EXPANDABLE STRUCTURES FOR SPACE APPLICATIONS

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ABSTRACT

During the past decade a great deal of expandable structure research has been conducted, also during this period investigators have proposed many expandable structure applications. This paper summarizes the major types of expandable structures which are as follows; inflatable balloon, rigidized membrane, airmatt, foamed-in-place, expandable honeycomb and variable geometry structures. Emphasis is placed on materials, system characteristics, and advancements required to perfect each type of expandable structure. Finally, a discussion is given on future significant expandable structures experiments that will be conducted by the Air Force.
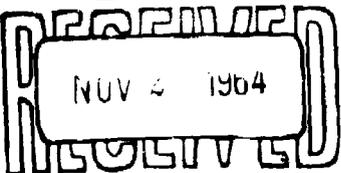
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INTRODUCTION

One of the most important decisions to be made when designing future space systems is the selection of materials and structures to satisfy the vehicle's mission requirements. Today's structures are required to resist extremes in temperature, high vacuum conditions, ultraviolet and electron radiation, and micrometeorite bombardment; while being as structurally efficient as possible. There are many types of structures being utilized in today's systems and this paper will deal with one general type, expandable structures, which are being applied to more and more applications. It is not the purpose of this paper to in ate that expandable structures are an answer to all problems of both today and the future. Obviously they are not, otherwise this type of struct would be in widespread utilization.

Before going into the details of expandable structures it would be wise to define the term "expandable structure". An expandable structure is considered to be any structure that can be expanded from a small package volume into a larger volume structure; it may or may not have a load carrying mission[1]. There is really only one reason to utilize an expandable structure, that is to reduce its package volume during shipment. Some believe that expandable structures have an inherently higher strength to weight ratio than conventional structures; this is not true, at best an expandable structure will have an equal strength to weight ratio as compared to the most efficient rigid structures. Finally, the reliability of the expandable structure is somewhat less than that of a rigid structure. This is because of the possibility of an expandable structure failing to deploy or rigidize.

There are some applications which lend themselves to expandable structures, for example, imagine fabrication, ground shipment, and launching into orbit an Echo I or II size rigid nonexpandable satellite.

There are six basic types of expandable structures. These are: (1) the thin skinned pressurized balloon, (2) rigidized thin skinned structures, (3) airmat, (4) foamed-in-place, (5) expandable honeycomb or sandwich, and (6) variable geometry structures.[2] Variable geometry structures as previously defined by the author were known as unfurlable structures.

APPLICATIONS

There are numerous applications being considered for expandable structures. These are passive communication satellites, decoys, antennae, solar energy collectors, space shelters, space stations, space maintenance hangars, re-entry vehicles, recoverable booster system, and furniture.

Passive Communication Satellite

Expandable structures have already made a significant contribution to the communication satellite area. Namely Echo I and Echo II launched into orbit on August 12, 1960, and January 25, 1964, respectively, by the National Aeronautics and Space Administration. The launching of these two satellites has actually given considerable impetus to the whole area of expandable structures. New trends are developing in this area of passive communication satellites. The current trend in expandable structures is toward the open grid structure rather than a solid skin structure. There are at least three companies (Viron, G. T. Schjeldahl, and Goodyear Aerospace), which are actively pursuing different expandable grid sphere materials approaches. The open grid satellite has the advantage that although it provides a large radio effective area it presents a minimal area to either air drag or solar pressure.

Solar Energy Collectors

The application of expandable structures to a solar energy collector is one of the most challenging areas being pursued by some investigators today[3,4]. A solar collector is a parabolic dish with a highly reflective coating on the concave surface which concentrates all of the sun's energy at a theoretical focal point. A solar energy collector must be lightweight; currently design goals are .2 lbs/sq ft of projected reflective area. This minimal weight requirement must be satisfied if a solar energy conversion system utilizing a solar collector is to be competitive to other systems[5]. A solar concentrator must also have the ability to hold its contour during repeated orbital thermal cycling. Investigators in the past have side stepped this area of research in solar concentrators; however, the Air Force has just recently initiated an in-house program to determine the effects of orbital thermal cycling on metal petal solar collectors, foam rigidized solar collectors, and expandable honeycomb solar collectors. Tests are to be conducted on 2 ft, 10 ft, and 44.5 ft diameter solar collectors. The collector will be cycled repeatedly through the maxima and minima heat fluxes to be encountered in lower orbit space missions. Temperature profile, strain, and deflection data will be ascertained from these tests.

Solar collectors must have a minimal package volume, otherwise a major space system may be required to carry excessively large canisters. For example, although the variable geometry metal petal solar collector is within the state-of-the-art, its package length is only about 50% of its diameter.

Thus, a 44.5 ft diameter solar collector would have a canister length of 23 ft, such a length would probably impose a severe hardship on a space system during boost.

Space Shelters

Since man has decided to explore the vast sea of space he has set up a number of major goals. One of these is manned flights to extraterrestrial bodies, and the exploration of these bodies. Expandable structures could play a very important role in providing man shelter on these extraterrestrial bodies. Complete shelters could be fabricated on the Earth, packaged, boosted to final destination, and finally deployed into a useful size shelter. Most likely the more probable application of expandable structures would be to expand large living or work areas on smaller more conventionally built rigid structures. The rigid structural component could contain all of the basic equipment required for initial survival of man.

Space Stations

Man has also had as a major target objective the establishment of permanent manned space stations. Permanent space stations must either be assembled in orbit from many separately launched prefabricated modules or it must be expanded in orbit from some type of expandable structure. Both approaches have advantages and disadvantages and it would be fortuitous to say at this time which system should be utilized for advanced space stations. Undoubtedly both modular in-orbit assembly and expandable structures will be utilized on several of these space stations.

Space Maintenance Hangars

The Air Force has a well established space maintenance program including the development of astronaut maneuvering units, remote controlled maneuvering units, space shuttles, space maintenance tools, adhesives, fastening techniques, and finally, extravehicular spacesuits. Approved DOD-NASA experiments on Gemini will establish the feasibility of man performing in-space maintenance and the Air Force will conduct more advanced space maintenance studies on the first space station. Space maintenance hangars would be one more tool in the maintenance worker's tool box which would insure the maintainability of future space vehicles. The principal advantage of utilizing a space maintenance hangar lies in elimination of the pressure differential between the inside and outside of the astronaut's space suit. Elimination of these differentials would give man the mobility of a nonpressure suit which would in turn greatly reduce space maintenance repair task times.[6] Secondary, but important advantages of such a hangar would be the ability to provide man a controlled lighting intensity conclusive to maintenance tasks, increased maintenance mission capability, and additional protection of man from the hostile environment of space. The author does not foresee expandable space maintenance hangars actually utilized for some time to come.

Expandable Rendezvous Docks

The maintenance of large space stations in orbit is very dependent on the ability to either by remote control or manual control rendezvous logistics vehicles with the orbiting space station. A semi-rigid expandable structure could provide even a rigid conventionally built space station with several advantages. During boost into orbit the space station would have a reduced volume in the area of the rendezvous dock, but during docking operations the expanded nonrigid dock would provide excellent shock or energy absorbing characteristics in the event of inaccurate rendezvous techniques.

Re-Entry Vehicles

The most formidable application of expandable structures lies in the expandable winged re-entry area. The elevated temperatures encountered during re-entry create numerous materials and structural problems. The Air Force and NASA have established expandable re-entry vehicle programs mainly in the paraglider area.[7,8] There is no doubt that the development of an expandable re-entry vehicle program would be extremely beneficial to the nation's space program in the area of allowing the astronaut to select a normal landing field. This would eliminate the necessity for a world wide recovery task force which is expensive to deploy. Expandable re-entry vehicles could also be utilized to rescue astronauts from damaged vehicles or to recover unmanned objects from space for subsequent inspection. Finally, such a recovery vehicle may someday be utilized to recover the first and second stages of boosters for reusage.

Miscellaneous Applications

Expandable structures have many other potential applications in space missions. Space furniture, fuel tankage, crew transfer tunnels, and solar sails are but just a few of these applications. Undoubtedly expandable structures will provide many solutions to major and minor subsystem requirements on future space vehicles

NONRIGID VERSUS RIGIDIZED EXPANDABLE STRUCTURES

There has always seemed to be some divergent opinions on whether expandable space structures should be rigidized or nonrigidized structures. Nonrigid proponents point out that if the space vehicle requires internal pressurization for human occupancy, it is efficient to maintain structural rigidity through this internal pressurization. Furthermore, they claim that although puncture would result in loss of internal pressure; the structure would not collapse due to the Zero "G" environment. Certainly these are valid points, but the author considers that if a rigidized structure can be made to have as high a strength to weight ratio as a pressure stabilized structure, why not utilize a rigidized structure for added structural confidence. In addition, manned space stations which would rotate to induce

artificial gravity would impose loads on a space structure when it had been depressurized due to some accident. Rigidized expandable structures are planned for future long term passive communication satellite applications to resist deformation caused from puncture and solar pressure. Early expandable re-entry vehicle concepts were based on inflatable nonrigid structures. One of the biggest technical problems to be encountered with these systems was developing flexible sealants for the fabric which would minimize porosity while resisting the re-entry temperature. A rigidized re-entry system would totally eliminate this problem. It should be realized that a nonrigid structure is advantageous for rendezvous docks and space maintenance hangars. Crew transfer tunnels, because of their relative size and mission application, may also utilize nonrigid structures.

INFLATABLE BALLOON

Definition: The balloon is defined as a fabric or film bag inflated with a gas. A balloon usually has the shape of a sphere, a cylinder with domed ends, cigar or a torus.[9] Since the author wrote "Expandable Structures for Aerospace Applications", there has been little advancement in the area of inflatable balloon structures. In reviewing the author's comments in the above document the following summary is presented.

Materials

Usually the inflatable balloon structures are fabricated from mylar, tedlar, H film, or polyethylene plastic films ranging from 1/2 mil to several mils thick. Quite often in the case of decoys, solar collectors or passive communication satellites, these films are aluminized to provide visual, heat, or radio reflectivity. These materials are all utilized in featherweight structures. Heavier duty higher load carrying structures employ the woven or filament wound structures to carry the structural load while utilizing an organic plastic gas barrier to retain internal pressure. All of the above cited materials systems are temperature limited, of course nickel base, boron fibers, or other high temperature fibers may be utilized to increase the temperature limit of the expandable structure materials.

Characteristics

Inflatable balloon structures have high strength to weight ratios and high ratios of expanded volume to packaged volume, and they are reusable; however, these structures are usually limited to bodies of revolution, and collapse if punctured.

Applications

These inflatable structures have been used for passive communication satellites (Echo I), booms on a paraglider structure, ground based shelters, drag ballutes, and other smaller structures. Inflatable structures are also utilized as a basic component of many chemically rigidized structures, such as honeycomb, foamed-in-place, and rigidized membrane structures.

