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Inflatable Transparent Structures for Mars Greenhouse Applications

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ABSTRACT

It is proposed to employ a greenhouse for life support on the Martian surface to reduce the equivalent system mass (ESM) penalties encountered with electrical crop lighting. The ESM of a naturally lit plant growth system compares favorably to an electrically lit system when corrections for area are made based on available light levels. A transparent structure should be more efficient at collecting insolation than collectors due to the diffusivity of the Mars atmosphere and inherent transmission losses encountered with fiber optics. The need to provide a pressurized environment for the plants indicates the use of an inflatable structure. Materials and design concepts are reviewed for their applicability to an inflatable greenhouse.

INTRODUCTION

The greenhouse is perhaps the ultimate combination of a bioregenerative life support system and in-situ resource utilization. As on Earth, greenhouses are appealing for use on Mars because they provide protection to crops from a harsh environment while allowing the use of natural insolation, i.e. daily integrated solar irradiance, instead of expensive electrical lighting. The use of plants for life support is based on exploiting photosynthesis and transpiration to generate oxygen, remove carbon dioxide, produce clean water from waste streams, and for their unique capability to regenerate food (Wheeler 2004). The idea of using plants as part of a recycling life support system for space missions is not a new one. Long before the advent of spaceflight, Tsiolkovsky not only proposed the use of plants for recycling during space missions, he envisioned the use of naturally solar lit greenhouse shown in Figure 1 (Tsiolkovsky 1926; Anon. 2003).

This paper examines the efficacy of a Mars greenhouse using equivalent system mass (ESM) estimates for plant production systems, the relationship between crop productivity and light, and estimates of the available light on Mars. Arguments are presented for using a transparent structure (i.e. a greenhouse) instead of solar irradiance collectors. Applicable materials and design concepts are presented and analyzed. Finally, some of the commonly cited threats to greenhouse viability are examined.

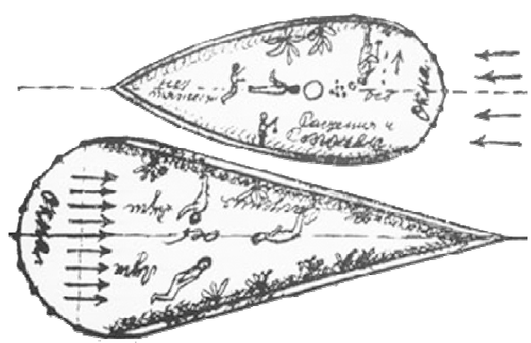

Figure 1 Tsiolkovsky's sketches showing space greenhouse concepts including weightless cosmonauts tending the crops (Tsiolkovsky 1932; Anon. 2003).

EFFICACY OF A MARS GREENHOUSE

Options for crop lighting can be divided into two main categories, electrical and natural. Electrical lighting uses power from generators or solar collectors to electrify lamps (e.g. incandescent, fluorescent, light emitting diode (LED) arrays, etc.) (Sager and Wheeler 1992). Natural lighting can be used directly through transparent structures or via irradiance collection and distribution systems.

Despite the advances in electrical lighting technology it still requires tens of kilowatts to support the crop area needed for even one crewperson. Salisbury and Bugbee (1988) suggested that as little as 24 m^2 of a highly productive crop (e.g. wheat) would be required to support one person and would use 14.4 kW of power for electrical lighting. This estimate has increased in the latest Baseline Values and Assumptions Document (BVAD) that estimates a system providing 1500 μmol m^{-2} s^{-1} requires 2.175 kWm^{-2} (Hanford 2004; Drysdale 2005).

Table 1 lists the lighting parameters used for crop performance testing within the Biomass Production Chamber (BPC) at Kennedy Space Center and provides a good target for the light levels required for life support crops (Wheeler, Sager et al. 2003). For a PPF of 1500 μmol m^{-2} s^{-1}, a 12 h photoperiod provides 64.8 mol m^{-2} day^{-1}, which is far more than most crops need except perhaps wheat.

Table 1 Environmental set points used for ALS candidate crops in KSC testing (Wheeler, Sager et al. 2003).

