

GREENHOUSE DESIGN FOR A MARTIAN COLONY

STRUCTURAL, SOLAR COLLECTION
AND LIGHT DISTRIBUTION
SYSTEMS

UNIVERSITY OF IDAHO

**GREENHOUSE DESIGN FOR A MARTIAN COLONY:
Structural, Solar Collection and Light
Distribution Systems**

UNIVERSITY OF IDAHO

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1.0 INTRODUCTION

In the coming decade, human presence is inevitably going to reach beyond Earth's boundaries. As the interest in space exploration increases, the United States and other spacefaring nations are looking toward the moon and Mars for the next "giant step for mankind." On the twentieth anniversary of the first landing on the moon, ambitious goals were set for the U.S. space program. These goals include launching Space Station Freedom, developing a colony on the moon, and undertaking a manned expedition to Mars.

With the ultimate goal being the colonization of other planets, it is clear that these colonies cannot be totally dependent on Earth for life support. With this in mind, the students of the University of Idaho Mechanical Engineering capstone design course have designed a greenhouse that is to sustain ten colonists for an indefinite period of time. 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 which 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 which 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.

2.0 DESIGN PROJECT DESCRIPTIONS

2.1 Structural Design

This section describes the design of the structure of the food production modules for the martian habitat. The structure is at a depth of 4 meters below the martian surface. The underground location of the structure shields the plants and colonists against harmful radiation, supports the structure, and moderates the extreme environmental variations that occur on the surface of Mars. The interior of the structure is at one atmosphere (101.3 kPa) in order to maintain a shirt-sleeve environment in which the colonists can work without the requiring the use of spacesuits.

2.1.1 Material selection

The first thing to be considered in the material selection is whether to use a rigid, pre-fabricated design or an inflatable structure. An inflatable structure has several advantages over the pre-fabricated design. A primary advantage is that it can be tested on earth, and then deflated and packaged easily for transport. A pre-fabricated design either needs to be assembled on Mars or some other outpost, then towed behind the spacecraft to Mars. Based on these considerations, the use of the inflatable structure is determined to be the best alternative. The material selected for this application is a pre-preg composite which can be cured to a permanent, solid structure. The selection is based on the potential for structural use, repairability, impact strength, specific tensile strength and

specific stiffness. For comparison, Table 1 shows several comparable structural materials along with their properties.

Material	Density (lb/in ³)	Spec Tensile Strength (X 10 ⁶ in)	Spec Stiffness (X 10 ⁸ in)	Repairability	\$/lb('88)
Stainless Steel	.29	.86	1.03	moderate	2.46
Al 2024-T6	.10	.57	1.05	moderate	1.87
Ti-6Al-4V	.16	.81	.99	low	20
Graphite/Al	.09	1.14	2.33	moderate	1000
Kevlar 49	.05	5	2.2	high	15

Table 1. Materials Comparison

Kevlar 49/Epoxy has a high rating for structural use and a high repairability rating. Its impact strength is rated very high and has a specific tensile strength of 5×10^6 inches. This compares to a value of 0.86×10^6 inches for stainless steel. The specific stiffness rating of 2.2×10^8 inches is also high in comparison to stainless steel which has a rating of 1.03×10^8 inches.² These excellent material properties are the primary reason for selecting Kevlar 49/Epoxy over other composites. This composite is pliable in an uncured state which allows it to be packaged efficiently for transport. After reaching the destination, the structure can be inflated and cured to a rigid state.

2.1.2 Growing area

The growing area that is required for this type of situation has been previously determined by a USRA sponsored design team at the University of Florida.³² In that study, the food supply was to support a colony of eight people. The current design is to support 10 people, so the growing area has been increased

proportionally. See Appendix 1 for calculations. The total growing area required 534 square meters, which is incorporates a safety factor of 1.5 into the design.

2.1.3 Structural dimensions

Three separate modules are required for food production, each with dimensions of 7.62 x 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 structure are also domed, yielding a total floor area of 136.7 square meters. The domed ends provide space for activities not accounted for in the growing area estimation, such as germination and harvesting. The total internal volume is 463.3 cubic meters.

The walls of the structure are corrugated to increase rigidity and stability in a loss of pressure situation within the greenhouse. See Figure 1 for corrugate detail.

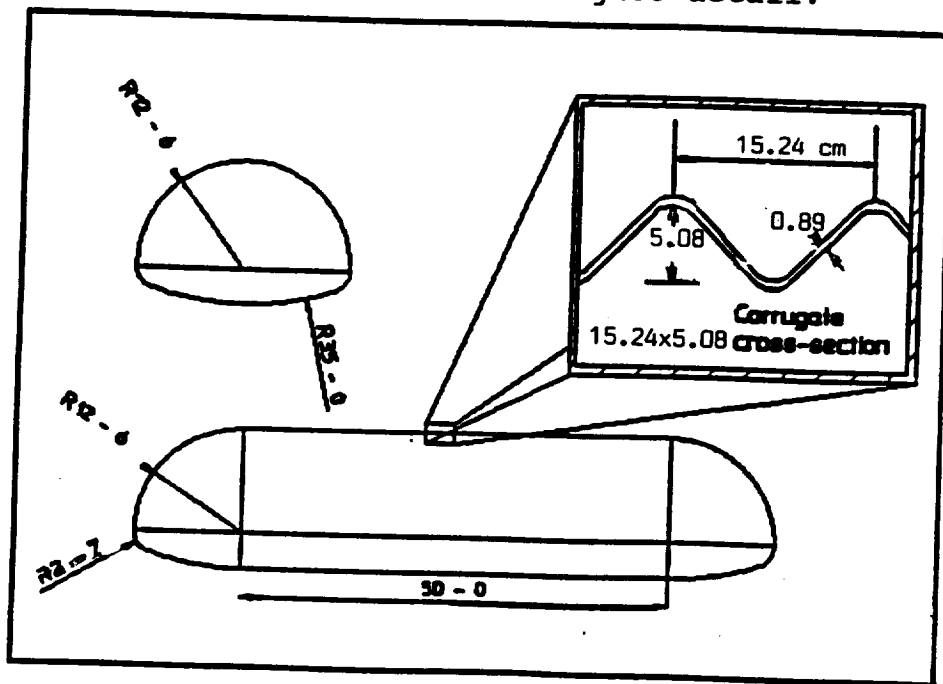


Figure 1. Corrugate Detail

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.²⁶ This analysis will be 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. The second analysis involves two procedures for culvert design:

- 1) a culvert design code,³ and
- 2) a soil-culvert interaction method.⁸

See Appendix I for calculations involving these methods. Based on these analyses, the loss of pressure condition was found to be the limiting factor in the design. With the remaining dimensions fixed, the wall thickness is the controlling parameter in this analysis. Using pressure vessel design theory and incorporating a safety factor of 2, the required wall thickness is 0.10 cm. Applying the culvert design code under a static soil load, incorporating a safety factor of 2, and using a 15.24 x 5.08 cm corrugated plate yields a required wall thickness of 0.81 cm. Finally, using the soil-culvert interaction method with the same loading conditions and corrugated plate, the required wall thickness is 0.89 cm. Table 2 lists a summary of the loading conditions, strength values and the resulting wall thickness associated with each method.

WALL THICKNESS

Method	Load Condition	Strength Used X 10 ³ psi	Thickness cm
1. Pressure Vessel	Hoop and Axial Stresses	100	0.10
2. Culvert Code	Compression	20.9	0.81
3. SCI Method	Compression and Buckling	20.9	0.89

Table 2 -- Summary of Wall Thickness Calculations

2.1.4 Failure Analysis

The modes of failure considered are wall crushing and buckling.¹⁴ Wall crushing involves either crushing, yielding or crimping of the walls and occurs when the compressive thrust in the plane of the wall exceeds the ultimate compressive strength.⁸ Buckling, due to flexural instability, is the primary and most catastrophic mode of failure. The culvert design code allows for wall crushing by using a higher design pressure, the corner pressure, calculated from the dimensions of the culvert. Buckling and compressive failure is accounted for in the soil-culvert interaction method through the use of coefficients derived from a finite element analysis. Due to the inherent safety of each method, no other failure criteria was considered.

2.1.5 Thermodynamic Analysis

Steady state heat transfer

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 meters beneath the surface, the natural insulation of the Martian regolith holds the steady state heat transfer to only 1.1 kW.

Because of foreseen difficulty in burying the structure at a depth of 4 meters, the heat loss from the greenhouse has been analyzed at different depths. Figure 2 shows the plot of steady state heat transfer versus the depth at which the structure is buried.

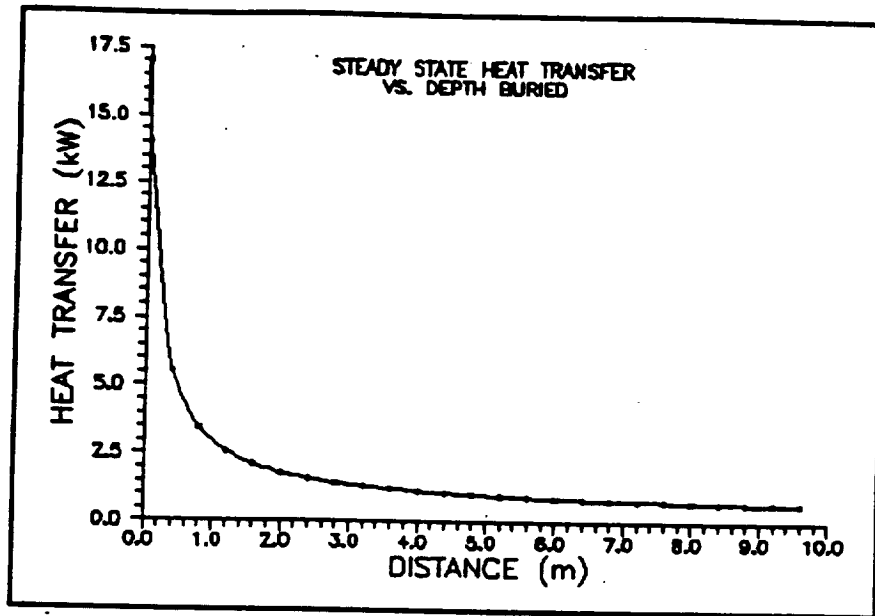


Figure 2. Steady state heat transfer vs. Depth Buried

At a more practical depth of 2.0 meters, the heat transfer is still remarkably low at a value of 1.7 kW.

Transient heat transfer

The large temperature gradient of 80°C 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.^{5,44} Calculations show that when the greenhouse is buried four meters below the surface, the heat transfer, after one week is approximately four times higher than the steady state heat loss, which is 1.1 kW. Figure 3 shows that the steady state condition is reached in approximately 25 weeks, but after six weeks the losses are already less than 2 kW.

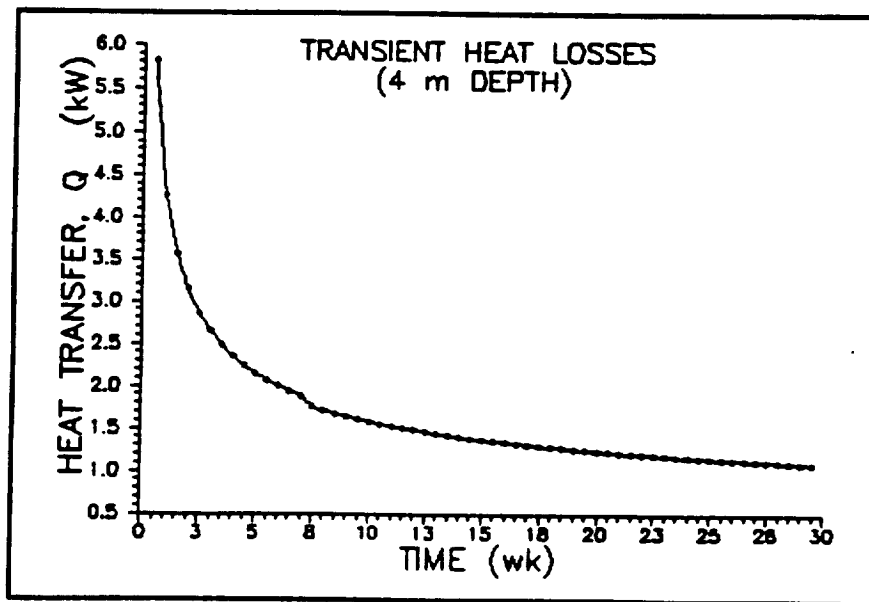


Figure 3. Transient heat loss

Using the same analysis at a depth of 2 meters, the heat transfer after one week is approximately 2.5 times higher than the steady state heat loss which is 1.7 kW, and is reached in only eight weeks. Comparing the results of burying the structure two meters rather than four meters, the steady state heat transfer is 55% higher at the two meter 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. The programs used for this analysis are found in Appendix II.

2.1.6 Summary

The structure of the greenhouse consists of three modules, each buried at a depth of 4 meters below the Martian surface. The modules are inflatable, and made of a pre-preg Kevlar 49/Epoxy composite. This composite is suitable as a structural material and can be shipped efficiently in an uncured state.

Decreasing the depth of the greenhouse to 2 meters below the surface causes an increase in steady state heat loss of 0.6 kW. Further investigation of the tradeoffs involving the depth of the structure versus the amount of power that is available for the greenhouse needs to be examined.

2.2 Solar Light Collection System

During the first semester, the students developed two concepts for the solar light collection system. The first concept is a flat plate collector in which light is concentrated through Fresnel lenses onto the ends of fiber optic bundles. The second concept is a geodesic parabola. It is designed to concentrate the incoming light onto a 0.91 m diameter lens. This lens then filters out the harmful radiation and focuses the visible light onto the end of a bundle of fiber optic cables.

The two designs were carried out to a finalized, conceptual stage. The second semester students evaluated the two concepts, then further developed the flat plate collector design. General information concerning the construction of the collector, the conceptual designs and the final design of the flat plate collector are presented.

2.2.1 Collector construction

The solar collector consists of four major parts: the light concentrating and filtering device, the tracking system, the light transport device, and the casing, or structure of the system.

Of the four major parts of the collector, the light concentrating and filtering device is the most important. The function of this device is to efficiently take light from the sun and concentrate the visible spectrum onto the ends of fiber optic cables, while filtering out the harmful ultraviolet and infrared wavelengths.

The tracking system can be either single-axis for daily solar tracking, or dual-axis for both daily and seasonal solar tracking. When this system is used as the primary light source for the food production module, it is necessary to maximize the collection of light. Therefore, a dual-axis tracking system is the superior choice. This tracking system would aim the collector directly toward the sun over the entire Martian day and year, allowing the maximum amount of light to be collected at all times when the sun is above the horizon.⁹

The function of the casing of the solar collector is to protect the collector from the harsh Martian environment, including extremely cold temperatures, magnetic dust, and harmful radiation. Material selection for the casing is based on expected performance in such extreme environmental conditions.

