Expandable Rigidizable Solar Shields for Protection of Cryogenic Propellants in Space

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A lightweight inflatable shield has been developed to protect cryogenically fueled space vehicles from solar heating by reflecting and reradiating the energy to space. This shield can be folded and stowed in a small volume for transport into space, then deployed, inflated, and rigidized in the space environment to form a stable structure after loss of pressurant gases. An expandable balloon ($\frac{3}{4}$-mil-thick aluminized Mylar trilaminate) is reinforced in the areas of high-inertial loading with a flexible polyurethane foam that is bonded to the expandable envelope and impregnated with a tetraethylene glycol dimethacrylate monomer solution that can be polymerized on command. Exterior and interior surfaces of the shield are covered with appropriately distributed thermal-control coatings. Operational, structural, and thermal performance tests conducted with spherical models verified the feasibility of the expandable, rigidizable shield concept. Resistance of the rigidizable material to simulated solar wind and to nuclear and ultraviolet radiation was also demonstrated.

Introduction

PREVIOUSLY reported studies[1-4] of inflatable solar shields for thermal protection of cryogenically fueled space vehicles resulted in two basic shield configurations. For the case where orientation of the vehicle's longitudinal axis toward the sun is permissible (interplanetary flight), a spherical shield deployed from the aft end of the vehicle (Fig. 1) best satisfies the desired thermal protection requirements. For cases where this orientation is not possible (Earth orbital or lunar flights), broadside vehicle orientation with the sun is assumed, and a flat shield (Fig. 2) deployed from the side of the vehicle and supported by a truss-type substructure is required. For many applications, only the combination of a solar shield and other passive and active thermal-control measures will produce a system that provides maximum protection with minimum mass.

The objectives of the work described in this paper were: 1) analysis of typical mission/vehicle requirements and establishment of shield structural design criteria; 2) development of a flexible, storable material that could be rigidized on command while subjected to the space environment; 3) determination of the mechanical properties of the rigidized material; and 4) determination of load-carrying capacities and operational characteristics of solar-shield models fabricated with this material.[5]

The inflatable structure concept has been successfully demonstrated in previous applications such as the Echo II satellite, in which an aluminum/Mylar/aluminum trilaminate material was inflated to a full spherical shape in space. For this application the inherent stiffness of the trilaminate was sufficient to maintain the spherical shape even after loss of internal pressurization. For solar-shield applications of expandable structures, some portions of such a trilaminate shell require additional reinforcement in order to withstand inertial loads resulting from vehicle attitude stabilization.

During deployment the inflatable envelope is subjected to tensile stresses that approach the yield strength of the material. The level of these stresses is set by the requirement that all storage folds must be removed and a smooth, accurately contoured surface produced. In the rigidized state, the shield design condition is determined by the loading resulting from vehicle accelerations. Other design considerations must include the effects of radiation, high vacuum, temperature extremes, high-velocity particles, and for certain applications the high-level gamma radiation associated with nuclear-powered vehicles.

The high probability of micrometeoroid encounters requires that the expanded structure be independently rigid without assistance from sustained internal pressurization and that it be capable of absorbing many impacts with no serious degradation of strength or stiffness. A structural concept such as a spherical shell with sections of continuous and uniform reinforcement provides maximum resistance to loss of integrity from repeated random projectile damage. A wide distribution of reinforcing material provides a high degree of structural redundance (numerous load paths), avoiding reliance on a few heavily loaded members vulnerable to critical damage by single impacts.

Estimations of shield inertial loads are based on a variety of applications to planned and proposed interplanetary vehicles. For example, for a nuclear-powered lunar logistics vehicle with an aft-mounted, solar-oriented spherical shield

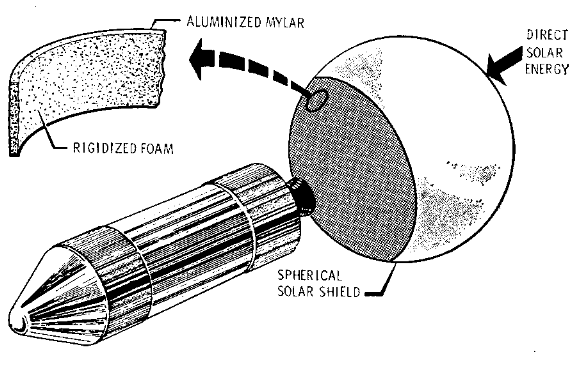

Fig. 1 Spherical solar-shield concept.

