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Expanded Use of Inflatables Through New Materials

G.T. Schjeldahl Co.

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Abstract

This paper covers the latest advances made in laminate materials which have made possible heavy load carrying balloons, long duration flights without ballast, space communication satellites, and space inflatables. Scrim-reinforced plastic films have made possible balloons capable of carrying loads like the 14,500 pound gross of the Stratoscope II program and 7,000-pound gross of the Stargazer program, and at the same time permit shock-free static launches in 20 MPH winds. Bi-lam Mylar spheres have demonstrated 30-day flights at a constant altitude without ballast. The Echo II communication satellite is built of a 7-layer laminate material which is less than 1 mil thick, yet when this thin plastic is deployed in space, it becomes rigid enough to hold its shape against the forces of solar pressure, drag, and micrometeorites.

1. INTRODUCTION

The last three years have brought a number of significant advances in balloon technology, expanding the usefulness to heavier payloads, longer duration flights, and to space inflatables. The most significant accomplishments are 1) the 13,500 pound Stratoscope II balloon system, incorporating a cable restrained pilot balloon attached to a reefed main balloon and permitting shock free static launches in moderate winds; 2) the 34-foot diameter spherical balloons flown by Air Force Cambridge which carried a 50-pound payload at a constant altitude of 66,000 feet for a flight duration of 30 days; 3) the 100-foot diameter Echo I communication satellite placed into orbit approximately three years ago.

The high altitude research balloon has always relied to a large degree on the packaging industry. The polyethylene balloon came as a result of the carrot bag and the very thin films available today are a direct result of a competitive substitute for paper in the dry cleaning industry. Mylar and other high performance plastics are also an outgrowth of the demand in the United States for a better, stronger, and more attractive package for marketing products. The relatively limited amount of film consumed in balloon work and the high cost of development of a new plastic film capability has been a prime factor in limiting the industry to basic packaging materials.

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These basic films have served well for the early research flights of the 40's and 50's which were in most cases light payloads and relatively inexpensive equipment. Today, however, with the more complex requirements of our space age, such as expensive and complex telescopes and research equipment, requirements for better balloon control in air-space, and special payload handling conditions, the payloads are becoming heavier and the requirements for reliability are more important. These more complex requirements require a good deal of time and work to design and set up. Ideal flight conditions cannot always be obtained with respect to geographical location, time of day, season, or cost of field operations. The balloon system, therefore, must be capable of survival with a high degree of reliability.

The standard packaging films by themselves have not been able to satisfy these advanced requirements. However, through combining the properties of existing materials in such a way as to produce a hybrid material approaching the balloon designer requirements, some outstanding results have been achieved. We have designed a material to meet a vehicle requirement, we have not designed the vehicle around an existing material.

2. DISCUSSION

2.1 Heavy-Load Balloons

Under Contract with ONR, a study was established to develop a heavy load material with the following requirements:

1. High tensile and impact strength.
2. Low service temperature -100 C.
3. Absolute tear stopping properties at low temperature and room temperature.
4. Weight equivalent to 2-mil poly or less.
5. Forgiveness, a high degree of latitude in handling and fabrication to reduce the probability of fabrication defects and flight damage. It is impractical to consider that a large plastic balloon can be given 100 percent inspection and, of course, it is impossible to pretest the balloon prior to flight. Therefore, it is important to design the reliability into the basic material and balloon design.

This study resulted in what we call the GT-10, GT-11, and GT-12 laminates consisting of 1/4-mil, 1/3-mil, and 1/2-mil Mylar respectively, laminated to a 12 by 4, two ply fill, 220 denier Dacron leno with GT-301 adhesive system (Figure 1). This all-polyester film has thermal properties similar to Mylar with added tensile and tear strength (Figure 2). The GT-10 weighs the same per unit area as 1.8-mil

