growing Area

The growing area that is required for this application has been determined by an USRA-sponsored design team at the University of Florida(2). In that study, the food supply was to support a colony of eight people. The current design is to support 10 colonists, so the growing area has been increased proportionally. The total growing area required is 534 m^2. This area incorporates a safety factor of 1.5 into the design.

Dimensions

Three separate modules are required for food production, each with dimensions of 7.62 × 15.24 m. Because of the excellent load-carrying ability as both a pressure vessel and an underground structure, a domed-shaped cylinder is used for the modules. The ends of the structures are also domed, yielding a total floor area of 136.66 m^2. The domed ends provide area for activities not accounted for in the growing area estimation, such as germination and harvesting. The total internal volume of each module is 463.26 m^3.

The walls of the structure are corrugated to increase rigidity and stability in a loss-of-pressure situation within the greenhouse. Before inflation of the structure is completed, an internal floor frame is inserted to help the structure retain its shape during the installation process. The internal flooring provides space for irrigation, heating, electrical, and other greenhouse-related systems.

In determining a suitable wall thickness for the structure, two loading scenarios are considered. For the first condition, the greenhouse is modeled as a pressure vessel$^{(3)}$. This analysis is applicable under normal operating conditions; however, a second approach must be considered in the event of a loss-of-pressure situation in the greenhouse. For the second condition, the greenhouse is modeled as an underground culvert. This analysis involves two procedures for culvert design: (1) a culvert design code$^{(4)}$ and (2) a soil-culvert interaction method$^{(5)}$. From these analyses it was determined that the loss-of-pressure situation is the limiting factor in the design. Using a 15.24 cm × 5.08 cm corrugation, as shown in Fig. 1, and incorporating a safety factor of 2, the required wall thickness is 0.89 cm.

Thermodynamic Analysis

The steady-state heat losses were determined by modeling the greenhouse as a cylinder without ends, having the same surface area as the greenhouse. When the structure is buried 4 m beneath the surface, the natural insulation of the martian regolith holds the steady-state heat transfer to 1.1 kW. Because of the foreseen difficulty of burying the structure at a depth of 4 m, the heat loss has been analyzed at different depths. Figure 2 shows the plot of the steady-state heat transfer vs. the depth at which the structure is buried. At a more practical depth of 2 m, the heat loss is still remarkably low at a value of 1.7 kW.

The large temperature gradient across the wall of the structure and the depth at which the structure is buried make the transient heat losses an important part of the heat transfer analysis. To approximate the time required for the soil to reach steady state, the soil around the structure is modeled as a semi-infinite slab with a sudden wall temperature change. Figure 3 shows that steady-state conditions are reached in approximately 25 weeks, but the losses are less than 2 kW after only 6 weeks. At a depth of 2 m, steady-state heat loss, which is 1.7 kW, is reached in only 8 weeks. The steady-state heat loss is 55% higher at the 2-m depth, but takes only one-third of the time to reach steady state. The tradeoffs between power requirements for heating and the difficulty in burying the structure need to be examined to determine the optimal depth for the greenhouse.

