2003-01-2326

Materials for Transparent Inflatable Greenhouses

James Clawson, Alex Hoehn and Kurt Maute
University of Colorado Aerospace Engineering Sciences

ABSTRACT

Long distance/duration human space missions demand economical, regenerative life support systems. With naturally available light and low atmospheric pressures, missions to the surface of Mars might employ higher plants in a bioregenerative life support systems housed within a transparent inflatable greenhouse. The primary advantages of an inflatable structure are low mass, derived from pressure stabilization of the structure, the ability to collapse into a small storage volume for transit and ease of construction. Many high performance engineering polymer films exist today that are either highly or mostly transparent. Selection of one of these materials for an inflatable greenhouse to operate in the Mars surface environment poses a number of challenges. First, materials must be strong enough to resist the differential pressure loading between the inside plant environment and the near vacuum of thin Martian atmosphere. It must also resist permeation to the contained gases and water vapor, which are 'expensive' to replace. At the designed thickness, the material must be transparent enough to allow sufficient natural solar irradiance to penetrate. Finally, these characteristics must prevail against the rigors of the Mars surface environment without catastrophic degradation. This paper reviews the characteristics of some available and emerging materials for their suitability for use in a Mars surface mission greenhouse.

INTRODUCTION

As space mission distance and duration increase, bioregenerative life support systems can become more economical and can enhance mission safety (Eckart 1996). On a long mission such as to the Martian surface, higher plants may play a primary role in the spacecraft life support system by recycling carbon dioxide into oxygen, transpiring wastewater streams into clean water, and are uniquely able to transform wastes back into food for the crew. The primary input to such a system is light energy for photosynthesis. However, light is an expensive form of energy if it is to be generated from mission resources. Fortunately, missions to Mars can utilize the natural, albeit limited, light available at the surface.

Mars' increased distance from the sun and occasional dust storms reduce the amount of sunlight available on the surface compared with Earth. Special care must be taken in selecting the approach to light harvesting. For example, dust storms not only attenuate total irradiance, but also increase the ratio of diffuse to direct light (Haberle, McKay et al. 1993). The increased proportion of diffuse light reduces the collection efficiency of reflector/collector systems, which already suffer from losses in transmission lines (Landis and Appelbaum 1991; Haberle, McKay et al. 1993; Badescu 1998; Cuello 1998). Transparent structures eliminate the need for transmission lines and are able to collect both direct and diffuse light.

High productivity plant growth may be possible at total pressures as low as 20 or even 10 kPa (Corey, Bates et al. 1996; Corey, Barta et al. 1997; Massimino and Andre 1999), but not for the <1 kPa Mars surface pressure. The resultant difference in pressure 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 delta pressure 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). However, the resultant >10 kPa delta pressure is several orders of magnitude higher than that used in existing transparent space inflatable antennas and reflectors (Grossman and Williams 1990; Freeland and Bilyeu 1993; Jenkins 2001). The chosen material must be strong enough to resist the differential pressure loading and also resist permeation to the contained gases and water vapor, which are 'expensive' to replace. At the designed thickness, the material must be transparent enough to allow sufficient natural solar irradiance to penetrate and, finally, these characteristics must prevail against the rigors of the Mars surface environment without catastrophic degradation.

For a given pressurized geometry, both light transmittance and membrane stress are inversely proportional to material thickness. Thinning the material increases the transmittance, but is limited by the increase in membrane stress. Changing the geometry can relieve the stress on the membrane allowing further thinning of the material and increasing transmittance.

However, surfaces highly inclined to the incoming light suffer from increased Fresnel reflection losses, which could negate the increase in transmittance gained when thinning the membrane by modifying the geometry.

The ideal material would have high tensile strength, high transmittance and low index of refraction. Additionally, another important property to consider is the modulus of elasticity, which determines how much the geometry will deform while under stress. A lower modulus allows for larger deformations, important for relieving localized stress peaks due to fabrication imperfections (Said, 2002). Unfortunately, all of these properties are affected by operation in harsh environments like spaceflight or planetary surfaces. Understanding the degradation of the materials in the target operational environment is crucial to predicting long term performance. Design limits and factors of safety must be based on degraded material characteristics.

TRANSPARENT FLEXIBLE MATERIALS FOR SPACE APPLICATIONS

The materials of choice currently used in space applications, either as thermal blanket materials or actual space inflatables, generally include polyesters, polyimides, and perfluorinated polymers. Newer materials are emerging on the commercial market with increased performance characteristics. Some have been used to construct ground prototypes, but their performance in flight has yet to be proven.

Polyesters, particularly polyethylene terephthalate (PET) sold under Dupont's Mylar® tradename has been used in a number of space inflatables including the Echo 1, launched in 1960, and the INSTEP inflatable antenna experiment launched in 1996 (Freeland, Bilyeu et al. 1998). Grossman and Williams (1990) used Mylar® to construct a ground prototype inflatable concentrator for solar thermal propulsion. Mylar® can be metalized to enhance reflectivity, but for the INSTEP experiment and the solar concentrator, unmetalized clear Mylar® was used for the canopy. Mylar® has excellent optical transparency and retains good properties from -70 to 150 C, but high ultraviolet and atomic oxygen degradation limit polyester's use to short exposure duration missions (Connell and Watson 2000).