Crop (Genus species)	Photosynthetic Photon Flux (PPF) (μmol m^{-2} s^{-1})		Photoperiod (hours)		Daily PPF (mol day^{-1})
Staple Crops	Min	Max	Light	Dark	
Wheat (Triticum aestivum)	750	800	24	0	69.12
Soybean (Glycine max)	500	800	12	12	34.56
Potato (Solanum tuberosum)	500	800	12	12	34.56
Sweetpotato (Ipomoea batatas)	500	800	12	12	34.56
Peanut (Arachis hypogaea)	500	750	12	12	32.4
Rice (Oryza sativa)	750	800	12	12	34.56
Bean (Phaseolus vulgaris)	350	400	18	6	25.92
Supplemental Crops					
Lettuce (Lactuca sativa)	300		16	8	17.28
Spinach (Spinacia oleracea)	300		16	8	17.28
Tomato (Lycopersicon esculentum)	500	750	12	12	32.4
Chard (Beta vulgaris)	300		16	8	17.28
Radish (Raphanus sativus)	300		16	8	17.28
Red Beet (Beta vulgaris)	300		16	8	17.28
Strawberry (Fragaria x ananassa)	400	600	12	12	25.92

This amount of light corresponds to 20.89 m^2 of growing area based on the crop area-to-light relationship in Figure 2. The corresponding power is 42.4 kW per person or 254.5 kW for a crew of 6. This amount of power is challenging to generate at a low ESM. For example, using solar panels to convert insolation into electrical power and then back into light is somewhat of a losing proposition. Cuello (1999) estimated that the result of these conversion losses is an overall efficiency of 3.9% to generate electric plant lighting via solar power. Even with a dramatic increase in solar cell efficiency, perhaps to 50% (Preuss 2002), combined with optimistic lighting efficiency of 35% (Hanford 2004), the light-electricity-light conversion rate would be no more than 17.5% requiring an incredibly large array. Nuclear power, although more efficient, also poses large mass penalties requiring 1.3 metric tons of reactor mass for the crew of 6 (e.g. SAFE-400 (Anon. 2003)).

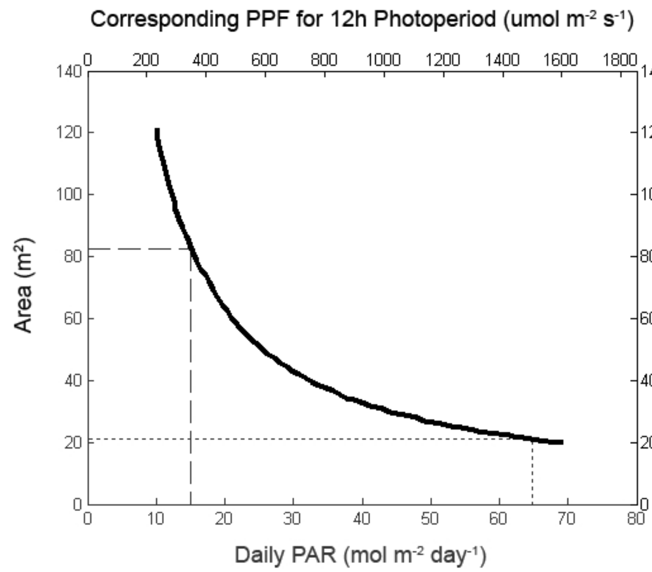

Figure 2 Relationship between light provided to crops and the growing area required for supporting one person's dietary energy (2500 kcal day-1). (Wheeler 2004)

The BVAD also provides an analysis of total Plant Growth Chamber (PGC) ESM per growing area (see Table 4.2.3 Hanford 2004). Assuming the previous light level, photoperiod, and corresponding area the ESM of plant growth systems can be determined per crew person. Table 2 shows the PGC ESM with and without lamps and ballasts. The ESM with lamps and ballasts is almost 4 times that without lamps and ballasts. Therefore, a system without lamps and ballasts (i.e. illuminated with natural lighting) could occupy almost 4 times the area of a system with lamps and ballasts for the same ESM assuming all other components are the same. Using Figure 2, the light required for this increased area corresponding to no lamps and ballasts is 16.21 $molm^{-2}d^{-1}$ to achieve the same performance as the electrically lit system.