2.2.2 Flat plate collector concept

The flat plate design is based on the Himawari design used in Japan.²⁹ It is a flat plate collector in which light is concentrated through Fresnel lenses onto the ends of fiber optic bundles. It has a dual-axis tracking system, which keeps it facing the sun over the entire Martian day and year. The advantage of this design is that harmful radiation can be easily filtered out of the light transported to the plants, thus letting only pure visible light reach the plants. A possible drawback of this system is the weight of the acrylic lenses which would prove costly to send to Mars.

The flat plate concept utilizes the light refracting properties of Fresnel lenses, and the light transporting properties of fiber optic cables. This conceptual design was developed from the values in Table 3.

PARAMETER	VALUE	RANGE
Growing Area	534.2 m ²	
Plant Light	300 W/m ²	200-450 W/m ²
Mars Light	286 W/m ²	200-300 W/m ²
Collector Efficiency	50 %	See text
Growth Efficiency	300 %	See text
Collector Area	373 m ²	See Appendix III

TABLE 3. Values and ranges incorporated in this design.

With the flat plate concept, twelve collectors are needed to provide a sufficient factor of safety in the event that the collectors are damaged. Therefore, each collector is approximately 4 X 8 m. The assembled collection unit might appear similar to that in Figure 4. The size suggested allows the collector plates to be transported as single, preassembled units. The collector is made up of four sub-units including the collector plate, the fiber cables, the tracking system, and the casing. Each will each be discussed separately in the following sections.

Collector plate

The collector plate is based on the Himawari light collector designed by Dr. Kei Mori of Keio University, Japan.¹² The basic principle of the light collection is shown in Figure 5. The sun's rays are to be perpendicular to the Fresnel lens. As light passes through the lens, the angle of refraction is dependent on the wavelength. Infrared radiation has a smaller angle of refraction than the ultraviolet radiation. If a polished fiber cable end is placed at the focal point of the green wavelength, the cable collects the light in the range of 350-850 nm: the light plants need for photosynthesis.

The lens design is shown in Figure 6. Each collector plate is made of 325 hexagon-shaped units. Each unit has 61 hexagon-shaped Fresnel lenses (42 mm x 36 mm) cast into it. Figure 6

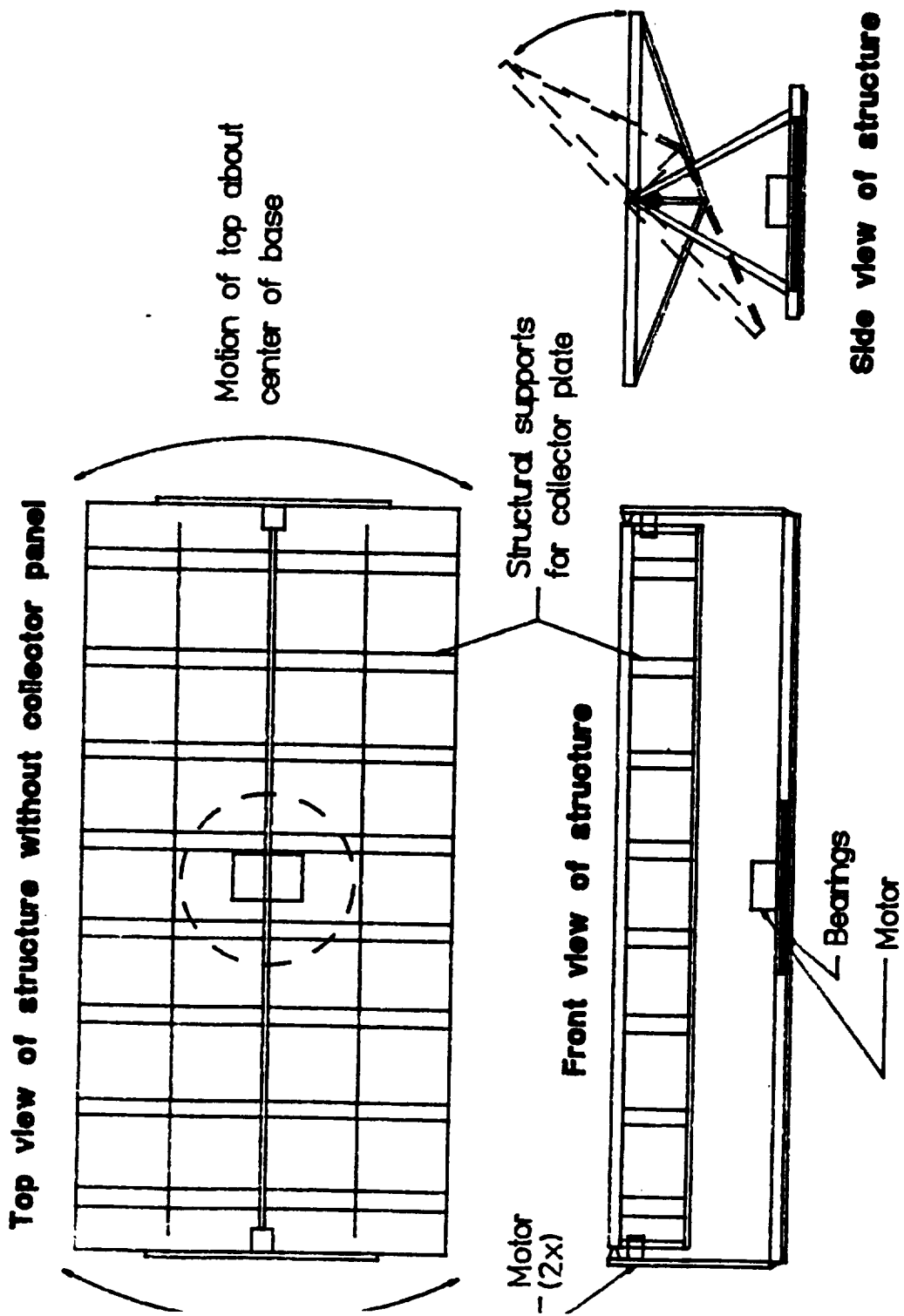


Figure 4. Flat plate collection unit

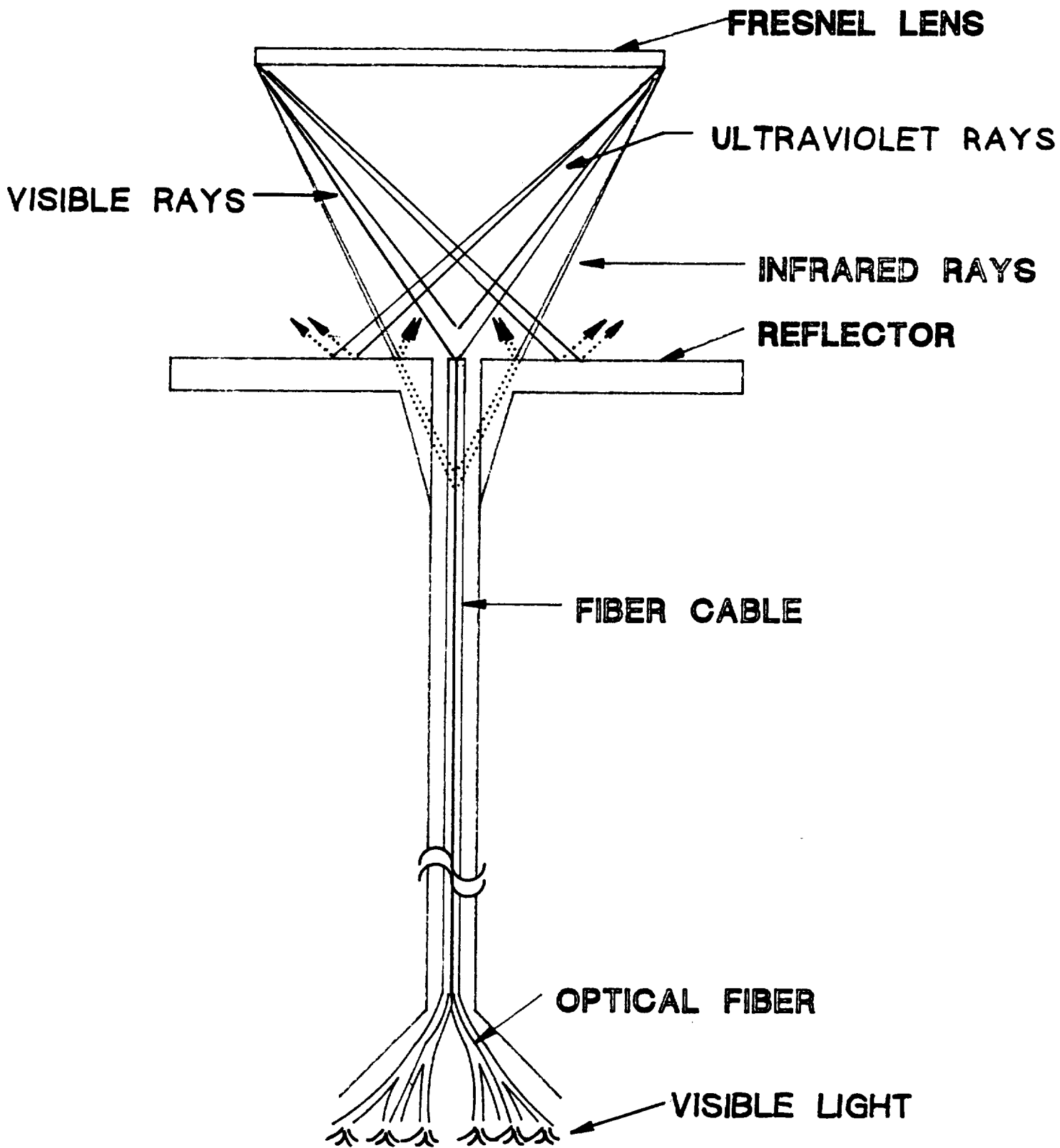
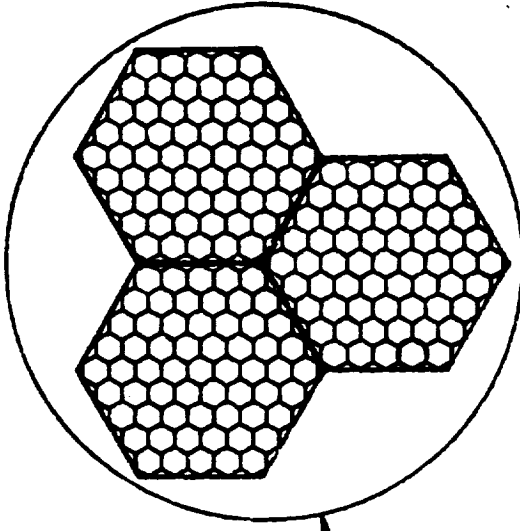


FIGURE 5. Fresnel lens

**Each hexagonal unit has 61
Fresnel lenses**



Top view of collector panel with 325 units

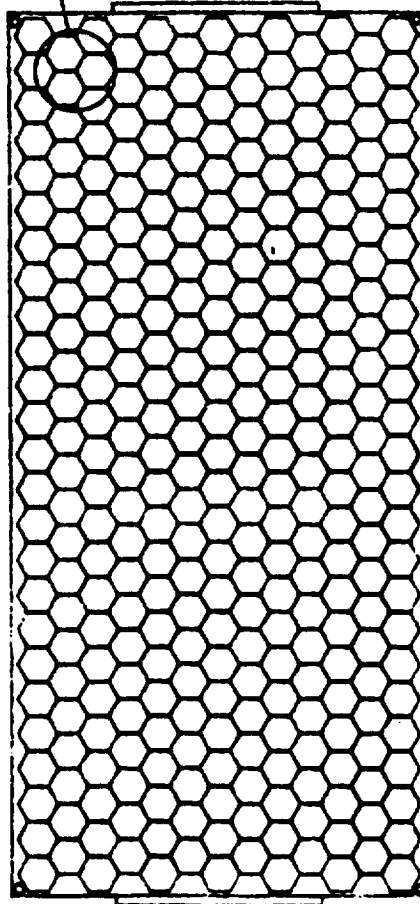


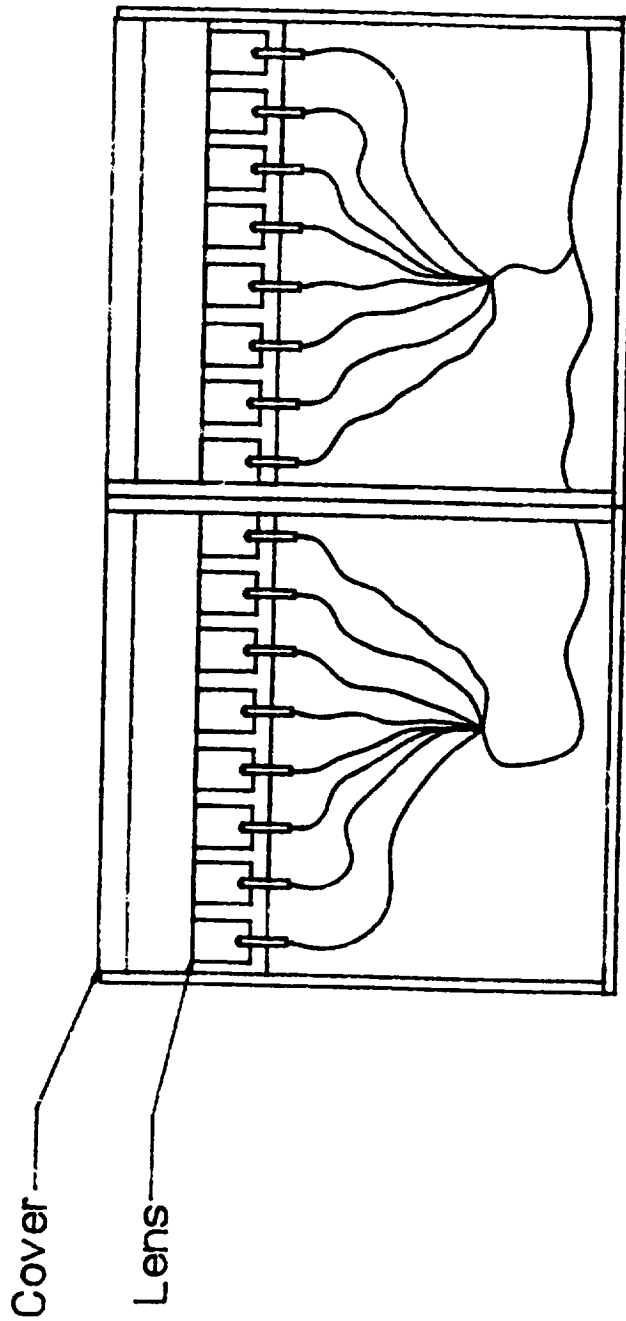
Figure 6. Top panel detail

shows the top view of three units (316 mm x 365 mm) and the 61 Fresnel lenses per unit. Each lens is focused onto one fiber optic cable (approximately 1 mm dia). A side view of two units is shown in Figure 7.

