L·GARDE

SMART SPACE TECHNOLOGY

L • GARDE INC. CORPORATE PRESENTATION

Inflatable Deployable Space Structures Technology Summary

R.E. Freeland, G.D. Bilyeu, M.M. Mikulas

IAF-98-I.5.01

INFLATABLE DEPLOYABLE SPACE STRUCTURES TECHNOLOGY SUMMARY

R. E. Freeland *
Jet Propulsion Laboratory
California Institute of Technology

G. D. Bilyeu †
G. R. Veal ‡
L'Garde, Incorporated

M. M. Mikulas §
University of Colorado

ABSTRACT

There has been limited interest in inflatable deployable space structures since the 1950's due to their potential for low cost flight hardware, exceptionally high mechanical packaging efficiency, deployment reliability and low weight. A number of significant technology developments focused on the demonstration of such potential include the Goodyear antermas in the early 1960's, the Echo Balloon series from the late 1950's to the early 1960's, the Contraves antennas and sun shades in the late 1970's to the mid 1980's and the L'Garde, Inc. inflatable decoys in the 1970's and mid 1980's and their space shuttle launched Inflatable Antenna Experiment (IAE) in May 1996. Results of this work, especially the IAE, have recently attracted user interest. The determination of how well the capability of this new class of space structures can meet the requirements of specific applications is based on a combination of issues that include structural concept maturity, technology data base and the capability for analytical performance simulation. The maturity of the IAE antenna concept and the associated technology data base are currently under evaluation for a number of potential missions. Current analytical simulations are addressing membrane reflector shape, reflector error sources, stiffness and thermal stability of rigidized inflatables and potential reflector shapes resulting from changes of boundary condition. Collectively, these hardware demonstration results, the current technology data base and the new analytical tools for projecting orbital performance will enable realistic estimates of the applicability of inflatable space structures for specific applications.

INTRODUCTION

Concepts for inflatable deployable space structures have been under development and evaluation for almost 50 years. The potential for this class of space structures for achieving low cost space hardware, exceptional mechanical packaging efficiency, deployment reliability, very small stowed volume and low weight was recognized by only a limited segment of the space structure community.

Over this period a number of different technology developments have contributed to the validation of mechanical performance and the establishment of credibility for this new class of space structures. Such validations were based on building inflatable deployable structures up to 30 meters in size for both ground based and on-orbit demonstrations. Such results are the basis of the current technology data base for a number of different structural concepts.

The results of these demonstrations have recently generated serious interest within the antenna user community. However, the determination of the applicability of this technology to a specific mission will require a) the capability for analytical simulation of mechanical performance for each candidate system, b) a well defmed structural concepts technology data base, and c) a system concept defmition for the specific application, which will be based on the most mature elements of the technology data base.

---

*Technical Manager, IN-STEP Inflatable Antenna Experiment

† Program Manager, Inflatable Antenna Experiment

‡ Inflatable Antenna Experiment Principal Investigator

§ Professor, Center for Aerospace Structures

This publication will a) identify and describe some of the most significant concept developments, b) discuss the inflatable structures technology data base associated with the IAE, c) overview previous analytical performance projection capability and identify new analytical capability along with sample results, and d) summarize the types of interaction of inflatable materials with the environment and show recent results on the effects of long term radiation on thin film materials.

SIGNIFICANT INFLATABLE STRUCTURES CONCEPT DEVELOPMENTS

A number of different technology developments, focused on inflatable deployable space structures, have taken place over the past 50 years. Some were very innovative for the time frame of their development and many were not well documented. As examples of significant structural concept developments, over a 40-year period, antennas developed by Goodyear, the Echo Balloons, the Contraves Antennas and Sunshades and the NASA Inflatable Antenna Experiment will be briefly summarized.

Goodvear Inflatable Structures

One of the original pioneers associated with the development of inflatable deployable space structures was Goodyear. In the time frame of the late 1950's to the mid 1960's, they developed inflatable structural concepts for their search radar antenna, radar calibration sphere and lenticular inflatable parabolic reflector.'

The inflatable search radar antenna is based on using a truss type rigidizable support structure and metallic mesh for the aperture surface, Figure 1. The demonstration hardware, shown in Figure 1, has an aperture of approximately 10 meters in length, 3 meters in width and has a parabolic profile. The mechanical packaging technique appears to be based on folding the long narrow structure into about 6 to 8 flat panels so that the stowed volume was rectangular in geometry.

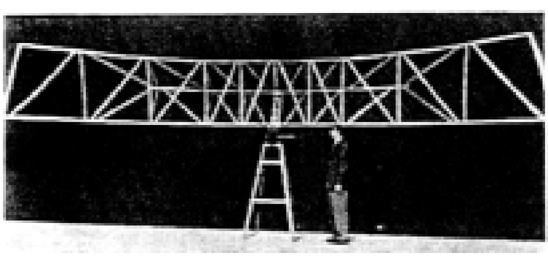

Figure 1. Inflatable Search Radar

The radar calibration sphere structural concept is based on using a large number of hexagonal shaped flat membrane panels that are bonded at their perimeters to adjacent panels to form a sphere when inflated, Figure 2. The demonstration hardware shown in Figure 2 is about 6 meters in diameter. Flight hardware would be metalized to accommodate high RF reflectivity.

The "lenticular inflatable parabolic reflector" concept consists of a lenticular reflector structure, which is supported around its periphery by a toroidal structure, Figure 3.

The reflector is made from a number of metalized "pie shaped" membrane gores that are bonded together to form a parabolic shaped surface. The canopy structure is identical to the reflector, but does not have to have the same high surface precision or metalized surface for RF reflectivity or solar energy collection. The torus is constructed from a number of curved segments that are bonded together to produce a "ring" shaped structure. The inflated structure, shown in Figure 3 is about 12 meters in diameter overall and the reflector itself is about 10 meters in diameter. Rigidization techniques for this type of inflatable structure have been evaluated[2], which include flexible and rigid foams of different density and thickness.