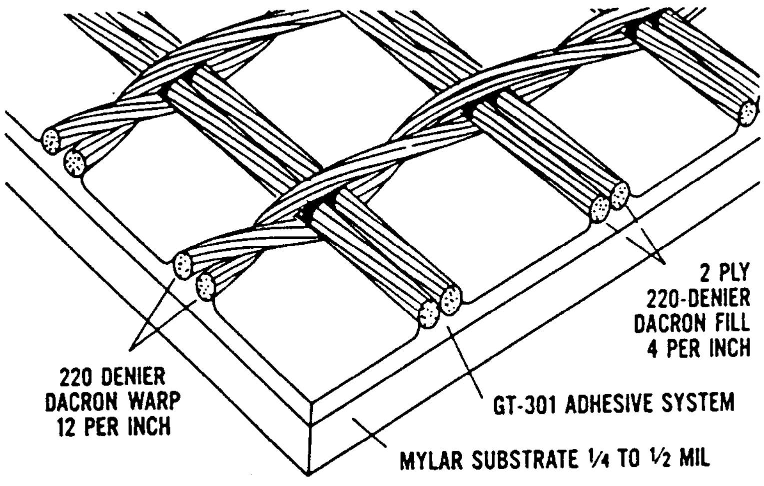

Figure 1. GT-10 Series Materials

	STRENGTH TO WEIGHT RATIO	TEAR RATIO
POLYETHYLENE	1	1
MYLAR	7	0.2
GT-10	17.2	40
GT-11	16.6	40
GT-12	15	40

Figure 2. Comparison of the Mechanical Properties of Five Balloon Films

polyethylene and has an ultimate tensile of 40 pounds per inch in the machine direction and 30 pounds per inch in the transverse direction. Seals can be made on this material which have the same strength as the film.

Other combinations of plastic films and woven materials were also investigated. However, this particular combination (Mylar-Dacron) resulted in the best balance of properties at a moderate cost. The substitute of less expensive materials, for example biaxially oriented polypropylene film, polypropylene fibers, rayon fibers, would reduce the cost of the material slightly; however, some loss in strength properties of the materials also resulted from the substitutions.

Although the GT-10 series material has been in existence only three years its records have been outstanding. Four of the five major telescope and camera flights are now being carried on GT balloons. Some 75 balloon flights have been made to date with no catastrophic failures in flight. These balloons have not been found to be sensitive to ascent rates, dynamic launches, high shears, or low temperature environments. Balloons built of these materials have carried payloads up to 11, 000 pounds and gross system weights of 13, 500 pounds. In the case of the Stratoscope II balloon system (Figure 3) the top balloon not only carries the gross system of 13, 500 pounds but also experiences an additional stress due to the superpressuring of the top balloon during gas transfer. This more than doubles the loading in the balloon skin.

Most balloon users today recognize the merits of the GT-10 balloon and would use them except for one factor: Cost. A GT-10 balloon sells for three times that of the tape poly balloon of the same size. However, I would like to emphasize that balloon costs alone are not a valid comparison in establishing which balloon is the most economical in a given application. Reliability, cost of a second flight, instrumentation calibration and possible loss, helium, flight operations, and most important, loss of valuable time on the part of the scientists should also be taken into consideration. In the case of most research flights, the operational costs of a second flight alone are greater than the cost of one GT-10 balloon.

A major part of the cost of these balloons is in the basic material. Polyethylene costs approximately 90 cents per pound while the Mylar used in GT-10 costs $3. 50 per pound and must then be processed by bonding to a woven fabric. The cost of these GT-10 balloons has over the past six months been reduced by a factor of 30 percent due to value engineering and a larger volume. The G. T. Schjeldahl Company is under contract with the Air Force Cambridge Research Laboratories for this value engineering and for the development of a lower cost material to extend the applications of these balloons to other programs. The present cost of the GT-10 series balloon along with the new non-woven material now being developed for Air Force Cambridge (GT-2929) are shown in the following table. (Figure 4) As volume increases through a broader use of these reinforced balloon materials, we expect the cost to be reduced even further.

Work is continuing on the recovery and reuse of these balloons. If provisions are made to reef or sleeve the balloon on descent, recovery with minimum damage is possible. Figure 5 shows a concept which is being evaluated for balloon recovery. The feasibility of recovery and reuse has already been demonstrated. Two balloons have been damaged in launch, repaired, and reflown. Two out of four 3. 2 million cubic feet GT-12 balloons flown at Holloman have been recovered and returned to the factory for inspection and repair. These balloons had no reefing sleeves or provisions for quick release of the gas on impact. They were merely picked up by the recovery crew in the field and placed in a large box with no protective sleeve.