The use of many small Fresnel lenses has several advantages over the use of fewer large lenses. The small lens has a shorter focal length, allowing the collector plate to be approximately one fourth the thickness than with lenses 316 mm x 365 mm. The small lens also has proven to be more efficient at transferring light into the fiber optic cable.²⁹ Heat is generated by the wavelengths that are not collected by the fiber optic cables. The use of the small Fresnel lens helps to alleviate high concentrations of heat. By their nature, the Fresnel lens concentrates all the UV light into a small area which creates large temperature gradients. The smaller lenses concentrate less UV per lens, distributing the total increase in heat over a larger area, thus producing a smaller temperature gradient. Refer to Appendix III for calculations of the heat analysis for the lens.

Cable system

A study done by Dr. Mori for a fiber optic system in an orbiting space station showed that a pure quartz fiber provided the best characteristics in flexibility, radiation resistance, wavelength characteristics, and allowable incidence angles.²⁸ Plastic fiber optic cables are currently manufactured, but their



**Side view of two hexagonal units
Each lens focuses onto a single cable**

Figure 7.

losses per meter are much greater than those of quartz. The losses for a pure quartz cable are 4% per 10 m of cable. A potential problem with quartz fibers is that the efficiency for light transmission drops markedly at temperatures below -20°C .²⁸ Therefore, it is necessary to insulate or heat the cables coming out of the collector.

As noted before, the flat plate concept has a single fiber cable for each lens. The 61 cables from each unit are combined into one cable as shown in Figure 7, and approximately ten unit cables are again combined into one cable. This means only 30 to 35 cables are exiting the collector panel. Although each connection does produce small losses, the ease of setup and repair will make up for these losses.

Tracking system

For the Fresnel lens to be most effective, the sun's rays need to be ± 2 degrees from perpendicular. A dual-axis tracking system can operate within ± 0.2 degrees, which provides the motion necessary to track the sun both daily and yearly. An on-board CPU will be incorporated in order to relocate the sun if it is temporarily obscured by dust storms. At sunset the CPU moves the collector to the sunrise position.

Casing

The structure and casing need to resist the environment and be of minimum weight and volume. The supports on the sides and back of the collector are made from a tubular composite material that can resist the harsh Martian environment. There are two base plates, one stationary plate located on the ground, and the other plate which rotates about the center on a ring of bearings. The base plates are approximately 2.54 cm thick, and made of a light weight composite material. A motor that controls the angle of the panel is mounted near each pivot on the collector. The motor that moves the top plate with respect to the bottom plate is mounted on the center of the base.

2.2.3 Geodesic parabola concept

This concept is based on a design that has been tested on Earth and evaluated for use on a space station. The efficiency of the collector will be assumed at 50%, a value which has been achieved here on Earth. If the efficiency can be improved, the size of the collector will be reduced substantially.

The geodesic parabola, the alternate solar collection concept, is designed to concentrate the incoming light onto a 0.91 m diameter lens. This lens filters out the harmful radiation and focuses the visible light onto the end of a bundle of fiber optic cables. It also incorporates a dual-axis tracking system which allows it to follow the sun over the Martian day and year. The advantages of this design are its light weight and its ability to filter out harmful radiation. The major disadvantages are the large amounts of heat that the geodesic parabola generates, and the reduction in efficiency as compared to the Himawari design.

The geodesic light collector, which moves with a dual-axis tracking system, collects enough light to support 92.9 m² of plant growth in each greenhouse module. This design incorporates the use of two parabolic collectors for each module. The 11 m diameter parabola focuses the light onto a three foot diameter circle. The design of the parabolic dish is achieved by geodesic construction. The light concentrating device is created by fitting reflective, light-weight panels into each triangular gap in the dish structure. The geodesic structure is shown in Figure 8.

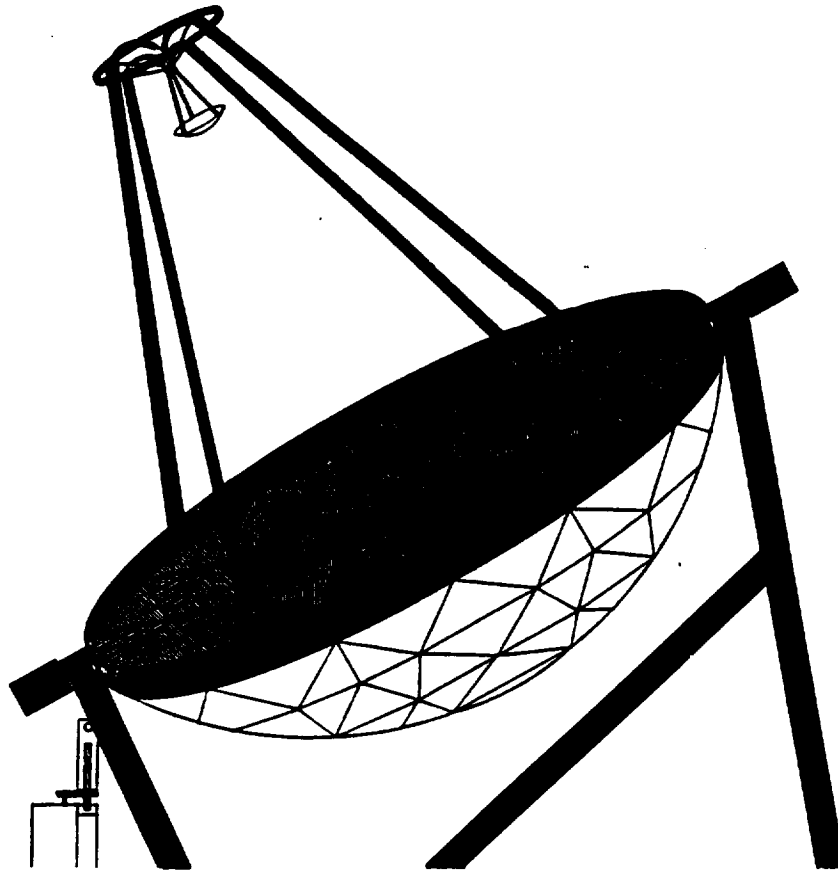


Figure 8. Geodesic Parabola

After the light is directed to the light concentrating device, there are three alternatives for collecting and distributing light to the greenhouse. These alternatives include a Fresnel lens, a reflecting mirror, and a converging lens. Each alternative is discussed in later sections.

The parabolic dish, which is approximately 9.75 m in diameter and 3.05 m deep, collects 92.9 m² of sunlight. As stated previously, the design of the parabolic dish is achieved by geodesic construction. Reflective, light-weight panels are fit into each triangular gap created by the tensile rods that form the dish structure. The panels are approximately 0.91 m on edge and are made of thin, highly reflective aluminum skin which

is stretched on a light weight frame. The panels are fastened to the tensile members, while allowing adequate freedom for the members to strain under normal loading conditions so that the panels do not become distorted while reflecting the light. Other important aspects of having the independent panels are that they can be fastened to the dish after the structure is built, and they can be easily replaced if damaged. Since the panels are independent of one another, the collector will continue to be operational in the event that a panel is damaged.

Parabolic collector

Incorporation of this design reduces the required number of collectors to six. Each collector has a surface area of 92.9 m². The flat panels which form the parabolic surface will reflect approximately 80 percent of the incoming light. A parabola maximizes system efficiency in both light focusing and light gathering ability.¹⁸

Lens system

Three possible configurations for the lens system are examined. These include a Fresnel lens design, which uses a glass lens to focus rays on a 0.91 m Fresnel lens network that filters the visible light range on to small fiber optic cables; a converging lens, which focuses on a light tube or oversized fiber cables; and a reflecting mirror which uses a converging lens to focus the light onto a tube or cable.

Fresnel Lens Network

As Figure 9 shows, the Fresnel lens consists of three major parts: the glass lens, the Fresnel lens, and the fiber optic cables.

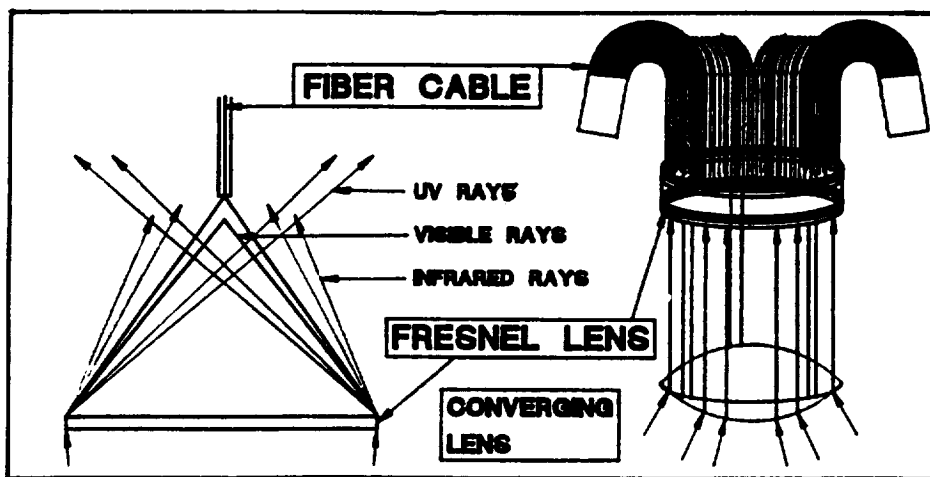


Figure 9. Fresnel lens network

The parabola focuses the incoming rays at a focal point approximately 7.92 m from the parabolic surface. A glass lens,

located at the focal point of the parabola, changes the angle of the light so that it strikes the Fresnel lens at 90 degrees. Precise placement of the fiber cables allows only the visible wavelengths that the plants need for photosynthesis to be collected. The supports for the collector lenses provide cable paths which allow for easy attachment as well as easy access for maintenance.

Converging Lens

Converging lenses cause chromatic aberrations. Chromatic aberrations are a type of focus defect that occur in lenses. The focus difference for various wavelengths is determined by the difference in the refractive index of the lens for those wavelengths. Making use of this phenomena allows two lenses to be eliminated. Figure 10 shows that the placement of a light tube or oversized optic cable at the focal point of a converging lens allows us to collect only the desired rays. Converging lenses transmit 90 percent of the incident light that strikes the surface.³⁶

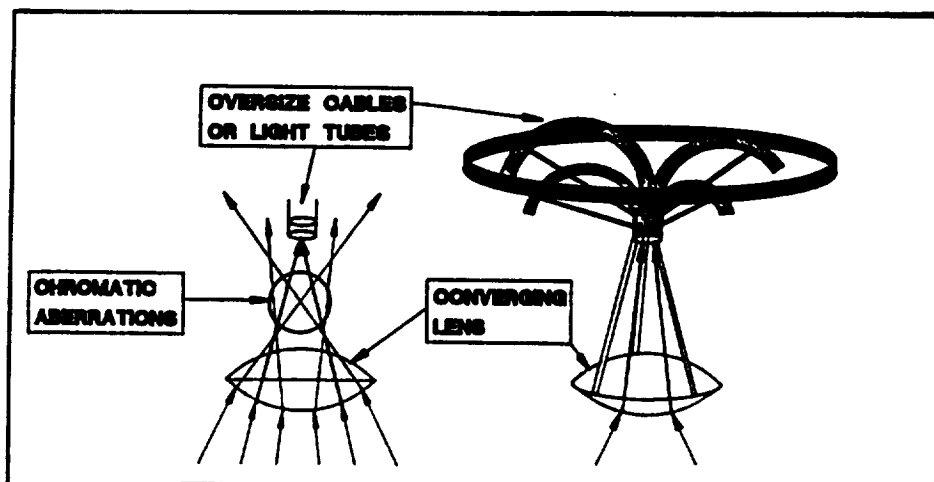


Figure 10. Converging lens

Reflecting Mirror

Figure 11 is an example of a reflecting mirror collection lens. The mirror reflects the rays to a lens which is located near the parabolic surface, and focuses the visible rays upon a light tube or oversized optic cable. The circular area around the collector receives incident radiation. Installation of a heat collector in this area can provide an additional heat source, which is an added advantage of the geodesic collector system.

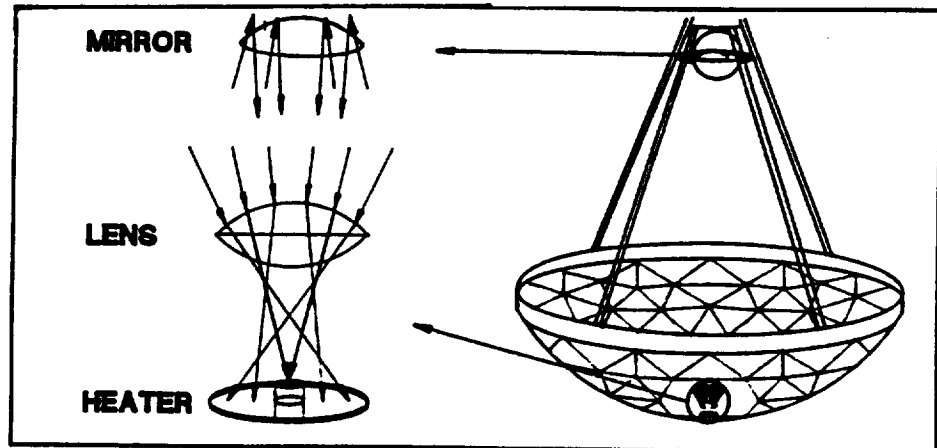


Figure 11. Reflecting mirror

Tensile Loading

Geodesics use tensile members to distribute forces over the entire structure. The structure is built with preloaded tensile members. When a load is applied to the surface of the structure, the preloading is alleviated and the force is distributed to all remaining structure members. Failure of geodesic structures usually does not occur at the point of the load, but to other members of the structure as a result of excess tensile loading.

2.2.4 Advanced flat plate collector design

The following section contains the results of design work which further develops the conceptual design of the flat plate collector. Design is based on, and is specific to, a location of 20 degrees North of the martian equator. Six collector panels provide natural light for each growing module. A single cylindrical column supports each collector's tracking system and trapezoidal panel of collector cells.

One option for a light collection system to provide natural light in underground living and growing modules to be located on Mars is presented. The design relies on known facts about Mars, anticipated technologies, and criteria inherent in the conceptual designs.