Polyimides are used extensively for thermal protection blankets and coatings. There are a number of commercial forms available under tradenames such as Upilex® (UBE Industries, Inc.), Kapton® (E.I. DuPont de Nemours and Company), Ultem® (GE Plastics), and Apical® (Kaneka High-Tech Materials, Inc.). Polyimides have high mechanical strength and a service temperature that can range from -270 °C to 400 °C. Ultraviolet exposure has less impact on polyimides compared to other polymers, but polyimides do experience erosion from atomic oxygen (AO) and require coatings to withstand long duration exposure (Connell and Watson 2000). Polyimides also suffer from high solar absorption as a consequence of their amber color, reducing their transparency.

Perfluorinated polymers, such as Dupont's polytetrafluoroethylene (PTFE) and fluorinated ethylene propylene copolymer (FEP) both sold under the tradename Teflon®, have excellent transparency, but lack mechanical strength and can exhibit significant creep under load. Perfluorinated polymers exhibit high atomic oxygen resistance, but in combination with thermal cycling and radiation exposure can cause severe degradation (Connell and Watson 2000). For example, the Hubble Space Telescope thermal protection blankets experience cracking of the outermost layer particularly around stress concentrations (Townsend, Hansen et al. 1998; Dever, Groh et al. 1999)

LaRC™-CP1 and LaRC™-CP2 are NASA developed resins licensed for manufacture by SRS Technologies. These new 'clear' polyimides are substantially more transparent than traditional polyimides such as Kapton. Their lower absorbtivity increases their performance as thermal blankets and coatings. The increased optical performance comes at the price of lower mechanical properties compared to Kapton. In particular, the virgin material exhibits both lower tensile strength and elongation, but both improve upon thermomechanical stretching (Connell and Watson 2000).

TOR™ (Triton atomic Oxygen Resistant) resins are also based on a polymer developed by NASA and is licensed to Triton Systems, Inc. for commercial manufacture. TOR™ resins are a class of phosphine oxides containing polymers that, when exposed to atomic oxygen (AO), interact to form a protective layer to the base polymer. These polymers are particularly applicable in low Earth orbit where AO degradation can be severe.

ENVIRONMENTAL DEGRADATION

Degradation is an important concern when using polymeric materials particularly in the space or planetary surface environment. Thermal extremes, electromagnetic and ionizing radiation, and oxidation pose a significant threat to the long term performance of many polymers. Several testing programs have sought to determine the performance of these polymers in the low Earth orbit (LEO) and geosynchronous Earth orbit (GEO) environments. Fortunately, Mars' orbital distance and significant atmosphere attenuate many of these components and even eliminates some (VUV, for example) when compared to LEO and GEO environments. However, extrapolation of material performance from one environment to another is difficult at best and is further complicated by the addition of higher operational stresses anticipated for greenhouse applications.

SIMULATED SPACE ENVIRONMENT TESTING ON MATERIALS

Stuckey et al. (1998) studied a number of materials that could be used to construct space based inflatable antennas. The candidate materials were exposed to an equivalent 5 years in both LEO and GEO environments including ultraviolet (200-400nm), vacuum ultraviolet (115-200nm) and electrons. LEO electron radiation exposure was simulated with three electron energy levels 10, 30, and 40 keV, while GEO exposure was simulated with four energy levels 10, 20, 40, and 100 keV. Vacuum ultraviolet exposure was simulated with a 150W deuterium arc lamp while a 2500W xenon arc lamp provided ultraviolet.

The primary motivation for the test was to determine degradation of the optical properties summarized in Table 1. Mechanical testing was performed, but not to obtain design properties, only to look for evidence of degradation in the properties of the film (Stuckey, Mexhishnek et al., 1998). They generally observed little change in apparent modulus of Kapton E, LaRC-CP1, LaRC-CP2, and TOR-LM samples. The GEO exposed Teflon and all of the COR samples degraded to the extent that no mechanical testing was possible. Average ultimate stresses are shown in Table 2, but failure stresses and strains varied widely and the authors cautioned use of these numbers as indicators of comparative behavior. The majority of the degradation was assumed to be caused by the exposure to electrons.

Table 1 Results of the effect on optical properties of simulated space exposure testing of candidate materials (Stuckey, Meshishnek et al. 1998).

	Transmittance (0.5 mil)		
	Pre-Test	LEO Post-Test	GEO Post-Test
Kapton E	0.683	0.679	0.674
CP1	0.830	0.796	0.745
CP2	0.834	0.809	0.805
Teflon FEP	0.955	0.945	NA
TOR-LM	0.776	0.772	0.705

Table 2 Results of the effect on tensile ultimate stress (in MPa) properties of simulated space exposure testing of candidate materials (Stuckey, Meshishnek et al. 1998).