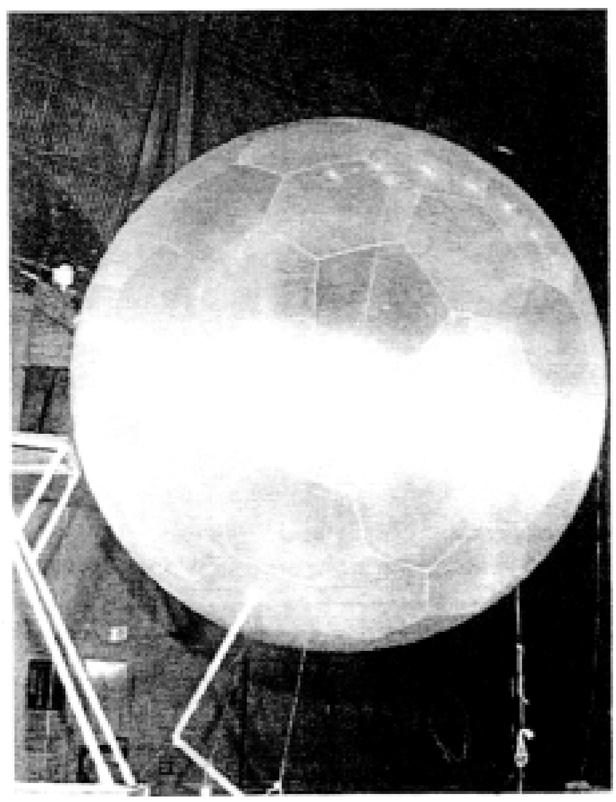

Figure 2. Radar Calibration Sphere

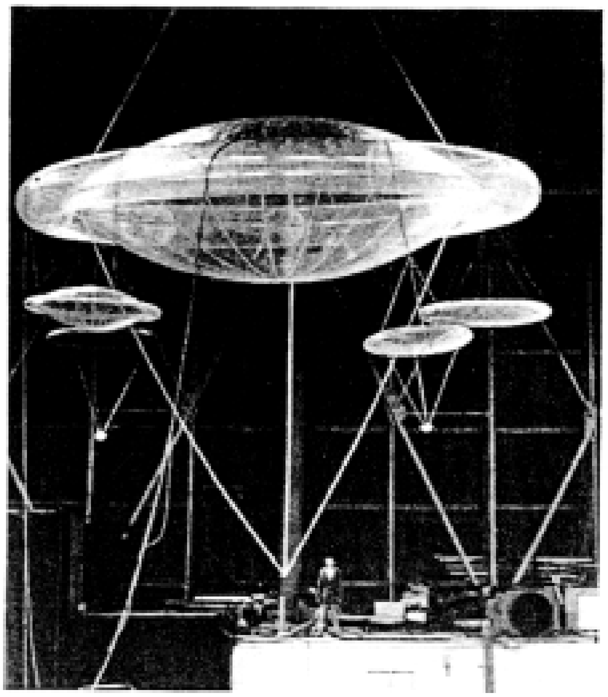

Figure 3. Lenticular Inflatable Parabolic Reflector

Echo Balloons

The flight of the Echo Balloons in the late 1950's and early 1960's represented a relatively unrecognized technical capability for the development, fabrication and launch of large, high precision inflatable space structures. This original and very innovative technology development was done at NASA Langley Research Center (LaRC) starting in May 1958 and the fmal project responsibility was assigned to NASA Goddard Space Flight Center (GSFC) at a later date. The objective of the balloon series was to provide passive, space based communications reflectors.

Echo I was made from a large number of gores of mylar that were 12 μm thick, coated with 2000 angstroms of vapor-deposited aluminum, and bonded together to form a sphere, Figure 4. The 100-ft. diameter sphere weighed 136 lbs. and was stowed in a 26 in. diameter, spherical container for launch. Thirty pounds of sublimating powers were sifted into the balloon structure to enable orbital deployment. Four inflation tests were made in 41-ft. diameter vacuum chambers at LaRC and five free-space environmental tests were made in ballistic flights with rockets from NASA's Wallops Island Test Station. These tests were used to develop and validate mechanical packaging, ejection and inflation techniques. which resulted in the successful deployment of Echo I on orbit.

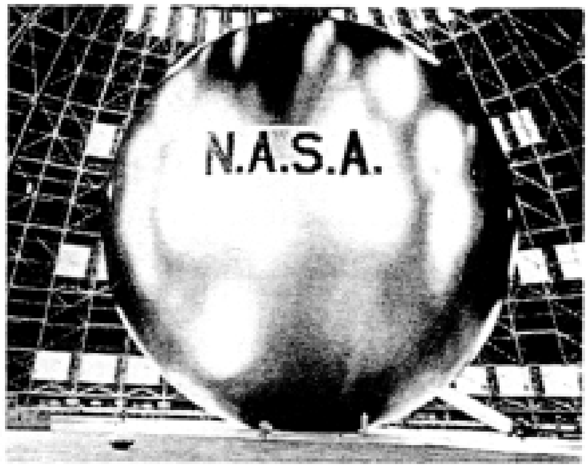

Figure 4. Echo I Balloon

Echo I was successfully launched on August 12, 1960 aboard a Delta to an initial orbit of 1000 miles, which changed over a period of months from the effects of solar pressure. The Echo I was operational for a number of months which indicated that it maintained a sufficiently large and reflective profile for this time period.

This original, innovative and significant activity was very well documented[3,4,5], with additional references therein.

Contraves Inflatable Structures

The European Space Agency's (ESA) interest in the potential of inflatable deployable space structures was signified by their sponsorship of the development of reflector antenna and sun shade structural concepts at Contraves Space Division in Switzerland. The technology focus was for axisymmetric reflector antennas for Very Large Baseline Interferometry (VLBI), offset reflectors for mobile communications and sun shade support structures for telescopes and large sensors. This significant development was initiated by ESA-ESTAC in the late 1970's and demonstrated in the late 1980's. A 6-meter diameter reflector antenna which was a 1/3 scale model of a VLBI antenna, was built in the early 1980's and evaluated[6]. Subsequent to this, a 10 x 12 meter offset reflector antenna for land mobile communications at L-band was built and evaluated for surface precision and other mechanical characteristics', Figure 5. The measured reflector precision inflated, but not rigidized was on the order of a few mm's rms, which was quite good for a structure that size. The construction of the antennas was based on using two parabolic membranes, supported at their periphery by a toroidal

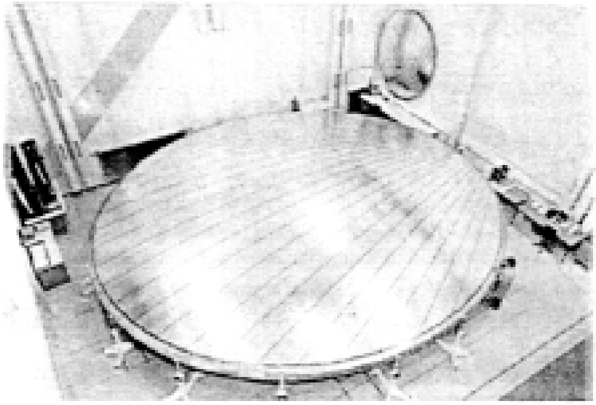

Figure 5. 10 x 12 Meter Reflector Antenna Structure

structure. The membranes were made from multiple, "pie shaped" gores, one being RF transparent and the other metalized with aluminum to enable RF reflectivity. The load carrying fibers in the gores were Kevlar and matrix material was designed to become rigid on orbit from solar heating, after deployment by inflation.

A new structural concept for a sun shade support structure for a submillimeter space telescope was developed to the point of a functional scale model[8], Figure 6. This structure was based on a truss type

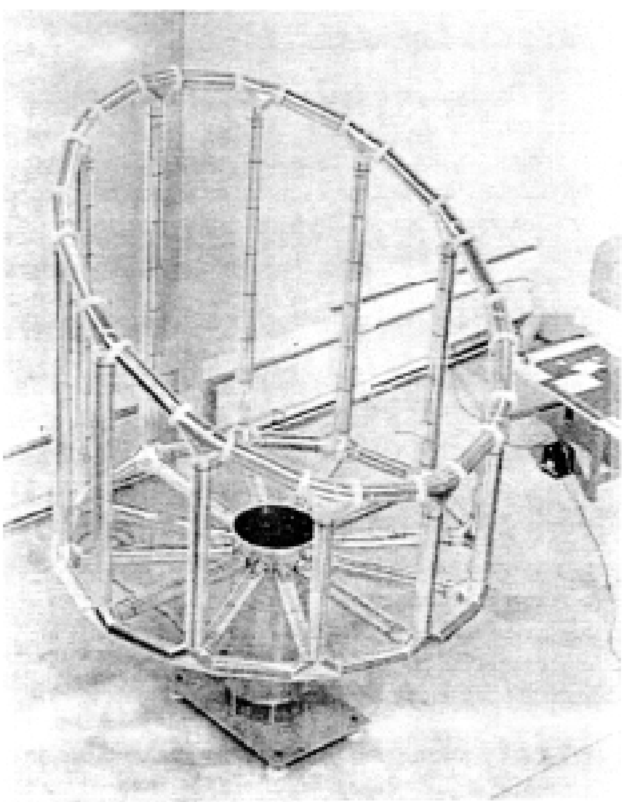

Figure 6. Telescope Sun Shade Support Structure

structure that utilized the same materials and rigidization techniques that were developed for reflector antenna structures. This support structure was intended to use flexible panels such as MLI blankets or equivalent in each bay. This would enable compact mechanical packaging to be achieved below the telescope structure in annular configuration, that is smaller in diameter than the telescope reflector structure.

These significant technology developments were very well documented[6,7,8] with additional references therein.

Inflatable Antenna Experiment

NASA's interest in demonstrating the potential of this relatively new class of space structure resulted in their sponsoring the IN-STEP Inflatable Antenna Experiment[9,10], which flew on STS-77 on May 29, 1996, Figure 7. The antenna structural concept used was developed by L'Garde, Inc. who have been designing, manufacturing, ground and flight testing inflatable space structures for the past 25 years. The experiment objectives were to a) verify that large inflatable space structures can be built at low cost, b) show that large inflatable space structures have high mechanical packaging efficiency, c) demonstrate that this new class of space structure has high deployment reliability, d) verify that large membrane reflectors can be manufactured with surface precision of a few millimeters rms, and e) measure the reflector surface precision on orbit.