Advancements Required

New flexible higher strength plastic film need to be developed which are tailor made for inflatable structures. Most of today's inflatable balloon materials were developed by private industry for commercial applications. In particular if some of the new exotic high temperature fibers are to be utilized efficiently in inflatable structure applications, new flexible high temperature sealing materials must also be developed. Finally, new and better adhesive jointing techniques must be developed to be utilized in the fabrication of these new materials.

RIGIDIZED MEMBRANE STRUCTURES

Definition: This type of structure is defined as an inflatable balloon structure that is either mechanically rigidized or chemically rigidized after deployment.

Materials

Generally two basic types of rigidization techniques are applicable to rigidized membrane structures. These are mechanical and chemical, significant advances have been made in both areas.

In the mechanically rigidized area, structures are fabricated from laminates of thin lightweight metallic foils sandwiched over a thin plastic film. Once these structures are inflated to proper design pressures the metallic foils yield and take a permanent set. In a "Zero G" environment this small amount of rigidity obtained from the stretched foil structure is sufficient to maintain a large passive communication satellite's shape without internal pressurization. Echo II, an example of this construction, utilized a material composed of .00018 inch foil sandwiched over a layer of .00035 inch mylar. Figure 1 is a photograph of Echo II.

The wire or metal grid sphere mentioned in the introduction of this paper is another example of a mechanically rigidized expandable structure. Currently there are three basic techniques which can produce these open wire grid structures. These are chemically etching foil, expanded metal fabric techniques and finally miniturization of conventional chicken wire fabrication techniques. Each type of open grid material has its advantages and disadvantages. For example, the technique which utilizes chemical etching to create the openings in the material can be utilized to provide a grid material which is extremely thin. Fabrication of a material of this type constitutes laminating a light gauge aluminum or metal foil to a plastic film, printing a non-etching grid on the foil, subjecting the material to an acid or alkali etching solution, and final naturalization of this solution.

Utilizing materials of this type, large passive communication satellites may be built which will have large radar cross sections, but minimal air resistance. One of the keys to this realization is the development of plastic films which will disappear in a space environment fairly rapidly. The open grid metallic materials are laminated to a plastic film to provide a temporary gas barrier for inflation or deployment purposes. Today's plastic films although they may eventually degrade in space, take far too long to disappear. It is desirable to eliminate this film immediately after deployment to prevent unfavorable orbital perturbations which would identify an orbital decoy or degrade the orbit of a communications satellite.

In the chemically rigidized structure area a number of chemical rigidization techniques have been developed which will rigidize films or impregnated fabrics. Plasticizer boil-off is an old technique which has been investigated for many space applications. Plastics which have been investigated for this area are vinyls, polyurethanes, acrylics, and gelatins or proteins. All of these systems require rather high plasticizer percentages of the total system weight. Once in space, the plasticizer constituting 20 to 30% of the structure's weight is released or discarded, which causes rigidization. Another disadvantage of the plasticizer boil-off system is that as soon as the structure is exposed to the space environment it begins to cure. For many space applications, the Air Force is desirous of having a system that cures on command. For example, it may well take one or two orbits before a large solar collector is accurately deployed; however, a solar collector cured by plasticizer boil-off technique would have already been cured before accurate contour is achieved.

Undoubtedly one of the most promising plasticizer boil-off systems involves gelatin. Gelatin, dehydrated cross linked films have been made with strengths exceeding 21,000 psi. Films containing 20 to 30% plasticizers, such as glycerine or glycols, are quite tack free and flexible. Ultraviolet and electron radiation tests on these specimens have shown that gelatin is quite suited to space applications. It is nearly transparent to ultraviolet radiation, and is relatively unaffected by electron radiation of 10^6 rads.[10] Gelatin is, however, water soluble. It might be added that there appear to be no rain clouds in space. Gelatin can be crosslinked to the point that it is no longer soluble in boiling water; however, it will swell under this condition. Gelatin has a high stiffness as a free film, 1,000,000 psi. Gelatin and fiberglass laminates fabricated and tested by Forest Products Laboratory exhibited the properties shown in Table 1. It should be noted that Monsanto Research Laboratory has prepared laminates that have significantly higher bending and tensile, and compressive strengths than shown in Table 1. Flexural strengths as high as 77,900 psi have been obtained on MRC laminates.[11] As one can see, gelatin fiberglass laminates have quite remarkable stiffness properties at elevated temperatures. The Air Force Aero Propulsion Laboratory has just awarded a contract to Viron Division of Geophysics (prime), Swift and Company (sub-contractor) and Monsanto Research Corporation (sub-contractor) to investigate plasticizer boil-off rigidized gelatin structures for space applications. Gelatin and other protein materials are to be modified to provide even better properties than are now reported. Monsanto Research has already come up with techniques to aluminize gelatin by vapor disposition

for solar collector or antenna applications.

Radiation has been utilized by some investigators as a method for rigidizing membrane structures. Hughes Aircraft Company has for a number of years, worked on both ultraviolet and infrared cured plastic resins.[12] Polyester resins seem to cure quite well on exposure to ultraviolet radiation, while epoxies can be made to cure with exposure to infrared radiation. Ultraviolet cured systems, once cross linked to complete rigidity, will then degrade with additional exposure to ultraviolet radiation. This problem may be eliminated by the addition of absorbers which are activated after final cure of the system. The author is concerned that the ionizing radiation level in space may cause rigidization of a polyester structure before it is fully deployed. British Patent 949, 191 records the curing and crosslinking of resinous films by electron irradiation. Coatings consisting of thin films of unsaturated polyesters were subjected to an electron beam of 100 Kev under nitrogen and cured in one (1) second.[13] Infrared or heat activated systems such as epoxies are cured by raising the temperature of the resin system to a point of high reactivity. This increase in temperature can easily cause a large solar collector of 44.5 ft diameter to lose accurate contour because of creep in the mylar reflective surface. Solar collectors that are rigidized by this process are fabricated from one (1) or two (2) mil mylar and the actual solar concentrator area is coated with the heat activated epoxy system. After deployment of this collector structure, but before final rigidization, the parabolic contour is held by inflation pressure. If the structure reaches a temperature above 150°F for any length of time during its uncured stage, the mylar will stretch or creep considerably causing the solar collector to lose contour.[14] These ultraviolet cured or infrared cured structures require that the structure have orientation equipment on board to insure that the plastic resin receives the proper dosage of the activation radiation.

Gas catalysis curing techniques have been developed in the areas of epoxies, urethanes and polyesters. Early pioneering work in this area was accomplished by R. Spain, Air Force Materials Laboratory and Wyandotte Chemicals Corporation. Gas cured urethane systems utilize water as a catalysis and with the earlier systems required four (4) to sixteen (16) hours to fully rigidize. Multi-layer laminates were prepared that exhibited flex strengths of about 20,000 psi, although periodically higher strengths have been achieved. Gas cured epoxy materials in general require longer cure times, but develop higher strengths. Cure times with some epoxy systems are in excess of 48 hours. Strengths in these early epoxy gas cured laminates were between 25,000 and 30,000 psi in flexure.[15, 16]

Characteristics

Rigidized membrane structures will not collapse if punctured and have a high ratio of expanded volume to packaged volume; although, these structures usually fail prematurely because of buckling stresses.

Applications

Rigidized membrane structures are very applicable to passive communication satellites because of their relatively light weight. The techniques for rigidizing these lightweight membranes are in the majority of instances directly translatable to expandable honeycomb structures.

Advancements Required

In the open grid material systems two advancements are needed, these are; improved seaming and joining techniques and a rapid migrating plastic film. The later requirement has previously been discussed. Advancements are required in the plasticizer boil-off systems, namely plasticizers are required which can be utilized in lower percentages of the overall system, but still produce flexability. A plasticizer which would only occupy ten (10) percent of the total resin system is a design goal. Ultraviolet or infrared cured resin systems need to have on-command curing capability. Today these systems will start to rigidize as soon as they are deployed in space. The systems designers would prefer to be able to deploy a structure, but have it cure on-command not on deployment. Further, ultraviolet absorbers or screening materials are required which after a predetermined period of time would absorb or reflect the ultraviolet radiation thus preventing degradation of the cured plastic resin system.

Gas cured rigidization systems require many advancements. The epoxy gas catalysis materials system needs to have its cure time reduced significantly. Design goals for a cure time are about fifteen (15) minutes. Urethane gas cured systems should have their cure time reduced, but these systems require improvements in shelf life. The majority of the gas cured resin systems cure by absorbing water vapor plus an accelerator. It is very difficult to prevent these urethane resins from prematurely hardening. A shelf life of six (6) months has been reported[17], but this is for a resin in a sealed container. Long shelf life for an impregnated packaged structure is much more difficult to achieve. All of the chemically rigidized structures should be investigated to determine the effects of the space environment, before and after rigidization, on the materials.

AIRMAT STRUCTURES

Definition: Airmat is an inflatable structure that is held into a predetermined shape by drop threads. These threads act as cross ties, and by tailoring the lengths of these threads flat, airfoil, or other shaped panels can be maintained. There are thirty (30) drop threads per square inch on the average, but as many as sixty (60) drop threads per inch may be utilized in some cases.

Materials

Organic and metallic fibers are utilized in the basic airmat structure and organics or inorganics are utilized to seal the woven material. Dacron,

nylon, and cotton fibers are often utilized for non-high temperature applica-
tions. Neoprene and other organics are commonly used as sealants, but silicone
rubbers are utilized for high temperature applicatons. Rene 41 and other
nickel base fibers are employed. A major consideration in the making of air-
mat is the loom which it is woven on. Just recently Goodyear Aerospace under
an Air Force contract developed a twenty (20) foot wide loom which can weave
very deep airmat panels of complex contours. This loom has the capability of
weaving not only organic fibers, but also metallic fibers into airmatt struc-
tures.

Characteristics

Airmat structures have a high strength to weight ratio, a high expanded
volume to packaged volume ratio, and a capability to maintain other than cir-
cular cross section shapes. Airmat structures have high deflections under
load, require deep members, otherwise inflation pressure is high, and these
structures collapse if punctured.

Advancements Required

Advancements required in the airmat materials systems are in the higher
temperature materials area. New high temperature sealants should be developed
that are capable of resisting temperatures of 1800 to 2000°F while maintaining
minimal porosity characteristics. Improved high temperature fibers should
also be developed which will operate at the above mentioned temperatures.
Finally, new flexible high temperature adhesives systems need to be developed
which will maintain structural integrity at these high temperatures. Since
airmat normal orbital temperature requirements are more or less within the
state-of-the-art, it would appear that a detailed investigation of the effects
of the space environment would be required before final space applications are
undertaken.

Applications

Airmat has many potential applications in the space age. Re-entry
vehicles, extensions on space stations, portable space shelters, rendezvous
docks, and space furniture are representative of applications for this struc-
tural concept.