	Ultimate Tensile Stress (MPa)		
	Pre-Test	LEO Post-Test	GEO Post-Test
Kapton E	240.9718	152.0294	192.3637
CP1	93.7687	77.91075	73.42916
CP2	94.45817	63.08703	91.35553
FEP	21.02901	17.92637	NA
TOR-LM	50.33173	35.85274	38.61064

On initial inspection, Kapton does not appear to be the best choice for a transparent structure due to its low material transmittance (e.g. 0.683 compared to 0.955 for Teflon or 0.834 for CP2). However, if other more transparent materials are used as a direct replacement for Kapton in a particular structure, their thickness would need to be increased to compensate for their generally lower tensile strengths. When material transmittance is normalized to tensile strength as shown in Figure 1, Kapton remains a competitive choice.

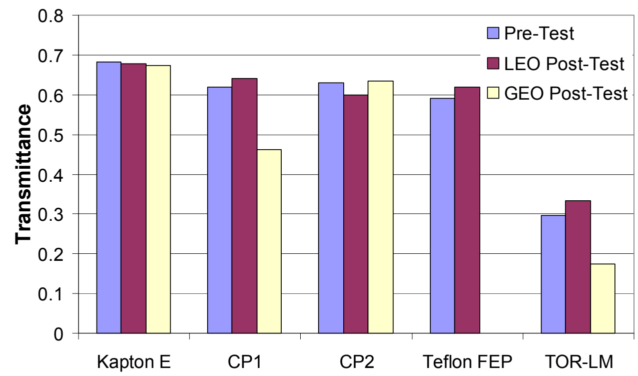

Figure 1 Material transmittance pre and post exposure to LEO and GEO environments with thicknesses normalized to ultimate tensile stress (Data from Stuckey, Meshishnek et al. 1998).

Russell, Fogdall et al. (2000) also studied a number of polymers for their degradation in the space environment. Their test setup exposed the samples to solar ultraviolet, electrons, and protons. The experiment simulated up to 5 years of electron and proton exposure, but only 1000 ESH (equivalent space hours) of ultraviolet and no vacuum ultraviolet. The test setup only simulated a maximum UV fluence equal to 1.5 suns and ran for approximately 2 months. Their measurements included solar absorptance, thermal emmittance, and tensile strength. The results indicated that irradiation decreased the failure stress of every film and decreased the modulus of every film except TOR-RC. Recommendations for future testing included higher values of UV since solar absorptance data did not level out for the exposure level tested.

Forsythe, George et al. (1995) exposed several polyimides to ultraviolet (<240nm) both in air and in a vacuum. The samples were then studied with ultraviolet/visible, electron spin resonance (ESR), Fourier Transform Infrared (FTIR), and X-ray Photoelectron (XPS) spectroscopies. Ultraviolet/visible spectroscopy results showed high absorption of ultraviolet. Forsythe cited estimates by Sonntag and Schuchmann (1977) that ultraviolet intensity is reduced by 95% in the first 10 nm of penetration and argue that ultraviolet irradiation of polyimides causes extensive surface degradation leaving the bulk polymer intact. They also found different rates of mass loss when materials were irradiated in a vacuum when compared to irradiation in air. They concluded that in a vacuum, stable surface radicals form rapidly and build up on the surface; however, in air, the surface radicals are volatized away exposing more raw material resulting in more degradation over time. They utilized a UV irradiance that was on the same order of magnitude as solar UV at 1 AU, but the exposure times were very short (few hundred minutes) in comparison to space mission lengths (thousands of hours). No mechanical testing of the materials was performed.

Dever, Semmel et al. (2002) exposed Kapton HN, Kapton E, Upilex-S, LaRC-CP1, LaRC-CP2, and TOR-LM materials to ten year equivalents of electrons and protons (40 keV each) to simulate the dose at the second Sun-Earth Lagrange point (L2). The LaRC-CP1, LaRC-CP2, and TOR-LM materials were also exposed to 5000 equivalent space hours of vacuum ultraviolet of which some was pre-electron/proton exposure and some was post exposure. Degradation of optical properties was observed for all materials except Kapton HN while degradation of mechanical properties was observed for all materials except TOR-LM. The optical properties of LaRC-CP1 and –CP2 were affected more by the electron and proton exposure than the vacuum ultraviolet exposure while their mechanical properties appeared to be affected by both exposures. The researchers postulated that further exposure to vacuum ultraviolet for a full mission's duration dosage is expected to degrade both mechanical and optical properties further.

DIFFERENCES IN THE MARS ENVIRONMENT

Despite the lack of a significant geomagnetic field around Mars, the Martian surface is partially protected from ionizing radiation due to its atmosphere. The solar wind electrons are deflected around the planet from interaction with the small geomagnetic field and upper atmosphere. Solar particle event (SPE) protons penetrate this protection, but Figure 2 shows the significant protection from SPEs provided by the Mars atmosphere, which can average around 15 g/cm^2 at the lower altitudes (Simonsen and Nealy 1993). The overall dose from galactic cosmic rays (GCR) is not attenuated, but is small in comparison to SPEs (Simonsen and Nealy 1993). The overall ionizing radiation dose experienced on the Mars surface is significantly attenuated when compared to the LEO, GEO, or interplanetary environments (kGy compared to MGy).