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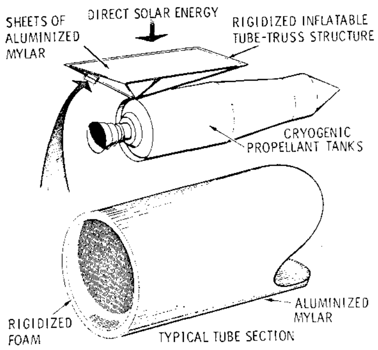


Fig. 2 Truss-supported solar-shield concept.

(5-ft shield standoff distance from the engine nozzle and a 60-ft sphere diameter), the distance from sphere center to vehicle center of gravity is 126.7 ft. For the attitude-stabilization system configuration and the thrust levels and inertia data for this vehicle,[6] the maximum yawing acceleration is approximately 0.0003 rad/sec. At the sphere center, this yawing acceleration results in a lateral inertial load of 0.001 g. For other applications it is possible for the magnitude of this lateral acceleration to be as high as 0.01 g. The range of loading criteria for an operational solar shield was therefore established as 0.001–0.01 g.

Materials Development and Testing

Three basic types of material are required for fabrication of an inflatable solar shield: the inflatable envelope or "skin," the rigidizing material, and the thermal-control-coating material. Based on the results of previous studies,[1,3] the material chosen for use as the skin of the solar shield was GT-15, a three-ply laminate consisting of 0.00035-in.-thick Mylar with 0.00018-in.-thick aluminum foil bonded to each side. This material was known to have sufficient strength and flexibility for use in an inflatable structure, but the need for some type of reinforcement in certain portions of a solar shield was apparent. The method selected for reinforcing the shield consisted of bonding a thin layer of flexible polyurethane foam to the GT-15 skin and then impregnating the foam with a material that could be made to rigidize after deployment and inflation in space. A polyester adhesive (Schjeldahl A-55) was selected as a bonding agent because of its compatibility with the space thermal environment, acceptable bond strength, and adaptability to machine lamination techniques. Machine lamination was considered an extremely important factor in adhesive selection, since it permits the large areas required for a full-scale solar shield to be fabricated with a thin, uniform adhesive layer.

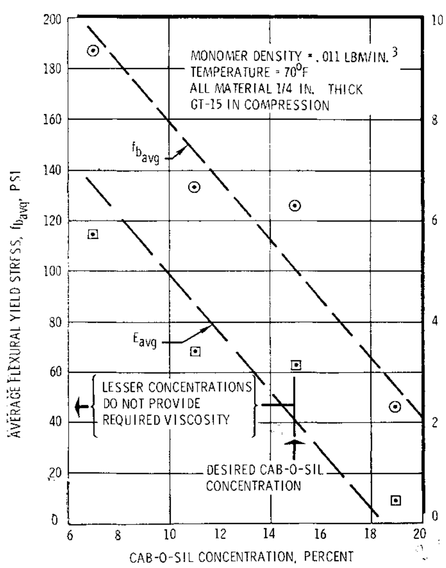


Fig. 3 Optimization of Cab-O-Sil concentration for elimination of monomer migration.

Rigidizer Development

Three candidate self-rigidizing materials (vinyl-type monomer, polyvinyl alcohol, and gelatin) were selected for evaluation. Each of these was applied to an 80-pore-per-in., open-cell, flexible polyurethane foam bonded to the GT-15 skin. Activation of the rigidizing material impregnated in the foam was then to be induced so that a rigid structure could be produced. The rigidization of each system may be described by 1) polymerization of the monomer by the introduction of a suitable "catalyst," or 2) evaporation of volatiles from the gelatin or polyvinyl alcohol by exposure to the space vacuum.

The gelatin resin rigidization system[7] consists of 1) an animal gelatin resin, 2) an ethylene chlorohydrin liquefier, 3) a methyl butynol defoaming agent, and 4) a water solvent. The system is attractive for use in space structures because of its ease of preparation, ease of impregnation, and good strength characteristics. However, a major disadvantage of the gelatin-resin/polyurethane-foam system is excessive wrinkling, curling, and loss of foam thickness during the rigidization process. Since deformations are unacceptable in a solar-shield structure, the gelatin system was eliminated from further consideration.