The structure of the food production module that is proposed divides the growing area into three modules. Each module is constructed of an inflatable material and the combined growing area is 534 m². The growing environment will be maintained at 30°C with an increased carbon dioxide concentration, approximately four times that of Earth levels. This improves photosynthetic efficiency, reducing the amount of light required for plant growth from 300 to 100 W/m².²⁷

Initial designs

The second phase of the collector design started with two conceptual designs inherited from the first semester design

group. The first concept is a flat plate collector and it is based on the Himawari, a Japanese manufactured collector. The flat plate design has approximately 20,000 hexagon light collection cells over a surface area of 373 m². The entire collector is supported by bearings at either end which are fixed to a swivel base. The collector is to be prefabricated and is sized to fit in the shuttle bay. Tubular composites are suggested for the structure in order to minimize weight and resist environmental effects, while small lenses are used to minimize the focal length and transfer light most efficiently. At the focal point of each cell is a single quartz fiber that is combined into 35 cables leaving the collector.

The second design is a geodesic parabola collector. This collector uses mirrored reflective panels to focus light into a fiber optic cable. The parabolic dish is 11 m across and 3 m deep. This design receives 95 m² of incident light per collector. It is constructed of very thin plates fit into a geodesic frame made of tubular composites. Three alternatives are proposed using a Fresnel lens, a reflecting mirror, or a converging lens to concentrate light into the fiber cable. The parabolic collector is to be constructed on Mars. It also requires a dual-axis tracking system. The structure that supports the collector has not been designed.

The two collector concepts are evaluated based on the degree to which the design satisfies the parameters listed below. Each parameter is weighted according to the level of impact it has on meeting the design objectives. By researching the background of

each collector and using intuitive analysis, both collectors are rated according to how well the design parameters are satisfied.

The foundational parameters for analysis were:

- a. Performance of the collector, including reliability, resistance to the martian environment, and efficiency of collection and transmission.
- b. Maintenance requirements, including safety, ease, and frequency of maintenance activities.
- c. Cost of transportation, research and development, and materials and manufacturing.
- d. Developmental stage of the concept.
- e. Safety and ease of assembly and setup.
- f. Potential for using natural martian resources in construction or maintenance.

The flat plate collector is expected to be more reliable and to have a much higher efficiency than the geodesic parabola. The flat plate concept offers potentially easier and safer maintenance due to its proximity to the surface and the limited number of parts that are exposed to the martian elements.

The only parameter for which the parabolic collector rates higher than the flat plate collector is cost. The weight and size of the unassembled parabolic collector makes it less expensive to transport to Mars. However, more extensive initial setup would be necessary.

Based on the fact that the flat plate collector satisfies a greater number of the aforementioned parameters, the design effort is concentrated on the further development of the flat plate collector concept.

2.2.5 Assumptions

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 a USRA sponsored design team at the University of Wisconsin determined that a location between zero and 20 degrees North of the martian equator is optimal. For the purpose of this design, a 20 degree North location is used. The average solar intensity is six percent less at this latitude than at the martian equator, but the seasonal intensity is much more uniform. More importantly, records of martian dust storms show that storm activity is much more frequent at the equator and in the Southern hemisphere than in the Northern hemisphere. During extended periods of dust storms at the 20 degrees North latitude, alternative light sources will be needed.

To make a practical estimate of the amount of light collector area needed to support the growth modules, a maximum optical depth and system efficiency must be determined for the design. Similar designs are expected to have efficiencies of 60 percent or better.⁴⁰ The optical depth is a natural exponential function of the fractional diffuse light. According to Viking Lander 1 data taken near 20 degrees latitude, the optical depth on a typical clear day is between 0.2 and 0.4, which means that between 18 and 33 percent of the light incident in the atmosphere is diffused. During 70 percent of the period data was taken, the optical depth was less than 0.8.³³ The collector is designed to meet or exceed the light requirements for that period,

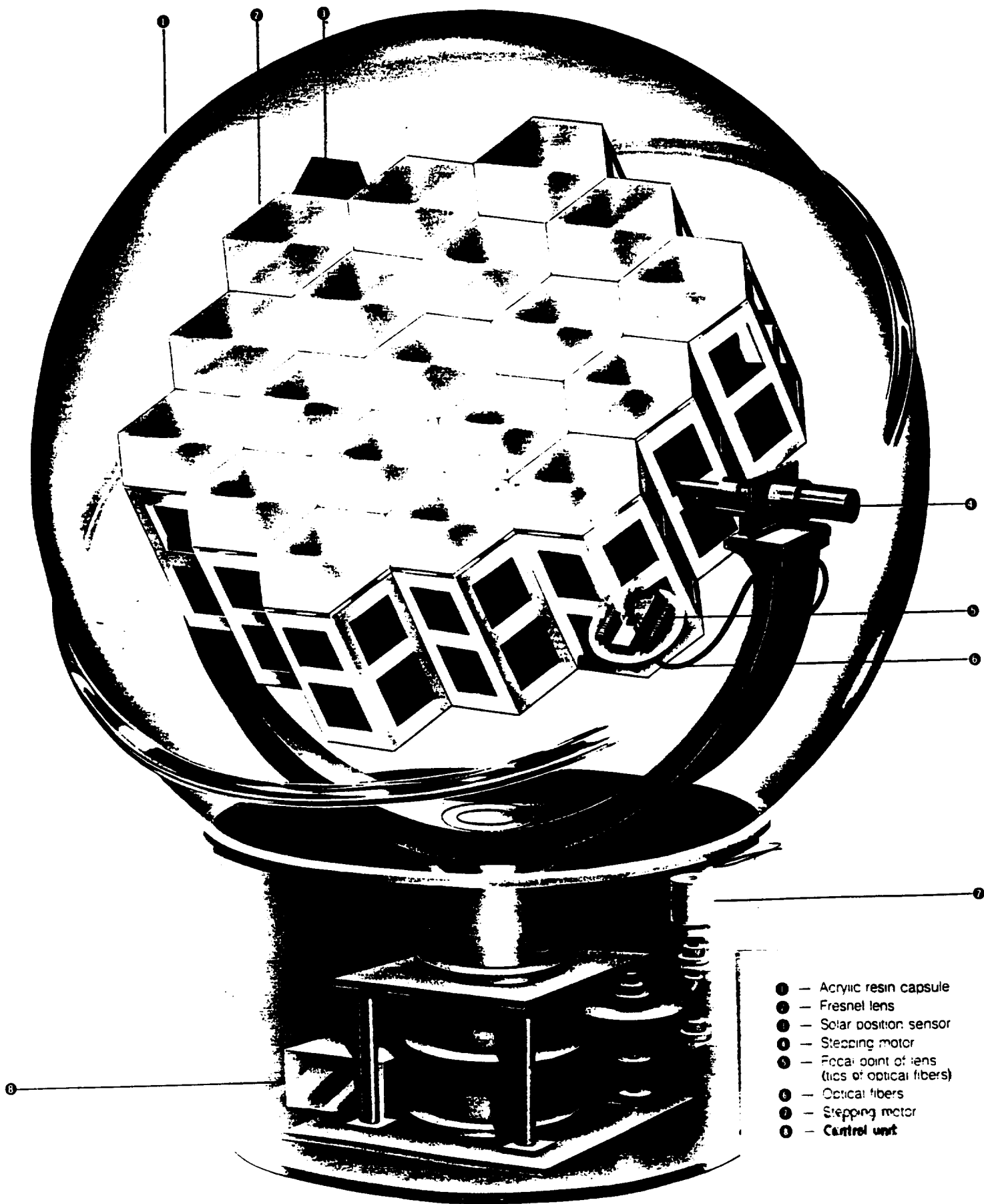
considering that only 45 percent (at an optical depth of 0.8) of the light incident in the atmosphere reaches the surface.

2.2.6 Design development

Himawari

The decision to develop the flat plate collector using Fresnel lens technology led to further examination of the Himawari collector. The Himawari collector, as shown in Figure 12, has a honeycomb configuration of light collecting cells and uses much larger Fresnel lenses than the proposed flat plate collector. 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 out ultraviolet radiation and protecting the system from weather and dust.

The Himawari collectors are available in several sizes, the largest having a light receiving area of 1.4 m². Using the largest size available, 250 Himawari collectors are needed to supply the three growing modules, with each collector weighing more than 600 kg. Since the quantity and size of the Himawari is not reasonable for this application, the collector panel design has been modified.



- ① — Acrylic resin capsule
- ② — Fresnel lens
- ③ — Solar position sensor
- ④ — Stepping motor
- ⑤ — Focal point of lens (tips of optical fibers)
- ⑥ — Optical fibers
- ⑦ — Stepping motor
- ⑧ — Control unit

Figure 12.

Collector panel

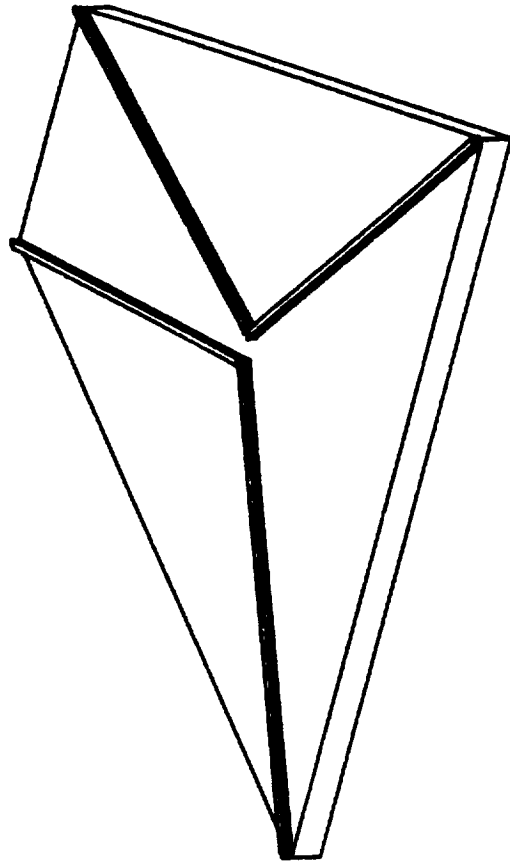
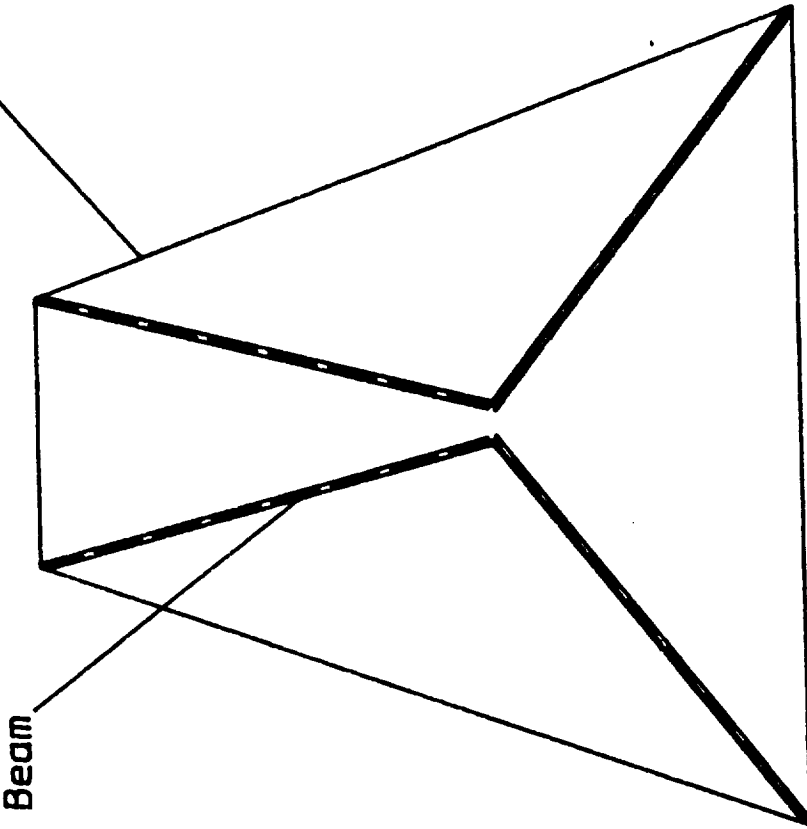
The light collected on the surface is traveling to an underground structure by way of fiber optic cables. The light then enters the greenhouse structure through junction boxes on the surface of the structure. A light distribution design group determined that six light junction boxes are needed in each growing module. These are the points where fiber optic cables from the collector units link to the internal light distribution network. To meet the lighting requirements, 119 m² of collector area is required for each growing module. Dividing that area equally between the six junction boxes, there are six collectors required per module, each having an incident collection surface area of 20 m².

The general shape of the collector evolved through several design iterations to maximize the collecting area and to keep the collector as close to the ground as possible. The final shape of the collector panel is trapezoidal, with a skewed edge that is parallel to the ground at sunrise and sunset. The general shape of the design, shown in Figure 13, is specific to a martian location of 20 degrees North. If another location is used, the same design technology can be applied to modify the shape.

Collector Plate Detail

229x76 Channel

I Beam



I Beam Cross Section

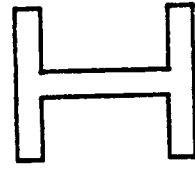


Figure 13.

Tracking system

Using a dual-axis equatorial tracking system, a 20 degree to horizontal (zero degree) motor axis follows the daily solar movement. The annual motor axis makes only small daily adjustments to complete 50 degrees 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 itself after sunset. During severe dust storms, the collectors can be set to a low drag profile.

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 speeds can be maintained.²¹ The harmonic gear can have as much as a 400:1 gear reduction for high torque loads. Harmonic gears have a long life cycle and require little or no maintenance.

2.2.7 Summary

Very few changes are made to the individual collection cells used in the Himawari collector. There are 750 cells per panel

with 18 cm diameter quartz glass Fresnel lenses that focus light onto the polished cable surface. A polished optical fiber is positioned and adjusted to the focal region of the appropriate frequency band of light. The optical fiber has a rounded face which refracts light down the fiber at slight angles, reducing the number of reflections in the transmitting fiber. This feature increases the efficiency of the light transmittance.

Light outside the frequency band of collection can be reflected, however, it is wasted energy. A system can be implemented to retrieve and convert this energy for utilization, especially in the ultraviolet and infrared bands. For example, thermal energy can be used to create a phase change in a liquid system and drive generator turbines. Alternatively, by the time of the martian mission, thermal-electric conversion may be a practical method of utilizing the heat energy. This technology is already used in radioactive generators in satellites.

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. A finite element analysis assessed the structural integrity under maximum wind and loading conditions (See Appendix IV). The plate is constructed of a rigid honeycomb composite and reinforced by four radial flange aluminum beams.