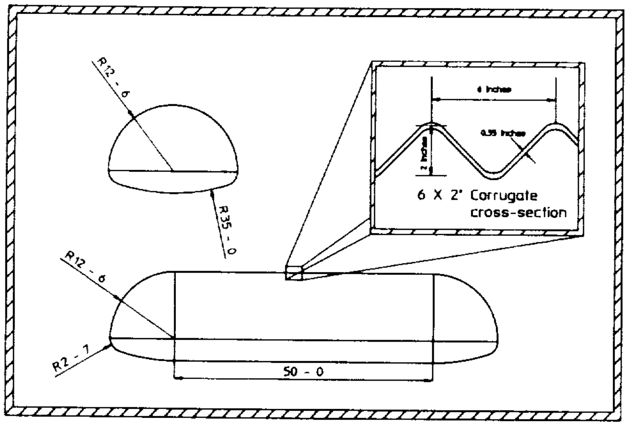

Fig. 1. Structure Configuration and Cross-Section

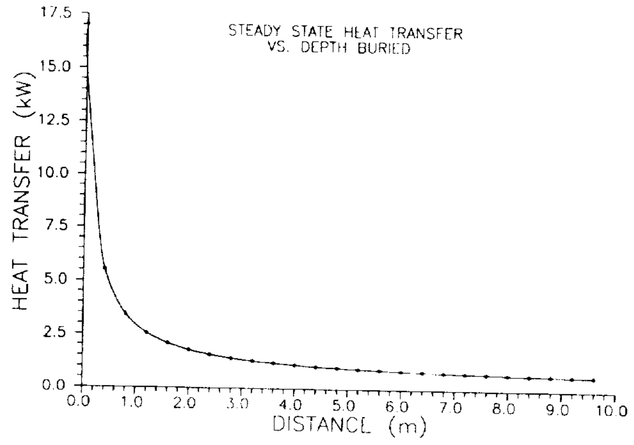

Fig. 2. Steady-state Heat Transfer vs. Depth Buried

SOLAR COLLECTION UNIT

The greenhouse is supplied with natural light that is collected on the surface and transported to the underground modules via fiber optic cables and light waveguides. The growing environment within the greenhouse is maintained at 30°C with a carbon dioxide concentraton approximately 4

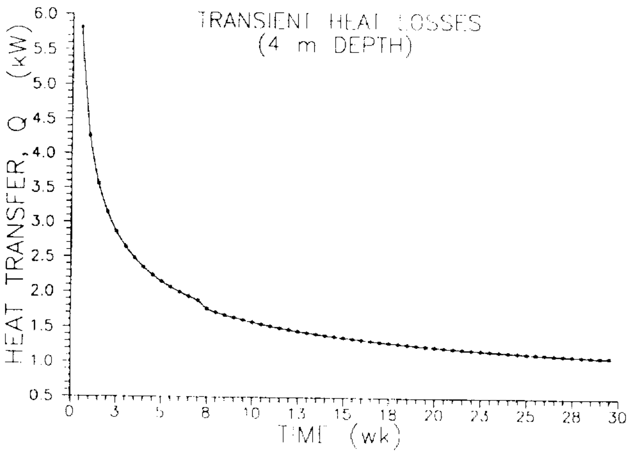

Fig. 3. Transient Heat Losses at 4-m Depth

times greater than Earth levels. This improves photosynthetic efficiency, which reduces the amount of light required for plant growth from 300 W/m^2 to 100 W/m^2(6).

The amount of collector surface area and the shape of the collector are dictated by the latitudinal location on Mars. A conceptual study conducted by an USRA-sponsored design team at the University of Wisconsin determined that a location 20° North of the martian equator is optimal(7). The seasonal intensity is much more uniform at this latitude, and martian dust storms occur less frequently in the northern hemisphere.

The solar light collector is modeled after the Himawari collector that is currently in use in Japan. The Himawari collector has a honeycomb configuration of light-collecting cells. The light is concentrated through Fresnel lenses onto the ends of fiber optic cable bundles. The ends of the collection unit are supported by bearings attached to a base that swivels for two axes of tracking. The entire unit is enclosed in an acrylic dome, which aids in filtering ultraviolet radiation and protects the system from weather and dust.

To meet the lighting requirements of the greenhouse, 119 m^2 of collector area is needed for each growing module. Six collectors are required for each module, with each having an incident collection surface area of 20 m^2. The shape of the collector is trapezoidal, as shown in Fig. 4, with the skewed edge parallel to the ground at sunrise and sunset. The shape of the design is specific to a martian location of 20° N.

Using a two-axis equatorial tracking system, a 20°-0° (horizontal) motor axis will follow the daily solar movement. The annual motor axis will make small daily adjustments to complete 50° of rotation between seasonal extremes.

Sensors are positioned in the panel of the collectors to provide feedback to a central computer system in each growing module. The motorized system makes small adjustments to the daily schedule when misalignment occurs, and automatically resets the collector after sunset.

Hybrid stepper motors are coupled to harmonic gear drives for adjustments to both axes. The characteristics of this motor make it ideally suited for high-torque applications requiring incremental motion and holding capability. When this type of motor is supplied from an electronic drive, accurate position control and precise speed control is maintained. The harmonic gear can have as much as a 400:1 gear reduction for high torque loads. Harmonic gears have long life cycles and require little or no maintenance.