The Martian atmosphere also provides protection from portions of the UV spectrum. Figure 3 shows the UV spectrum in various locations including Mars surface, Mars orbit, and Earth orbit (Kuhn and Atreya 1979; Cockell and Andrady 1999; ASTM-E-490-00a 2000). At 1.52 AU, the UV spectrum at the top of the Martian atmosphere is already 43% of that found at the top of Earth's atmosphere. The Martian atmospheric CO_2 absorbs wavelengths below 190nm virtually eliminating concerns with VUV. However, the atmosphere does allow significant amounts of UV above 200nm depending on atmospheric density and dust loading.

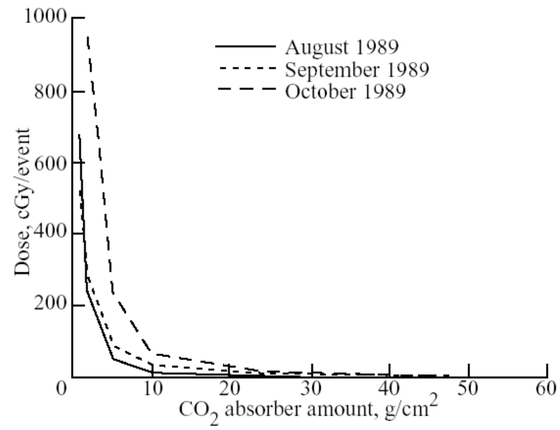

Figure 2 Radiation dose from solar particle events versus carbon dioxide absorber (Mars Atmosphere) amount (Simonsen and Nealy 1993).

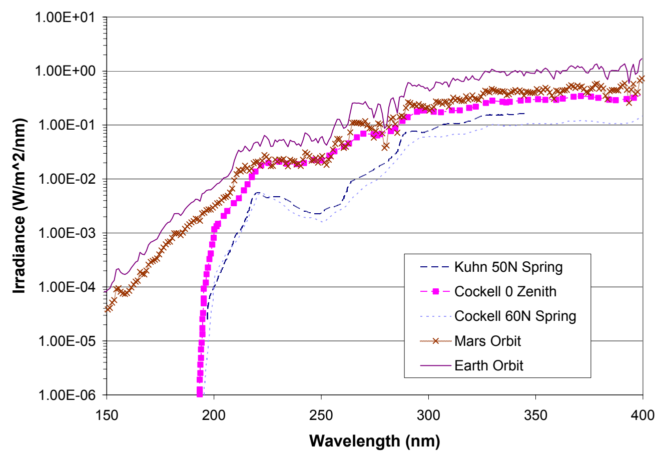

Figure 3 UV spectrums at various locations.

The Martian surface environment seems to be much more forgiving than the environmental parameters to which materials have been tested. However, it is difficult to determine the impact to degradation rates given the complexity of the mechanisms involved. For example, without knowing the material's action spectra for degradation under UV irradiation it's impossible to quantify the impact to degradation even if one can quantify the change in exposure spectrums (Searle 2000; Torikai 2000). New testing is needed if the performance of these materials in the Mars surface environment is to be established.

STRESS ACCELERATED PHOTODEGRADATION

Most irradiation exposure experiments on polymers are conducted with the polymer samples in an unstressed state. There is evidence, however, that simultaneous exposure of materials to both radiation and stress will accelerate degradation compared to radiation exposure alone (O'Donnell 1989). For example, Teflon® FEP samples retrieved from the Hubble Space Telescope after exposure to the space environment were significantly embrittled and cracked (Dever, Groh et al. 1999; Dever, de Groh et al. 2000). Close inspection of the FEP revealed through-thickness cracks in areas with the highest solar exposure and stress concentration (residual or thermally induced) (Zuby, de Groh et al. 1996).

Studies on the combined affects of UV irradiation and mechanical stress have been done with various polymers including polypropylene (Li, O'Donnell et al. 1994; Busfield and Taba 1996; Tong and White 1996; Shyichuk, Stavychna et al. 2001), polyethylene (Busfield and Monteiro 1990; Busfield and Taba 1996), and polystyrene (O'Donnell and White 1993; O'Donnell and White 1994; Tong and White 1996), but little research was found for the space-rated materials listed previously. However, in each case of the tested polymers, simultaneous application of stress and irradiation accelerated material degradation beyond that of only stress or irradiation alone. Both irradiation and mechanical stress cause radical formation in polymers. Additionally, mechanically stretching a chain is also thought to reduce the energy needed to rupture it, therefore increasing the probability of chain scission from irradiation alone (Baumhardt-Neto and Depaoli 1993). The resultant microcracking initiated by photo- and mechanoradicals is thought to propagate under mechanical loading (Raab, Kotulak et al. 1982; Rabek 1995). The combined affect of irradiation and mechanical stress must be understood for these materials in the stress limited application of high pressure transparent inflatables.

STRUCTURAL DESIGN CONSIDERATIONS

Until now, transparent space inflatable structures have had the primary role as high precision optical reflectors/concentrators (e.g. Figure 4) and antennas (Freeland 2001). The membranes are unrestrained thus carrying the full force of the inflation pressure, but inflation pressures are very low (e.g. 2 Pa for the INSTEP inflatable antenna - Freeland 2001). The low pressures are set by balancing the need to keep a fully taught membrane while limiting deformation or creep and leakage in the event of a puncture during operation. These low inflation pressures result in low membrane stresses even for their large radii of curvature and thin materials. Despite their high transparency, these designs offer little design guidance for a greenhouse application because of their low pressure carrying capability.