Using ANSYS 4.4, the maximum stresses were approximated by modeling the worse-case loading conditions. The collector was modeled as turned on its side, and perpendicular to a 100 m/s wind. An approximate model of the lower hinge showed a maximum stress of 26.2 MPa. This value yields a factor of safety of

eight. Point welds are used in the model as opposed to fillet welds, so the anticipated stress concentrations are even less. Under worse-case wind and loading conditions, stresses in the support column are a maximum of 5.5 MPa.

Since weight is an important consideration in order to minimize transport costs, dimensional optimization is necessary. The Earth weight of each collector is estimated to be 11,079 N (See Appendix IV). The large factor of safety values associated with aspects of this design suggest that the collector size can be reduced by optimization of this design.

2.3 Light Distribution System

This section presents recommendations for the construction of the interior light distribution system for the greenhouse. Specifically, it details the light piping system from the hull to the plant beds, and the diffusing system that delivers light to the plant growth beds.

Light enters the greenhouse via fiber optic bundles extending from a light collector on the planet surface. The fiber bundles enter through the top of the greenhouse at six locations. The light emanating from the end of the 317.5 mm diameter fiber bundle is channeled into an 60 mm diameter, hollow dielectric pipe through a junction box at the greenhouse surface. This pipe, precisely machined into an optical waveguide, is made of tempered, low expansion borosilicate (Corning Glass #7052). The light travels through the waveguide and is sent into a light

diffusing pipe that is placed over the plant growth bed. This diffuser, a hollow dielectric tube, is made of clear, fused silica (Corning Glass #7940), and is coated on the inside, top surface with magnesium oxide. As the light passes through the diffuser, it strikes the coating and is reflected down onto the plants.

The light distribution system for the greenhouse must meet several criteria. Primarily, it must efficiently transmit incoming light from a junction at the greenhouse surface to the growing beds inside. Secondly, it must be able to withstand a cyclic load from 0 to 100 Hz. This will protect the system against Mars quakes, machinery vibration, and other cyclic loads that may occur. Also, the system must be able to withstand an impact force of 10 pounds from a blunt object, which is an estimate of the highest force that a human may accidentally apply to the system. Finally, the system must be able to support its own weight.

2.3.1 Assumptions and constraints

Assumptions:

- 1) The necessary amount of light required for plant growth will be supplied to the junction from the collector.

- 2) The geometry and set-up of the greenhouse structure is that which is presented previously.

Constraints:

- 1) The greenhouse will be placed four meters under the Martian surface.
- 2) Light will be supplied from a collector on the planet surface through junctions by way of fiber optics.
- 3) The design of the light distribution system will begin at the junction.
- 4) The cost to transport the system to Mars is extreme, therefore, weight must be minimized in order to minimize cost.

2.3.2 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 10 degrees. If the light enters at an angle greater than the acceptance angle, it suffers high losses down the waveguide. Any light entering at an angle smaller than 10 degrees travels through the pipe until it hits the reflective material, then it is reflected down the pipe.

There are two main types of waveguides, hollow and solid. The hollow waveguide is recommended for this application. The

hollow waveguide is made of borosilicate glass tubing (Corning Glass #7052) that is honed to a uniform diameter. Inside the pipe is a vacuum, which allows the light to travel through the pipe without any of it being absorbed or scattered by interior material.

2.3.3 Photosynthesis

To understand how different types of light distributions effect plants, a brief discussion on photosynthesis is necessary. During photosynthesis, plants convert light energy into chemical energy. The wavelength of the light greatly influences the photosynthetic rate of the plant. Figure 14 shows light absorbance versus light wavelength for green plants.

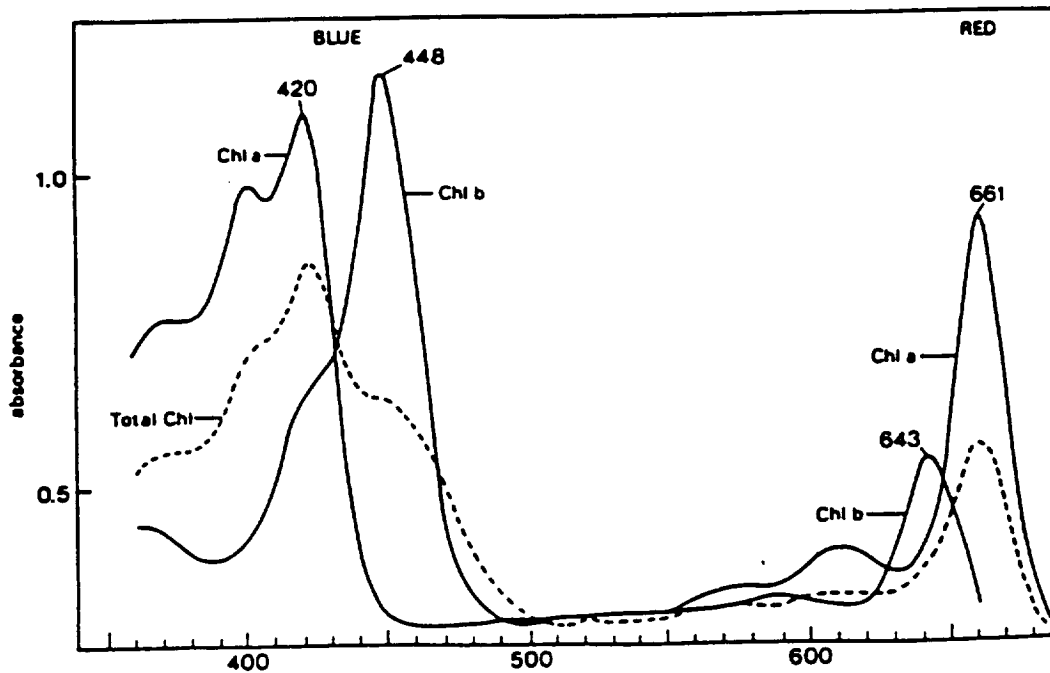


Figure 14. Light Absorbance Spectra of Plants

This graph shows that the plants will not effectively absorb light at a wavelength of 550 nm, which is the green wavelength. The plants reflect this wavelength, which is why most plants appear to be green. For efficient use of light, the plants require wavelengths of 430 nm and 670 nm. ¹⁰

2.3.4 Light distribution system

Light Transportation

Light collected from the planet surface is transported into the greenhouse via fiber optic bundles. Each bundle is approximately 317.5 mm in diameter. The calculation for this is found in Appendix V. The light exiting from the end of the fibers is channeled through a junction and into a 60 mm diameter dielectric pipe.

In making the decision to use a hollow dielectric pipe, several alternatives are examined. The first consideration is to pipe the light by continuing the fiber optic bundle into the greenhouse and taking it to a light diffuser directly over the plants. Secondly, the use of a solid dielectric pipe to transport the light to the diffuser is considered. Finally, the use of a hollow dielectric for the light transportation is examined. The hollow dielectric is chosen because it has the lowest weight and the highest efficiency. A complete analysis of the three alternatives is given in Appendix VI.

The material recommended for the hollow dielectric is tempered, low expansion borosilicate (Corning Glass #7052).²⁴ This is chosen for its high strength and low expansion properties which will protect the pipe from thermal expansion. The stock piece of tubing is honed to a uniform internal diameter, after which the inside is polished to an optical finish. The pipe is then coated on the outer surface with a thin aluminum oxide film. This coating increases the pipe's efficiency to transport light by directing the light that radiates into the glass back into the pipe. Borosilicate is a non-ductile material and has to be protected. Therefore, an aluminum sheathing is incorporated to protect the pipe while still allowing the heat to be dissipated. The webbed sheathing protects the pipe against impact while allowing adequate ventilation for heat dissipation. Aluminum is used because it is lightweight and inexpensive.

The pipe is secured to the structure at the plant beds by two braces which give adequate support to the system both horizontally and vertically. The force analysis is given in Appendix VII.

Pipe Connections

The light traveling vertically in the optical waveguide is directed into the horizontal diffuser by an angled connection. Two different connections are needed for the system. First, a connection is needed that directs half of the light into the upper diffuser while allowing half of the light to continue

downward to the lower diffuser (T-joint). Second, a connection is required to direct all of the light traveling in the lower section of pipe into the bottom diffuser (angle joint). These two joints have basically the same design. The optimum material for these joints has not been determined, however, nylon is recommended because of its flexibility, strength, and low weight. The angle joint uses a completely reflective mirror placed at a 45 degree angle as shown in Figure 15.

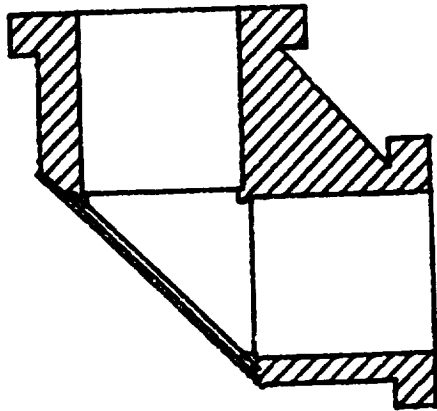


Figure 15

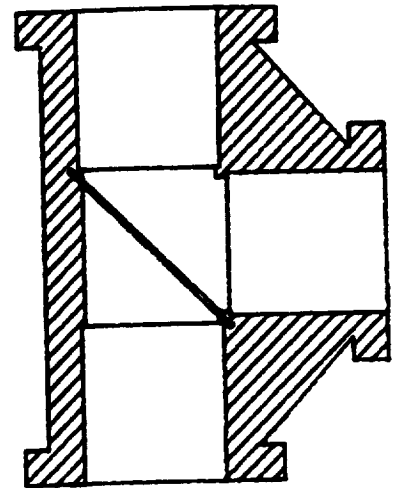


Figure 16

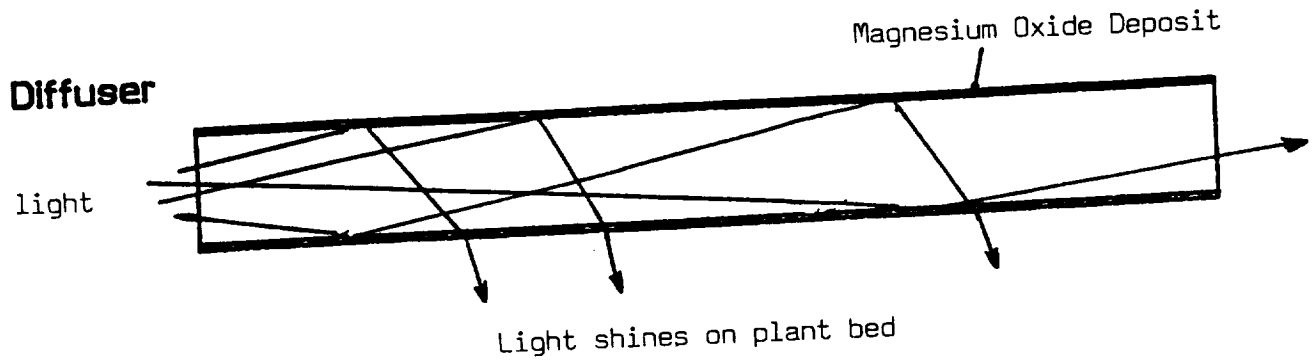
This mirror redirects all the vertical light from the waveguide into the horizontal diffuser. The T-joint, shown in Figure 16, uses a partially reflective mirror placed at a 45 degree angle which reflects half of the light that enters the joint, while allowing half of it to pass through. This partially reflective mirror is approximately 90% efficient, however, further research into mirrors could yield a mirror with a higher efficiency.³⁹

Light Diffuser

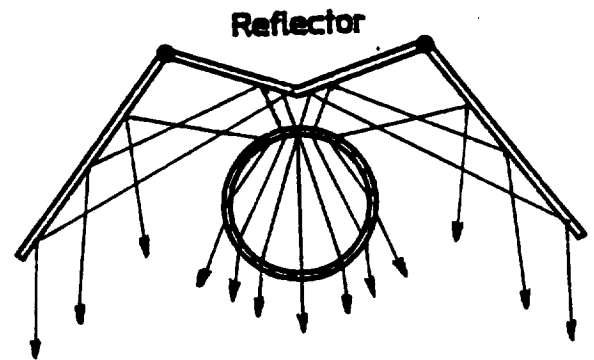
The light diffuser, placed above the plant bed, is designed to diffuse the light from the pipe to the plants in a uniform and efficient manner. To accomplish this, two alternatives are considered. Both consist of an optical diffuser. The first shines the light down onto the plants while the second shines the light up to a mirror that is above the pipe and then back down onto the plant bed. The advantage of having the mirror is that it could direct the light over the entire width of the plant bed. However, the diffuser that reflects downward weighs much less and is more efficient because there are no reflection losses. A combination of these alternatives is used in this design. The downward light diffuser is chosen for its efficiency, but a reflector is placed overhead to capture any light that may be lost through the top of the pipe. This reflector has moveable sides that can be adjusted to cover more area as the plants grow. The sides also help shield the diffuser from human contact. For calculations and the diffuser analysis, see Appendix VIII. The diffuser and overhead reflector are shown in Figure 17.

The material recommended for the diffuser is clear fused silica (Corning Glass #7940). This material has very good light transmission characteristics at all wavelengths.²⁴ The diffuser is coated on the top inside surface with a magnesium oxide powder. This coating is 98% efficient for light reflection in a diffuse manner.³⁹ To get an even intensity of light over the entire 15.2 m long plant bed, several techniques are used.

SIDE VIEW OF DIFFUSER



END VIEW OF DIFFUSER AND REFLECTOR



MATERIAL:

Fused Silica

Refractive index = 1.46

Wall thickness = 1.7 mm

Outside diameter = 60 mm

NOTE:

1. Lightwave is trapped inside the waveguide when incident angle is less than 10 degree.
2. Waveguide has 99% transmission efficiency.
3. Magnesium Oxide has 98% reflectivity.
4. Need to experiment to verify that linear MgO concentration gradient gives uniform diffusion.