A polyvinyl alcohol resin was considered next. The basic ingredients of this rigidization system are 1) a polyvinyl alcohol (PVA) resin, and 2) a solvent composed of a mixture of ethyl alcohol and water. The advantages of the PVA system include ease of preparation, ease of impregnation, and good strength characteristics after rigidization. Preliminary studies of this rigidization system were conducted for comparison with the vinyl monomer system. Some of the problems encountered were: 1) partial rigidization may occur during fabrication as a result of air-drying; 2) the material must be stored in a sealed canister until deployment; 3) unless all of the solvent is removed from the solution, soft spots and a semirigid condition results; and 4) long rigidization times are required for thick sections. Excellent strength is realized, however, when all solvent is successfully removed.

The vinyl monomer was selected as the most desirable rigidizing material. Earlier investigation[8] had shown it to be compatible with the polyurethane foam carrier. The monomer, tetraethylene glycol dimethacrylate, is mixed with a benzoyl peroxide initiator, a methyl ethyl ketone diluent, and a Cab-O-Sil thixotropic agent to produce a chemically active solution. The foam is impregnated with this solution, resulting in a flexible material that can be stored under controlled-temperature conditions (20–40°F) until rigidization is desired. The thickener is used to provide a means of retaining the monomer mixture on the cell walls of the foam. Ideally, the foam should be impregnated with only that quantity of monomer solution required to wet the cell walls. This leaves sufficient void space within the foam so that the material may be folded during stowage without excessive resin squeeze-out. Rigidization of the foam occurs when the monomer polymerizes. The polymerization process is an exothermic reaction that results in a clear, rigid, cross-linked polymer. This cross-linkage provides the desired rigidity in the foam/GT-15 structure.

Difficulties encountered early in the development of the vinyl monomer system consisted primarily of 1) monomer migration within the foam, causing subsequent soft or weak spots in the rigidized article, 2) monomer buildup on the surface of the foam during impregnation, and 3) premature polymerization of the monomer-impregnated material during storage. The storage problem evolves from the nature of the monomer components and of the polymerization reaction.

The initiator (benzoyl peroxide) in the tetraethylene glycol dimethacrylate (TEGMA) monomer slowly decomposes to yield free radicals. If the concentration of these radicals exceeds a certain value, polymerization of the monomer may begin. Oxygen is an effective polymerization inhibitor because it reacts with the free radicals and renders them inactive. The open-cell polyurethane foam serves as an excellent matrix for exposing the monomer-initiator mixture to air. If the supply of oxygen is limited, polymerization will occur when the oxygen is depleted. This may occur when the foam is folded and compressed for storage in a canister. If migration of the monomer-peroxide mixture occurs, polymerization may start in the areas of maximum monomer concentration. Tests conducted by placing folded impregnated foam in a sealed polyethylene bag and applying simulated storage pressures of 10 and 20 psi at room temperature showed that increasing the concentration of Cab-O-Sil kept migration to a minimum but only at the expense of material strength (Fig. 3). A concentration of 15% Cab-O-Sil was found to be the most satisfactory. At 11% concentration, some resin squeeze-out was still observed, and at 19% no advantages could be seen over the 15% concentration. With a concentration of 15%, room-temperature storage for 96 hr at 10 psi followed by 24 hr at 20 psi produced no adverse effects on the specimens.

The vinyl monomer rigidization system is particularly well suited for space applications because of its capability for "on-command" polymerization. The reaction is initiated by exposing the monomer-impregnated foam to a polymerization accelerator or "catalyst." Any one of the tertiary amines is theoretically suitable, but factors such as reactivity and vapor pressure at the monomer storage temperatures resulted in the selection of N,N-diethylaniline (DEA) for use in this investigation. In order to utilize DEA as a polymerization accelerator, some thermodynamic properties (specific heat of liquid DEA, vapor pressure at low temperatures, and heat of vaporization) were required which were not available in the open literature. Results of these property determinations[9] and an evaluation of the polymerization characteristics of TEGMA when initiated by DEA[10] provided a basis for design of the DEA distribution system.