FOAMED-IN-PLACE STRUCTURES

Definition: Foamed-in-place structures utilize an inflatable balloon
structure to form the desired configuration before it is foam rigidized.
After deployment, plastic foam reactants are activated and the structure is
foamed-in-place or rigidized.

Materials

There are a number of plastic foams which are being investigated for
space foamed-in-place applications, these are epoxies, urethanes, and phenol-
ics. Most investigations have eventually centered on the polyurethane foam

family. Basically three types of foamed-in-place techniques have been investigated, mechanically mixed pressure distributed foams, solid reactant predistributed foams, and encapsulated reactant predistributed foams. Foaming-in-place in a space environment poses several formidable problems, these are effect of Zero "G", high vacuum, and space radiation on the foaming reaction.

Most investigators have studied the effects of high vacuum of the foaming reaction. Some investigators[18] have tried to engineer around the high vacuum problem by foaming between two (2) walls; however, this technique is not practical as in a solar collectors case, the wall materials are one (1) or two (2) mil mylar. The pressure build-up within the walls or backflap will seriously distort the structure beyond the desired contour. Small sized structures with heavy backflap or double wall materials may be foamed successfully, but the larger lightweight structures are impractical for backflap applications. Basic foam formulations are not compatible with the high vacuum environment of space. A standard foam formulation when activated in the presence of a vacuum will rise up rapidly, similar to atmospheric foams, but the uncured foamed structure will then collapse back to nearly its original volume. The added pressure differential causes the foam to rise before the urethane resin has built up jell strength, thus, the individual bubbles of foam rupture after expansion. The liquid reactants of normal foam if exposed to a vacuum for prolonged periods before activation of the foaming reaction will out gas and prevent or retard foaming. Several companies, Hughes Aircraft, National Cash Register, Monsanto Research under Air Force contracts and Goodyear Aerospace under NASA contract, have developed polyurethane foams capable of foaming in a vacuum. The vacuum foams developed to date do not have as good quality cell structure as an atmospheric foam. The thinner the section of the rigidized foam the coarser the cell structure. A very thick slab of vacuum cured foam will have a reasonably good cell structure, but fortunately many applications for foam rigidized structures require thin section structures, such as solar collectors. Current estimates for large diameter collectors indicate a maximum foam structure thickness of two (2) inches.

The effects of Zero "G" on the polyurethane foaming reaction was heretofore unknown. Authorities on polyurethane foam could make a strong case for or against Zero "G", significantly affecting the foaming process. The Air Force set up an in-house program to determine the effects of Zero "G" and higher "G" effects of the foaming reaction of polyurethane foams. A special fast reacting foam was developed by Monsanto Research under Air Force contract which from the time of mixing to full rigidization required only fifteen (15) seconds. The rapid foaming formulation was prepared from commercially available materials--a resin mixture of LA-700 pentol and LK 380 triol, with Mondur MR polyisocyanate. Freon F-11 was used as the blowing agent. The viscosity of this formulation was 1000 cp at 25°C. The foam rise time of only 15 seconds was achieved by means of a mixture of stannous oleate and piperazine catalysts. The foams produced from this formulation were 1.5 to 2.0 lb per cu ft with a 25 psi compressive strength and possessed good dimensional stability. This fast reaction was activated in a mechanical mixing device, but the foam was allowed to rise as an unrestrained column during expansion. Thirty-two specimens were foamed on board the KC-135 Zero "G" Aircraft. No detectable

visual changes in cell structure or density was found in the resulting foamed structures. Similar tests were run on a centrifuge utilizing a semi-capsule atmospheric foam prepared by National Cash Register under Air Force contract. Foams were made at simulated "G" levels up to 30g. No significant effects were noticed until approximately 15g force levels were encountered. Figure 2 shows comparison photographs of a One "G" foam and Zero "G" foam. A One "G" foam rises out of the mixing container and overflows to form a bell shape. The Zero "G" foam rises straight up in a column of about the cross section of the container.

Effects of space radiation on polyurethane foams have not been investigated in detail to date. Tests need to be conducted to determine what effects, if any, different types of radiation have on both unreacted and reacted polyurethane foams. Exposing unreacted components of a urethane foam to space radiation may cause premature hardening of the resin, prevent or retard foaming, or may improve or have deleterious effects on the final foam properties.

Hughes Aircraft pioneered the solid foam reactants area for space applications under Air Force contract. The approach of the Hughes Aircraft Company was to mix an initially solid diol, esocyanate, triol, dibutyl tin di-2-ethyl hexoate, and a surfactant, in correct properties. This mixture is partially reacted and then ground into powder. This powder is then made to adhere to an inflatable balloon structure which, after inflation, is allowed to heat up to 180°F to 250°F which in turn triggers the foaming reaction.[19]

Goodyear Aerospace Corporation has developed another more or less solid predistributed foaming system. The foam is of a urethane type which utilizes a polyol resin and diisocyanate. Goodyear's diisocyanate is derived from three sources; these are prepolymerization of the resin, a Curtius rearrangement of the azide, and a blocked isocyanate. Controlling factors are proper proportioning of the isocyanate for good crosslinking and adiabatic temperature rise during the reaction. The formulation is mixed to form a paste of high viscosity. The foaming reaction is initiated by allowing the formulation to heat up to about 200°F after which the reaction is exothermic.[20] In the past this formulation either required prolonged heating of several hours to achieve foaming or it would react very fast and the exothermic reaction would damage a mylar substrate. Current formulations require one (1) minute of heating at about 180°F and requires about twenty (20) minutes to solidify. This formulation develops about a 350°F exotherm.

National Cash Register under Air Force contract attempted to develop an encapsulated foam reactant system. To date, a total capsule operable system has not been achieved. Polyols and isocyanates have been encapsulated, but these encapsulated materials either release prematurely or not at all depending on the wall material and thickness. The intent of this program was to develop encapsulation technology to provide the capability of encapsulating any liquid polyurethane foaming systems. This all-capsule system would be initiated by thermally rupturing the capsules which should significantly reduce the total energy required to activate a predistributed foam system. NCR has developed a very good technique for rigidizing flexible polyurethane foams in space. This technique will be discussed later in this paper.

Monsanto Research directed their contract effort toward the development of a one-package composition which, in space environment, on localized thermal initiation would self-propagate a reaction to give a rigid polyurethane foam. Calculations and calorimetric measurements showed theoretical possibility of a self-propagating reaction from localized initiation. However, in practice this goal was not attained. This was due, it is believed, to heat transfer problems and inability to use efficiently all heat reaction liberated. Improved formulations were developed based on tolidine diisocyanate and polyoxypropylene polyols. These compositions, when thermally initiated under vacuum (2×10^{-5} torr), foam and cure to rigid foams. Initiation temperature and heat input requirements are somewhat better than previously developed formulations. One-package formulations, thermally convertible at atmospheric pressure to polyurethane foams, were also completed.[21] Figure 3 shows a Monsanto unreacted and reacted solid reactant foam.

Characteristics

Foam rigidized structures have several advantages; these are high ratio of expanded volume to unexpanded volume, puncture does not cause collapse, and foams are a good micrometeorite bumper material. Foams have a number of negative points. Currently it is nearly impossible to make quality foams in the high vacuum environment of space as previously discussed. Because of the poor cell structure obtained in current space foams, it is very difficult to determine effective design properties of these materials.

All current urethane or plastic foam systems require high inputs of thermal energy to initiate or sometimes maintain the foaming reaction. Severe and impractical power requirements would be imposed on a vehicle if other than solar energy were utilized to initiate this reaction. If solar energy is the thermal energy source, a technique such as turning the structure for shading would be required to provide on-command capability of initiation of the foaming reaction. Another major drawback to foamed-in-place structures is that the exothermic reaction of the foam system can cause creep in the lightweight mylar inflatable balloon structure utilized to provide accurate contour. In the case of solar collectors or antennae applications, changes of contour because of creep caused by the foam exotherm would negate utilization of the antennae or collector. Finally, foamed-in-place structures have a poor strength to weight ratios as compared with other expandable structures systems.

Applications

Foamed-in-place structures are applicable (when successful predistributed minimum exothermic foam formulations are developed) for solar collectors, antennae, space furniture, expandable micrometeorite bumpers, space shelters, and recovery of objects from space.

Required Advancements

Polyurethane predistributed foam systems should be developed which are capable of providing good quality predictable foam structures similar in quality to atmospheric foamed structures. The strength to weight ratio of

plastic foams need to be improved significantly. Figures 4 and 5 show strength properties of a mechanically mixed semi-vacuum foam developed by Goodyear Aerospace Corporation. These material samples were foamed under optimum conditions, thus, this data may be conservatively optimistic.

EXPANDABLE SELF RIGIDIZING HONEYCOMB STRUCTURE

Definition: Expandable self rigidizing honeycomb or sandwich structures utilize the chemical rigidization processes described in the rigidized membrane section of this paper to rigidize a three (3) dimensionally woven honeycomb or sandwich structure. The resulting rigidized woven structure is similar to conventional earth fabricated rigid plastic honeycomb structures.

Materials

This materials and structural concept was conceived by the author and Mr. S. Allinikov both of the Research and Technology Division. Currently there are two basic components involved in this system; these are a woven flexible three dimensional fluted core and the rigidization system.

Today there are several commercial sources available which produce various configurations of integrally woven core materials. Figure 6 illustrates the three (3) most common woven core configurations commercially available. The woven sandwich consists of integrally woven outer skins separated by woven separators. It is the separators that are the main variables of a configuration, as shown in Figure 6, there are truss web cores, vertical web cores, and drop thread cores available. Currently no weaver can integrally weave, what is considered the optimum configuration, a true honeycomb core and faces integrally woven. The types of cores commercially available can be easily obtained in heights of 1/8 to 2 inches in almost any weave and thread material. Currently fiberglass fibers are utilized for heavy duty space structures while nylon, dacron, and silk are utilized for lighter weight structural applications.

Viron Division of Geophysics Corporation of America has been awarded three (3) separate contracts to develop the expandable honeycomb concept. At the writing of this paper one of these contracts has been successfully completed. Archer Daniels Midland Company has been a prime materials sub-contractor on these efforts. These contractors have developed several types of rigidization systems capable of rigidizing the flexible woven sandwich material. Table 2 compares the physical properties of three (3) of these systems that have been developed to date.

Currently the most commonly utilized rigidization system, developed under Air Force contract, is a gas cured urethane. Archer Daniels Midland has formulated a new faster curing, higher strength, and lower shrinkage gas cured urethane system. A prepolymer containing a high netting index has been developed. This higher netting index creates a tendency for the unconnected polymer chains to interconnect and become more thermosetting. The higher netting index will also cause less polymer shrinkage during and after rigidization. Branched polyols possessing a high hydroxal equivalent were used to

obtain high strength and rigidity. The significant reduction in cure time was achieved by utilizing m-phenylene diisocyanate in place of the commercially available tolidine diisocyanate. This urethane system is rigidized by a gaseous mixture of mostly water vapor with a small amount of tri ethyelamine.[22] Typical properties, as shown in Table 2, for this gas cured urethane are fiberglass laminate tensile strengths of 27,500 psi, flex strengths of 25,000 psi and cure times of 15 to 30 minutes. Nonreinforced film strengths of this urethane are 15,700 psi which is exceptionally high for a urethane film.