The need to contain higher pressures at low membrane stresses requires shrewd structural design solutions. Scientific ballooning offers design alternatives to reduce membrane stress. Until recently, most scientific balloons have been of the ‘zero-pressure’ type. Lightweight film materials are used to construct a balloon that is only partially filled at release. The extra volume in the balloon allows the gas to expand as the atmospheric pressure decreases during ascent maintaining a near zero delta pressure on the membrane.

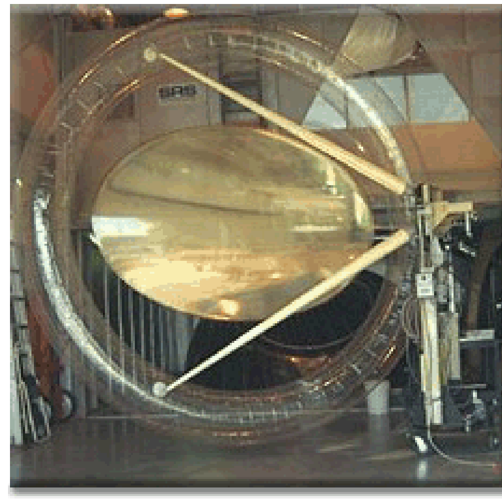

Figure 4 Example of current transparent space inflatable (Gierow 2000).

The freedom to expand and contract poses problems for controlling altitude during diurnal cycles. Control is usually achieved through venting inflation gas to descend and offloading ballast to ascend, both of which are limited resources that limit the lifetime of the balloon mission. These issues have been addressed by super-pressure balloons

A super-pressure balloon is pressurized above ambient to maintain a constant geometry at all times. They are usually capable of withstanding the pressure swings associated with diurnal heating and cooling of the gas in order to maintain their geometry and resultant buoyancy. The required skin strength grows approximately with the cube root of the volume of the lifting gas so super-pressure balloons were designed with high strength membranes that were generally made from a laminate of fabrics for strength and polymer films for gas retention. Despite the increased membrane strength, the higher membrane mass of super-pressure balloons have limited their use to rather small sizes in the past (Said 2002).

The desire to carry greater payloads has forced balloon designers to consider alternative designs to achieve lighter weight structures. The ‘pumpkin’ balloon promises both lighter weight and larger structures to increase payload capability of super-pressure balloons.

As the name implies, Figure 4 (top) shows that the shape is derived from the pumpkin due to the use of three dimensional longitudinal gores in its construction. The gores are attached to longitudinal restraints. Upon inflation, the gores' shape provides local curvature relief to the membrane between the restraints as in Figure 4 (bottom). The membrane stress remains relatively low while the load is carried mainly by the restraints.

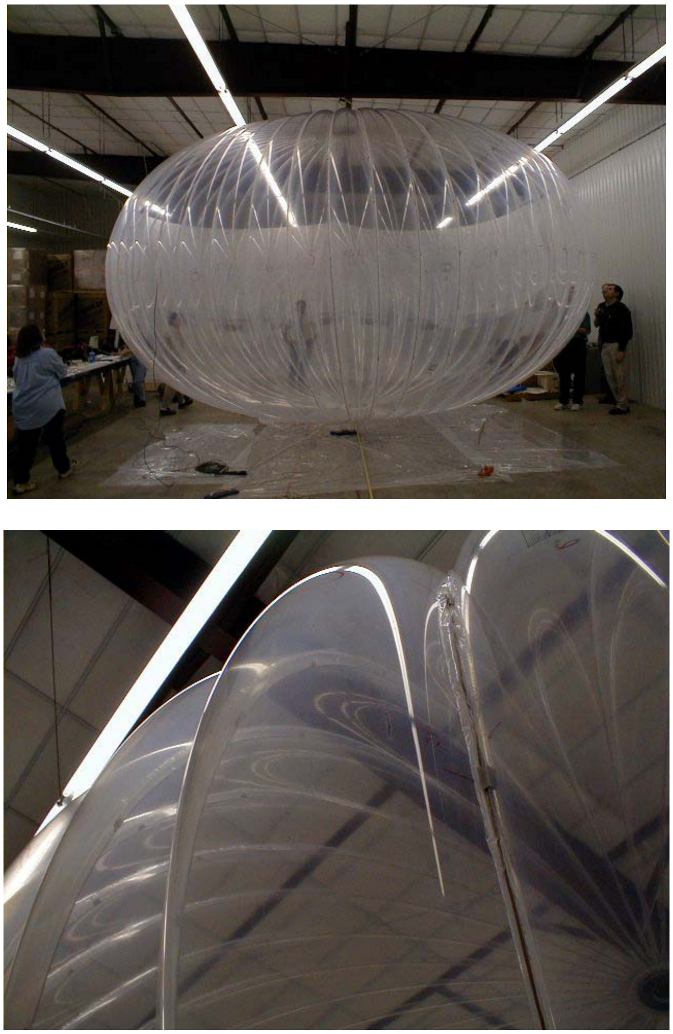

Figure 5 Ultra Long Duration Balloon (ULDB) super-pressure 'pumpkin' balloon prototype (Anon. 2000).