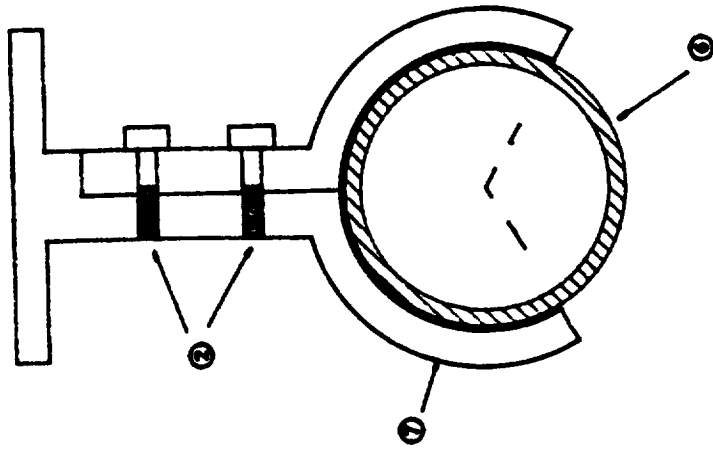
Figure 17. Diffuser and overhead reflector

First, the coating is placed on the top inside surface of the diffuser in a 30 degree arc. This arc increases linearly down the length of the pipe until it is a full 180 degrees at the end of the diffuser. A polished aluminum shield is placed over the diffuser. This shield reflects any light transmitted through the coating, or out the sides and top of the diffuser, down onto the plant bed. The shield also protects the diffuser pipe from accidental human contact. A second way to insure uniform light intensity on the plants is to coat the glass with magnesium oxide. The first part of the glass is coated with a very fine grain of magnesium oxide and the coarseness of the powder is increased as it is applied down the length of the pipe. The very intense light that shines into the front of the pipe is not reflected as much with the fine powder, while the coarse powder near the end of the pipe reflects more light. The texture of magnesium oxide powder that produces the best effect has not been determined in this analysis. Further experimentation and development is recommended.

The diffuser consists of two pieces of a hollow dielectric tubing. Each piece is 7.62 meters long. It is more efficient to have one single piece of material for the entire diffuser, but a 15 meter long pipe is impractical. The pipes are coupled together and the ends of the pipes are sealed with lenses that allow light to pass through while keeping a vacuum inside the pipe.

The upper diffuser is connected to a support above the upper plant bed and the lower diffuser is connected to the bottom of

BRACKET TO SUPPORT DIFFUSER



BRACKET TO SUPPORT WAVEGUIDE

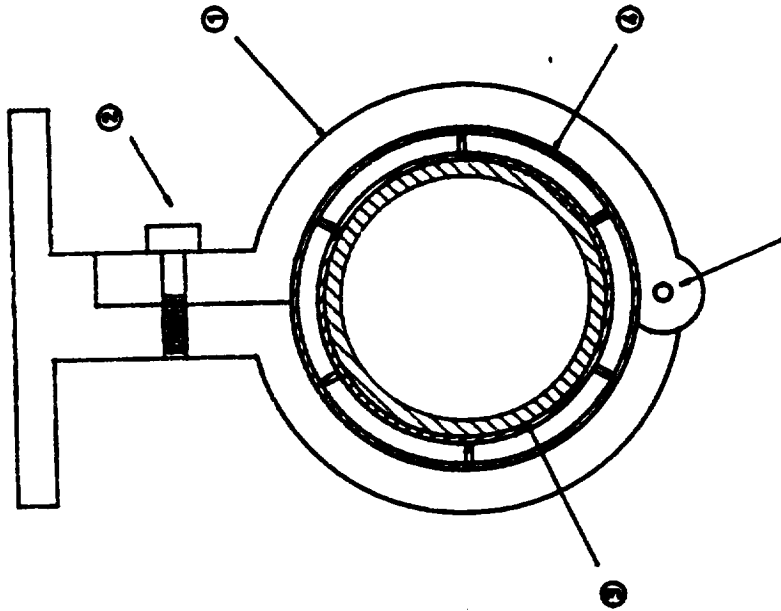


Figure 18. Diffuser Supports

the upper bed. The supports, shown in Figure 18, are circular clamps that can easily be tightened and locked once the diffuser is in place.

2.3.5 Summary

The overall light distribution system consists of the junction (fiber optic - hollow dielectric interface), the light transportation system, the diffuser, and the connections. The overall weight of the entire system is 84.7 lbs. The calculations of the weight of this system are found in Appendix VIII. The efficiency of the system can be increased with more advanced manufacturing techniques and higher quality material, thus reducing the weight of the system. This, in turn, would reduce transportation cost. For these reasons, the cost analysis is based only on the transportation cost related to the weight. For the transportation cost estimated at \$20,000 per pound, the cost of the entire system is \$1,700,000.

The size of the hollow waveguide is determined from a light intensity analysis and the light wavelength theory. The total intensity of the system for a 60 mm pipe is 1330 kW/m^2 . This is a very high intensity and therefore, it is recommended that sensors are installed in the system that stop the light if the system is ruptured. The light can be shut off by the central control which overrides the tracking control and points the affected collectors away from the sun. If the system ruptured, the light would be so intense that it could cause serious damage

to the greenhouse or the colonists. For this reason the sensor and shut off mechanisms are necessary.

The overall efficiency of the light distribution system is 80%. The majority of losses come from the mirrors and the diffuser, both of which perform at 90% efficiency. The waveguide reflective efficiency is negligible at only 10 decibels per kilometer.

3.0 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.

REFERENCES

1. Adams, D.F., Advanced Materials and Processes, University of Wyoming, 1989.
2. Adams, D.F., "Descriptions of Candidate Materials of all Types," University of Wyoming, 1987.
3. American Iron and Steel Institute, Modern Sewer Design, 1985.
4. Boeing Aerospace Co., Conceptual Design Option Study - CELSS Contract NAS2-11806. Seattle, WA, 1985.
5. Carlslaw, H.S., and Jaeger, J.C., Conduction of Heat in Solids-2nd edition, Oxford at the Clarendon Press, 1978.
6. CRC Press, 66th ed. pp. f-129.
7. Creyke, W.E.C., Design With Non-Ductile Materials, Applied Science Publishers, 1982.
8. Duncan, J.M. "Soil-Culvert Interaction Method for Design of Metal Culverts," University of California, Berkeley, 1978.
9. ERDA Conference of Solar Concentrating Collectors, Tucker-Castleberry Printing Inc. 1977.
10. Foyer, C.H., Photosynthesis, Wiley Press, 1984.
11. Gardner, Pearce and Mitchell, Physiology of Crop Plants, Iowa State University Press, Ames, 1985.
12. Gilmore, "Sunflower over Tokyo", Popular Science, May, 1988.
13. Graf, J., Leroy, S., Monyette, T., and Myrhum, M., "Providing Light for a Mars Plant Growth Module." University of Wisconsin, 1985.

14. Hardcastle, J.H. and Sharma, S., "Finite Element Analysis of Long-Span Corrugated Plate-Arch Culvert, January, 1989.
15. Izawa, T., Optical Fibers: Materials and Fabrication, KTK Scientific Publishers, 1987.
16. Kapany, N.S., Optical Waveguides, Academic Press, 1972.
17. Kenner, G., Geodesic Math and How to Use It, University of California Press, Los Angeles, 1976.
18. Kingslake, R., Applied Optics and Optical Engineering, Academic Press, New York, 1967.
19. La Foret Engineering and Information Services Co. Ltd., Minatoku, Tokyo, Japan.
20. Lacy, Fiber Optics, Prentice Hall, 1982.
21. Laramore, R.D. and McPherson, G., Electrical Machines and Transformers. 2nd edition. John Wiley & Sons, New York, 1990.
22. Love, S.F., Planning and Creating Successful Engineered Designs: Managing the Design Process. Advanced Professional Development Incorporated, California, 1986.
23. Mastalery, "Greenhouse Environment", Biotechnology and Bioengineering Symposium, #15 1985, pp 197-201.
24. McLellan and Shand, Glass Engineering Handbook, McGraw-Hill, 1984.
25. McKay, C.D. "A short guide to Mars", NASA/Ames Research Center.
26. Megyesy, E.F., Pressure Vessel Handbook, 6th edition. Pressure Vessel Handbook Publishing Co., July, 1983.
27. Milthorpe and Moorby, An Introduction to Crop Physiology, Cambridge University Press, London, 1974.

28. Mori, K, "Photoautotrophic Bioreactor using Visible Solar Rays Condensed by Fresnel Lenses and Transmitted through Optical Fibers", Space Solar Power Review, Vol 5(2), 1985.
29. Mori, K., "Visible Solar Ray Supply System for Space Station," ATCA Astronautica, Vol 13(2) 1986,pp 71-79.
30. Murray, "PlSc 462, Greenhouse Management", University of Idaho Plant Science Dept, 1989.
31. Nenryo-Kyokai-Shi, v66 n11, 1987, pp 948-959.
32. Nevill, "Design Study of a Prototype Closed Loop Life Support System", University of Florida, Dept. of Aerospace Engineering, Mechanics and Engineering Sciences Dec. 1988.
33. Pollack, J.B., "Properties of Dust Particles Suspended in the Martian Atmosphere," Journal of Geophysical Research. Vol 84(B6). June, 1979.
34. Rabl, Ari, Active Solar Collectors and their Applications, Oxford University Press, 1985.
35. Roberson and Crowe, Engineering Fluid Mechanics, 3rd Edition, Ch. 11.
36. Serway, Physics for Scientists and Engineers with Modern Physics, 2nd Edition, James Madison University, 1983.
37. Seymour, Guide to Self Sufficiency, 1976.
38. Shigley, J.E., and Mischke, C.R., Mechanical Engineering Design, McGraw-Hill, 1989.
39. Smith , W.J., Modern Optical Engineering: The Design of Optical Systems, McGraw-Hill, 1966.
40. St. George, D.R., "A Fiber Optic Lighting System For Horticulture Production." University of Alberta, Edmonton, Alberta, Canada. 1989.

41. Takanori, O., Optical Fibers, Academic Press, 1982.
42. Tesar, M., Physiological Basis of Crop Growth and Development, American Society of Agronomy, 1984.
43. Vinson, J.R. and Sierakowski, R.L., The Behavior of Structures Composed of Composite Materials, Martinus Nijhoff Publishers, 1986.
44. White, F.M., Heat and Mass Transfer, University of Rhode Island, Addison-Wesley Publishing Co., 1988.

APPENDIX I

APPENDIX I

STRUCTURAL CALCULATIONS:

STRUCTURE SIZING:

- Required growing area to support eight people = 3066 ft²
- Increased for ten people, $(10/8) \times 3066$ = 3833 ft²
- Based on a two-tiered growing system, required floor area: = 1918 ft²
- Additional 25% for equipment and access = 2395 ft²
- @ 50% food production per module, with three modules, required floor area per module: = 1198 ft²
- Add floor area of domed ends: = 491 ft²
- Resultant floor area: = 1741 ft²

PRESSURE VESSEL CALCULATIONS:

- Internal pressure, P_i = 14.7 psi
- External pressure, P_o = 4.0 psi
- Design pressure, $P = P_i - P_o$ = 10.7 psi

Calculation of wall thickness based on hoop stress of pressure vessel:

$$t = n * P * D / (2 * S_{ut})$$

where:

t = wall thickness

n = factor of safety (2)

P = design pressure (10.7 psi)

D = diameter (300 inches, 25 feet)

S_{ut} = ultimate tensile strength of Kevlar 49/Epoxy
(100,000 psi)

Wall thickness: = .032 inches

WALL THICKNESS CALCULATIONS - LOSS OF PRESSURE

- In using the following methods, it has been assumed that the properties of Kevlar 49/Epoxy can be substituted into equations used for steel design.

1. Culvert Design Code

The corner pressure generated in the domed cylinder is greater than the pressure in the backfill. Therefore, the corner pressure becomes the practical limiting design factor. For a 6 x 2 inch corrugate:

- Backfill soil density, rho = 46.9 lbf/ft³
- Height of cover, H = 13.1 ft
- Span, S = 25.0 ft
- Corner radius, R_c = 2.58 ft
- Rise, R = 12.5 ft

- Radius of gyration, r = 0.695 in
- Ultimate compressive stress:
 - $f_b = 0.63 * [40,000 - 0.081 * (S/r)^2] = 15,700$ psi
- Design stress, $f_c = f_b/n$ ($n=2$) = 7850 psi
- Design pressure, $P_v = \rho * H$ = 615 lbf/ft²
- Corner pressure, $P_c = P_v * R/R_c$ = 2990 lbf/ft²
- Ring compression, $C = P_c * S/2$ = 37250 lbf/ft²
- Required wall area, $A = C/f_c$ = 4.75 in²/ft
- Wall thickness, $t = 0.668 * A$ = 0.32 inches

2. Soil Culvert Interaction (SCI) Method

- This is a simple method which considers both ring compression forces and bending moments. This method has been found to give values which are in agreement with published fill-height tables and observed behavior of culverts in the field.

The following calculations are based on a 6 x 2 inch corrugate with a thickness of 0.35 inches.

- R, S, ρ and H are same as above
- Cross-sectional area, A [3]: = 5.21 in²/ft
- Moment of inertia, I [3]: = 2.52 in⁴/ft
- Ultimate compressive strength, S_{uc} = 20900 psi
- Ring compression coefficient for backfill,
 - $K_{p1} = 0.2 * (R/S):$ = 0.10
- Ring compression coefficient for cover,
 - $K_{p2} = 0.9 - 0.5 * (R/S):$ = 0.65
- Ring compression force,
 - $P = K_{p1} * \rho * S^2 + K_{p2} * \rho * H * S:$ = 12,930 lbf/ft
- Axial force at failure, $P_p = A * S_{uc}:$ = 109,900 lb/ft
- Soil modulus, E_s (assumed): = 0.363 psi

- Modulus of elasticity, E: = 6 x 10⁶ psi
- Maximum distance for neutral axis, c: = 1"
- Flexibility number, $N_f = E_S * S^3 * (144)^2 / (E * I)$: = 7.79
- Moment coefficient,
 $K_{m1} = 0.0046 - 0.001 * \log N_f$: = 0.00371
- Moment reduction factor, $R_b = 2 * (R/S)$ = 1
- Bending moment due to backfill,
 $M = K_{m1} * R_b * \rho * S^3$: = 2718 ft-lb/ft
- Fully plastic bending moment,
 $M_p = 1.5 * S_{ut} * I / (12 * c)$: = 6,573 ft-lb/ft
- $F_1 = P_p / P$ = 8.62
- $F_2 = M / M_p$ = 0.414
- Factor of safety against buckling failure,
 $F_B = 0.5 * F_1 * [(F_1^2 * F_2^2 + 4)^{0.5} - F_1 * F_2]$: = 2.25

APPENDIX II

APPENDIX II: HEAT TRANSFER CALCULATIONS

The heat transfer analysis includes both a steady state and transient response which is shown below. Refer to the programs and data sheets on the following pages for the calculation procedures and results. The results obtained by modeling the heat transfer from the inside of the structure to the soil surface ($T_s = -55^{\circ}\text{C}$) are slightly conservative since the soil at the surface will be heated somewhat by the underground structure. The energy losses at the surface due to radiation and convection have been ignored in this initial model.