Archer Daniels Midland has also developed a gas cured polyester resin system under the above mentioned contracts. Unsaturated polyesters diluted with reactive polyfunctional (di, tri, and tetra) acrylates have been utilized for vapor phase catalysis. These systems have been successfully cured by vaporizing volatile peroxides. Free radical accelerators have been mixed with the resin to reduce cure times. A peak exotherm of 145°F has been recorded with this system in about 8 minutes. Rigidization times of 30 minutes have been obtained with resulting properties of 47,000 psi in flexure.[23]

Archer Daniels Midland has also been able to develop a faster curing epoxy gas cured system. This system is capable of curing in about four to six hours and develops a flex strength of about 30,000 psi in a three (3) ply laminate.

Viron and Archer Daniels Midland, sub-contractors, have been awarded an Air Force contract to develop a gas cured gelatin rigidization system for expandable honeycomb. At the date of this writing this effort is only one (1) month old.

Plasticizer boil-off has also been utilized for rigidization of the woven core; however, this concept has been discarded because it is not a rigidize-on-command system.

Expandable Honeycomb Experiments

A more detailed discussion will be made on the experimental hardware programs of expandable honeycomb. These experimental hardware programs are in the following areas; micrometeorite resistance, solar collectors, and finally space shelter structures.

Micrometeorite resistance - The author had always anticipated that the expandable honeycomb would provide good micrometeorite protection because of its double wall construction. However, this was purely speculation. Thus, an Air Force in-house program was established to determine the effects of high speed particle impact on expandable honeycomb. The Air Force Materials Laboratory micrometeorite facility was utilized for these tests. Mylar discs, 1/8 inch diameter by .01 inch thick, were fired at velocities of 28,000 to 32,000 fps into solid 1/2 inch aluminum blocks which created a hemispherical crater about 1/8 inch in diameter in the aluminum, as shown in Figure 7. The same size particles were fired into a lightweight woven fiberglass gas cured urethane structure at similar velocities. Figure 7 shows the front and back

surfaces of one of these materials. The particle penetrated the outside facing creating about a 1/8 inch diameter hole; however, little damage to the fiber structure is caused to the rear face. The only visual damage to the rear face is very minor spallation of the urethane resin. This data is of course very preliminary and should be treated as so. Plans are underway to test various configurations of expandable honeycomb which are applicable to solar collectors and shelters. Micrometeorite tests are also planned to be conducted on stressed structures as well as unstressed structures.

Solar Collector Experiments

Under Air Force contract Viron Division of Geophysics Corporation of America has prepared a number of expandable honeycomb solar collectors. These solar concentrators have been constructed of the following components; inflatable aluminized mylar layup, magic coating, woven core, and rigidizing resin system. The aluminized mylar collector layups are fabricated similar to the Echo balloons, by seaming gores together. Goodyear Aerospace currently supplies the Air Force with accurate solar collector layups ranging from 2 ft diameter to 60 ft diameter. One mil aluminized mylar is utilized in the fabrication of these collector layups because of packaging considerations. The magic coating is then applied to the back face of the solar collector. A magic coating is a flexible plastic layer which prevents mark-off or show thru of the texture of the woven honeycomb core. Currently Viron uses a formulation of Epon 872-X-75, Epon 828, Epon Agent U, plus cab-o-sil and other solvents.[24] This formulation is sprayed over the mylar in several coats to a thickness of between 10 to 20 mil. This layer also prevents sharp permanent creasing of the mylar during packaging and storage.

The woven honeycomb backup core material utilized in fabricating solar collectors is a 1/2 to 1 inch high core which utilizes either geometric or random placed drop threads. These cores weigh between 2 to 8 ounces per square yard and are currently woven from either dacron or nylon. Cores have been woven from both mono filament and multi filament yarns.

To date all solar collectors have been rigidized with a gas cured urethane resin system. Solar concentrators have been successfully rigidized in vacuums up to 10^{-6} mm Hg with cure times of 30 minutes to 1 hour. Two (2) ft and five (5) ft solar collectors have been rigidized successfully to date. Figures 8 and 9 show a 5 ft diameter solar collector packaged and rigidized. This particular collector weighed about 0.3 lb/sq ft of projected reflector area. This year 2 ft and 10 ft diameter solar collectors will be rigidized under spatial conditions. The collector contour will also be checked before, during, and after rigidization. Next year expandable honeycomb solar collectors 10 ft and 22.25 ft diameter will be fabricated and rigidized under vacuum conditions. The 10 ft diameter collectors will have spherical end caps attached which will permit preliminary packaging and deployment tests.

SPACE SHELTER STRUCTURES

Viron has also under Air Force contract designed and fabricated several

space shelter structures. Figures 10 and 11 show the package size of a 7 ft
diameter by 8 ft high space shelter and the final rigidized shelter. This
shelter was designed to sustain internal pressures of 14 psia and weighed
less than 100 lbs. Viron also cured numerous half size models of this struc-
ture under atmospheric conditions. This year a limited war shelter, floor
plan 26 X 30 ft, will be air dropped, deployed, and rigidized. This shelter
is designed for 100 mph wind loads, and a roof load of 25 psf. In addition,
it is to have a floor inside of it capable of withstanding the wheel loading
of an aircraft. This shelter will be packaged into a 4 X 4 X 4 ft package
and will weigh about 3000 lbs. Erection and cure time will be less than two
(2) hours. Figure 12 is an artist's concept of this 26 X 30 ft Limited War
Snelter.

Finally, a program has been authorized to determine the feasibility of
fabricating, expanding and rigidizing a space station type structure from
expandable honeycomb. Figure 13 is an artist's concept of this space station.
This structure will be 10 ft diameter and about 25 ft long. The structure
will be divided into two compartments and will have floor running the entire
length of the structure. Figure 14 shows a cross section of this structure
and a typical wall structure. These structures will be deployed in a vacuum
chamber at 10^{-6} mm Hg pressure. Cure time will be less than one (1) hour.

Characteristics

Expandable honeycomb appears to have the highest strength to weight
ratio of any rigidized structure. It looks extremely promising for resisting
micrometeorite penetration, and even if it is punctured it will not collapse.
Finally it will work on the Earth as well as in space.

Applications

Expandable honeycomb can be utilized for solar collectors, space sta-
tions, extraterrestrial shelters, earth shelters, and possibly re-entry
vehicles.

Advancements Required

Many advancements must be made in order to permit designers to apply
expandable honeycomb to the above applications. First a new weaving machine
must be designed and fabricated which will weave three dimensionally honey-
comb and skins simultaneously. The development of a true honeycomb core
would certainly increase its strength to weight characteristics. Faster
curing resin system with long shelf life must also be developed. Finally,
research should be directed toward an expandable honeycomb system that would
be capable of surviving re-entry.

VARIABLE GEOMETRY STRUCTURES

Definition: Variable geometry structures otherwise known as unfurlable
structures are composed of a number of conventionally built rigid sections
that either hinge, spring, or telescope into shape.

Materials

The Aeronutronics Company and the Martin Company have studied telescoping space structures under Air Force contracts. The Martin Company determined that their structures are about 50% heavier than a rigid nonexpandable structure. The increase in weight is attributed to seals, bulkheads, and expansion mechanisms required in a telescoping concept. Normally conventional materials are utilized in the construction of telescoping structures which provides the designer with a high confidence level in the design of future vehicles.

Spring open type structures have also become interesting of late. The G. T. Schjeldahl Company is developing a unique spring open grid structure. Figure 15 shows one of these spring open structures packaged, being deployed, and fully deployed. This structure is composed of a grid of multi filament glass fibers coated with silicone rubber. This type of structure is very applicable to the passive communication satellite area. Its main advantage lies in the potential elimination of the plastic film required for inflating conventional wire grid structures.

Narmco and Goodyear Aerospace have developed a spring open structure utilizing the elastic recovery characteristics of a flexible polyurethane foam. Figure 16 shows a flexible foam structure collapsed and expanded. The foam structure is only utilized to spring the structure open and for a micrometeorite bumper. Goodyear Aerospace reports that flexible polyurethane foam is an excellent micrometeorite bumper material.[26] This type of structure is a nonrigid structure and is pressure stabilized. The actual load carrying part of the structure is either a woven fabric, or a filament wound structure with a flexible organic bladder inside to eliminate porosity.

The National Cash Register Company under Air Force contract has developed a chemical rigidization technique for rigidizing flexible polyurethane foam structures. A flexible foam structure is impregnated with a vinyl resin. An encapsulated aromatic amine can be utilized to cure the vinyl resin. The encapsulated catalyst can be released via small nichrome heating elements.[27] Cure times of ten (10) to twenty (20) minutes have been achieved under vacuum conditions for two ft diameter structures. This technique is currently being studied for solar collector and space shelter application.

Characteristics

The variable geometry structure's principal advantage is that it is entirely fabricated on the ground and can thus be inspected prior to launch. Telescoping or hinged structures usually only reduce the launch packages size in one direction. The spring open grid or flexible foam structures offer minimal structural integrity without pressurization.

Applications

Variable geometry structures have many applications. Telescoping or unfurlable structures can be applied for utilization as solar collectors, antennae, space stations, extraterrestrial shelters and re-entry vehicles.

The spring open grid structure's primary applications are in the passive communication satellite and decoy areas. The spring open flexible foam covered structure may be utilized for portable extraterrestrial shelters, space station rendezvous docks, and space vehicle crew transfer tunnels.

Advancements Required

Improvements in sealing techniques are required to bring variable geometry structures to an operational status. Research efforts should be directed toward improving chemical rigidization techniques of flexible urethane foams.

SIGNIFICANT EXPANDABLE STRUCTURES MILESTONES

A number of significant expandable structures milestones are now within the predictable future. Among these milestones are proposed space experiments on manned space stations, actual space stations, crew transfer tunnels, and re-entry vehicles.

Space Experiments on Manned Space Stations

Several experiments are planned to be conducted on future manned space stations. Basically these experiments fall into two (2) categories; space structures technology and recovery of space objects.

One experiment would consist of deploying from a space vehicle various expendable structure components such as solar collectors, antennae, and structural cylinders. Various types of structural components would be demonstrated; among these candidate structural systems would be expandable honeycomb, airmatt, and foamed-in-place structures. Most likely solar collectors of ten (10) to twenty (20) ft diameter would be utilized in these experiments. Contour accuracy would be checked by photometric techniques. In addition, thermal orbital profiles, strain rates, and leak rates would be monitored and recorded on board the space vehicle. Figure 17 is an artist's concept of a proposed expandable structures experiment. Another experiment that is in the planning stage would be the utilization of expandable structures materials for recovery of space objects. Various materials system could be utilized for this experiment; expandable foams, woven metal fabric structures, and possibly expandable honeycomb. Figure 18 is an artist's concept of this experiment being performed.