Table 2 Comparison of plant growth chamber ESM with and without lamps and ballasts.

PPF	1500	umol m^{-2} s^{-1}
Photoperiod	12	h
Light	64.8	mol m^{-2} d^{-1}
Area from Light (Figure 1)	20.89	m^2 $person^{-1}$
Total $ESM_{w/\ Lamps\&Ballasts}$	82159	kg
Total $ESM_{w/o\ Lamps\&Ballasts}$	20773	kg
$ESM_{w/\ L\&B} / ESM_{w/o\ L\&B}$	3.96	
Area * ESM Ratio	82.62	m^2 $person^{-1}$
Light from Area (Figure 1)	15.07	mol m^{-2} d^{-1}
PPF	418.48	umol m^{-2} s^{-1}

MARS SURFACE PAR - Ono and Cuello (2000) used data from the Viking 1 landing site calculated by Appelbaum, Landis et al. (1993) to estimate the PPF at the Mars surface. They determined a factor for converting the measured irradiance (Wm^{-2}) to PPF (4.568 $\mu molm^{-2}s^{-1}/Wm^{-2}$ for Mars versus 4.609 $\mu molm^{-2}s^{-1}/Wm^{-2}$ for Earth) given an estimated Mars surface spectrum from Crisp, Paige et al. (1994). The estimated daily PPF averaged over the whole Martian year was 19.4 $molm^{-2}d^{-1}$. A more detailed analysis of the same data can reveal the variation of this estimate throughout the Martian year. Using the same conversion for irradiance to PPF from Ono and Cuello, Figure 3 shows the averaged daily PAR calculated from the average daily irradiance data from Appelbaum, Landis et al. The maximum was observed during the northern spring and summer when the PPF averaged ~25 $molm^{-2}d^{-1}$. Mars passes through perihelion during the northern autumn and winter and should have produced higher irradiances than observed, but there were two major planet-encircling dust storms during the measurement period making it one of the worst years observed (Appelbaum, Landis et al. 1993).

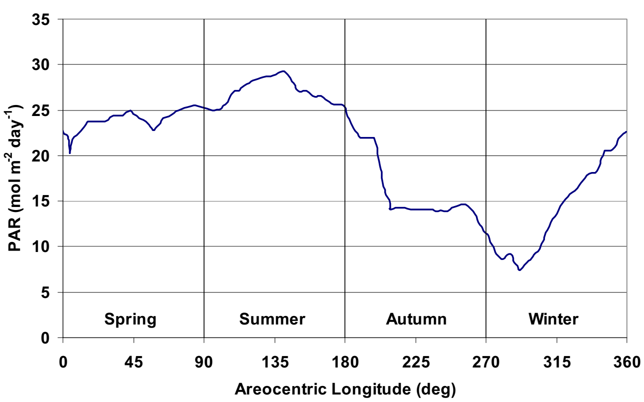

Figure 3 Averaged daily PAR incident on a horizontal plate at the Viking 1 landing site. Adapted from Appelbaum, Landis et al. (1993) using the relationships from Ono and Cuello (2000)

The average light available is 120% of that required for a greenhouse to be competitive with a fully electrically lit plant growth system. It is questionable whether this would provide enough margin to account for transmittance losses and safety factors, but again note that the analyzed light data represents one of the worst years observed. Obviously, there is a need to quantify the estimate of Mars surface PAR on a global scale that is averaged over a longer time period to further elucidate the utility and efficiency of natural solar insolation and a favorable location at which to operate a greenhouse. Regardless, it is at least qualitatively clear that the available natural insolation can alleviate some if not all of the high equivalent system mass associated with electrical lighting if it can be harnessed efficiently.

HARNESSING NATURAL INSOLATION

The low pressure at the Mars surface necessitates the use of a pressurized structure to house the plants. The challenge to using the natural solar insolation efficiently, therefore, is that the containment structure stands between the plants and their light source. This can be overcome either by collecting and transferring the light through fiber optics to the interior or by designing a transparent structure through which the light can pass efficiently.