The pumpkin style super-pressure balloon does achieve stress reduction in the membrane, but primarily in the tangential, or circumferential, direction. The longitudinal, or meridinal, direction still maintains a relatively large radius of curvature thus a higher stress. This is the weak point of the design as demonstrated by the ULDB prototype, which burst in the center of a gore, presumably at the 'equator' (Anon. 2000).

Higher pressure human-rated space inflatables generally offer little design solutions for a transparent structure because of their opaque elastomeric bladders and full coverage restraint fabrics or tightly spaced restraints bands. However, a concept for the Human Lunar Return Mission habitat does provide some useful design concepts applicable to transparent structures. Stein, Cadogan et al. (1997) proposed a structure with an inflatable cylindrical section with composite endcaps. Both the circumferential and axial restraints are spaced apart as shown in Figure 6 (top). The inner fabric restraint and membrane are allowed to bulge or pillow between the restraints shown in Figure 6 (bottom). The pillowing relieves the local membrane radius of curvature in both directions as opposed to the single direction relief in the pumpkin balloon.

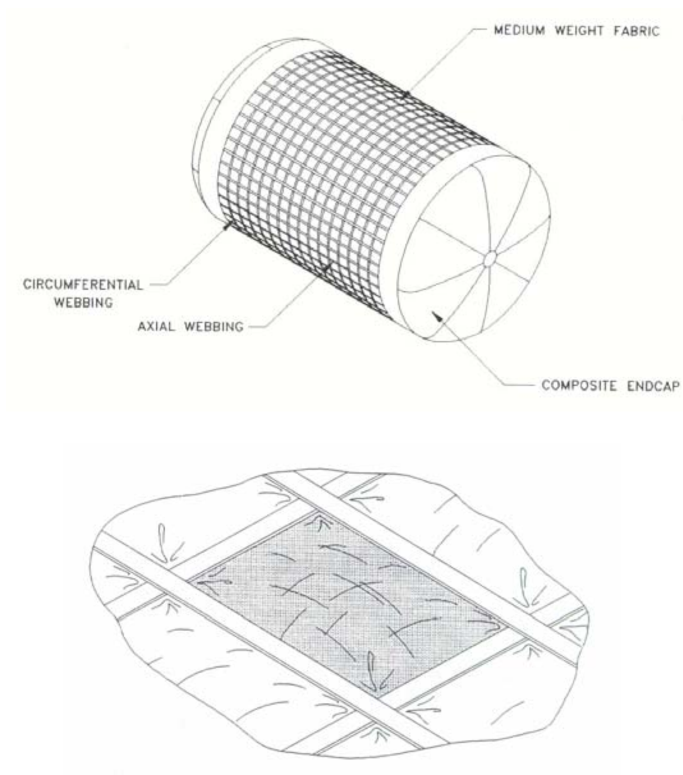

Figure 6 Human Lunar Return Mission inflatable habitat restraints (top) and (bottom) pillowing of underlying fabric between spaces in the restraint (Stein, Cadogan et al. 1997).

If pillowing by deformation alone reduces the membrane stress then pre-shaping the membrane will further reduce the membrane stress allowing thinning of the membrane for increased transmittance. For example, a flat circular patch of material three inches in diameter under 20 kPa would need to be 0.15 mm thick to maintain a membrane stress of 34.5 MPa (based on Hencky 1915). With a material transmittance of 0.9 per 0.0254 mm and an index of refraction of 1.5, the overall transmittance of the patch would be about 0.44 (based on Born and Wolf 1980). If the membrane is pre-shaped to a partial spherical cap with a radius of curvature 1.25 times the patch radius, the membrane thickness decreases to 0.013 mm, which increases the overall patch transmittance to 0.77. Therefore, a widely spaced restrained membrane that is pre-shaped can facilitate large pressure differentials with high transmittances.

CONCLUSION

The idea of a transparent inflatable greenhouse offers a lightweight transportable option for food, air, and water regeneration on long duration space missions such as to the Martian surface. A review of literature for current state-of-the-art in space rated transparent polymer materials and transparent inflatable structures has been completed to determine the applicability to greenhouses. Current applications of transparent inflatable structures are not capable of supporting the internal pressures needed for efficient plant growth. Extrapolating concepts from higher pressure inflatable designs can allow the use of flexible transparent polymers for greenhouse applications.

Environmental degradation of polymer materials plays an important role in their selection for a design. The Martian surface environment promises to be a more hospitable environment than Earth orbit or interplanetary space for flexible transparent polymers. Electrons, protons, and GCR are significantly attenuated with the most significant remaining degrading component being UV. However, quantifying the reduction in degradation is more problematic without the knowledge of material action spectra and the affects of combining higher stress with environmental exposure. Testing is needed to determine the allowable membrane stress based on photodegradation under load for the unique environmental parameters of the Martian surface. Once established, more detailed design can be accomplished.

ACKNOWLEDGMENTS

.This work was supported by the NASA Graduate Student Research Program.