1. Steady State Heat Transfer, Q

Q = steady state heat transfer (kW) = T/R_{th}

T = temperature gradient ($^{\circ}\text{C}$) = $T_i - T_s$

T_i = greenhouse temperature (25°C)

T_s = average soil temperature (-55°C)

R_{th} = total thermal resistance ($^{\circ}\text{C}/\text{kW}$)

= conductive + convective resistances

2. Transient Heat Transfer

The transient heat transfer analysis uses the steady state heat transfer equation and an error function method⁴⁴ to find the total heat transfer and time taken to reach steady state. This analysis shows, for a given distance, how long it takes the soil to reach a certain temperature. For soil properties, refer to "A Short Guide to the Planet Mars," by C.P. McKay - NASA Ames.²⁵

theta = temperature ratio $(T - T_o)/(T_i - T_o)$

T = penetration temperature ($^{\circ}\text{C}$)

T_o = initial soil temperature (-55°C)

T_i = induced soil temperature ($^{\circ}\text{C}$)

n = error function = $x/[2 * (a * t)^{0.5}]$

x = thickness of soil layer above greenhouse

a = thermal diffusivity (m^2/s)

t = time (s)

Conductivity of Kevlar 49/Epoxy

k_f = conductivity of Kevlar 49 fibers (1.05 W/m*K)

k_m = conductivity of matrix (0.25 W/m*K)

V_f = percent volume of Kevlar 49 fibers in layup (60%)

f = $[(k_f/k_m - 1)/(k_f/k_m + 1)] * (0.615)$

k_{kev} = conductivity of Kevlar 49/Epoxy composite

= $K_m * [1 + f*V_f]/[1 - f*V_f] * (0.54 \text{ W/m*K})$

DEPTH BURIED VS. HEAT TRANSFER

```

C   PROGRAM ANALYZES THE HEAT TRANSFER FROM THE MARS
C   GREENHOUSE

      REAL*8 HIN, KINS, KSOIL, KKEVL, TIN, TSOIL, RIN, THKEVL,
      .THSOIL1, THINSUL, THSOIL2, RKEVL, RSOIL1, RINSUL, RSOIL2, L, AIN,
      .RESIN, RESKEVL, RESSOIL1, RESINS, RESSOIL2, RESTOT, RESPART, Q,
      .TININS, THETA, ETA, TIME, TOUTKEV, TPEN, ALPHA, THICK, TIMEWK, RAD,
      .RESSOIL1N, RESINSN, RESOIL2N, QST, DEPTH
      INTEGER I

      OPEN(UNIT=7, FILE='QOUT.DAT')
      OPEN(UNIT=8, FILE='IN.DAT', STATUS='OLD')
      OPEN(UNIT=9, FILE='DEPTH.DAT')

C   SET CONDUCTIVITIES AND HEAT TRANSFER COEFFICIENTS
C   H IS IN (W / m K)
C   Ks ARE IN (W / m^2 K)
      HIN=15.D0
      KINS=0.025D0
      KSOIL=0.08372D0
      KKEVL=0.54D0
      ALPHA=1.022D-7

C   SET INSIDE AND SOIL TEMPERATURES
C   T IN (C)
      TIN=25.D0
      TSOIL=-55.D0

C   READ THE INSIDE RADIUS AND THE THICKNESSES OF THE
C   MATERIALS
      READ(8,10) RIN, THKEVL, THSOIL1, THINSUL, THSOIL2
10  FORMAT(1X, F4.2, T10, F6.4, T20, F6.4, T30, F6.4, T40, F6.4)

C   WRITE(*,*)
C   WRITE(*,*) 'RIN, RKEVL, RSOIL1, RINSUL, RSOIL2'
C   WRITE(*,*) RIN, RKEVL, RSOIL1, RINSUL, RSOIL2

C   THERMAL RESISTANCES
C   LENGTH IS 50ft=15.24m,
C   EQUIVALENT LENGTH (INCLUDING ENDS) IS 20m
C   EQUIVALENT AREA IS 390m^2
      L=23.34D0
      AIN=440.D0

      RESIN=1.D0/(HIN*AIN)

C   WRITE(7,*) 'RESIN, RESKEVL, RESSOIL1, RESINS, RESSOIL2'
C   WRITE(7,*) RESIN, RESKEVL, RESSOIL1, RESINS, RESSOIL2

```

```

C*****
C    CALCULATE THE STEADY STATE HEAT TRANSFER
C*****

C    CALCULATE THE RADIUS OF KEVLAR
      RKEVL=RIN+THKEVL

C    INCREMENT THE DEPTH BY INCREMENTING THE SOIL THICKNESS

      THSOIL1 = 0.D0
DO 1000 I=1,25
C    CALCULATE THE RADII OF THE MATERIAL
      THSOIL2=THSOIL1
      RSOIL1=RKEVL+THSOIL1
      RINSUL=RSOIL1+THINSUL
      RSOIL2=RINSUL+THSOIL2

C    CALCULATE THE RESISTANCES OF THE MATERIALS
      RESKEVL=DLOG(RKEVL/RIN)/(2*3.1416*KKEVL*L)
      RESSOIL1=DLOG(RSOIL1/RKEVL)/(2*3.1416*KSOIL*L)
      RESINS=DLOG(RINSUL/RSOIL1)/(2*3.1416*KINS*L)
      RESSOIL2=DLOG(RSOIL2/RINSUL)/(2*3.1416*KSOIL*L)

      RESTOT=RESIN+RESKEVL+RESSOIL1+RESINS+RESSOIL2

C    CALCULATE THE STEADY STATE HEAT TRANSFER
      QST=(TIN-TSOIL)/RESTOT
WRITE(7,*)'STEADY STATE HEAT TRANSFER, Q [W] = ',QST
WRITE(*,*)'STEADY STATE HEAT TRANSFER, Q [W] = ',QST
      DEPTH = 2*THSOIL1
      Q=QST/1000.D0
C    SEND THE DEPTH AND HEAT LOSS DATA TO AN OUTPUT FILE
      WRITE(9,100) DEPTH,Q
100  FORMAT(1X,F5.2,T10,F5.2)

C    INCREMENT SOIL THICKNESS BY 20 cm
      THSOIL1 = THSOIL1 + 0.2D0
1000 CONTINUE

      END

```

TRANSIENT HEAT TRANSFER PROGRAM

```

C     PROGRAM ANALYZES THE HEAT TRANSFER FROM THE MARS
C     GREENHOUSE

      REAL*8 HIN,KINS,KSOIL,KKEVL,TIN,TSOIL,RIN,THKEVL,
      .THSOIL1,THINSUL,THSOIL2,RKEVL,RSOIL1,RINSUL,RSOIL2,L,AIN,
      .RESIN,RESKEVL,RESSOIL1,RESINS,RESSOIL2,RESTOT,RESPART,Q,
      .TININS,THETA,ETA,TIME,TOUTKEV,TPEN,ALPHA,THICK,TIMEWK,RAD,
      .RESOIL1N,RESINSN,RESOIL2N,QST
      INTEGER I

      OPEN(UNIT=7,FILE='QOUT.DAT')
      OPEN(UNIT=8,FILE='IN.DAT',STATUS='OLD')
      OPEN(UNIT=9,FILE='TIME-Q.DAT')

C     SET CONDUCTIVITIES AND HEAT TRANSFER COEFFICIENTS
C     H IS IN (W / m K)
C     Ks ARE IN (W / m^2 K)
      HIN=15.D0
      KINS=0.025D0
      KSOIL=0.08372D0
      KKEVL=0.54D0
      ALPHA=1.022D-7

C     SET INSIDE AND SOIL TEMPERATURES
C     T IN (C)
      TIN=25.D0
      TSOIL=-55.D0

C     READ THE INSIDE RADIUS AND THE THICKNESSES OF THE
C     MATERIALS
      READ(8,10) RIN,THKEVL,THSOIL1,THINSUL,THSOIL2
10  FORMAT(1X,F4.2,T10,F6.4,T20,F6.4,T30,F6.4,T40,F6.4)

C     CALCULATE THE RADII OF THE MATERIALS
      RKEVL=RIN+THKEVL
      RSOIL1=RKEVL+THSOIL1
      RINSUL=RSOIL1+THINSUL
      RSOIL2=RINSUL+THSOIL2

C     WRITE(*,*)
C     WRITE(*,*) 'RIN,RKEVL,RSOIL1,RINSUL,RSOIL2'
C     WRITE(*,*) RIN,RKEVL,RSOIL1,RINSUL,RSOIL2

C     THERMAL RESISTANCES
C     LENGTH IS 50ft=15.24m,
C     EQUIVALENT LENGTH (INCLUDING ENDS) IS 20m
C     EQUIVALENT AREA IS 440m^2
      L=23.34D0
      AIN=440.D0

```

```

RESIN=1.D0/(HIN*AIN)
RESKEVL=DLOG(RKEVL/RIN)/(2*3.1416*KKEVL*L)
RESSOIL1=DLOG(RSOIL1/RKEVL)/(2*3.1416*KSOIL*L)
RESINS=DLOG(RINSUL/RSOIL1)/(2*3.1416*KINS*L)
RESSOIL2=DLOG(RSOIL2/RINSUL)/(2*3.1416*KSOIL*L)

```

```

RESTOT=RESIN+RESKEVL+RESSOIL1+RESINS+RESSOIL2

```

```

C      WRITE(7,*)'RESIN,RESKEVL,RESSOIL1,RESINS,RESSOIL2'
C      WRITE(7,*)RESIN,RESKEVL,RESSOIL1,RESINS,RESSOIL2

```

```

C*****
C      CALCULATE THE STEADY STATE HEAT TRANSFER
C*****

```

```

QST=(TIN-TSOIL)/RESTOT
WRITE(7,*)'STEADY STATE HEAT TRANSFER, Q [W] = ',QST
WRITE(*,*)'STEADY STATE HEAT TRANSFER, Q [W] = ',QST

```

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C*****
C      CALCULATE HEAT REQUIRED DURING THE TRANSIENT STAGE
C*****

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C      FOR THE TRANSIENT STAGE, THE SOIL IS MODELED AS A
C      SEMI-INFINITE SLAB WITH A SUDDENLY CHANGED WALL
C      TEMPERATURE. SINCE THE TIME TO HEAT THE KEVLAR IS
C      NEGLIGIBLE COMPARED WITH THE TIME TO HEAT THE
C      SOIL, THE STEADY STATE TEMPERATURE OUTSIDE OF THE
C      KEVLAR IS USED FOR THIS NEW WALL TEMPERATURE.

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```

C      CALCULATE THE OUTSIDE TEMPERATURE OF THE KEVLAR AT
C      STEADY STATE

```

```

RESPART=RESIN+RESKEVL
TOUTKEV=TIN-(QST*RESPART)

```

```

WRITE(*,*)'TEMPERATURE OUTSIDE THE KEVLAR = ',TOUTKEV
WRITE(*,*)

```

```

C      THE TIME FOR THE SOIL TO HEAT UP IS ESTIMATED
C      USING THE METHOD DESCRIBED IN 'HEAT AND MASS
C      TRANSFER', BY FRANK M. WHITE, ON PAGE 201. THE
C      SMALLEST THETA AND THE LARGEST ETA WHICH CAN BE
C      READ ON FIG. 4.4 (THETA=0.0303, ETA=1.5) IS USED
C      TO FIND THE POINT IN THE SLAB WHERE THE

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C          TEMPERATURE CHANGE IS ONLY 3.03% OF THE INITIAL
C          SOIL TEMP - APPROXIMATELY THE OUTER BOUNDARY OF
C          HEAT TRANSFER.

C          THIS "PENETRATION THICKNESS" IS CALCULATED FOR
C          INCREMENTS OF TIME.

          THETA = 0.0303D0
          ETA   = 1.5D0
C          TPEN = THE PENETRATION TEMPERATURE
          TPEN = TSOIL + THETA*(TOUTKEV-TSOIL)

C          INCREMENT TIME AND CALCULATE THE THICKNESS TPEN HAS
C          GONE THROUGH BY THEN.

          WRITE(9,450)
          WRITE(9,475)
450  FORMAT(3X,'TIME',T10,'HEAT TRANSFER')
475  FORMAT(1X,'[WEEKS]',T11,'[KILOWATTS]')
          TIME = 0
          TIMEWK = 0

          DO 1000 I=0,100
            THICK=SQRT(ALPHA*TIME)*2.D0*ETA
            RAD=THICK+RKEVL
            IF(RAD.LE.RSOIL1) THEN
              RESOIL1N=DLOG(RAD/RKEVL)/(2*3.1416*KSOIL*L)
              RESPART=RESIN+RESKEVL+RESOIL1N
              WRITE(*,*)'IN SOIL1, RESSOIL1 =',RESOIL1N
              WRITE(7,*)'IN SOIL1, RESSOIL1 =',RESOIL1N
            ELSE IF(RAD.LE.RINSUL .AND. RAD.GT.RSOIL1) THEN
              RESINSN=DLOG(RAD/RSOIL1)/(2*3.1416*KINS*L)
              RESPART=RESIN+RESKEVL+RESSOIL1+RESINSN
              WRITE(*,*)'IN INSULATION, RESINS=',RESINSN
              WRITE(7,*)'IN INSULATION, RESINS=',RESINSN
            ELSE IF(RAD.LE.RSOIL2 .AND. RAD.GT.RINSUL) THEN
              RESOIL2N=DLOG(RAD/RINSUL)/(2*3.1416*KSOIL*L)
              RESPART=RESIN+RESKEVL+RESSOIL1+RESINS+RESOIL2N
              WRITE(*,*)'IN SOIL2, RESSOIL2=',RESOIL2N
              WRITE(7,*)'IN SOIL2, RESSOIL2=',RESOIL2N
            ELSE IF(RAD.GT.RSOIL2+.01) THEN
              WRITE(*,*)'OUT OF BOUNDS'
              WRITE(7,*)'OUT OF BOUNDS'

          WRITE(*,*)'THICKNESS=',THICK,'RAD=',RAD,'RSOIL2=',RSOIL2
              WRITE(*,*)'TIME TO HEAT UP [Wks] =',TIMEWK-.5
              GOTO 2000
            ENDIF
            Q=(TIN-TPEN)/RESPART

          WRITE(*,*) 'TIME [Wks] =',TIMEWK,'Q =',Q
          WRITE(*,*) 'THICKNESS =',THICK,'RESPART =',RESPART
          WRITE(*,*)
          WRITE(7,*) 'TIME [Wks] =',TIMEWK,'Q =',Q

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WRITE(7,*) 'THICKNESS =',THICK,'RESPART =',RESPART

C      WRITE TIME AND HEAT TRANSFER TO OUTPUT FILE
500    WRITE(9,500) TIMEWK,Q/1000.DO
      FORMAT(3X,F4.1,T13,F8.3)

C      INCREMENT TIME BY A HALF WEEK (1 WEEK = 7*24*60*60
C      SECONDS)
      TIMEWK=TIMEWK+.5
      TIME=TIMEWK*(7*24*60*60)