IRRADIANCE COLLECTION AND TRANSMISSION - Solar Irradiance Collection, Transmission, and Distribution Systems (SICTDS) (e.g. Himawari, Optical Waveguide) have been conceived to collect solar irradiance without using electricity and transmit it to where it is needed (Cuello, Jack et al. 1999; Nakamura, Case et al. 1999). However, one of the drawback's to naturally lit systems is that they are more at the mercy of the local conditions. The atmosphere on Mars would play an important role in determining the utility of SICTDS-type concentrators since only direct light can be collected (Haberle, McKay et al. 1993).

Appelbaum, Landis et al. (1993) compared the actual optical depth measured at the V1 landing site to a constant optical depth of 0.5. At this optical depth, as much as 40% of the incoming insolation is diffuse, making it uncollectible via concentrators. From the remaining 60%, Nakamura, Case et al. (1999) forecast that 66% of it can be delivered to the plants via concentrators coupled with optical waveguides. The resulting ~26% transmittance compares well to the efficiency of photovoltaic-powered electrical lighting, but is still low. Regardless, like the mass of photovoltaic arrays, the mass of collection and distribution devices is a burden to the system as is the loss in efficiency with increased atmospheric dust loading and the requirement for complex two-axis pointing devices to keep constant track of the sun's position.

TRANSPARENT STRUCTURE - Ideally one would like to use the naturally available light with a minimum of extra equipment with which to capture, concentrate, convert, or transmit it. A true greenhouse, or a transparent structure that allows natural light to reach the plants, accomplishes this task. A Mars greenhouse could perform as both a mechanism for crop lighting and an atmosphere containment vessel eliminating mass penalties from 'extra' equipment.

The overall transmittance or 'collection' efficiency of a greenhouse is dependent on many variables including material choice, material thickness, latitude, greenhouse geometry/orientation, and the solar zenith angle. Terrestrial greenhouses vary widely in their transmittance due to a number of the factors mentioned. Papadakis, Manolakos et al. (1998) used a scaled acrylic model to measure greenhouse transmittance of more than 85% at different solar zenith angles corresponding to different times of the years. Van den

Kieboom and Stoffers (1985) estimated their greenhouses in the Netherlands transmit 71% averaged throughout the year. Alternatively, Li, Kurata et al. (1998) utilizing reflectors internal to the greenhouse to boost the light at the plants above the incoming light alone. For the average available insolation determined earlier, a greenhouse would need to be 84% transmittant in order to provide the required light. Although apparently achievable by terrestrial standards, it would be difficult to attain with a Mars greenhouse because the need to retain pressure and survive in the Mars surface environment increases the thickness and restricts choices of materials, respectively.

HYBRID SYSTEM – It has been proposed that in the case where the local insolation or greenhouse transmittance are too low for adequate plant performance, a transparent greenhouse can be augmented by either an electrical lighting system or an SICTDS to create a hybrid system (Rygalov, Bucklin et al. 2000). However, a SICTDS-greenhouse hybrid is less practical because at the times when the performance of the transparent structure suffers due to environmental conditions, the SICTDS will suffer even more. Partial electrical lighting within a greenhouse can balance variations in environmental conditions while the transparent structure relieves some of the power burden experienced with full electrical lighting. On their own or as part of a hybrid system, transparent greenhouses offer an attractive method for utilizing natural solar insolation for plant growth.

GREENHOUSE CONCEPTS

Plants require an atmosphere of greater pressure than the <1.0 kPa found on the Martian surface. Plants can survive at pressures as low as 10 kPa depending on the partial pressures of oxygen, water, and carbon dioxide (see review in Wheeler 2004). A more realistic pressure might be 25 kPa to ensure adequate crop performance. The difference in pressure created by the higher internal plant atmosphere compared to the lower pressure of the Martian surface environment is the ideal situation in which to employ an inflatable structure. Inflatable, or pneumatic, structures can have very high packaging efficiencies, are easy to construct at remote locations and are lightweight because the pressure difference provides structural stabilization without the need for rigid supports or internal framework (Cassapakis and Thomas 1995; Freeland, Bilyeu et al. 1998; Cadogan, Stein et al. 1999; Jenkins 2001).