In the original concept of the inflatable solar shield, the foam was to be placed on the inside surface so that hot DEA vapor (375–400°F) could be injected into the shield from a single source. This meant that the foam would be exposed to convective cooling by the inflation gas during the entire polymerization process. The results of later studies showed this to be a significant factor retarding the reaction. As a result, the solar-shield design concept was modified. The foam was placed on the outside of the shield and was shrouded with two aluminized-Mylar sheets for radiation shielding. This arrangement allowed the shield to be inflated without direct contact occurring between the foam and the inflation gas. The shrouds were vented to prevent residual air from inhibiting polymerization. DEA was distributed over the foam from four separate containers.

Mechanical Properties Tests

Mechanical properties of small-strip specimens of rigidized-foam-reinforced GT-15 were measured over a range of probable design variables and environmental conditions applicable to the solar-shield operational concept. Thicknesses of the polyurethane foam were selected as $\frac{1}{8}$ and $\frac{1}{4}$ in. to correspond to actual thicknesses planned for use in the 15-ft-diam models and 60-ft-diam prototype shields. Monomer impregnation density (including mass of foam, GT-15, and solvents) was varied as 0.0066, 0.011, and 0.015 lbm/in.^{3} Rigidized-foam samples were tested in both tension and flexure at temperatures of +70°, −150°, and −250°F. Results showed that the strength of the rigidized-foam material is extremely temperature dependent. Temperature

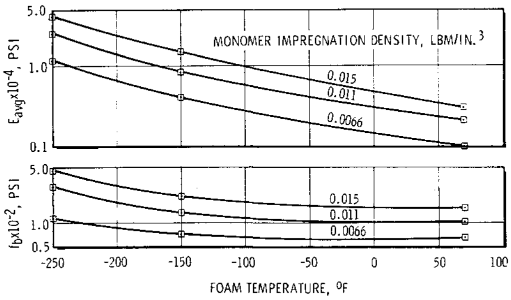


Fig. 4 Average modulus of elasticity and flexural yield stress of rigidized foam.

cycling prior to rigidization, however, did not affect material strength.

Typical variation of the mechanical properties of the rigidized monomeric material with temperature and monomer impregnation density are shown in Fig. 4. In general, the yield stress and modulus of elasticity increase with decreasing material temperature. At a nominal monomer impregnation density of 0.01 lbm/in.^{3}, the modulus of elasticity of the rigidized foam varies from about 2000 psi at 70°F to about 22,000 psi at −250°F. These same strength parameters also increase with increasing monomer-impregnation density. At −250°F, for example, the modulus of elasticity varies from about 10,000 psi at an impregnation density of 0.0066 lbm/in.^{3} to about 40,000 psi at a density of 0.015 lbm/in.^{3} These values are based on data obtained with the optimum thickener concentration of 15% noted earlier in Fig. 3.

Although the mechanical properties and the weight of the material were of primary importance, it became apparent during the material development that other factors would also influence final selection of monomer impregnation density. Densities of 0.0066 lbm/in.^{3} and less were so low that uniform impregnation was very difficult to achieve. Specimens at this nominal density exhibited widely varying properties, such as some relatively dry areas of lower-than-average resin content. On the high side, densities of around 0.015 lbm/in.^{3} approached the saturation point of the foam material, resulting in compaction and matting of the foam. Also, for high densities the mass of the structure is great. As a compromise intended to minimize weight, provide adequate strength, and facilitate satisfactory resin distribution in the foam, a nominal impregnation density of 0.01 lbm/in.^{3} was selected for the design and testing of solar-shield models and components.

Nuclear Radiation Effects

The effects of nuclear radiation on the properties of the rigidizable material were investigated by exposing flexible specimens to gamma radiation from a Cobalt-60 source and to nuclear-reactor-produced radiation. The degree of rigidization of the material was found to increase with accumulated gamma dose (Fig. 5), with specimens becoming completely rigid after a dose of 8×10^6 ergs/gm(C) at 30°F, and a dose of 2×10^6 ergs/gm(C) at 70°F. These results indicate that the rigidizable material is not noticeably affected by gamma doses of up to 1×10^6 ergs/cm(C) for material temperatures of up to 70°F in either an oxygen or vacuum environment. The material will remain sufficiently flexible and can be successfully folded and stored and then deployed after exposure in a vacuum at 30°F to an accumulated gamma dose of up to about 4×10^6 ergs/gm(C). This is well above the anticipated dose from a NERVA engine on a manned Mars flight.