REFERENCES

1. Anon. (2000) ULDB 60 m3 Pumpkin Balloon Test, Internet, http://www.wff.nasa.gov/~uldb/tests/pumpkin60m3balloontest.html.
2. ASTM-E-490-00a (2000). Standard: Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables. West Conshohocken, PA, ASTM: 16.
3. Badescu, V. (1998). "Different strategies for maximum solar radiation collection on Mars surface." Acta Astronautica **43**(7-8): 409-421.
4. Baumhardt-Neto, R. and M. A. Depaoli (1993). "Photooxidation of Polypropylene under Load." Polymer Degradation and Stability **40**(1): 53-58.
5. Born, M. and E. Wolf (1980). Principles of Optics: Electromagnetic Theory of Propagation Interference and Diffraction of Light. Cambridge, Cambridge University Press.
6. Busfield, W. K. and M. J. Monteiro (1990). "The Photo-Oxidation of Stressed Polyethylene Tapes and the Influence of Prior Cross-Linking." Materials Forum (Previously: Metals Forum) **14**(3): 218-223.
7. Busfield, W. K. and P. Taba (1996). "Photo-oxidative degradation of mechanically stressed polyolefins." Polymer Degradation and Stability **51**(2): 185-196.
8. Cadogan, D., J. Stein, et al. (1999). "Inflatable composite habitat structures for lunar and Mars exploration." Acta Astronautica **44**(7-12): 399-406.
9. Cassapakis, C. and M. Thomas (1995). "Inflatable Structures Technology Development Overview."
10. Cockell, C. S. and A. L. Andrady (1999). "The Martian and extraterrestrial UV radiation environment - 1. Biological and closed-loop ecosystem considerations." Acta Astronautica **44**(1): 53-62.
11. Connell, J. W. and K. A. Watson (2000). Materials for Inflatables in Space. Gossamer spacecraft: membrane and inflatable structures technology for space applications. C. H. Jenkins. Reston, VA, AIAA. **191:** 243-256.
12. Corey, K. A., D. J. Barta, et al. (1997). "Photosynthesis and Respiration of a Wheat Stand at Reduced Atmospheric Pressure and Reduced Oxygen." Advances in Space Research **20**(10): 1869-1877.
13. Corey, K. A., M. E. Bates, et al. (1996). "Carbon Dioxide Exchange of Lettuce Plants Under Hypobaric Conditions." Advances in Space Research **18**(1/2): (1/2)301-(1/2)308.
14. Cuello, J. (1998) Harnessing Solar Irradiance for Space Life Support, NASA Grant No. NAG5-4456, University of Arizona, Tuscon, AZ
15. Dever, J. A., K. K. de Groh, et al. (2000). "Environmental exposure conditions for Teflon fluorinated ethylene propylene on the Hubble space telescope." High Performance Polymers **12**(1): 125-139.
16. Dever, J. A., K. K. d. Groh, et al. (1999). "Effects of radiation and thermal cycling on Teflon FEP." High Performance Polymers **11**(1): 123-140.
17. Dever, J. A., C. Semmel, et al. (2002). Radiation Durability of Candidate Polymer Films for the Next Generation Space Telescope Sunshield. Third Gossamer Spacecraft Forum, Denver, Colorado, American Institute of Aeronautics and Astronautics, AIAA-2002-1564 (NASA-TM-2002-211508).
18. Eckart, P. (1996). Spaceflight Life Support and Biospherics. Torrance-Dordrecht/Boston/London, Microcosm Press-Kluwer Academic Publishers.
19. Forsythe, J. S., G. A. George, et al. (1995). The effect of simulated low earth orbit radiation on polyimides (UV degradation study). LDEF: 69 Months in Space. Third Post-Retrieval Symposium, Part 2, NASA Langley Research Center, (SEE N95-23896 07-99),