Boston (1981) proposed a transparent inflatable greenhouse for a Mars research station (Figure 4 top left). An undefined "reinforced flexible UV-resistant plastic" was proposed as the greenhouse cladding material and an aluminized Mylar® reflector curtain was proposed to control nighttime heat loss. A similar configuration, shown in Figure 4 (top right), was studied by Hublitz (2000). Combitherm, a coextruded laminate of polyamide and polyolefin, was proposed as the cladding material because of its use as the TransHab gas retention bladder, but its durability in the space environment has not been established (Kennedy 2000; Anon. 2003). Sadler (1999) also proposed a horizontal cylindrical greenhouse, shown in Figure 4 (bottom), emphasizing the method of "wire culture" to ease production logistics, but little attention was given to greenhouse structural details or cladding material.

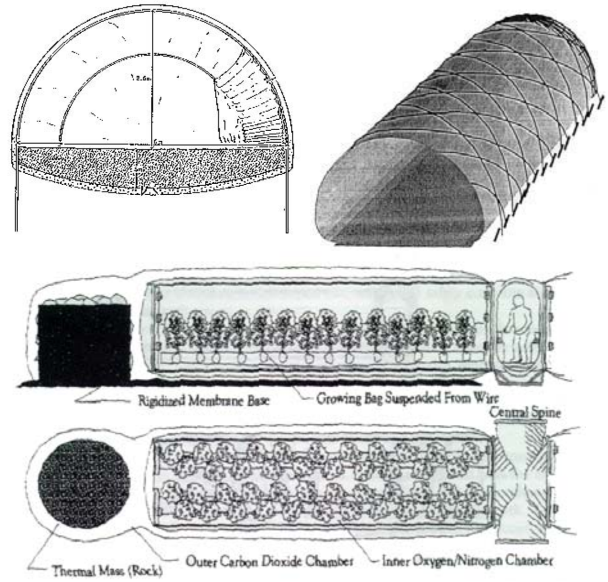

Figure 4 Greenhouse concept sketches from Boston (1981) (top left), Hublitz (2000) (top right) and Sadler (1999) (bottom).

Our own proposals discuss a modular greenhouse concept where the traditional large volume, man-tended approach is replaced with a number of smaller volumes not intended for human occupancy (Clawson 2000; Clawson, Hoehn et al. 2000). This concept, shown in Figure 5, was developed further by students in Aerospace Engineering Sciences at the University of Colorado for the 2002 MarsPort Mars Deployable Greenhouse Student Design competition (Ries, Bockstahler et al. 2003). A combination insulation/reflector system was added to increase the solar illumination during the day, and closed around the structure at night to limit heat loss. Kapton, a proven space environment durable polyimide, was chosen as the cladding material.

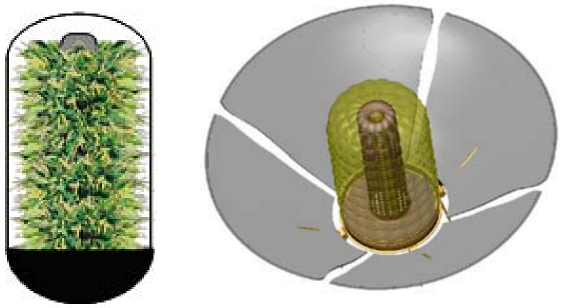

Figure 5 The AG-Pod concept for a surface deployable greenhouse module.

MATERIALS - The transmittance of an inflatable greenhouse is dependent on the choice and thickness of material. Current terrestrial greenhouse cladding materials lack the strength and/or resistance to environmental degradation needed to operate as a pressurized structure in the harsh Mars environment. However, there are materials that are currently used in space applications as either thermal blanket materials or actual space inflatables that are candidates for greenhouse applications. These include polyesters, polyimides, perfluorinated polymers and some emerging materials with new capabilities (Connell and Watson 2000). One promising material is LaRC™-CP1, a NASA developed polyimide resin licensed for manufacture by SRS Technologies. This new 'clear' polyimide is substantially more transparent than traditional polyimides such as Kapton. Unfortunately, the increased optical performance comes at the price of reduced mechanical properties (Connell and Watson 2000). However, when normalizing the film thickness needed to carry similar loads, Figure 6 shows that CP1 compares more favorably to Kapton E than other materials. Further, the transmission spectrum of CP1 is shifted toward shorter wavelengths (blue), allowing it to transmit more photosynthetically active radiation (PAR). After correcting for both stress and PAR, CP1 has a higher transmittance than Kapton E, making it attractive for greenhouse applications.