The inflatable structure comprised two basic elements, the inflatable reflector assembly and the

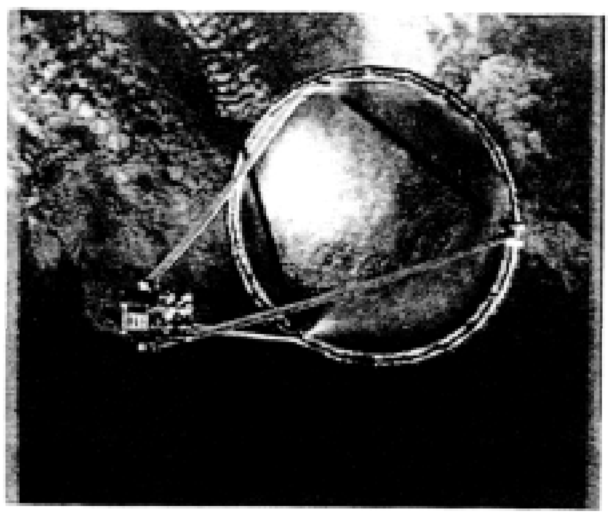

Figure 7. IAE on Orbit

torus/strut supporting structure, Figure 8. The reflector assembly formed a 14 meter off-axis parabolic aperture with a f/d of 0.5. The surface accuracy goal was 1.0 mm rms as compared to a best fit parabola. The reflector film, ¼ mil aluminized mylar, was stressed to approximately 1200 psi by the inflation pressure of 3 x 10^{-4} psi. This stress level was sufficiently high to assure a good reflective surface for the accuracy measurement system. The canopy was also constructed with 62 gores of ¼ mil mylar but was left transparent. The torus/strut structures were 24 and 18 inches in diameter, respectively, and were made with 12 mil thick neoprane coated Kevlar and locate the reflector assembly at the effective center of curvature of the reflector parabola as required for operation of the Surface Accuracy Measurement Subsystem. The torus also provides the rim support for the reflector assembly without which the reflector assembly, when inflated, will take a spherical shape.

The experiment was successfully flown on the recoverable Spartan Spacecraft. A new, unique and low cost space structures technology was demonstrated on orbit by a) building a large inflatable space antenna structure for on the order of $l,OOO,OOO, b) demonstrating extremely efficient mechanical packaging by stowing a 14 by 28 meter inflatable structure in a container the size of an office desk, c) manufacturing an offset membrane reflector structure with a surface precision on the order of a few mm's rms, and d) demonstrating the robusmess of deployment for this new class of structure. The results of this experiment were used specifically to establish the technology data base and were the basis of a technology road map for the continued development of this type of space structure.

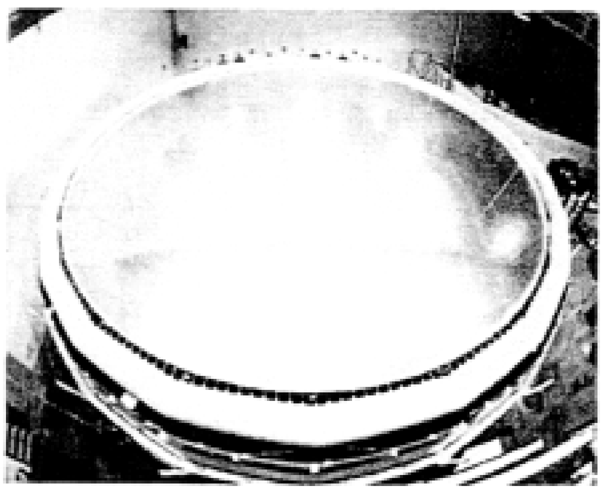

Figure 8. Reflector Structure

The results of this experiment are very well documented[9,10] with many additional references therein.

CURRENT INFLATABLE STRUCTURES TECHNOLOGY DATA BASE

The current data base for space inflatable structures comes from both ground testing and flight experience. The vast majority of the flight experience is a result of the Air Force decoy programs at L'Garde, Inc., plus the NASA/JPL/L'Garde Inflatable Antenna Experiment[9,10]. An overview of membrane materials, rigidization techniques, deployment methods, inflation techniques, and finally manufacturing and assembly of large inflatable structures is provided.

Membrane Materials Characteristics/Orbital Radiation

Use of membrane materials in inflatable structures is primarily for the lenticular structure used by parabolic reflectors". These reflectors fmd application in solar concentrators and radio frequency (RF) antennas and others. The reflector portion of the lenticular is normally metallized to reflect and focus the solar or RF energy while the canopy which forms the other half of the pressure vessel must be transparent to the wavelength of interest. The material thickness for these applications is normally on the order of ½ to 1 mil with the operating stress level ranging from 100 psi to 3000 psi, depending on the application. The lower the stress level, the lighter the support structure and the lower the make up gas weight. Usual applications for these types of structures require a lifetime of 5 to 10 years during which time the structure must be able to retain its integrity, shape and surface accuracy. Figure 9 lists the most important properties of membrane materials and the current most promising candidate materials along with their corresponding properties". Of the materials listed in Figure 9, only the Kaptons are readily available in production quantities and in the desired thicknesses. The remainder are in various stages of development.

The damage threshold levels for ionizing radiation are not available for several of the materials in Figure 9. However, the results of tests for the Vacuum Ultraviolet (VUV) and particle radiation levels expected at Geosynchronous Earth Orbit (GEO) and a typical Low Earth Orbit (LEO) orbit[13] indicated that Kapton E, Aorimide, and CP2 performed well. Atomic Oxygen (AO) reaction efficiencies also are not available for many of the materials, however, tests with exposure levels expected at LEO show Kapton E

Property		Kapton H (Dupont)	Kapton V (Dupont)	Kapton E (Dupont)	Aorimide (Triton)	PBO (Fost. Milr.)	CP1&2 (SRS)
Coefficient of Thermal Expansion	PPM/C	20 @-14-38C	24 @50-200C	12 @50-200C	(Yellow, TOR) 42 @-75 to 2ooc	MD -7.6 TD +7.6	47 to 51
Shrinkage	%	0.17	0.03	0.03	NA	NA	NA
Coefficient of Hygro-scopic Expansion	PPM/%RH	22	17	9	NA	0.8	NA
H2O Absorption	% %50RH@23C	1.8 to 2.8	1.8 to3	2.4	2 to 8	0.8	NA
Modulus	KPSI	370	400	7.50	450	MD 6000 TD 3000	315 to 420
Yield Strength TD MD	PSI	10000	10000	15000	8800 9600	27500	NA
Creep (Total strain after 76 days)	% (@applied stress)	NA	N A	0.0065(300psi)	NA	0.0055 (1500psi)	NA
Solvent Resistance		excellent	excellent	excellent	excellent	excellent	sol. in MEK MIBK, CHC13
Uniformity (thickness), Mils	rmsx100	NA	NA	2.4-2.5	2..7-11.7	15.9	10
Space Env. A0 VUV/AO W V Ionizing Rad.	Re(cc/AO)x10^-24 Re(cc/AO)x10^-24 % Prop. Retained Rad Thresh, Rad, TS Rad Thresh, Rad, %E	3 3.07 100(TS)@1000Hrs 5x10^9 1x10^9	3 3.07 100(TS)@1000Hrs 5x10^9 1x10^9	NA NA	0.14 0.17 EXCEL@4500ES H NA NA	0.6 NA NA NA NA	NA NA NA NA NA
Outgassing CVCM TML	% %	0.02 0.77	0.02 0.77	NA NA	<2	NA NA	NA NA
Bondability Metallizability		Yes Yes	Yes Yes	Yes Yes	Yes Yes	Yes Yes	Yes Yes

Figure 9. Membrane Materials Properties

performs as well as Kapton H and that PBO, as well as CP1, performed satisfactorily. The Aorimide mass loss was roughly 20% of the other materials. Evaluation testing of these materials is continuing in order to obtain values for the remainder of the properties shown in Figure 9.