There was no noticeable change in the mechanical properties of material chemically-rigidized after pure gamma or reactor irradiation. The gamma irradiation tests did reveal the possibility that the material underwent a "B-staging" (in-

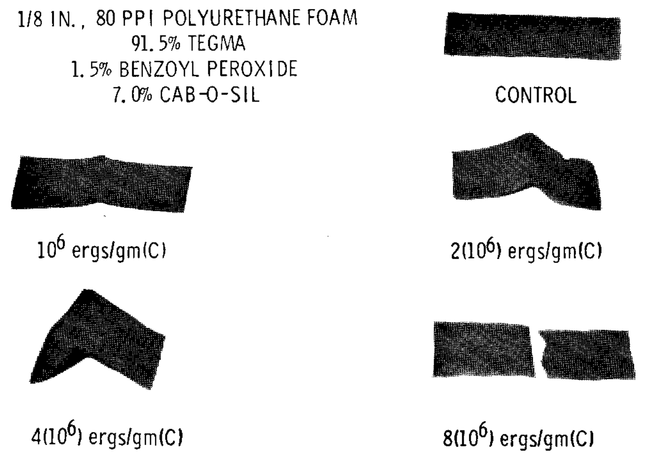


Fig. 5 Increase in foam rigidization due to gamma irradiation in vacuum at 30°F.

termediate-stage rigidization) mechanism as a result of the irradiation. If so, gamma-irradiated materials can possibly be stored without need for thermal control.

Thermal-Control Coatings

The effects of the space environment on three candidate thermal-control coatings (silicon oxide, alodine, and a carbon-doped polyester deposited on a GT-15 substrate)[3,5] were investigated by exposing them to various doses of solar-wind protons, ultraviolet radiation (uv), and combined solar wind and uv. Results of these tests, based on radiation dose levels anticipated for an Earth-Mars mission, showed all three materials to be highly resistant to solar-wind protons; changes in solar absorptance α_s of less than 5% were produced by 3.2×10^{15} p/cm^2. The silicon oxide was found to be highly susceptible to uv; 155 equivalent solar days of uv resulted in a 95% increase in α_s, compared with a 3% increase for the other coatings. These results show that the alodine and carbon-doped polyester coatings meet solar-shield requirements but that silicon oxide does not.

Model Design and Testing

Small-Scale Spheres

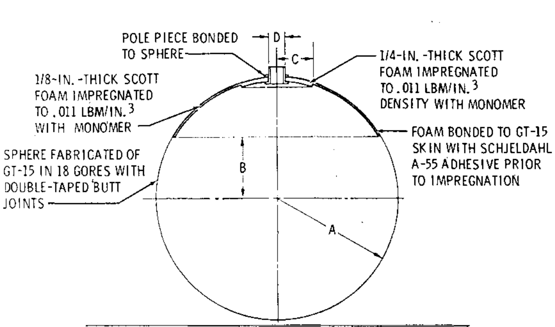
Verification of the basic solar-shield design concept and provision of experimental data upon which to base the final design of the large-scale (15-ft-diam) model were accomplished by a series of small-scale model tests. Because of the ultra-light design of a full-scale solar shield, ordinary model scaling techniques were not applicable. With a full-scale sphere diameter of 60 ft, the sphere skin thickness is 0.00075 in. and reinforcing foam thicknesses are 0.25 and 0.125 in. The 0.00075-in. skin is already approaching the limits of existing manufacturing, fabrication, and handling techniques. Lamination and impregnation of foam less than $\frac{1}{8}$ in. thick is also extremely difficult. The alternative approach was to fabricate the models by using material thicknesses identical to those of the full-scale structure. With this approach, the ratio of radius to shell thickness r/t becomes smaller as the model size is reduced. At these lower r/t ratios, the spherical shells are capable of carrying higher inertial loads. An added advantage of this type of model construction and scaling is the reduced effect of gravity as the model diameter is decreased, enhancing the simplicity of the test as well as increasing confidence in the quality of the data.

Spherical models were fabricated in 15- and 30-in.-diam sizes and were reinforced with rigidizable foam in the highly loaded portions of the sphere as shown in Fig. 6. (Note that the foam is on the inside surface for these model tests. Later polymerization tests, mentioned earlier, resulted in the foam being moved to the outside surface.) The type 1 configuration consists of a GT-15 skin reinforced over one-fourth of its surface area with a $\frac{1}{8}$-in.-thick layer of monomer-impregnated foam bonded to the GT-15 skin. Type 2 is reinforced with foam over the same area of the sphere, but the foam thickness in the region of highest loading near the pole piece is increased to $\frac{1}{4}$ in.