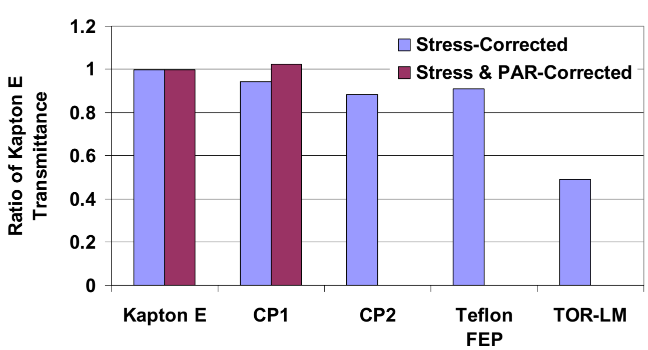

Figure 6 Transmittance of materials after exposure to LEO environment. Transmittance is corrected for thicknesses that are normalized to ultimate tensile strength and also corrected for PAR spectral contribution for Kapton E and CP1. (Data from Stuckey, Meshishnek et al. 1998)

DESIGN SOLUTIONS – The thickness of the material is critical to light transmittance. Material thickness is proportional to the contained pressure and the radius of curvature of the membrane and inversely proportional to the allowable stress (Young 1989). Unfortunately, this means that even for small geometries at relatively low pressures, the required thickness for an unrestrained structural membrane would be prohibitively non-transparent. For example, a 2m diameter cylinder at 25kPa made from CP1 would be less than 15% transmittant. In the AG-Pod design study, the required growing volume was deliberately divided among several smaller volumes to reduce the size of the structure and the resultant membrane stress. Particular attention was also paid to the restraint of the membrane in which the membrane material was designed to 'pillow' between restraints to relieve the membrane stress, a technique illustrated in Figure 7 and described by Stein, Cadogan et al. (1997). Kennedy (2000) also emphasized the concept of a large open weaved restraint for the bladder.

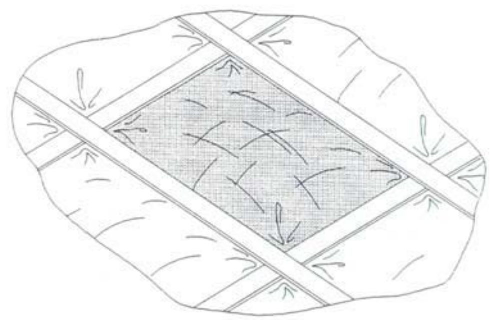

Figure 7 Illustration of membrane pillowing between widely spaced restraints (Stein, Cadogan et al. 1997).

One can look to the design and construction of super-pressure, high altitude balloons for an application proving the validity of the pillowing technique (Anon. 2000; Izutsu, Yajima et al. 2002). Super pressure balloons are fairly large structures, as demonstrated in Figure 8. They are capable of containing impressive delta pressures perhaps on the same order as required for plant growth in a Mars surface greenhouse. In the super pressure balloon, longitudinal tendrils permit circumferential lobing of the material to reduce membrane stress. The design techniques successfully demonstrated by super pressure balloons legitimize the possibility to construct a large transparent inflatable with operating pressures within the realm of those needed for a greenhouse on Mars.

Figure 8 Ultra Long Duration Balloon (ULDB) super-pressure ‘pumpkin’ balloon prototype (Anon. 2000).

THREATS TO VIABILITY

The tenuous nature of the resulting structures raises questions of reliability and safety. Tending to the crops could expose crew to the threat of micrometeorite impacts or depressurization of the structure from a puncture. Diurnal temperature extremes could threaten the plants while both the plants and crew might be exposed to higher radiation. These and many other factors must be evaluated to determine whether or not a transparent inflatable greenhouse is even feasible. A cursory examination of some of primary concerns follows.