Crew Tunnel Applications

Several proposed space systems utilize existing re-entry capsules in conjunction with a space station cylindrical module. Unfortunately, the ingress and egress doors in these vehicles are mounted on the side of the vehicle which does not facilitate crew transfer without going extra-vehicular. An expandable crew transfer tunnel which would be packaged against the side of the vehicle during boost, but which would expand into shape once in orbit, could provide a shirt sleeve enclosed environment conduciv; for efficient crew transfer. **Figure 19 is an artist's concept of an expanded crew transfer tunnel.**

Space Station Structure

Many investigators have proposed launching into orbit an expandable space station.

Currently the Air Force under contract is building an expandable space station structure as previously shown in Figure 14. This effort is primarily a ground based vacuum chamber feasibility. Expandable structure technology has progressed to the level of being directly applicable to large space structure designs.

SUMMARY

Types of Structures

There are several classifications of expandable structures, these are; inflatable balloon, rigidized membrane, airmat, foamed-in-place, expandable honeycomb, and variable geometry structures. Figures 20 through 25 summarize these various types of structures, materials, applications, and characteristics.

RECOMMENDATIONS

The following recommendations are made:

1. Increase strength to weight ratios of expandable structures.

2. Increase shelf life of chemically rigidized systems.

3. Investigate in detail the effects of the space environment on all types of expandable structure systems.

4. Increase the temperature resistance of expandable honeycomb structure materials.

5. Improve the reliability of expandable structures.

6. Demonstrate the feasibility of expandable structures by orbital demonstrations.

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TABLE 1

PHYSICAL PROPERTIES OF A GLASS REINFORCED
PLASTIC LAMINATE HAVING POLYACRYLIC-GELATIN RESIN

Panel No	Barcol Hardness	Specific Gravity	Resin Content
1	62	1.87	32
2	61	1.90	32

TENSILE PROPERTIES

TEM °F	WT Hr.	E Million psi	STRESS PROP LIMIT 1,000 psi	MAX STRESS 1,000 psi	STRAIN MAX STRESS In. per in. x 100
Room	.....	6.37	14.8	45.6	0.80
150	:	5.41	15.2	40.0	....
	504	5.55	19.5	40.4	.77
275	.5	4.55	....	26.9	....
	10	4.30	27.0	34.7	.67
	1,000	5.46	16.1	5.5	.6

TABLE 1

(Cont'd)

COMPRESSIVE PROPERTIES

TEMP	DUR.	E	STRESS PROP LIMIT	MAX STRESS	STRAIN MAX STRESS
°F	Hr.	Million psi	1,000 psi	1,000 psi	In. per In. x 100
Room	.....	3.56	23.2	43.9	1.41
150	5	2.21	4.7	13.6	1.05
	504	3.11	19.7	27.1	.73
275	.5	1.64	1.2	2.3	.36
	50	3.70	21.2	31.7	.94
	1,000	3.50	16.5	37.5	.91

FLEXURE PROPERTIES

TEMP	DUR.	E	STRESS PROP LIMIT	MODULUS OF RUPTURE	WEIGHT LOSS	INTER SHEAR
°F	Hr.	Million psi	1,000 psi	1,000 psi	Per-cent	1,000 psi
Room	.....	3.58	34.7	64.3	....	7.1
150	5	2.74	17.8	*57.9	0.57	4.8
	504	3.01	28.7	49.8	3.29	3.9
275	.5	.68	2.6	* 7.2	.35	Rubbery
	50	3.26	27.9	51.3	3.45	4.0
	1,000	3.26	19.8	43.8	4.02	4.0

*The maximum load occurred at a large deflection. If the end thrust were taken into account, these modulus of rupture values would be increased by about 5 percent.

TABLE II

COMPARISON OF PROPERTIES OF
THREE GAS CURED RIGIDIZATION SYSTEMS

TYPE	CURE TIME	FLEXURAL STRENGTH OF FIBERGLASS LAMINATES
Gas Cured Urethane	15-30 Minutes	27,000 psi
Gas Cured Polyester	30 Minutes	47,000 psi
Gas Cured Epoxy	3-4 Hours	30,000 psi

Figure 2 – Echo II Satellite Structure
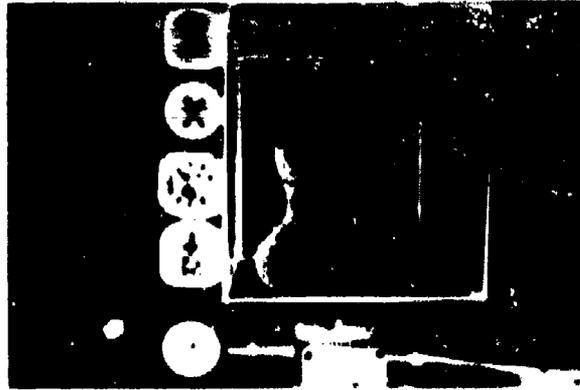
One "G" Foam
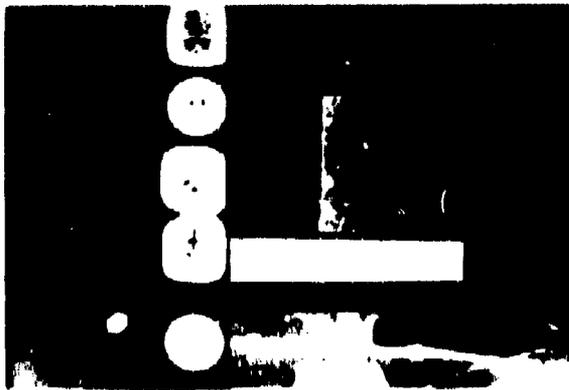
Zero "G" Foam

Figure 2 - Comparison of One "G" and Zero "G" Foaming

A

Unreacted System

B
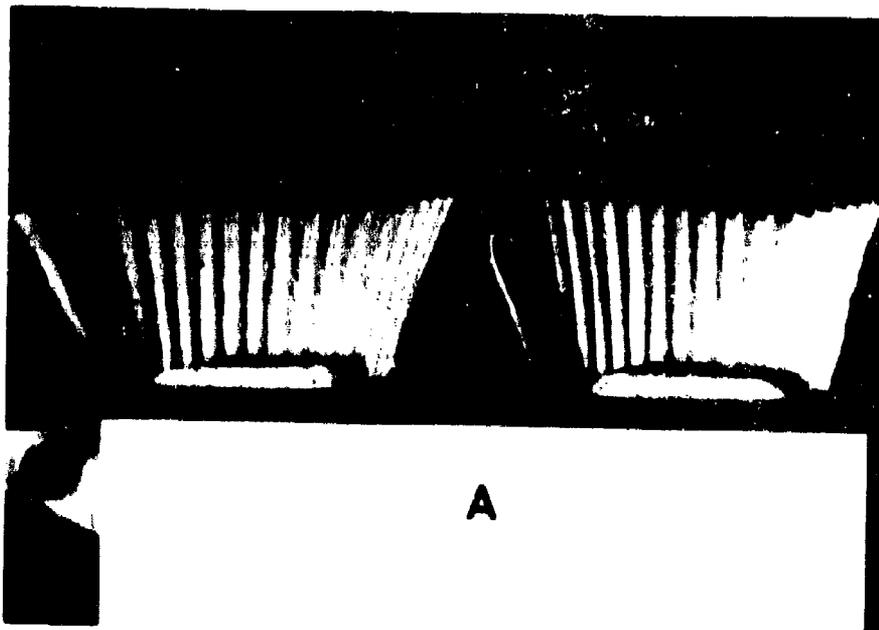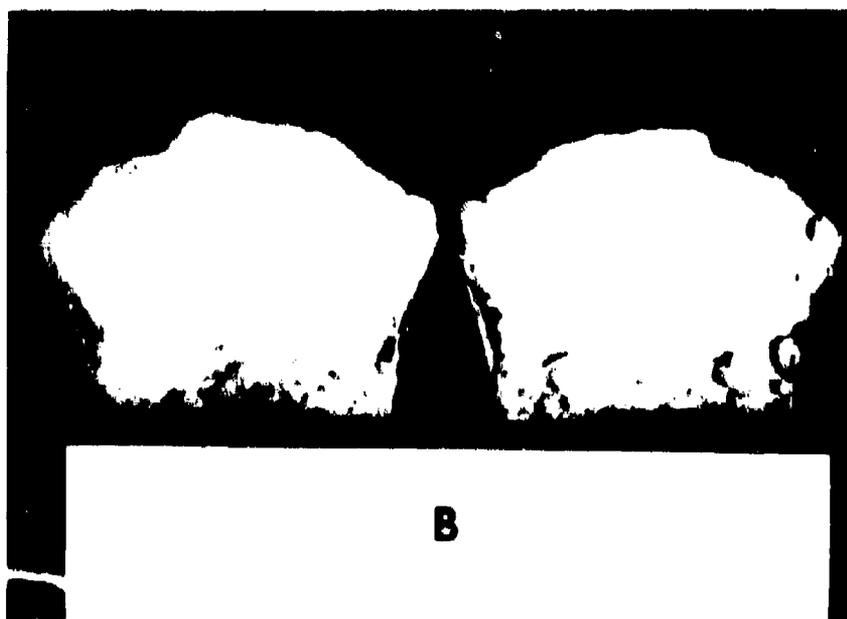
Reacted Foam System