The small-scale spherical model tests were conducted in a centrifuge in order to simulate the operational loading expected on a solar-shield structure. The objective of these tests was to establish an empirical relationship of structural and geometric parameters with measured load-carrying capability. Particular emphasis was placed on the evaluation of load-carrying capacities of spherical models because of the lack of any available analytical method for use with thin-shell, asymmetrically loaded spheres.

The approach used in the centrifuge tests was to apply a purely inertial load (Fig. 7) to the rigidized spherical-shell structure. As this loading is increased by increasing the angular velocity of the centrifuge, the level of stress at the support area or "neck" of the shell will reach a value corresponding to the local elastic buckling stress of the shell. At this point an increase in deflection occurs with no corresponding increase in loading. This condition is defined as a structural failure, and testing is terminated. Aerodynamic forces on the models were eliminated by placing them in a closed test chamber on the centrifuge arm. A low-temperature test environment simulating the operational thermal conditions in space was maintained by precooling the externally insulated chamber walls with liquid nitrogen.

Of the two reinforcement configurations tested, only the type 1 spheres were tested to failure. Except for some apparently defective specimens, spheres reinforced with $\frac{1}{4}$-in.-thick foam around the polar cap withstood the maximum available centrifuge acceleration of 30 g without failure. A correlation of earlier data,[2,3] with the experimental data obtained in this investigation, is shown in Fig. 8. These data are presented in terms of the ratio of radius to wall



DIMENSION IN INCHES	15-IN.-DIA. TYPE 1	15-IN.-DIA. TYPE 2	30-IN.-DIA. TYPE 1	30-IN.-DIA. TYPE 2
A	7.5	7.5	15.0	15.0
B	3.75	3.75	7.5	7.5
C	N/A	2.25	N/A	4.5
D	1.0	1.0	2.0	2.0

Fig. 6 Foam reinforcement of small-scale spherical solar-shield models.

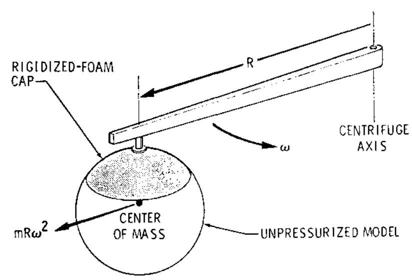


Fig. 7 Centrifuge test arrangement.

thickness of the sphere and in terms of a loading parameter, r^3n (where r is the sphere radius and n is the equivalent gravitational acceleration applied to the structure). The loading parameter r^3n is the variable portion of the bending-moment expression for a reinforced spherical shell loaded as a cantilever by a transverse inertial force. The complete moment expression for a spherical shell reinforced over a cap of one-quarter of the total surface area and adjacent to the support point can be shown to be

$$M = 0.25\ \pi\ r^3n\ (W_1 + 15W_2)$$

where M = bending moment at support point, r = sphere radius, n = inertial acceleration in Earth g's, W_1 = unit weight of sphere surface in reinforced area, and W_2 = unit weight of sphere surface in nonreinforced area.

Extrapolation of the results of the small-scale tests indicates that a 60-ft-diam shield can successfully withstand accelerations up to about 0.01 g, which is the upper limit on the design conditions. Test results for gamma-irradiated models did not differ significantly from those of nonirradiated models.

Tubular Components

An alternate form of the solar shield is the truss-supported flat shield shown in Fig. 2. The part of this shield which is of structural significance is the truss, which must carry inertial loads resulting from its own mass and that of the flat thermal-protection portion of the shield. The truss members consist of small-diameter inflatable tubes of GT-15 material reinforced with a rigidizable foam identical to that of the spherical shield concept.

An experimental test program was conducted to determine the structural characteristics of rigidized-foam-reinforced tubes in bending and compression, and to compare these characteristics with basic material properties. The test specimens, approximating full-scale dimensions in diameter and thickness, were 2-in.-diam × 12-in.-long tubes fabricated from GT-15 material prelaminated with the flexible polyurethane foam. Specimens were prepared with foam thicknesses of $\frac{1}{8}$ and $\frac{1}{4}$ in. Impregnation density for all specimens tested was constant at 0.011 lbm/in.[3]

Specimens were tested in flexure by use of a special test fixture so that only a constant bending moment would be applied to the tubes. The intent was to avoid predetermination of the failure point either by loading variation or by points of concentrated loading. Experimentally determined values of applied load and resulting total angular deformation of a tubular specimen were used to calculate values of the modulus of elasticity of the material.