THREAT FROM MICROMETEORITES - Even though the thin Martian atmosphere provides some protection, micrometeorites pose a moderate threat to equipment and personnel on the surface of Mars. The influx of meteorites entering Mar’s atmosphere can be estimated as

$$\log N = -0.689 \log m + 4.17$$

where N is the number of meteorites per year having masses greater than m grams incident on an area of 10^6 km^2 (Bland and Smith 2000).

Atmospheric entry simulations indicate that particles from 10 to 1000 μm in diameter are slowed below 1 km/s before impacting the surface of the planet (Flynn and McKay 1990). If the wall thickness for an inflatable greenhouse is approximated to be 0.001 in, the critical diameter of a particle that would puncture the structure for impacts normal to the surface is 16 μm [Hyde, J., 2001, personal communication]. Assuming a spherical shape, the volume of the particle can be estimated. The particles are assumed to have a density of 1 g/cm^3, which is consistent with the range of 0.7 – 2.2 g/cm^3 measured for micrometeorites recovered from the Earth’s stratosphere (Flynn and McKay 1990). Therefore, 1.39 x 10^{10} particles equal to or greater in mass than the critical size can be expected to impact an area of 10^6 km^2 per year or 0.0139 particles m^{-2} $year^{-1}$. The probability of *x* particle impacts in *t* years with enough energy to puncture the inflatable structure can be estimated as

$$P = \frac{(vx)^x}{x!} e^{-vt}$$

where *v* is the rate of impacts in one year. If *x* is taken to be zero in order to determine the probability that the structure would not be punctured, and it is assumed that a protective blanket is placed over the structure at night, the probability of no punctures in 1 m^2 of structure during 1 year is 0.993. When this is applied to the area required to support the crew, it is probable that a puncture would eventually occur. However, a puncture does not necessarily mean total failure of the structure nor does it mean that these micrometeorites would have enough remaining energy to injure the crew. If an AG-Pod approach is taken, the crew would not be endangered at all and the extent of the event would be localized to a single module. Further, the relatively short life cycle of the crop would lessen the impact of a puncture. Obviously, more detailed studies are needed to evaluate patching of punctured structures and the threat that micrometeorites pose to crew tending crops in an inflatable greenhouse.

THERMAL ISSUES – Mars is a cold place compared to terrestrial standards. For example, the diurnal temperatures at the Viking 1 Lander site ranged from 184K to 242K (-89°C to -31°C) (http://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html). With thin transparent walls and such low temperatures it would be easy to conclude that the internal temperature of an inflatable greenhouse would be too low for plants. However, the waste heat from internal equipment can help to offset the heat lost through the structure. Additionally, the thin Martian atmosphere provides little in terms of convective heat transfer to cool the walls and Martian regolith is fairly insulative, thus reducing conduction into the surface.

Neglecting internal heat generation, Hublitz (2000) determined that a low pressure transparent greenhouse maintaining adequate temperature would lose about 900 Wm^{-2} during a mid-summer’s night at the Viking landing site location. During the day, the incoming solar irradiance balances the radiation losses resulting in no net heat flux. To deal with the nighttime heat losses several authors have suggested covering a transparent greenhouse with an insulating cover (Boston 1981; Clawson 2000; Hublitz 2000). Hublitz determined that a nighttime multi-layer insulation cover could cut the heat loss to less than 100 Wm^{-2}. Waste heat from internal atmosphere treatment, dehumidification, and other systems could easily balance this loss. Alternatively, excess heat accumulated during the day could be stored in an indigenous thermal mass (i.e. rocks) or phase change material (e.g. water) for use at night (Sadler 1999; Ries, Bockstahler et al. 2003). The problem of thermal control may actually become one of getting rid of excess heat during the day instead of producing heat solely to increase temperature. Again, more detailed analyses are needed to determine operational balance of proposed concepts.

RADIATION - The higher radiation environments anticipated during a Mars exploration mission poses a possible threat to crop survival. Two different phases of a Mars mission pose unique threats to plants due to different environments as well as the different life cycle of the plants during each phase. During the transit, stored seeds must contend with interplanetary radiation environments from within a cargo transport or crew transit vehicle. In contrast, vegetative plants housed in an inflatable greenhouse must deal with the surface radiation environment.