Figure 3 - Solid Reactant Atmospheric Foam
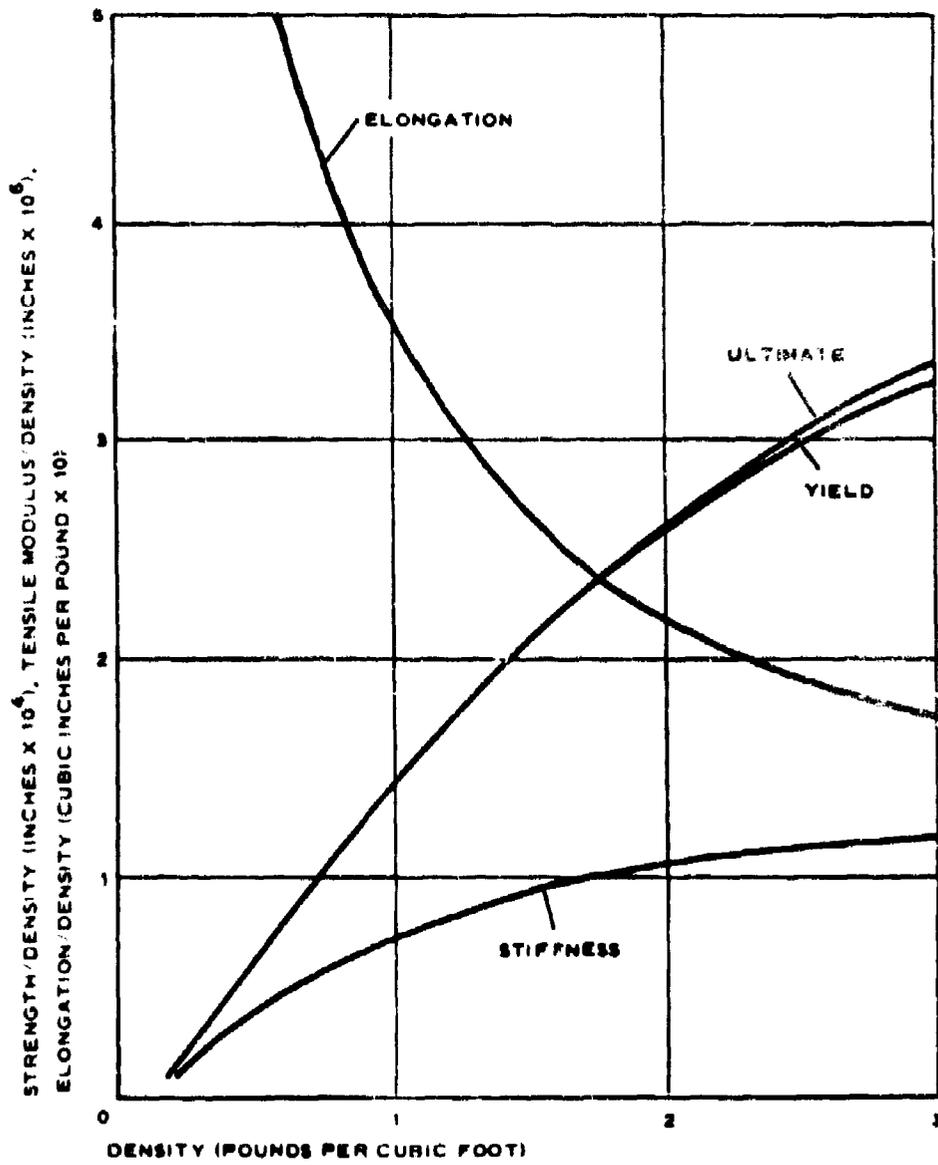
Figure 4 - Strength versus Density of Vacuum-Formed Polyurethane Foams
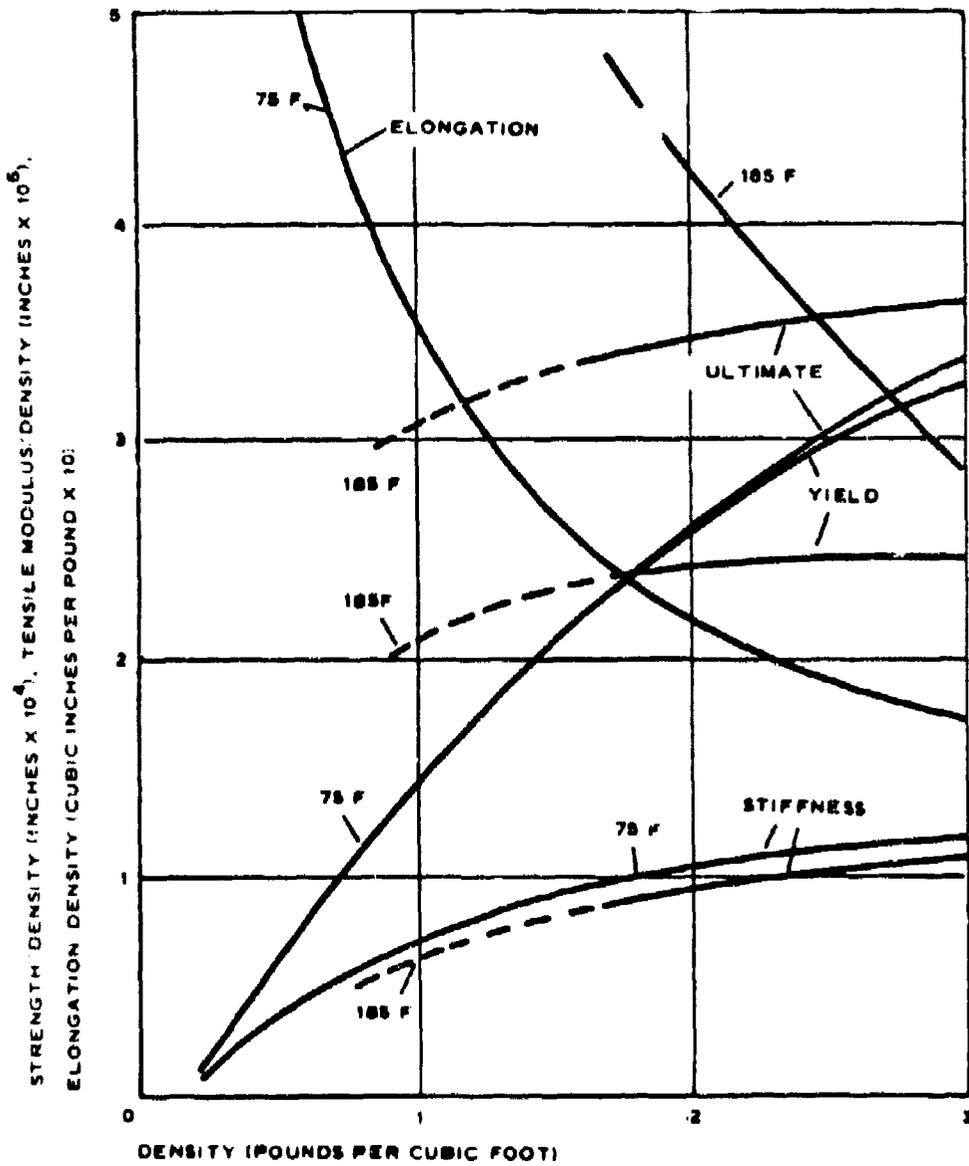
Reference (3)

Figure 5 - Strength versus Density at 75 and 185 Fahrenheit

TRUSS SANDWICH
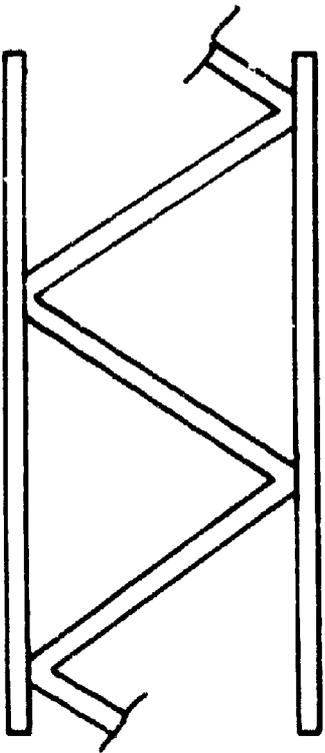
VERTICLE WEB CORE
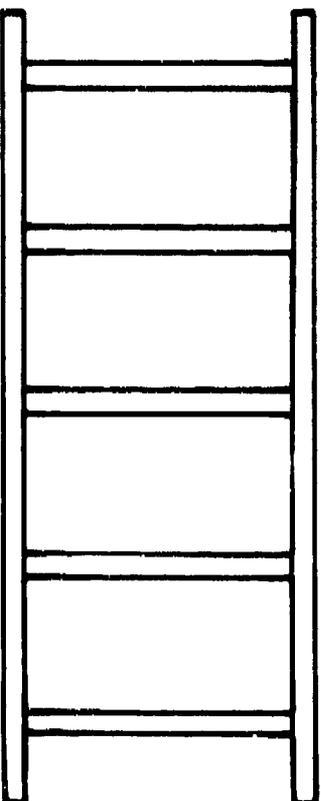
RANDOM DROP THREAD CORE
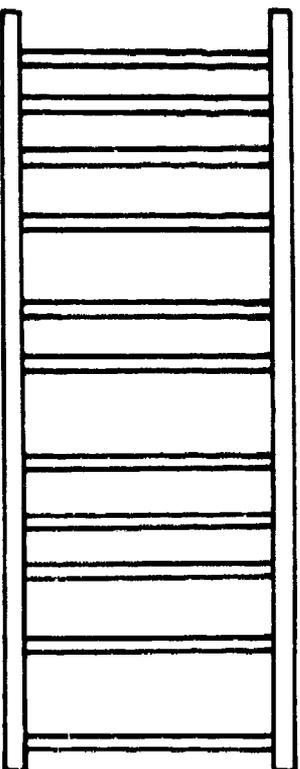
Figure 6 - Comparison of Three Common Commercially
Available Expendable Honeycomb Cores

Figure 7 - Comparison of High Speed Particle Damage to
Solid Aluminur and Rigidized Expandable Honeycomb Material
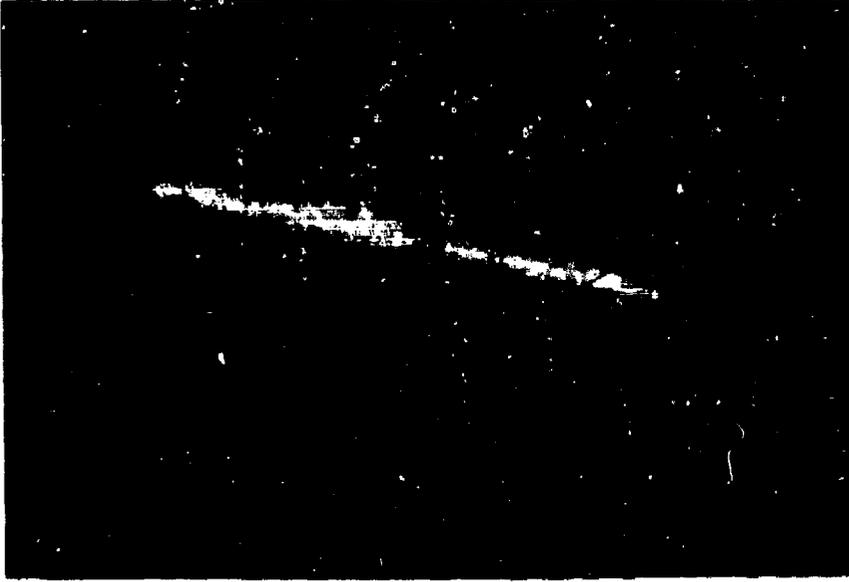
Figure 8 - Packaged 5 ft dia Expandable Honeycomb Solar Collector
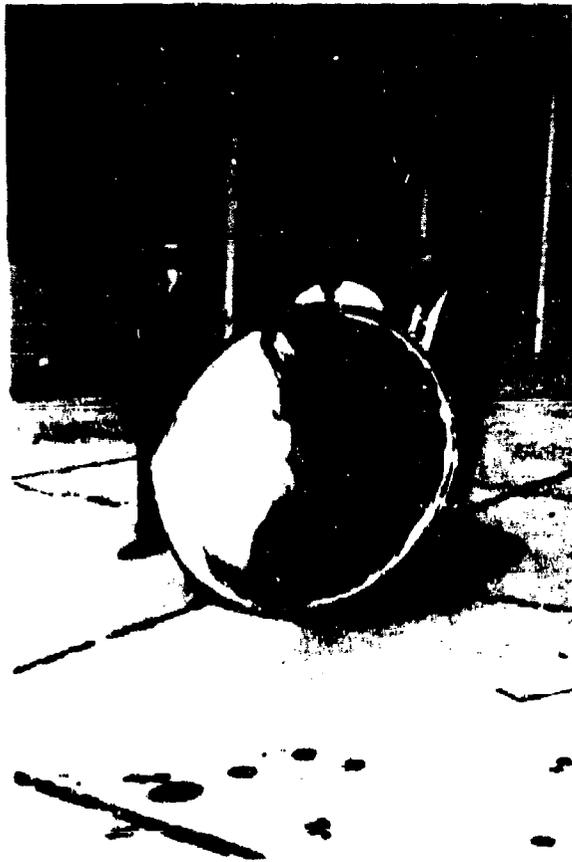
Figure 9 - Deployed and Rigidized 5 ft dia Solar Collector