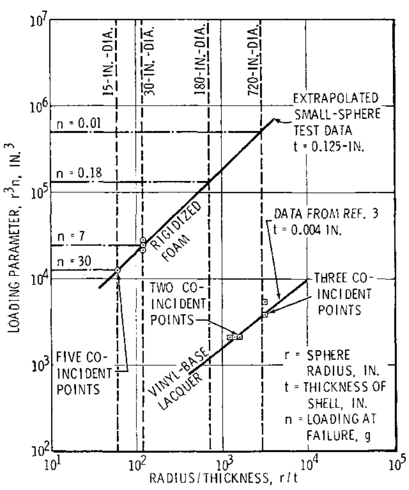


Fig. 8 Correlation of failure loading of spherical solar-shield models with dimensionless sphere size at −150°F.

Average values of the modulus of elasticity varied from 1300 to 2570 psi. The average yield compressive stress obtained from standard tube compression tests varied from 18 to 29 psi. While these values, based on a 70°F test temperature, are not acceptable for structural applications, they increase rapidly with decreasing temperature. The results

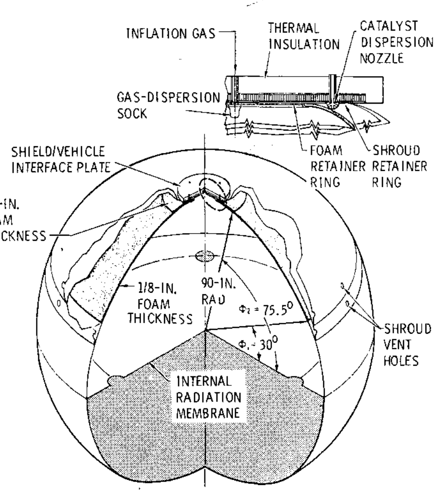


Fig. 9 Operational $\frac{1}{4}$-scale solar-shield model.

of these tube bending and compression tests, in conjunction with the basic property data obtained in the strip-specimen tests, provide an adequate basis for the design of truss-type solar shields, since the loading of the individual truss members may be analyzed by conventional methods.

Large-Scale Spheres

The data obtained from the material properties tests, the tubular components tests, and the small-scale sphere tests provided a basis for design of large-scale operational models. The large-scale (15-ft-diam) model design resulting from these structural/operational criteria is shown in Fig. 9. The basic spherical shape is retained to provide maximum thermal performance in accordance with the results of previous studies.[1] The skin and the shrouds covering the foam reinforcing cap are of GT-15 material. An enlarged view of the method of attachment of the reinforced shield to the interface plate is also shown, illustrating the injection systems for inflation gas and catalyst.

Three $\frac{1}{4}$-scale models (15-ft-diam) were fabricated and tested as a part of the development program. The tests, conducted under simulated space conditions (10^{-5} torr, −320°F surroundings), were designed to verify the operational feasibility and structural load-carrying capability of the spherical solar-shield design concept. Thermal simulation was considered very important because of the inhibiting effect of low temperature on the rigidization reaction.

The operational objectives were to demonstrate 1) canister lid ejection and subsequent deployment of the shield into a

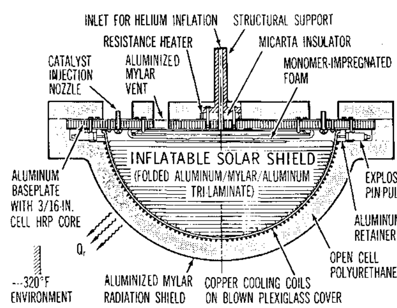


Fig. 10 Solar-shield test canister.