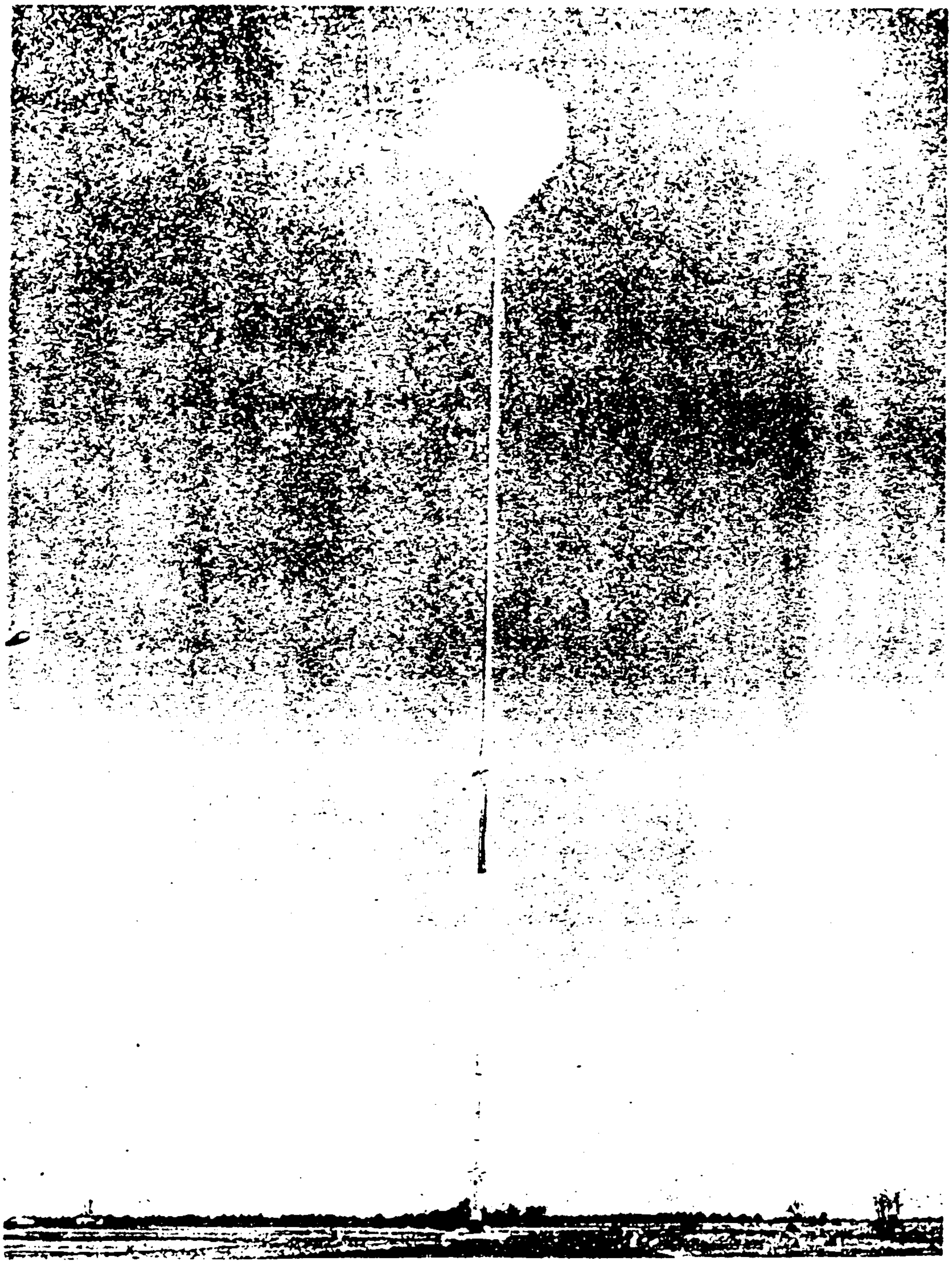

Figure 3. Stratoscope II Balloon System Ready for Launch

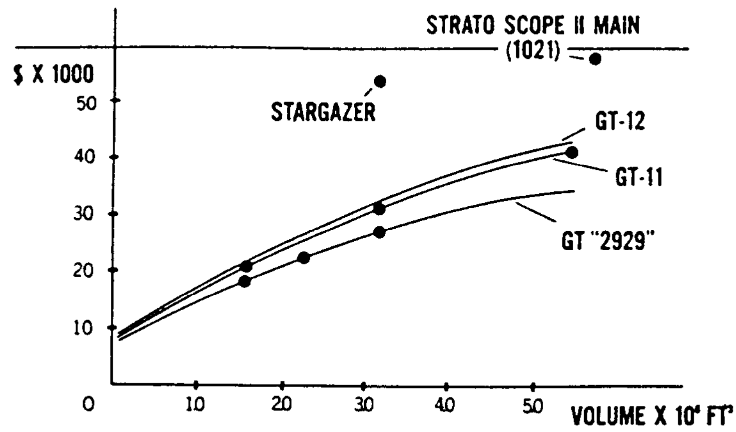

Figure 4. Balloon Costs for GT-Scrim Reinforced Balloons

3. SUPERPRESSURE SYSTEM

Materials development also played a very important part in the superpressure balloon program. Some success had been achieved with a plain Mylar sphere with flight durations of from two to ten days. In each case, however, the pressure in the sphere gradually reduced each day until the balloon descended. The permeability rate of Mylar balloons as determined from small model balloons indicate leakage and permeability rates which would permit flight durations of several months or longer. It appears therefore that the leakage problem is not due to the permeability of the Mylar, the seams, or the minimal handling given the small model balloons used in this evaluation. Rather the leakage is due to gross pin holes resulting from either a lack of quality control on the fabrication of larger balloons or developed from abrasion of the Mylar against itself.

In order to correct this problem the Schjeldahl Company developed a bi-laminate Mylar (Figure 6) which exhibited a high degree of abrasion resistance and appears to cancel inherent materials defects. This, coupled with a bi-tape seam gave a tight balloon system capable of flight durations of 30 days or longer. Air Force Cambridge Research Laboratories has flown a number of these bi-lam Mylar spheres with a high degree of success. One of these spheres, a 34-foot diameter made of a lamination of 3/4-mil by 3/4-mil Mylar carried a 50 pound payload to 66, 000 feet for a flight duration of 30 days. No ballast was used on this flight. The flight was terminated after 30 days on command indicating that even longer flight durations may be possible.