Figure 10 - Packaged 7 ft dia Space Structure

Figure 11 - Deployed and Rigidized 7 ft dia Space Structure

Figure 12 - Artist's Concept of Expandable Honeycomb 26 x 50 ft Inflated air Shelter
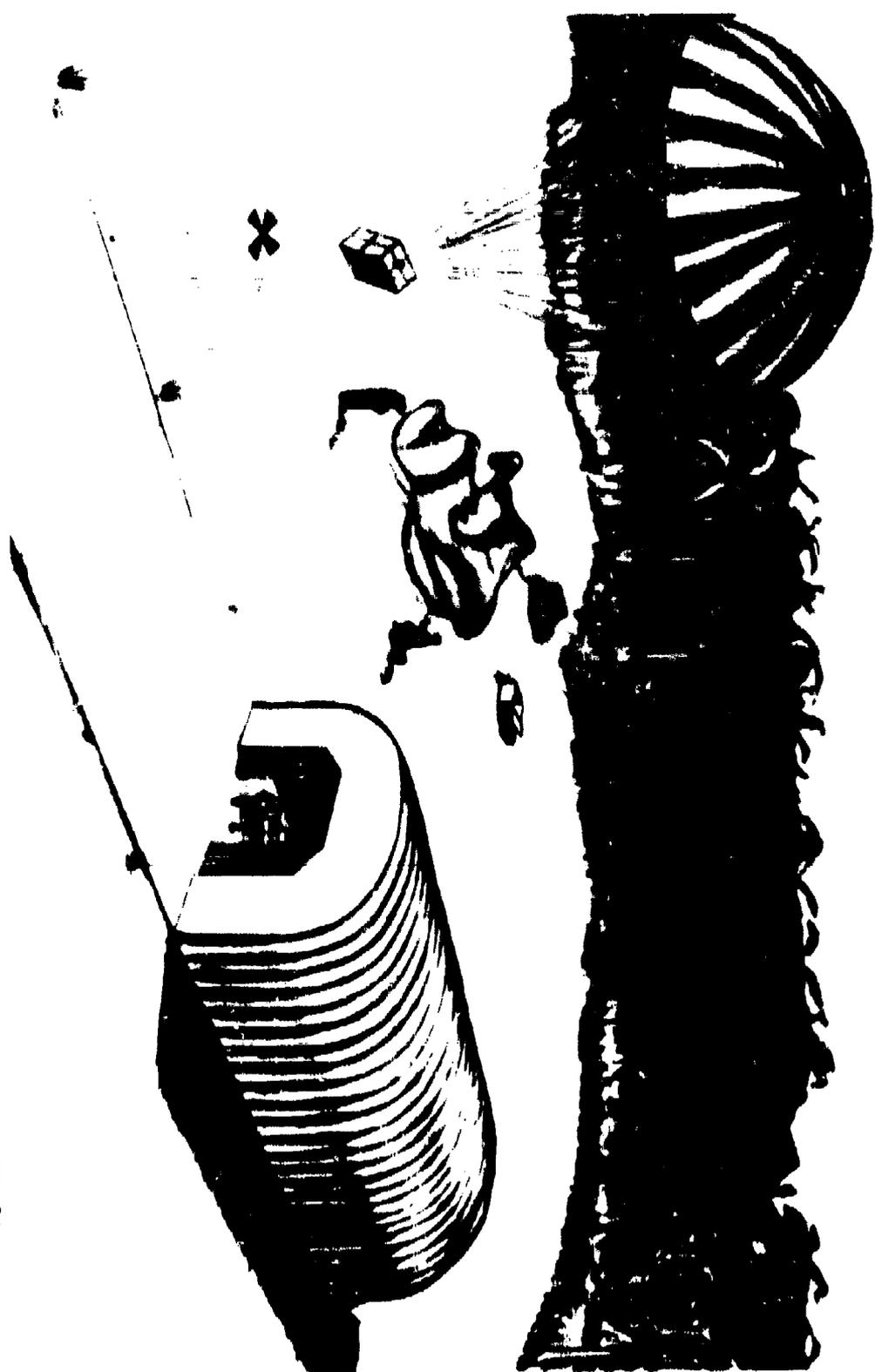
Figure 13 - Artist's concept of an Expandable Honeycomb Space Station

FLEXIBLE PLASTIC BLADDER

⅜ IN. FLEXIBLE FOAM LINER

2 IN. WOVEN FIBERGLASS TRUSS CORE RIGIDIZED WITH GAS CURED URETHANE

TYPICAL MATERIAL DETAIL

FORWARD RIGID BULKHEAD

CENTER BULKHEAD RIGID SECTION
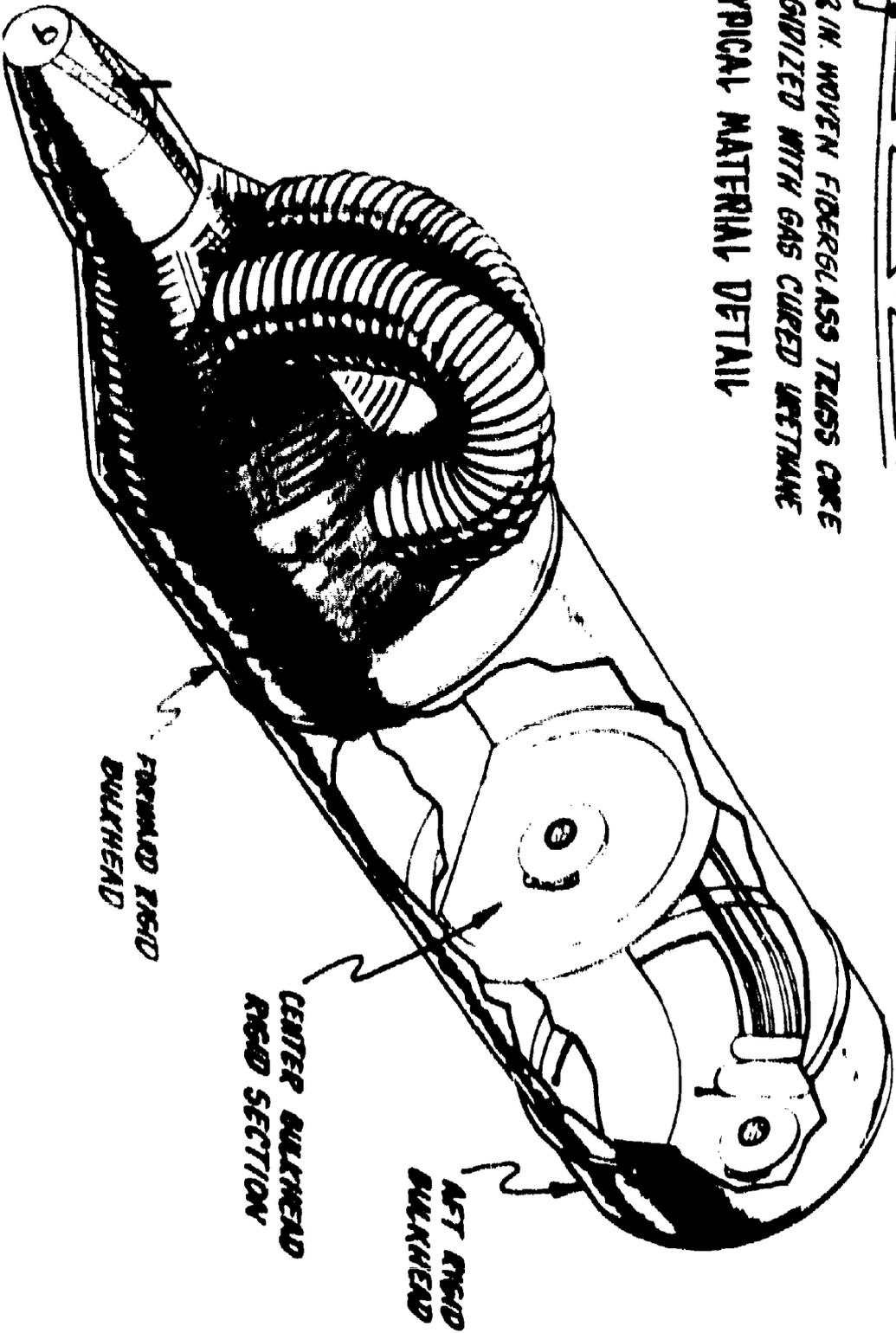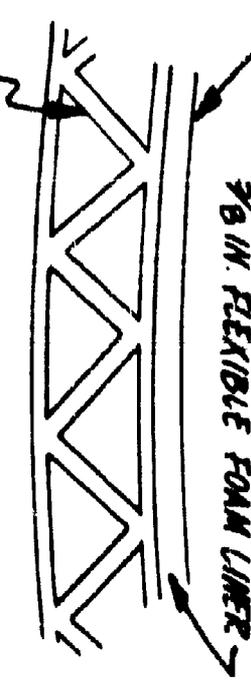
AFT RIGID BULKHEAD