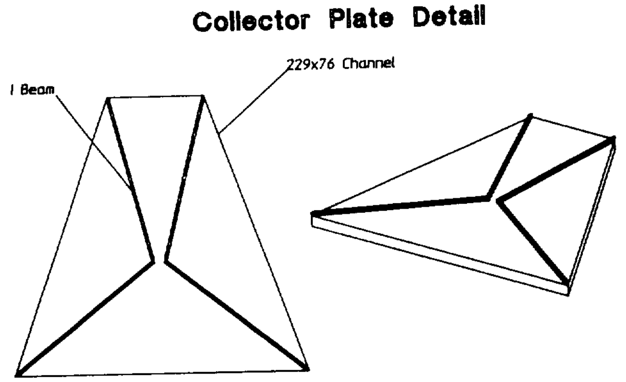

Fig. 4. Collector Plate

The collector and tracking axis are mounted on a 40-cm-diameter support column that houses the optic cables and computer link to the controls. The plate is constructed of a rigid honeycomb composite and reinforced by four radial flange beams.

The maximum stresses were approximated by modeling the worst-case loading conditions in a finite element analysis. The collector was modeled as turned on its side and perpendicular to a 100-m/sec wind. A model of the lower hinge showed a maximum stress of 26.2 MPa, which yields a factor of safety of 8. The maximum stresses in the support column are 5.5 MPa.

LIGHT DISTRIBUTION SYSTEM

Light enters the greenhouse via bundles of fiber optic cables that extend from the light collector on the planet surface. The fiber bundles enter through the top of the greenhouse at six junction boxes. Light emanating from the end of the 317.5-mm-diameter fiber bundle is channeled into a 60-mm-diameter, hollow dielectric pipe. This pipe, precisely machined into an optical waveguide, is made of tempered, low-expansion borosilicate. The light travels through the waveguide and is sent into a light-diffusing pipe that is placed over the plant beds. The diffuser is a hollow dielectric tube made of clear, fused silica. The upper section inside the tube is coated with magnesium oxide. As the light passes through the diffuser, it strikes the coating and is reflected downward to the plants.

Waveguide Theory

Light entering the optical waveguide is transmitted down the pipe by way of small angle reflections. The light enters the pipe at an acceptance angle of 1°. If the light comes in at an angle greater than 10°, it suffers high losses down the waveguide. Any light entering at less than a 10° angle travels through the pipe until it hits the reflective material, then it is reflected down the pipe.

The hollow waveguide used in this design is made of borosilicate glass tubing that is honed to a uniform diameter. The inside of the pipe is a vacuum, which allows light to travel without any of it being absorbed or scattered. The outside of the pipe is coated with a thin aluminum oxide film that will serve to direct light that radiates into the glass back into the tube. A webbed sheathing, which protects the tube, is placed over this film while allowing adequate ventilation for heat dissipation.

Light Diffuser

The light diffuser is designed to distribute the light from the pipe down to the plants in a uniform and efficient manner. For this application, a downward light diffuser is used in conjunction with a reflector panel that is placed above the pipe to capture any light that may be lost through the top or sides of the pipe.

The diffuser is made of clear, fused silica, which has very good transmission characteristics at all wavelengths(8). The upper inside surface of the tube is coated with magnesium-oxide powder, which is 98% efficient for diffuse light reflection(9).

In order to get an even intensity of light over the entire plant bed, the coating is placed at a 30° arc at the point where light enters the diffuser. The arc increases linearly down the length of the pipe, reaching a 180° arc at the end of the diffuser. The coarseness of the powder increases as it is applied down the length of the pipe in order to reflect more light.

The diffuser consists of two pieces of hollow dielectric tubing, each piece being 7.62 m long. The pipes are coupled together, and the ends of the pipes are sealed with lenses that allow the light to pass through while keeping a vacuum inside each portion of the diffuser. The upper diffuser is connected to a support above the upper plant bed and the lower diffuser is connected to the bottom of the upper plant bed.

CONCLUSION

The inflatable structure serves as an ideal greenhouse while being feasible to transport and easy to assemble on Mars. Locating the structure underground protects it from the extreme environmental variations on the surface. The proposed lighting system provides all the necessary light for photosynthesis with little external power demand. These considerations make the proposed greenhouse design a viable means of providing an ongoing food supply for a martian colony.

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