Rigidization Techniques

The only practical applications of purely inflatable space structures are for reflector and concentrator structures. These structures are made of light-weight thin films and, therefore, are very lightly loaded. They are usually operated at very low pressures - on the order of 10^{-6} psi. It is therefore possible to provide make-up gas to account for the losses due to leakage through punctures caused by space debris and micro meteoroids. This is true especially for lifetimes of 5 or 10 years. All other inflatable space structures would need to operate at considerably higher pressures in order to carry the much greater applied loads. So, unless their lifetime is extremely short, it is necessary to rigidize them after deployment.

The ideal rigidization system would exhibit the following properties: a) high modulus after rigidization for structural stiffness, b) process reversibility for testability, c) high flexibility for dense packaging, d) zero coefficient of thermal expansion for thermal stability, and e) resistance to the space environment, and f) minimal change of shape during the rigidization process.

There are many rigidization techniques that have been developed to date. The most common of these are: a) fabric impregnated with resin that is cured by exposure to ultraviolet light, b) fabric impregnated with water soluble resin that rigidizes as the water evaporates, c) fabric impregnated with a resin that rigidizes when it is cooled below its glass transition temperature, d) thermal set plastic resin that cures upon the application of heat, e) a laminate of aluminum foil and thin Kapton film that rigidizes when the aluminum is strained beyond its yield point. Examples of these are shown in Figures 10 through 14. While all of these rigidization systems meet some of the requirements, none meet all of them.

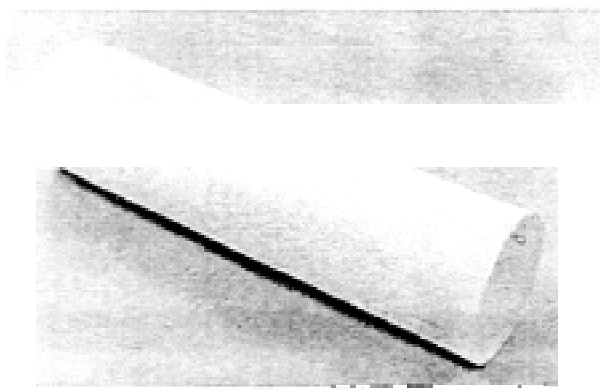

Figure 10. ***W*** Cured, Gloss Fabric Impregnated with ***W*** Cured Resin

Figure 11. Kevlar Fabric Impregnated with Water Soluble Resin

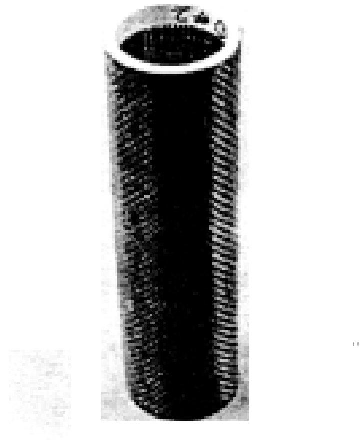

Figure 12. Carbon Fabric Impregnated with Low Temperature Rigidized Resin

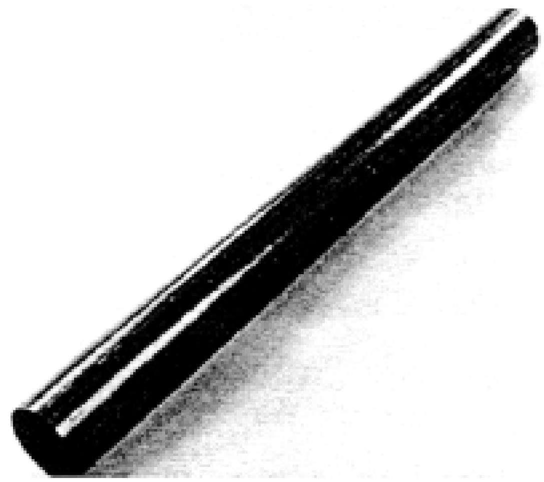

Figure 13. Carbon Fabric Impregnated with Thermally Activated Epoxy

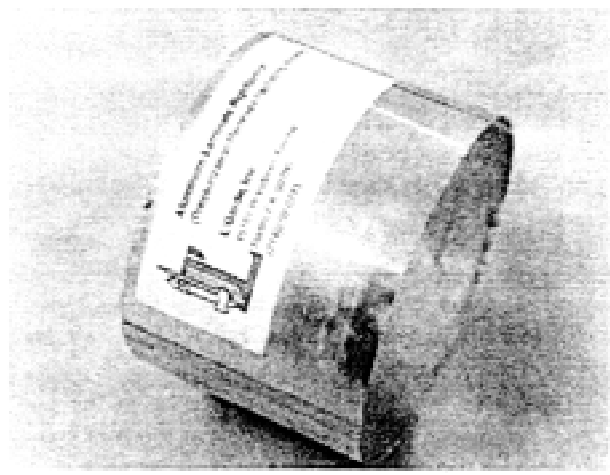

Figure 14. Kapton, Aluminum Foil, Kapton Laminate

With proper selection of a structural fabric, all of the resin/fabric systems can be designed for a modulus greater than 10×10^6 psi, which is also about the value of the aluminum laminate. The UV cured and thermally cured thermoset plastic systems have the disadvantage of being non-reversible and, therefore, it is not possible to test the rigidized configuration that is to be flown. The aluminum laminate system is not reversible; however, it can be rigidized for ground testing, then repackaged for flight and rigidization in space. All of the systems can be packaged to volumes much smaller than their deployed dimensions. The fabric based systems can be packaged somewhat more densely than the aluminum laminate. None of the current systems have a zero coefficient of thermal expansion, therefore, it is necessary to provide Multilayer Insulation (MLI) to reduce the temperature gradients sufficiently to prevent warping due to non-uniform heating. This is a major disadvantage for the UV cured systems, since they require exposure to the sun to cure. A disadvantage of the water soluble resin system is that as the water evaporates for rigidization, it could possibly condense on nearby surfaces, but only if they are extremely cold, such as the case for infrared telescope mirrors. All of the systems developed to date have exhibited resistance to the space environment.

Deplovment Techniques

The current deployment techniques are directed at members such as tubes and struts. Normally these members are used to move the remainder of the inflatable system into position for inflation. For example, the struts on an antenna would be used to move the torus and lenticular into position where they would simply be inflated. Deployment methods must keep the deploying inflatable structure within a predictable envelope, and provide a well-defined deployment rate that is slow enough to prevent significant loads on the spacecraft. They must also provide restraint for the structure during launch, as well as large well-defined passages to vent entrapped gas during ascent to orbit. There are several techniques available to satisfy these requirements, three of which are shown in Figures 15 through 17.

Roll-Out Method

This method is similar to the well known party favor. The primary difference is that the coiled spring that provides the deployment resistance in the party favor is replaced with Velcro@ on the top and bottom of the tube. By varying the area and location of the Velcro@ it is possible to vary the pressure necessary to