1000  CONTINUE
2000  CONTINUE

C      TININS=TIN-(RESPART*Q)
C      WRITE(7,*) 'T INSIDE INSULATION = ',TININS
C      WRITE(*,*) 'T INSIDE INSULATION = ',TININS

C      TIME FOR SOIL TO HEAT UNTIL TEMP ON THE INSIDE OF THE
C      INSULATION IS EQUAL TO ITS STEADY STATE TEMP--MUST
C      READ OFF FIG 4.4
C      THETA=(TININS+55)/(25+55)
C      WRITE(*,*) 'THETA= ', THETA
C      WRITE(*,*) 'ERROR FUNCTION ETA = ? '
C      READ(*,*) ETA
      ETA=.58

      TIME=((RSOIL1-RIN)/(2.DO*ETA))**2/ALPHA
      TIME=TIME/(7.DO*24.DO*3600.DO)
C      WRITE(*,*) 'TIME IN WEEKS TO REACH STEADY STATE =',TIME
C      WRITE(*,*)
C      WRITE(*,*)
      WRITE(*,*) 'THICK'
      WRITE(*,*) THICK
END

```

APPENDIX III

APPENDIX III:

COLLECTOR AREA REQUIRED

Area to be lighted:	534.2 m ²
Percent increase in photosynthesis due to temperature and CO ₂ concentration:	300%
Solar light incident on earth:	375-595 W/m ²
Light incident on Mars as compared to Earth:	50%
Visible range reaching Mars:	187-297 W/m ²
Light required for plant growth:	200-500 W/m ²
Collector size:	
Range from:	534.2 m ² * [100/300] * [1/187 W/m ²] * 200 W/m ²
to:	534.2 m ² * [100/300] * [1/297 W/m ²] * 500 W/m ²
	= 120 m ² to 476 m ²

HEAT ANALYSIS FOR LENS

PROBLEM: Heat generation in glass lens due to a high concentration of solar radiation.

ASSUMPTIONS:

- * Only radiation heat transfer

ANALYSIS:

- * Total light gathering area for 1 dish = 1000 ft²
(92.9 m²)
- * Area of lens that concentrated light will fall
= 7 ft² (.65 m²)
- * Ambient radiation incident on dish surface = R_i
R_i = 1000 W/m² (70% of solar constant)
- * R_d = radiation incident on lens
= R_i * (92.9m² / .65m²) * 80% efficiency
= 114,340 W/m²
- * Assuming lens is 90% efficient
- * Total radiation retained in lens
= (100% - 90%) * 114,340 W/m²

$$= 11,440 \text{ W/m}^2$$

* Normally this 10% loss is due to reflection or absorption but we assumed reflection is zero and this 10% is totally absorbed.

$$q/A = E * \sigma * (T_s^4 - T_a^4)$$

$$q = \text{energy flux (W/m}^2\text{)} = 11,440 \text{ W/m}^2$$

$$A = \text{area of surface} = .65 \text{ m}^2$$

$$E = \text{emissivity of transparent lens} = .93$$

(for quartz)

$$\sigma = \text{Stefan-Boltzmann constant} = 5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$$

$$T_s = \text{temperature of lens surface} = ???$$

$$T_a = \text{ambient temperature at infinity} = 170 \text{ K}$$

(assumed)

SOLVING FOR T_s :

$$T_s = 760 \text{ K} \quad (487^\circ\text{C})$$

This temperature is well below the melting temperature for quartz.

APPENDIX IV

APPENDIX IV: LOAD ESTIMATES

WEIGHT

$$W_{\text{Total}} = W_{\text{Collector}} + W_{\text{Base}} + W_{\text{Hinge}}$$

$$W_{\text{Collector}} = W_{\text{glass}} + W_{\text{aluminum}} + W_{\text{mechanism}}$$

$$W_{\text{glass}} = n V p g = 2575 \text{ N}$$

$$n = \text{number of lenses} = 750$$

$$V = \text{volume of glass} = 140 \times 10^{-6} \text{ m}^3$$

$$p = \text{density of glass} = 2500 \text{ kg/m}^3$$

$$g = \text{gravity} = 9.81 \text{ m/s}^2$$

$$W_{\text{aluminum}} = n A t p g = 2256 \text{ N}$$

$$n = 750$$

$$A = 0.071 \text{ m}^2$$

$$t = 1.60 \text{ mm}$$

$$p = 2700 \text{ kg/m}^3$$

$$\begin{aligned} W_{\text{mech}}^* &= (L A p g)_{\text{frame}} + (L A p g)_{\text{under frame}} \\ &= 2580 \text{ N} \end{aligned}$$

frame:

$$L = 21.4 \text{ m}$$

$$A = 3.32 \times 10^{-3} \text{ m}^2 \quad (229 \times 76 \text{ channel})$$

$$p = 2700 \text{ kg/m}^3$$

under frame:

$$L = 15.5 \text{ m}$$

$$A = 1.7 \times 10^{-3} \text{ m}^2$$

$$p = 2700 \text{ kg/m}^3$$

* does not include the weight of the optic cells

$$W_{\text{Collector}} = 2575 + 2256 + 2580 = 7411 \text{ N}$$

$$W_{\text{Base}} = V \rho g = 3414 \text{ N}$$

$$V = 0.1289 \text{ m}^3$$

$$\rho = 2700 \text{ kg/m}^3$$

$$W_{\text{Hinge}} = V \rho g = 254 \text{ N}$$

$$V = 9.60 \times 10^{-3} \text{ m}^3$$

$$\rho = 2700 \text{ kg/m}^3$$

$$W_{\text{Total}} = 7411 + 3414 + 254 = 11,079 \text{ N}$$

WIND LOADING - maximum

$$F_{\text{Drag}} = 1/2 C_{\text{Drag}} \rho A V^2$$

$$C_{\text{Drag}} = 1.2 \quad (\text{Re} = 775 \times 10^5)$$

$$\rho = 0.0618 \text{ kg/m}^3 \quad (\text{T} = 130 \text{ K}, \text{P} = 1.51 \text{ kPa})$$

$$A = 25.75 \text{ m}^2$$

$$V = 100 \text{ m/s}$$

$$F_{\text{Drag}} = 9546 \text{ N}$$

HINGE MOMENT LOADS

$$M_{\text{moment}} = (r \text{ radius} \times F \text{ force}) n \text{ direction}$$

BOTTOM HINGE

$$\begin{aligned}(r \times F) &= (-0.445k)(-981j)_{\text{glass}} + (-3.55k)(-851j)_{\text{alum}} \\ &\quad + (-0.355k)(-743j)_{\text{mech}} \\ &= -1013 \text{ Nm } i\end{aligned}$$

$$n = 0.9397 i + 0.3420 j \quad (20 \text{ degree axis})$$

$$M_{\text{bottom}} = 951 \text{ Nm}$$

TOP HINGE

$$\begin{aligned}(r \times F) &= (0.212)(-981)_{\text{glass}} + (0.141)(-851)_{\text{alum}} \\ &\quad + (0.141)(743)_{\text{mech}} \\ &= -433 \text{ Nm}\end{aligned}$$

$$n = 1 k$$

$$M_{\text{top}} = -433 \text{ Nm}$$

APPENDIX V

Appendix V: Fiber Optic Bundle Calculation.

Assumptions:

1. Intensity of the sun's light on the planet is 50% that of earth.
2. The efficiency of the system is 70%.

Total Growing Area:

$$\begin{aligned}A(\text{total}) &= \text{Area}(\text{per bed}) * \# \text{ of beds.} \\ &= (50 \text{ feet} * 5 \text{ feet}) * 6 \\ &= 1500 \text{ square feet}\end{aligned}$$

For the 50% and 70% efficiency, the total light collection area needed = 4300 square feet

Area of each fresnel lens of the collector:

$$A(\text{lens}) = 9 \text{ square inches} = 0.0625 \text{ square feet}$$

Number of fibers required:

$$\# \text{ fibers} = A(\text{total})/A(\text{lens}) = 4300/0.0625 = 68,800$$

Area of each fiber optic:

diameter = 3 mm including the cladding

$$A(\text{fiber}) = 3.14 * 3 * 0.00328^2 / 4 = 7.4 \text{ E}(-5) \text{ sq ft}$$

Area of bundle:

$$\begin{aligned}A(\text{bundle}) &= A(\text{fiber})/\# \text{ fibers} \\ &= 7.4\text{E}(-5) * 68,800 \\ &= 5.1 \text{ square feet} = 735.4 \text{ square inches}\end{aligned}$$

Diameter of each bundle (for six junctions):

$$\text{Diameter of each fiber bundle} = 317.5\text{mm}$$

APPENDIX VI

Appendix VI: Light Transportation Analysis.

Alternatives:

1. Fiber optics. This is a continuation of the incoming fiber optic bundle to the diffuser.
2. Solid dielectric. A solid dielectric pipe is connected to the incoming fiber optic bundle.
3. Hollow dielectric. A hollow dielectric pipe is connected to the incoming fiber optic bundle.

Decision Matrix:

Criteria:	Solid		Hollow			
	Fiber Optics	Dielectric	Dielectric	Dielectric		
(50%) Reliability	8	4.0	8	4.0	9	4.5
(30%) Efficiency	6	1.8	7	2.1	9	2.7
(5%) Assembly	1	0.05	7	0.35	8	0.40
(10%) Maintenance	6	0.6	6	0.6	6	0.6
(5%) Cost	5	0.25	7	0.35	9	0.45
Total		6.7		7.4		8.65

The hollow dielectric is chosen based on this analysis.

Explanation of criteria:

1. Reliability. The three systems were rated the same for this criteria because they are all based on the same principle. If the systems are manufactured and installed correctly, they should all be very reliable.
2. Efficiency. The efficiency of the fiber optics is rated lowest because there are losses in each fiber. The solid dielectric is rated higher because the losses in one large fiber are much less than in many smaller fibers. The hollow dielectric is rated highest because the vacuum inside allows the light to travel through it at very high efficiencies.

3. **Assembly.** The assembly of the fiber optic bundle is rated very low because to connect the system, each fiber would have to be connected precisely to the end of each of the fiber coming from the collector. This would be an extremely difficult task. The hollow and solid dielectric are rated higher because they can be made to snap into place very easily, however, the solid dielectric is heavier, and therefore, harder to handle.
4. **Maintenance.** All three systems are rated equally for maintenance considerations.
5. **Cost.** The cost of the system is directly related to the weight. The fiber optics weigh the most because cladding is needed to cover each fiber and extra fibers are needed due to the lower efficiency. The solid dielectric weighs more than the hollow dielectric.

APPENDIX VII

Appendix VII: Light Diffuser Analysis.

Alternatives:

1. Upward light diffusion. Light in the diffuser is radiated upward onto a mirror that reflects the light down onto the growing area.
2. Downward light diffusion. Light in the diffuser is radiated down directly onto the growing area.

Decision Matrix:

Criteria	Upward Diffuser		Downward Diffuser	
(50%) Performance	7	3.5	9	4.5
(15%) Shipping	5	0.75	7	1.05
(5%) Fabrication	6	0.3	6	0.3
(20%) Installation	7	1.4	8	1.6
(10%) Human Factors	7	0.7	5	0.5
Total	6.65		7.95	

Therefore, the downward diffuser is chosen.

Explanation of criteria:

1. Performance. The upward diffuser has a lower performance because the reflection from the mirror has losses associated with it.
2. Shipping. This criteria considers the bulk of the and the weight of the system, which also means cost. The upward diffuser again is rated lower due to the weight and size of the reflective mirror that is required.
3. Fabrication. Each of the systems are rated equally for fabrication considerations.
4. Installation. This criteria is rated approximately the same for both systems, except that the upward diffuser must have a mirror installed, and therefore, is rated slightly lower.

5. Human Factors. Both systems would have to be kept clean and need protection from accidental impact. The mirror placed over the diffuser aids both of these, so the upward diffuser is rated highest.

In modeling the downward diffuser, it is found that some light is lost out the top of the pipe. Therefore, an overhead mirror is added to the downward diffuser system in order to maintain a high efficiency, catch all of the light lost through the top of the diffuser and protect the pipe from accidental human contact.

APPENDIX VIII

Appendix VIII: System Weight Calculation.

A. Transport System.

Length:

Center pipe length = 9 feet
Side pipe length = 6.3 feet

For the six junctions, there are two center pipes and four side pipes. Hence, the total length is:

$$\text{Length} = 4 * 6.3 + 2 * 9 = 43.2 \text{ feet}$$

Area:

Outside diameter = 60 mm.

Wall thickness = 1.5 mm.

$$\begin{aligned} \text{Area} &= 3.14 * (\text{Dout}^2 - \text{Din}^2) / 4 = 1.4\text{E-}4 \text{ m}^2 \\ &= 1.4\text{E-}4 \text{ square meters} \\ &= 0.0015 \text{ square feet} \end{aligned}$$

Volume:

$$\begin{aligned} \text{Volume} &= \text{area} * \text{length} \\ &= 0.0015 * 43.2 \\ &= 0.0648 \text{ cubic feet} \end{aligned}$$

Density:

$$\text{Density} = 140.45 \text{ pounds per cubic foot}$$

Weight:

$$\begin{aligned} \text{Weight} &= \text{density} * \text{volume} \\ &= 140.45 * 0.064 \\ &= 9.1 \text{ pounds} \end{aligned}$$

B. Diffuser.

The diffuser has the same diameter (therefore the same area) and density as the light transport pipe.

Length:

length of each diffuser = 50 feet
for the six diffusers, the total length is:
Length = 300 feet

Volume:

$$\text{Volume} = 300 * 0.0015 = .45 \text{ cubic feet}$$

Weight:

$$\text{Weight} = 140.45 * 0.45 = 63.2 \text{ pounds}$$

C. Sheathing.

Area:

$$\text{Area} = A(\text{out}) - A(\text{in}) + \text{thickness between air gaps}$$

$$= 3.14/4 * (.375^2 - .25^2) + 6 * .125 * .25$$

$$= 0.249 \text{ square inches}$$

$$= 0.0017 \text{ square feet}$$

Length:

The length of the sheathing is the same as the length of the transport pipe.

$$\text{Length} = 43.2 \text{ feet}$$

Density:

$$\text{Density is} = 169 \text{ pounds/cubic foot}$$

Volume:

$$\begin{aligned} \text{Volume} &= 43.2 * 0.0017 \\ &= 0.073 \text{ cubic feet} \end{aligned}$$

Weight:

$$\begin{aligned} \text{Weight} &= 169 * 0.073 \\ &= 12.4 \text{ pounds} \end{aligned}$$

D. Total Weight of the System:

$$\begin{aligned} \text{Total Weight} &= 12.4 + 63.2 + 9.1 \\ &= 84.7 \text{ pounds} \end{aligned}$$