Figure 15 - Spring Open Grid Structure - packaged, during deployment, and deployed
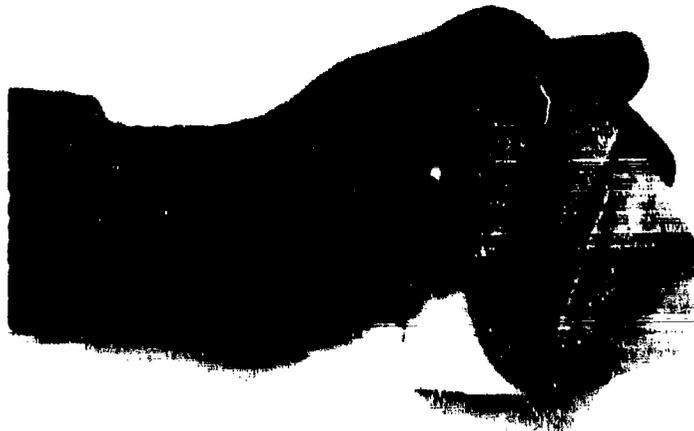
Collapsed Material Sample
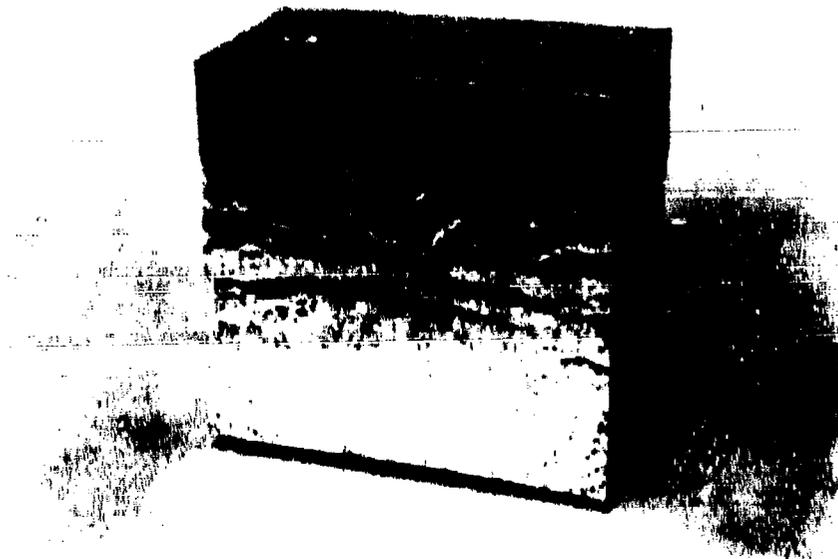
Expanded Material Sample

Figure 16 - Elastic Recovery Structure Compressed and Deployed
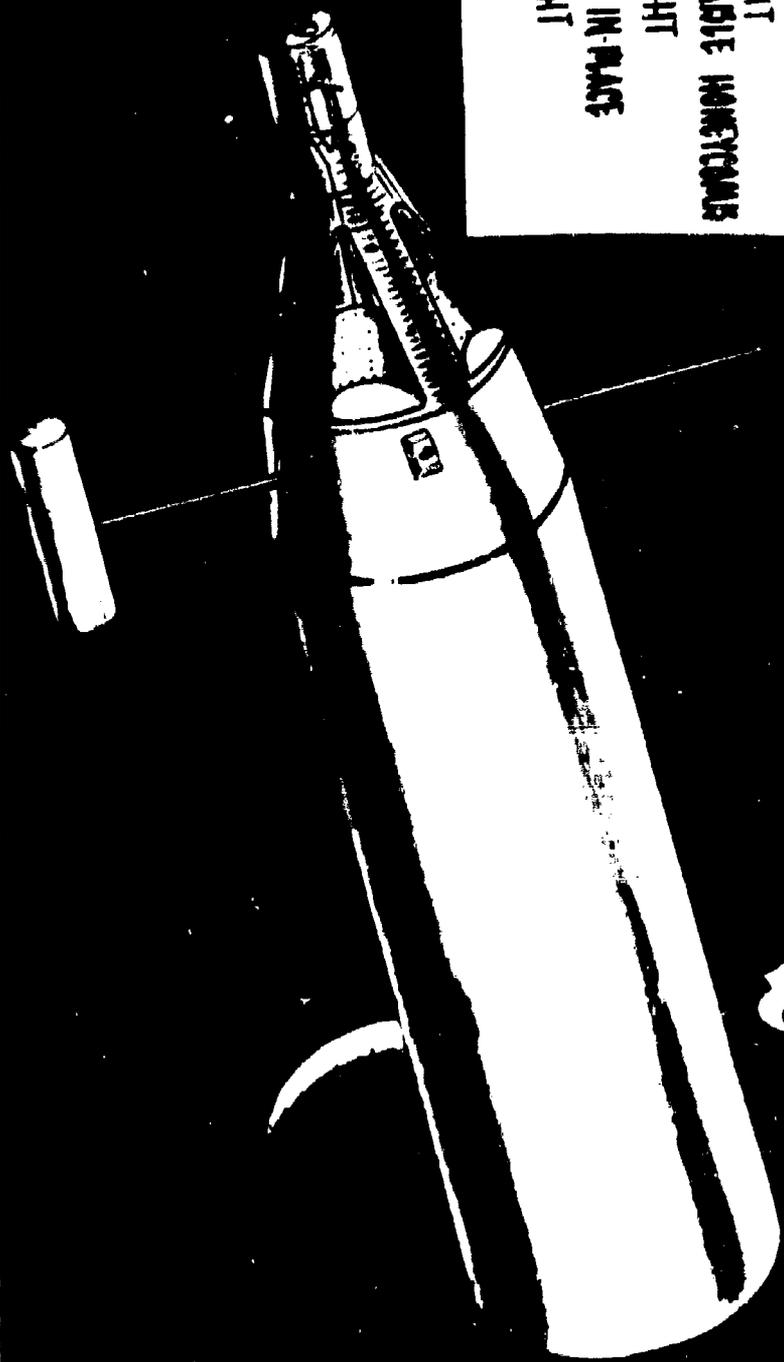
Figure 17 - Expandable Structures Space Experiment

Figure 18 - Proposed Space Object Recovery Experiment

Figure 19 - Artist's Concept of Expandable Crew Transfer Tunnel

INFLATABLE BALLOON STRUCTURES

DESCRIPTION: FLEXIBLE MEMBRANES EXPANDED and
RIGIDIZED BY INTERNAL PRESSURIZATION.

APPLICATIONS: ECHO I DECOYS, DRAG DEVICES, ANTENNAE,
SPACE MAINTENANCE HANGAR, ROCKING TUNNELS, PARAGLIDER

MATERIALS: MYLAR, POLYETHYLENE, H FILM, METALLIC FABRIC

ADVANTAGES: LT. WEIGHT, EASILY ERECTED, SMALL LAUNCH
PACKAGE, REUSABLE

DISADVANTAGES: LIMITED TO BODIES OF REVOLUTION,
PUNCTURE PROBLEM

Figure 20 - Summary of Inflatable Balloon

AIRMAT STRUCTURES

DESCRIPTION: STRUCTURE WHICH MAINTAINS ITS SHAPE BY DROPS THREADS and INTERNAL PRESSURIZATION

APPLICATIONS: INFLATAPLANE, SPACE STATIONS, RE-ENTRY GLIDER SHELTERS, DOCKING TUNNELS, MAINTENANCE HANGARS

MATERIALS: WOVEN FABRICS OR METALLICS, SEALED WITH ORGANICS OR INORGANICS (HI TEMP)

ADVANTAGES: LT. WEIGHT, SMALL PACKAGE VOLUME, HI-STRENGTH, ASSUME ANY SHAPE, REUSABLE

DISADVANTAGES: HI DEFLECTIONS, REF DEEP BEAM, GAS DIFFUSION PROB, AT HI TEMP, PUNCTURE PROBLEM

Figure 21 - Summary of Airmat Structures

RIGIDIZED MEMBRANE STRUCTURES

DESCRIPTION: INFLATABLE OR EXPANDABLE MEMBRANE STRUCTURE, BUT AFTER EXPANSION MEMBRANE RIGIDIZES

APPLICATIONS: RECOVS, ECHO II, SOLAR COLLECTORS, SHELTERS, SPACE STATIONS

MATERIALS: METALLIC FOILS, EXPANDED METAL MESH, PLASTICIZER BOIL OFF, V.V., INFRA RED, VAPOR CURED PLASTICS

ADVANTAGES: LT. WEIGHT, EASILY ERECTED, SMALL PACKAGE VOLUME, RIGID STRUCTURE

DISADVANTAGES: LOW BENDING RESISTANCE, NOT DOUBLE WALLED

Figure 22 - Summary of Rigidized Membrane

FOAMED IN-PLACE STRUCTURES

DESCRIPTION: INFLATABLE STRUCTURE RIGIDIZED BY FOAM REACTANTS

APPLICATIONS: SOLAR COLLECTORS, FURNITURE, SHELTERS, MICRO METEORITE BUMPERS, CLOCKING AREAS EMERGENCY RECOVERY UNITS

MATERIALS: POLYURETHANE FOAMS VIA MECHANICAL MIX, POWDERED FOAM REACTANTS, ENCAPSULATED FOAM REACTANTS, and SPRAY FOAM TECHNIQUES. OTHER FOAM AVAILABLE

ADVANTAGES: LT. WEIGHT MINIMIZES METEORITE DAMAGE, RIGID STRUCTURE, SMALL PACKAGE VOL.

DISADVANTAGES: MODERATE STRENGTH, HI EXTHERM, SHRINKAGE DURING USE, HI COEFFICIENT OF LINEAR THERMAL EXPANSION

Figure 23 - Summary of Foamed-In-Place Structures

EXPANDABLE SELF-RIGIDIZING HONEYCOMB STRUCTURES

DESCRIPTION: STRUCTURE THAT EXPANDS INTO A RIGID CONVENTIONAL HONEYCOMB STRUCTURE

APPLICATIONS: SPACE STATIONS, SHELTERS, SOLAR COLLECTORS, FURNITURE, RE-ENTRY DEVICES

MATERIALS: WOVEN THREE DIMENSIONAL FLEXIBLE FLUTED OR HONEYCOMB CORES, RIGIDIZED WITH ORGANICS OR INORGANICS VIA U.V., INFRA RED, PLASTICIZER BOIL OFF, OR VAPOR PHASE CATALYSIS

ADVANTAGES: U.V. WEIGHT, DOUBLE WALLED, RIGID, LOW REFLECTION, SMALL PACKAGE VOLUME

DISADVANTAGES: REFOLDABLE OR REPACKAGEABLE

Figure 24 - Expandable Self Rigidizing Honeycomb Structures

VARIABLE GEOMETRY STRUCTURES

DESCRIPTION: STRUCTURE THAT IS COMPOSED ON HINGED OR SLIDING RIGID ELEMENTS WHICH WHEN DEPLOYED FORM A RIGID STRUCTURE

MATERIALS: CONVENTIONAL ORGANICS and METALS

APPLICATIONS: SOLAR COLLECTORS, SHELTERS, SPACE STATIONS, RE-ENTRY VEHICLES

ADVANTAGES: MODERATE PACKAGE VOLUME, RIGID USES OFF THE SHELF MATERIALS

DISADVANTAGES: JOINTS ARE PROBLEM, HEAVIER THAN OTHER CONCEPTS, USUALLY ONLY LENGTH IS REDUCED IN PACKAGE STATE.

Figure 25 - Summary of Variable Geometry Structures