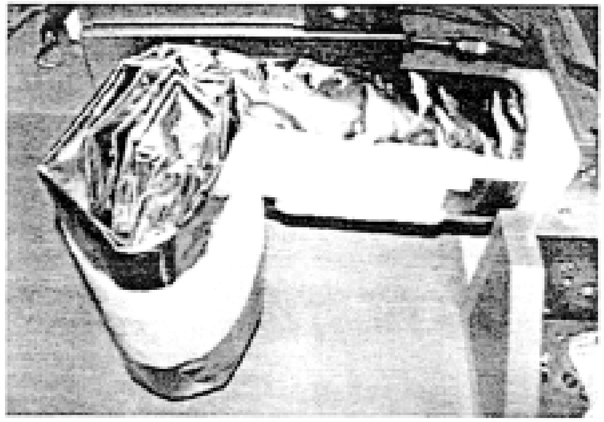

Figure 15. Roll-Out Method

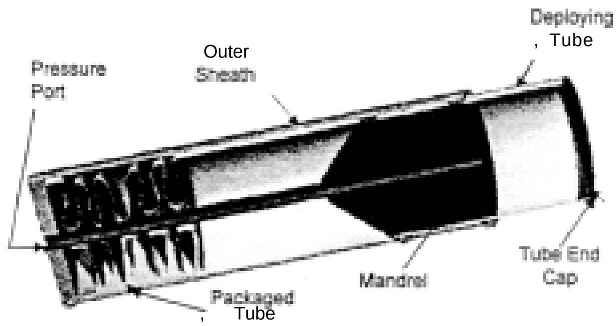

Figure 16. Fan Fold Method

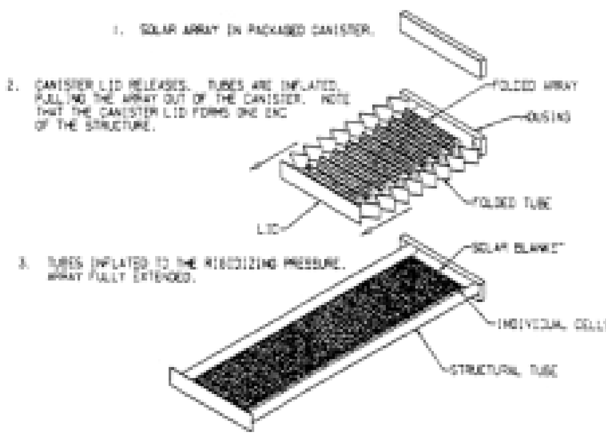

Figure 17. Mandrel Method

deploy the tube, hence, its rigidity during deployment. Depending on the flexibility of the strut material, it may be necessary to provide a method to assure the vent path.

Mandrel Method

The Mandrel method shown in Figure 16 features well defined venting paths to the packaged strut. The strut is packaged beneath a mandrel with a conical shaped lead in. Application of pressure causes the packaged tube to be pulled over the mandrel. The mandrel provides the directional control of the deploying strut. In addition, friction between the mandrel and interior surface of the tube provides the resistance to deployment, which in turn controls the rate of deployment and strut stiffness during deployment.

Fan Folded Method

This method was used for the ground test space chamber tests of the ITSAT solar array[14]. Directional control for this example is provided by folding the rigidizable tube 90° to the solar array folds. The deployment resistance is provided by the bending strength of the tube itself which, in this case, is made of Kapton-Aluminum-Kapton laminate. Because of the stiffness of the tube material, well defmed vent paths were inherent in the folded tubes.

Inflation Subsvstem

Numerous types of inflation systems have been used for inflatable space structures. The most used are systems using nitrogen gas and subliming powders. High vapor pressure fluids have been used where the pressures from sublimating powders are not adequate and using nitrogen is impractical. Hydrazine systems are now being evaluated because of their capability to give medium level inflation pressures with low weight and volume when compared to nitrogen systems. Hydrazine application issues are handling, safety and cost.

Nitrogen systems are used where moderate hardware cost and low development cost are of prime importance. In the case of IAE[9,10], component hardware common to the Spartan was the majority portion of the system since it was already Shuttle qualified. Weight and space optimization was not a primary requirement for IAE, whereas cost, reliability, qualification, and availability were very important considerations.

The key design drivers for the IAE inflation subsystem included a) high-pressure nitrogen gas storage for the inflatable structure, b) sensors, valves, and regulators for implementing the control of inflation, c) using a functional concept based on previous successful L'Garde, Inc., designs, and d) maximizing the use of Spartan cold-gas attitude control-system components.

The functional design of the nitrogen inflation subsystem is nearly identical in concept to the ones successfully flown by L'Garde, Inc., for much smaller inflatable structures. Analysis of mass flow was used to establish component requirements. Component selection was based on previously qualified hardware used for the Spartan attitude-control, cold-gas system and on previous L'Garde, Inc., flight systems. The supporting structure used for mounting the tanks, plumbing, and components was an aluminum honeycomb panel similar to that used for the canister. The two large structural composite gas tanks utilize the same mounting configuration as that for Spartan to minimize re-qualification costs. No attempt was made to develop a light-weight, highly compact inflation system for this experiment because of cost limitations.

Sublimating inflation systems have been used since the first orbital test of the Echo balloons. The operating principle for sublimating powders is to release the powder within the interior of the inflatable structure after orbit insertion. In space conditions the powders will sublime into a gas that provides vapor pressures in the range of 10^{-5} to 10^{-6} atmospheres, depending on the gas temperature within the inflatable. Temperature control of the balloon interior is maintained through proper thermal design of the balloon system. These powders provide self pressure regulation if excess powder is carried and allowed to sublimate as makeup gas. Sublimating systems have the advantage of handling ease by being non-corrosive and solid at room temperature. Their toxicity is reasonably low and they are low cost. L'Garde has used these systems in flight tests of target balloons launched from sounding rockets.

Manufacturing and Assembly Methods

Inflatable structures require unique manufacturing methods and techniques because of the thin flexible materials that are used. For the IAE one-fourth mil (.00025 inches) polyester films were used for the lenticular structure. For the torus and struts eleven mil rubberized Kevlar© fabric was used. The handling and cutting of gores from these materials present unique challenges, especially because of the dimensional precision required to attain overall system performance. Precision cutting of gores from thin films is a very important factor in the making of an accurate reflector or structure such as those used for the IAE. Precision templates are often used for cutting of the gores for smaller reflectors/concentrators. This method gives a high degree of gore dimensional control, but the templates become very expensive as the size of the reflector or structure increases. There is a practical limit on how large the templates can be and still give reasonable handling and cutting results. This method is also labor intensive. A more desirable method is to make use of an automated cutting system that can produce accurately cut gores with greater precision and lower cost. L'Garde's computer controlled gore cutting machine is show in Figure 18. This equipment has the capability to produce gores for reflectors up to 25 meters, and larger with the addition of table segments.

The gores are seamed together using tape and space qualified adhesive. The finished membrane is then mounted on a fixture that allows the membrane to be pressurized for accuracy measurement. This is accomplished using photogrammetry.

Photogrammeny, as its name implies, is a 3-dimensional coordinate measuring technique that uses photographs **as the** fundamental medium for metrology (measurement). The basic principle used is triangulation. By taking photographs (or videographs) from at least two different locations, so-called "lines of sight" can be developed from each camera to points on the object under test. These lines of sight (sometimes called rays owing to their optical nature) are mathematically intersected to produce 3-dimensional coordinates of the points of interest. The technique of photogrammetry is used in the V-STARS system by Geodetic Services, Inc. of Melbourne, Florida. In the VSTARS, the film camera is replaced by a high resolution digital camera and the pictures - video images in this case are stored in the computer. The system includes user-friendly software that carries out all the laborious calculations to determine the coordinate points of interest from the video images of the same article. The accuracy of the VSTARS is about 0.001 inch for every 100 inches.

Supporting structures, such as struts or torii, are generally constructed using similar techniques, except the materials are generally thicker and the accuracy requirements a little less stringent.

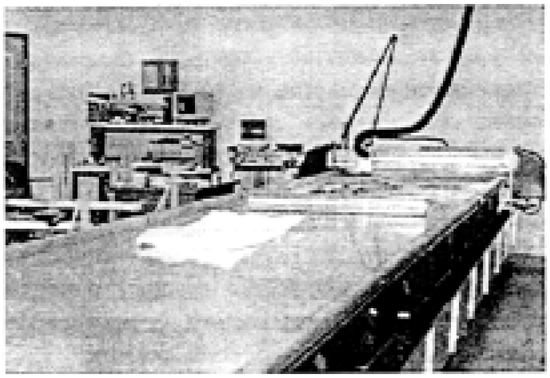

Figure 18. Automated Gore Cutting Machine

ANALYTICAL CHARACTERIZATION OF MEMBRANE REFLECTORS

The analytical characterization of mechanical performance of inflatable deployable space structures involves many different possible approaches depending on type of the structure involved. The most challenging is the characterization of the pressurized membrane reflector structures, in particular the reflector surface precision as a function of the parameters that contribute to the error. A review of previous analytical work on the shape of inflated membrane reflectors has been done and new capability has been developed and experimentally verified. Additionally, these new tools have been used to determine the sensitivity of reflector error sources and to characterize the change of reflector shape as a function of edge displacement.