20. Freeland, R. E. and G. Bilyeu (1993). "IN-STEP Inflatable Antenna Experiment." Acta Astronautica **30**: 29-40.
21. Freeland, R. E., G. D. Bilyeu, et al. (1998). Inflatable Deployable Space Structures Technology Summary, IAF-98-1.5.01.
22. Freeland, R. F. (2001). History of Relevant Inflatable High-Precision Space Structures Technology Developments. Gossamer Spacecraft: Membrane and Inflatable Structures Technology for Space Applications. C. H. Jenkin. Reston, VA, AIAA. **191**.
23. Gierow, P. A. (2000) Advanced Upper Stage Propulsion Systems, SRS Technologies, Internet, http://www.stg.srs.com/atd/STP.htm.
24. Grossman, G. and G. Williams (1990). "Inflatable Concentrators for Solar Propulsion and Dynamic Space Power." Journal of Solar Energy Engineering **112**(4): 229-236.
25. Haberle, R. M., C. P. McKay, et al. (1993). Atmospheric Effects on the Utility of Solar Power on Mars. Resources of Near-Earth Space. J. Lewis, M. S. Matthews and M. L. Guerrieri. Tuscon & London, The University of Arizona Press**:** 845-885.
26. Hencky, H. (1915). "Uber den Spannungszustand in kreisrunden Platten." Z. Math. Phys. **63**: 311-317.
27. Jenkins, C. H. (2001). Gossamer spacecraft : membrane and inflatable structures technology for space applications. Reston, Va., American Institute of Aeronautics and Astronautics.
28. Kuhn, W. R. and S. K. Atreya (1979). "Solar-Radiation Incident on the Martian Surface." Journal of Molecular Evolution **14**(1-3): 57-64.
29. Landis, G. A. and J. Appelbaum (1991). "Photovoltaic Power Options for Mars." Space Power **10**(2): 225-237.
30. Li, T., B. O'Donnell, et al. (1994). Deformation and fracture of polypropylene exposed to ultraviolet irradiation under stress. Institute of Materials (UK), 1994,
31. Massimino, D. and M. Andre (1999). "Growth of wheat under one tenth of the atmospheric pressure." ADV SPACE RES (Life Sciences: Artificial Ecosystems) **24**(3): 293-296.
32. O'Donnell, B. and J. R. White (1993). "Stress-Accelerated Photo-Oxidation in Polystyrene." Polymer Preprints (USA) **34**(2): 137-138.
33. O'Donnell, B. and J. R. White (1994). "Photooxidation of Polystyrene under Load." Journal of Materials Science **29**(15): 3955-3963.
34. O'Donnell, J. H. (1989). Radiation Chemistry of Polymers. The Effects of Radiation on High-Technology Polymers. E. Reichmanis and J. H. O'Donnell. Washington, DC, American Chemical Society**:** 1-13.
35. Raab, M., L. Kotulak, et al. (1982). "The Effects of Ultraviolet Light on the Mechanical Properties of Polyethylene and Polypropylene." Journal of Applied Polymer Science **27**: 2457-2466.
36. Rabek, J. F. (1995). Polymer Photodegradation: Mechanisms and Experimental Methods. London, Chapman & Hall.
37. Russell, D. A., L. B. Fogdall, et al. (2000) Simulated Space Environmental Testing on Thin Films, CR-2000-210101, The Boeing Company, Seattle, WA
38. Said, M. A. (2002). "A Review On The Recent Progress In Materials Selection, Development And Characterization For Ultra Long Duration Balloon (ULDB) Missions." Adv Space Res **30**(5): 1173-1182.
39. Searle, N. D. (2000). Activation Spectra of Polymers and Their Application to Stabilization and Stability Testing. Handbook of Polymer Degradation. S. H. Hamid. New York, Marcel Dekker**:** 605-643.
40. Shyichuk, A. V., D. Stavychna, et al. (2001). "Effect of tensile stress on chain scission and crosslinking during photo-oxidation of polypropylene." Polymer Degradation and Stability **72**(2): 279-285.
41. Simonsen, L. C. and J. E. Nealy (1993) Mars Surface Radiation Exposure for Solar Maximum Conditions and 1989 Solar Proton Events, 3300, NASA Langley Research Center, Hampton, VA
42. Sonntag, C. v. and H.-P. Schuchmann (1977). "Phytolysis of Saturated Alcohols, Ethers, and Amines." Advances in Photochemistry **10**: 59-127.
43. Stein, J., D. Cadogan, et al. (1997) Deployable Lunar Habitat Design and Materials Study, Phase I Study Program Results, ILC Dover, Inc.,
44. Stuckey, W. K., M. J. Meshishnek, et al. (1998) Space Environment Test of Materials for Inflatable Structures, SMC-TR-98-24 (NASA 19980217097), Aerospace Corporation, Technology Operations, Mechanics and Materials Technology Center, El Segundo, CA
45. Tong, L. and J. R. White (1996). "Photo-oxidation of thermoplastics in bending and in uniaxial compression." Polymer Degradation and Stability **53**(3): 381-396.
46. Torikai, A. (2000). Wavelength Sensitivity of Photodegradation of Polymers. Handbook of Polymer Degradation. S. H. Hamid. New York, Marcel Dekker**:** 573-603.
47. Townsend, J. A., P. A. Hansen, et al. (1998). "Analysis of retrieved Hubble Space Telescope thermal control material." Sci. Adv. Mater. Process Eng. Ser. **43**: 582–93.
48. Zuby, T. M., K. K. de Groh, et al. (1996) Degradation of FEP thermal control materials returned from the Hubble Space Telescope, NASA-TM-104627, NASA Goddard Space Flight Center, Greenbelt, MD

CONTACT

Jim Clawson is a PhD. student at the University of Colorado in the Aerospace Engineering Sciences Department.

Email: clawson@colorado.edu

Phone: 303-492-2341

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AO	Atomic Oxygen
CO2	Carbon Dioxide
COR	Conductive atomic Oxygen Resistant
ESH	Equivalent Space Hours
ESR	Electron Spin Resonance
FEP	Fluorinated Ethylene Polymer
FTIR	Fourier Transform Infrared
GCR	Galactic Cosmic Rays
GEO	Geosynchronous Earth Orbit
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
PET	Polyethylene Terapthelate
PTFE	Polytetrafluoroethylene
SPE	Solar Particle Event
TOR	Triton atomic Oxygen Resistant
ULDB	Ultra Long Duration Balloon
UV	Ultraviolet
VUV	Vacuum Ultraviolet
XPS	X-ray Photoelectron Spectroscopy