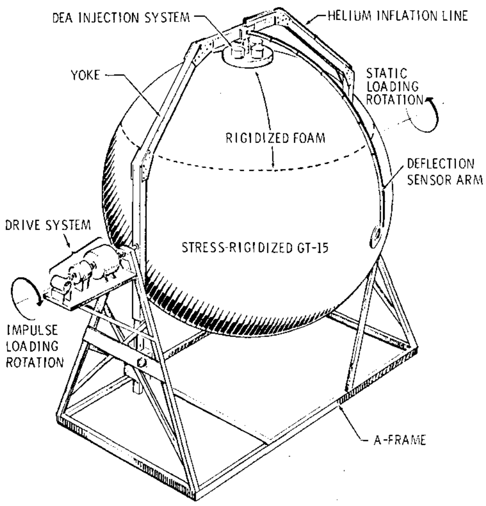


Fig. 11 Test fixture for $\frac{1}{4}$-scale model operational and structural tests.

vacuum without incurring damage from blocking or tearing of layers, 2) operation of an adequate inflation system which would allow inflation of the shield without uncontrolled expansions or large deviations from the desired path during deployment, and 3) the ability to initiate and complete rigidization of the expanded envelope while exposed to a space environment. The structural objective was to extend the buckling data obtained in small-scale tests (Fig. 8) by determining the equivalent inertial loading corresponding to structural failure of the $\frac{1}{4}$-scale model. Data from all the scale-model tests could then be extrapolated to estimate the load-carrying capacity of structural shell sizes representative of operational solar shields.

The test canister (Fig. 10) used for the deployment and structural tests consisted essentially of an insulated hemispherical storage container, or lid, and an aluminum/fiberglass-honeycomb/aluminum sandwich baseplate. The solar-shield model was folded and packaged into the hemispherical dome and connected to the baseplate with fiberglass retainer rings. The baseplate was fitted with all support components required for model thermal control, deployment, inflation, rigidization, and structural testing. These were all mounted so that the hemispherical lid could be separated and jettisoned from the baseplate at the time of model deployment.

The basic test fixture consisted of a rotatable yoke mounted in an A-frame, with an arm attached to the yoke for measuring model deflections. Figure 11 shows the yoke in the vertical position and locked in the positive-stop latches. Static loading tests are accomplished by slowly rotating the model and test fixture about a pivot axis that passes through the center of the spherical model. This rotation produces a lateral load on the model structure induced by the downward weight vector or gravity component. If the model does not fail from static loading, impulse loads are then applied by disengaging the electric clutch and allowing the yoke to free-fall from successively larger rotation angles, stopping it in the vertical position with the rigid latches.

The operational performance tests involved all of the operational phases required for a full-size shield; fabrication, storage, deployment, inflation, rigidization, venting, and loading. Two of the tests were successful in establishing the operational feasibility of the solar-shield concept. In both of these tests, the shield was placed in the simulated space environment, remotely deployed from its storage canister, inflated to a full spherical shape, and then chemically rigidized over the entire area of the reinforcing foam cap (Fig. 9). Because of test fixture mechanical malfunctions in the first two tests and a foam-impregnation problem in the third test, verification of the structural performance of the 15-ft-diam model was not accomplished. In one of the tests, however, the model supported itself under a 1-g load acting vertically downward on the rigidized-foam cap. The anticipated loading at failure (Fig. 8) was 0.18 g acting laterally through the model centroid. Thus, even though the loading conditions were not the same as those for the small-scale spheres, the simple fact that the large-scale sphere was able to withstand the vertical 1-g load is indicative of the relative strength of the structure.

The results of the $\frac{1}{4}$-scale tests show that a large, rigidizable structure such as a solar shield can be successfully fabricated, folded, packaged, shipped, and stored under controlled-temperature conditions. The performance of these tests represents the first known deployment, inflation, and chemical rigidization of a large-scale, lightweight, expandable structure under simulated space conditions.

Conclusions

The most important conclusion derived from this research is that a lightweight, flexible structure can be reinforced with open-cell polyurethane foam and impregnated with a monomeric compound, stored under controlled-temperature conditions, and then deployed, inflated, and chemically rigidized while subject to a simulated space environment. A lightweight, flexible material has been developed that can be chemically rigidized on command and that can be subjected to a gamma dose of up to 4×10^6 ergs/gm(C) at 30°F without undergoing premature polymerization. This means that the inflatable solar-shield concept described here is feasible for use on nuclear as well as chemically fueled vehicles. Mechanical properties of the rigidized material show good strength-to-weight ratios, and sphere buckling data indicate load-carrying capacities sufficient for solar-shield and other space applications. The effects of the space environment on candidate thermal-control coating materials indicate that alodine and a carbon-doped polyester on a laminated aluminum/Mylar/aluminum substrate meet typical solar-shield mission requirements, whereas silicon oxide does not.

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