Reflector Shape Analysis

Interest in the analysis and design of pressurized film structures can be traced back to the 1910's, when the power series solution of a homogeneous isotropic linear elastic circular membrane under lateral pressure --- Hencky's problem" --- was published. This paper and subsequent contributions (which include advances of Hencky's approach, variational solutions based on assumed pressurized shapes, and other theoretical works) are generally restricted to an initially flat circular geometry and typically render the problem solvable via approximations on slopes and rotations. These approximate solutions remain of interest today, even in the age of advanced numerical solutions with fmite difference and fmite element methods. The reasons for this include that the numerical solution of membrane problems can be very fragile and that the verification of the results is difficult. Available pressurized membrane test results are limited and original tests are costly and delicate. In this scenario of several solution options with mixed advantages and disadvantages, it is important to be aware of the errors associated with different approaches. Murphy[18] tended to this need in 1987 when he compared the accuracy of a number of solutions in the context of solar concentrators. His study, however, is limited in a number of respects. First, it is restricted to initially flat membranes. Second, the accuracy requirements addressed are those for heliostats: error tolerances for the high precision RF reflectors currently considered are much more restrictive. Third, Murphy measures accuracy via slope, rather than wavefront errors, while for RF application the latter is relevant. Finally, analytical solutions based only on approximate variational formulations are included.

Precision space reflector applications are associated with accuracy beyond the customary tolerances of structural engineering. This makes the reliability of related analytical predictions critical whenever test verification is difficult, as is the case for large inflatable membrane reflectors. For pressurized membranes, however, numerical analysis can be troublesome and classic solutions exist only for the simplest configurations. Furthermore, the accuracy of classical solution options is not well understood due to approximations made to facilitate the exact solutions. Research" was conducted which contributes to filling this gap by exploring the impact of representative solution approximations on the accuracy of analytical shape predictions. The selected approximations were individually addressed via a parametric study of axisymmetric linear elastic isotropic membranes. Limits of applicability were considered for pressurization levels and accuracy requirements of current professional interest for radio frequency (RF) applications. Initially flat and curved membranes were studied; the latter designed to assume exact parabolic shapes when pressurized. Although specific diameters were studied, the results are applicable via newly developed scaling laws to any dish diameter. A software package, AM (Axisymrnetric Membrane)", is a high precision numerical tool for the study of pressurized axisymmetric membranes capable of modeling wrinkling and of determining initial shapes which inflate to desired pressurized contours. In the development of AM, both large rotations and displacements are included in the analytical formulation. While the guideline tolerance for the parametric study" reflects current interest in RF applications, AM surpasses that accuracy with a precision applicable to optical frequencies. Results from the AM study were compared with the FEM programs FAIM[18], and NASTRAN, for initially flat membranes and correlation was obtained well within the range of accuracy requirements for RF applications.

To provide benchmark solutions and to serve as a testbed for parametric studies, the software package AM for the high precision analysis of pressurized axisymmetric membranes was exercised on several problems for demonstration purposes. AM is written in C and it consists of a number of modules which are easily combined into special purpose or general programs. These modules include: a) numeric shape solver, to calculate via direct integration the loaded state (shape, stresses, and strains) for axisymmetric membranes of arbitrary initial shapes subject to pressure, thermal, and kinematic (edge displacement) loads. The modeling of wrinkling, as well as simulating various analytical approximations are optional; b) symbolic solver, for classical axisymmetric membrane solutions. AM currently includes Hencky's solution, as well as other approximate solutions; c) inverse solver, to provide the initial shape for a desired pressurized contour and pressure; d) shape comparator, to compare axisymmetric shapes and evaluate the error between via any of a number of error measures; e) shape optimizer, to adjust a given shape (via axial translation and/or scaling) to achieve a best fit to a particular surface; and f) parabolic assessor, to produce the best-fit paraboloid to a given membrane shape and evaluate the (RF rms or other) error between. The numeric shape solver at the heart of the numeric solver module is an integrator to solve the meridian as an initial value problem from any known point onward. In each integration step along a discretized contour, the state and position of a point is iteratively determined from the known adjacent point. The point iteration continues until, the equilibrium, constitutive, and kinematic equations are satisfied. Complete details of the program and solution methods are presented in detail[17,18].

Reflector Error Sources

As discussed earlier, the dimensional requirements for precision space reflectors involve accuracy beyond the customary tolerances of structural engineering. Thus, to achieve a high precision reflector, consideration must be given to all possible error sources. A listing of possible error sources is as follows:

- Material stiffness properties and area1 variation
- Material thickness and area1 variation
- Creep
- Moisture effects
- Material "wrinkling" or creasing due to handling and packaging
- Fabrication
- Analytical shape prediction
- Edge support conditions
- Pressure level
- Thermal distortions
- Gravitational effects in earth testing.

A primary purpose of the analytical work[17,18] was to understand the relative accuracy of available analytical tools in predicting the shape of thin film structures. The results of that study indicate that the commonly used tools for shape analysis, FAIM and NASTRAN can readily provide acceptable accuracy for RF class precision reflectors. The application of these tools to higher precision applications such as optics will require further careful study and evaluation. Thus, it would seem that observed errors in ground tests are the result of the other sources listed above

The major advantage of inflatable thin film reflectors over mechanically deployed structures lies in the fact that these structures can be packaged into extremely small volumes for launch. This advantage increases for very large diameter reflectors; diameters in the 25 to 50 meter range. Additionally, for these reflectors to be practical, the internal pressure must be kept very low to minimize the amount of makeup gas required for leakage through micrometeoroid punctures. This in turn requires that the operational stresses in the thin films be very low. On the other hand, it would be desirable for the elastic deformations due to pressure to be large compared with fabrication errors so that the reflector would achieve its desired analytically predicted shape under load. This then leads to the observation that it would be highly desirable to have thin films with a very low modulus. Current space qualifiable thin polymeric films have a modulus on the order of 500,000 to 800,000 psi. A challenge for the materials community would be to develop thin polymeric films with an order-of-magnitude lower modulus than currently available. This would significantly enhance the feasibility of reliably achieving high precision inflatable reflectors. Another major factor in inflatable reflector accuracy is the thermal distortions. For precision RF reflectors, it would be desirable to have a coefficient of thermal expansion less than the current value of 12 ppm per degree F that exists for KAPTON E.

To provide confidence that these large diameter reflectors will perform as expected in space will require the development of a ground validation program. This ground validation program will involve a systematic protocol consisting of carefully conducted tests coupled with high accuracy simulation analyses to properly bridge the gap between ground tests and space operation. It is likely that ground tests on 25 to 50 meter diameter reflectors will be impractical and possibly impossible. For example. if desired materials are developed to enable reflector operation at extremely low pressures, the effects of gravity could be greater than that of the pressure. In fact, for large diameter reflectors, the weight per unit area of the film may be greater than the internal pressure. For such cases it would be impossible to provide test verification through earth based tests. However, it is possible to find a smaller diameter reflector for which this pressure anomaly is not an issue. A set of constant thickness scaling laws have been developed by the authors which permits the results of the small scale tests to be scaled up to larger diameters in a rational fashion. Such small-scale tests along with the scaling laws will play a critical role in the development of a ground based verification protocol for large inflatable reflectors.

One-Meter Tests – A series of tests on pressurized flat membranes one-meter in diameter as shown in Figure 19 were recently conducted as part of a program to validate analytical tools and to understand the roll of small scale testing in verifying antenna performance. The test procedure, metrology system, and results are presented". As part of the program, careful tests were conducted on the constituent materials to establish the elastic properties to be used in the analysis for correlation. Because of availability, the materials selected for testing were 1/2-mil MYLAR and KAPTON HN. Two materials were used to better understand the roll of material properties. During the modulus testing of the MYLAR, highly anisotropic properties were observed as shown in Figure 20. The material was not only orthotropic but the principal material axes were found to occur at an angle to the machine and transverse directions of the material. Subsequent discussions with Dupont revealed that this anisotopy is a function of the manufacturing process and could vary among batches. Thus, the use of this material for structural testing must be accompanied by stiffness testing of the batch used. The KAPTON material tested was very isotropic and a completely different manufacturing process explains this.