In general, seeds are less radiosensitive than vegetative plants. Tomato seeds that were flown aboard the Long Duration Exposure Facility (LDEF) were analyzed to determine the effects of radiation. The study provided evidence that tomato seeds can survive space flight without adverse effects on germination, emergence, and fruit yield (Kahn and Stoffella 1996). Casarett (1968) reported that the water content of seeds influences their radiosensitivity with minimum effects experienced at air-dry conditions. It would appear that minimal precautions would enable safe transport of seeds on an interplanetary journey to Mars.

Table 3 shows the effects of acute radiation exposure on the vegetative growth of vegetable and field crops. Doses required to produce slight effects and the lethal dose for 100% of the organisms (LD_{100}) are shown. The levels are adapted from Casarett (1968) by converting roentgens to rads (1:1 for water and soft tissue) and then to Gy (1Gy=100rads) and finally to a human dose equivalent (Sv), assuming a quality factor of 1 (x-rays and gamma rays), for comparison to existing estimates.

Table 3 Effects of acute radiation on vegetative growth of vegetable and field crops (Casarett 1968)

Species	Predicted levels of human effective dose equivelant required to produce	
	Slight Effects	LD_{100}
	(Sv)	(Sv)
Allium cepa (onion)	3.77	14.91
Triticum aestivum (wheat)	10.17	40.22
Zea mays (corn)	10.61	41.97
Solanum tuberosum (potato)	31.87	126.08
Oryza sativa (rice)	49.74	196.77
Phaseolux vulgaris (kidney bean)	91.37	361.49

Table 4 NCRP recommended human dose equivalent limits for space flight activities (Anon. 1989).

Exposure interval	Dose equivalent (Sv)		
	BFO	Skin	Ocular Lens
Career	1-4	6	4
Annual	0.5	3	2
30 days	0.25	1.5	1

Striepe, Simonsen et al. (1994) estimated the radiation exposure for long duration Mars missions. Assuming GCR and the occurrence of an SPE on the order of the Oct 1989 event, they estimated a dose of 1.33 Sv over ~500 days of total transit time. For ~600 day surface stays, the GCR dose is under 0.25 Sv with SPE doses less than 5 cSv due to the protection provided from the Mars atmosphere. While these environments are marginal for the humans limits shown in Table 4, they pose little threat to plants, especially considering their shorter life cycle. The greenhouse shell should also provide additional protection particularly if it is a polymer (Wilson, Cucinotta et al. 2000).

CONCLUSION

In-situ crop production promises to reduce the ESM of long duration crewed space missions. Maximizing the use of indigenous resources, such as solar insolation, increases the practicality and safety of these systems and, consequently, the mission. This paper has addressed several issues that have been raised about the use of an inflatable transparent structure as a greenhouse on the Mars surface. The following conclusions are offered:

- Even with lower light levels at Mars, a naturally lit greenhouse compares favorably to electrically lit systems on the basis of ESM versus productivity.
- A transparent, inflatable structure capable of retaining adequate pressure for plant growth is achievable with the appropriate combination of existing materials technologies and design solutions.
- Even though the harshness of the Mars environment poses many challenges to an inflatable greenhouse, the risk appears manageable with judicious design solutions.

Despite this optimism many unanswered questions remain. For example, the acceleration of polymer degradation due to combinations of stress and environmental factors (e.g. ultraviolet radiation) should be examined. Better estimates of Mars surface PAR are needed to refine the analysis of greenhouse ESM to ensure accuracy. Finally, further consideration should be given to the myriad of environmental factors that can pose a threat to a greenhouse.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

BPC: Biomass Production Chamber

BVAD: Baseline Values and Assumptions Document

ESM: Equivalent System Mass

GCR: Galactic Cosmic Rays

LDEF: Long Duration Exposure Facility

LED: Light Emitting Diode

PAR: Photosynthetic Active Radiation

PGC: Plant Growth Chamber

PPF: Photosynthetic Photon Flux

SICTDS: Solar Irradiance Collection, Transmission, and Distribution Systems

SPE: Solar Proton Event