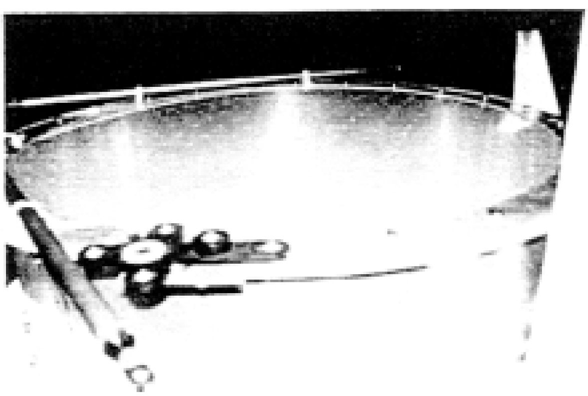

Figure 19. One-Meter Diameter, ½ Mil Mylar, Flat Circular Test Specimen

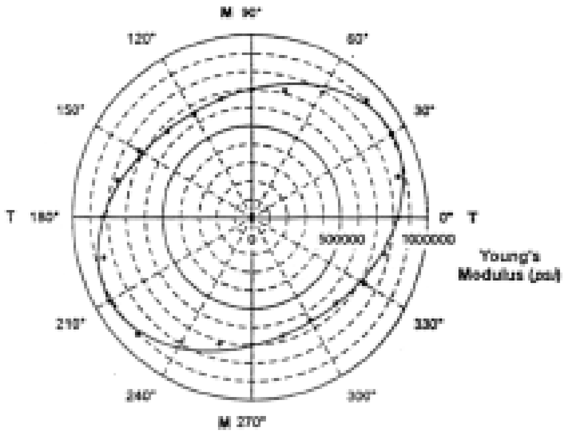

Figure 20. Youngs Modulus for ½ Mil Mylar as a Function of Angular Orientation

The correlation between test results and the fmite element analysis FAIM are shown in Figure 21 for the MYLAR specimens. The results are shown for two different pressure levels corresponding to maximum film stresses of 636 psi and 3076 psi. These two widely different film stresses were chosen to provide correlation with analysis over a large range of loading. It should be noted that the analysis conducted in this study was nonaxisymmetric due to the anisotropic nature of the material. As can be seen in Figure 21 the global correlation between test and analysis appears excellent. However, due to the extreme nature of the accuracy requirements for precision reflectors, this

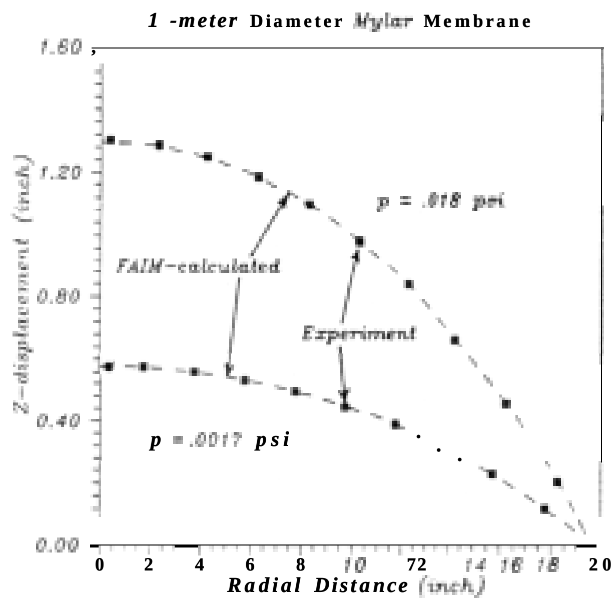

Figure 21. Measure Mylar Profile from Figure 19 Test Article. Membrane Center Stress Equals 636 psi and 3076 psi

global look at correlation is not adequate. To enable a finer look at the correlation, the differences between test and analysis are plotted in Figure 22. The maximum difference between test results and analysis is for the high stress case a with a value of 0.006 in(6-mils). This difference amounts to about 0.5% of the total elastic deformation. This range of error is within the level of accuracy of the materials properties (modulus and thickness variations). It is concluded that modem numerical analysis tools are able to predict membrane deformations under ranges of loading of interest in realistic designs. Thus, the majority of errors that occur in thin film reflectors will be a result of the other errors discussed previously. Since it may be practically impossible to eliminate all of these error sources, it may be prudent or even necessary to consider on-orbit shape adjustment as a means of obtaining and ensuring required shape accuracy.

Potential shape adjustment approaches - The major approaches for providing shape adjustment of a pressurized membrane reflector are as follows:

- Adjust feed position
- Adjust edge radial displacements
- Change internal pressure
- Provide thermal gradient over reflector surface
- Integrate electro-piezoelectric into the thin film surface.

To evaluate the feasibility of these different shape adjustment approaches it is necessary to be able to conduct reliable shape change simulation analyses. The research” and validation” have demonstrated that such simulations can be carried out with existing structural analysis tools. Each of these shape

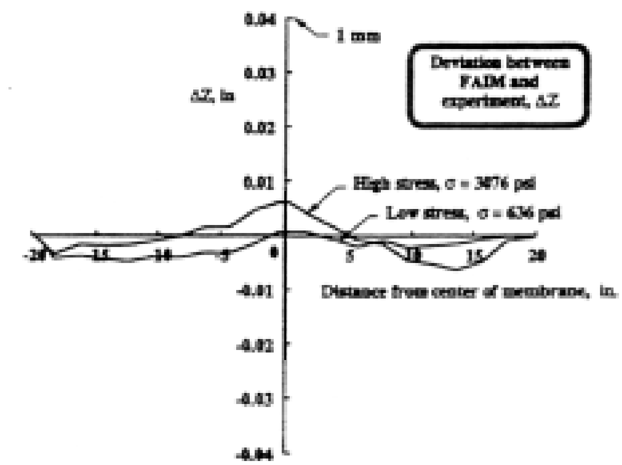

Figure 22. Deviation in Membrane Later Displacement Between Finite Element Code FAIM and Experiment of Figure 19

adjustment approaches are being studied by different researchers as to their effectiveness and practicality.

Of the above mentioned shape adjustment potential approaches, the concept of adjusting the edge radial displacement is particularly attractive due to the relative implementation simplicity of the concept. Results” demonstrate the potential shape changes that can result from the application of radial edge displacement. The results of that study are shown in Figure 23. In this figure the shape deviations from a perfect paraboloid are plotted as a function of radial distance from the center for three different f/Ds. In order to provide shape control of a reflector surface by changing the radial edge displacement, it would be necessary for the resulting effect to be transmitted throughout the surface. As can be seen in Figure 23, the effect of an applied edge displacement is a strong function of the reflector curvature (f/D). For shallow reflectors (f/D = 2), the effects of an applied radial edge displacement are dramatic and provide a change over the entire surface. However, for deep reflectors, (f/D = 0.5), the effect of the edge displacement results primarily in a 2 translation of the surface with nonuniform effects occurring only in a boundary layer near the edge. The implications of this study are that radial edge control will not be effective for deep reflectors, while some control can be achieved for shallow reflectors. Since most reflector applications involve f/D values greater than 1, the approach of using edge displacements for shape control will not be possible.

STRUCTURES/ENVIRONMENTAL INTERACTIONS

Of all the known types of space structure at this time, the inflatable structures have the most significant interaction with the space environment. This is a consequence of the materials used, the large size structures that are needed for many applications, the rigidization techniques used and, in particular, the need to maintain inflation pressure in some of the structural elements such as the reflector/canopy structure.

A major challenge for space inflatable structures at this time is the development of flexible materials for both inflated and rigidized membranes. Thin membrane materials are usually used for high precision reflector structures that are under constant pressure loading and planar array structures that are under constant in plane tension loading. In addition to being resistant to the orbital radiation environment, these membrane materials usually have stringent requirements for mechanical properties such as ultra-low modulus, low long-term creep, while at the same time lending themselves to handling, processing, metalizing, bonding and high density mechanical packaging. Rigidizable flexible inflatable materials also have stringent requirements for mechanical properties such as high-deployed stiffness, low thermal expansion, and low long-term creep while operating in high radiation environments such as orbiting the moons of Jupiter.

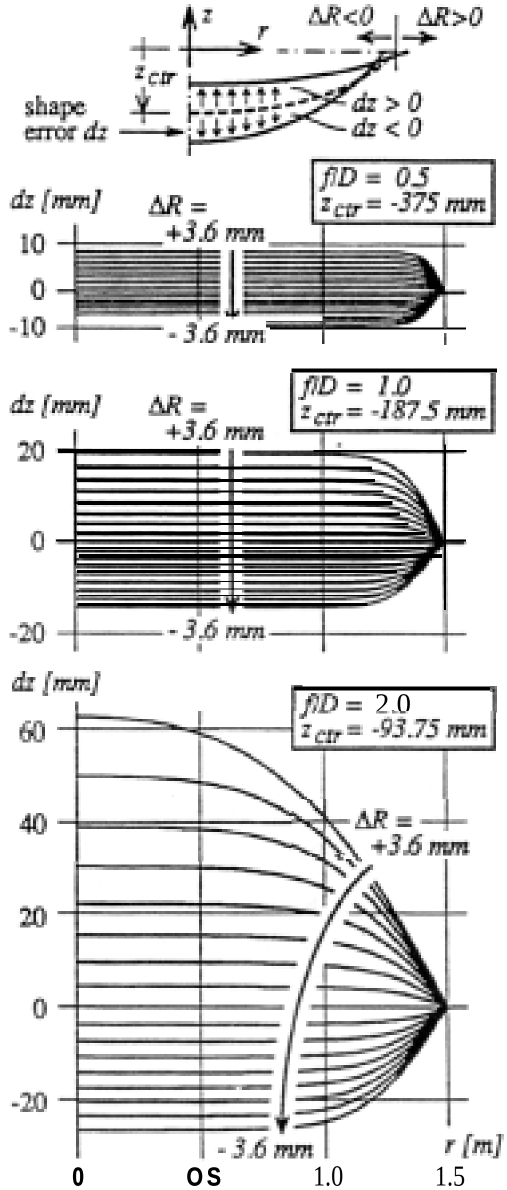

Figure 23. Effect of In-Edge Displacement on Deflected Shape

These interactions and others such as the effects of solar pressure and micrometeoroid penetration must be accounted for in the design, materials selection, structural configuration, and orbital scenarios for all applications under consideration for this new class of space structure.

CONCLUSION

The potential of inflatable, deployable space structures for enabling some specific classes of application seems to have been recognized for about 50 years. At that time innovative and unique technology developments were initiated. Such developments continued at a relatively low level of investment until the advent of the IAE in 1996. The results of that experiment provided a) a technology data base for a reflector antenna structural concept, b) validation of the potential for this new class of space high precision structures and c) illumination of the specific technologies needed to enable such a concept and project the potential performance for specific applications. Subsequent to 1996 a number of different technology developments were implemented. In particular, a) the analytical characterization of inflatable structures mechanical performance has been addressed and the results are significant, b) the experimental characterization of the effects of orbital radiation on a number of different thin film materials has been initiated and c) the concept development for rigidization techniques, fabrication of seamless membrane reflectors and others at a number of different manufacturing organizations. Collectively, the current technology data base for specific structural concepts, structural designs that account for environmental interactions and the new analytical tools for, projecting orbital performance will enable realistic estimates of the applicability of inflatable structures for specificapplications.

ACKNOWLEDGMENTS

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors would like to acknowledge and thank Richard M. Dickinson of Jet Propulsion Laboratory for providing technical data, information, photographs and references for the inflatable structures developments accomplished by Goodyear.

REFERENCES

1. Dickinson, Richard M. and Cramer, P.W. Jr.,"A Survey of Unfurlable Spacecraft Antennas" presented at the IEEE Antenna and Propagation Society Meeting, Boston, MA 1966.
2. Harris, J. T., and Stimler, F. J., "Expandable Structures for Space", Astronautics, Volume 6, No. 4, pp. 30, 31, 92-94, April 1961.
3. Jaffe, Leonard, 'Project Echo Results," Astronautics, May 1961.
4. Wilson, A., "A History of Balloon Satellites", British Interplanetary Society, Volume 34, pp. 10-22, Jan. 1981.
5. Hansen, James, "The Big Balloon", Air & Space, April/May 1994.
6. Reibaldi, G.G. and Bemasconi, M.C. (1985) "QUASAT Programme: The ESA Reflector" Paper IAF-85-400 presented at the 36th International Astronautical Congress, Stockholm, Oct. 7-12; also: Acta Astronautica 15 (1987), 181-187.
7. Bemasconi, M.C., E. Pagana and Reibaldi, G.G. (1987) "Large Inflatable, Space-Rigidized Antenna Reflectors: Land Mobile Services Development" Paper IAF-87-3 15 presented at 38"' International Astronautical Congress, Brighton (UK), October 10- 17.
8. Bemasconi, M.C. and Koese, S. (1988) "The Space-Rigidized Thermal Shield for the ESA Far-Infrared Space Telescope (FIRST)" Paper presented at the 3rd European Symposium on Space Thermal Control and Life Support Systems, Noordwijk (NL), October 3-6, ESA SP-288, 165-173.
9. Freeland, R. E., Bilyeu, G.D., Veal, G.R., Steiner, M.D. and Carson, D.E., "Large Inflatable Deployable Anterma Flight Experiment Results," IAF Paper 97-1.3.01, presented at the 48th Congress of the International Astronautical Federation, Turin, Italy, October 6-10, 1997.
10. Freeland, R.E. and Veal, G.R., "Significance of the Inflatable Antenna Experiment Technology" presented at the 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, AIAA/ASME/AHS Adaptive Structures Forum, April 20-23, 1998, Long Beach, California.
11. Jenkins, C.H., Freehand, R.E., Bishop, J.A., and Sadeh, W.Z. An Up-to-Date Review of Inflatable Structures Technology for Space-Based Applications," presented at the Space 98 Conference, Albuquerque, NM, April 27, 1998.

12. Stuckey, WK., Meshishnek, M.J., Hanna, W.D., and Ross, F.D., Space Environment Test of Materials for Inflatable Structures, Aerospace Corporation Report No. TR-98(1055)-1, dated 16 April, 1998.
13. Space Environmental Effects on Spacecraft: LEO Materials Selection Guide, NASA Technical Report #466 1, August 1995, Two Volumes
14. Malone, P.K., Williams, G.T., "Lightweight Inflatable Solar Array", Journal of Propulsion and Power, Vol. 12, No. 5, September-October 1996.
15. Henky, H. Uber den Spannungszustand in kreisrunden platten mit verschwindender Biegungssteifigkeit. Zeitschrift fur Mathematik und Physik, 63:311-317, 1915.
16. Murphy, L.M. Moderate axisymmetric deformations of Optical Membrane Surfaces. Journal of Solar Energy Engineering, Transactions of the ASME, 109(2):111-120, May 1987.
17. Greschik, G., Mikulas, M.M., Palisoc, A. Approximations and Errors in Pressurized Asisymmetric Membrane Shape Predictions. 39th AIAA SDM Conference Proceedings, Long Beach, CA, April 20-23, 1998. AIAA-98-2101-CP.
18. Greschik, G., Palisoc, A., Cassapakis, C., Veal, G., Mikulas, M.M. Approximating Paraboloids with Axisymmetric Pressurized Membranes. 39th AIAA SDM Conference Proceedings, Long Beach, CA, April 20-23, 1998. AIAA-98-2102-CP.
19. Palisco, A., Veal, G., Cassipakis, C., Greschik, G., Mikulas, Martin. Geometry Attained by Pressurized Membranes. SPIE Paper Number 3356 46, February, 1998.

L•Garde Inc
15181 Woodlawn Avenue
Tustin, CA 92780-6487
www.LGarde.com