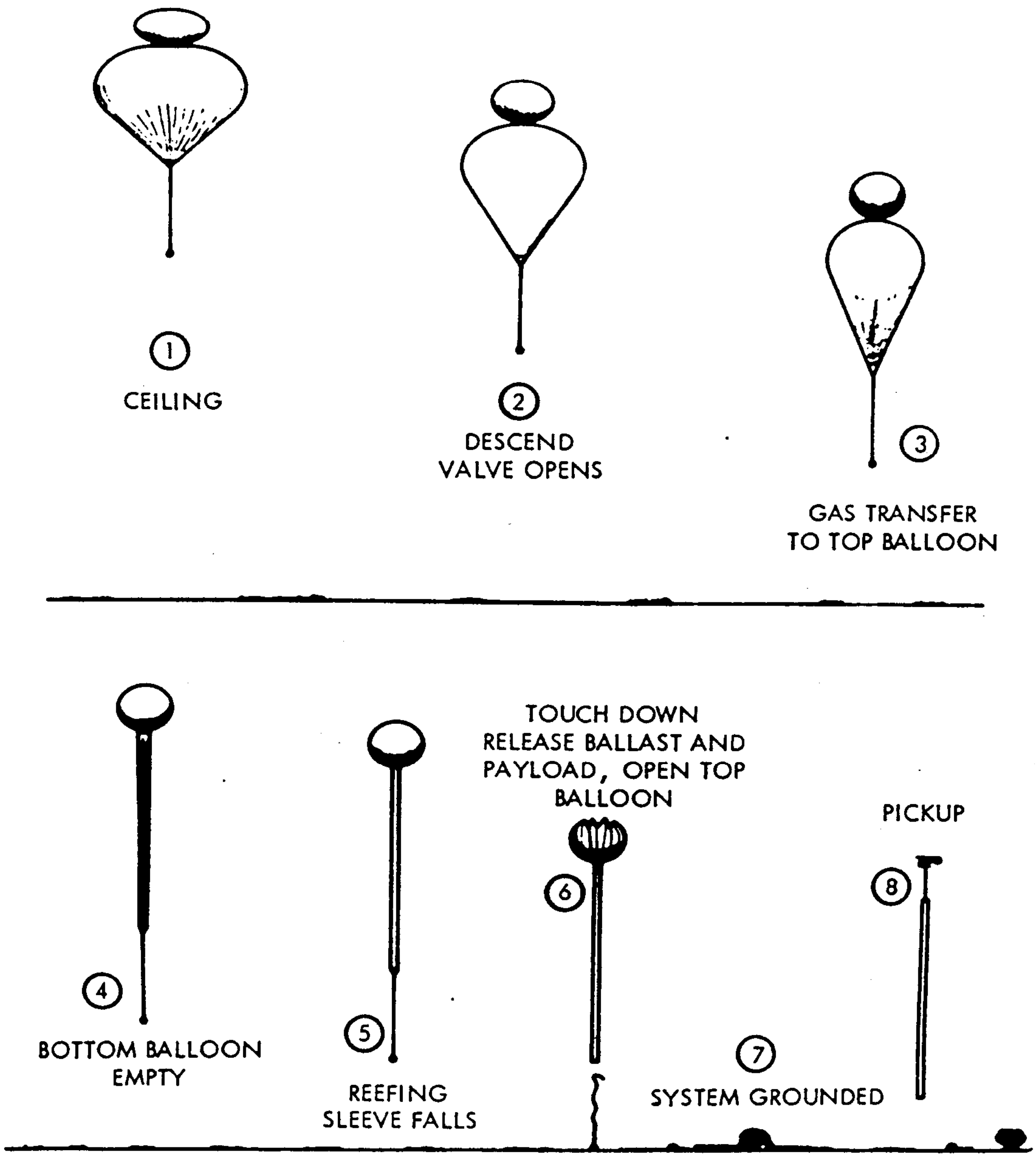

Figure 5. Schematic of a Two-Balloon Recovery System

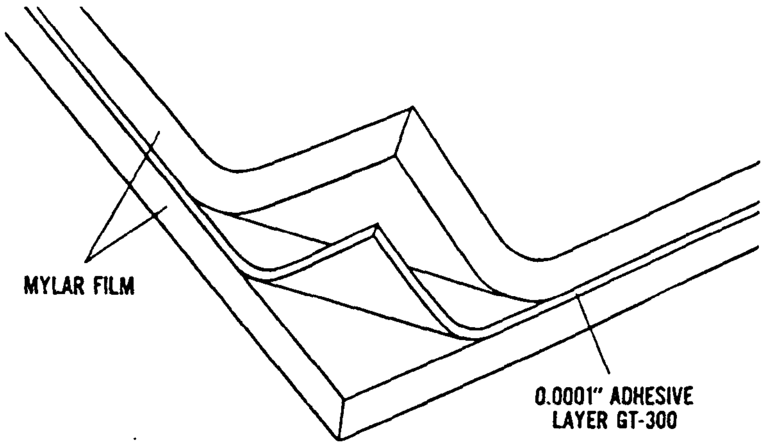

Figure 6. Bi-Lam Materials

With Mylar film available in various thicknesses from 0.15-mil, 0.25-mil, 0.35-mil, 0.50-mil, 0.75-mil, 1.0-mil, and so on, multi-layer laminations can be made to satisfy most balloon design requirements. Although at the present time the heaviest payload carried on a Mylar superpressure balloon has been approximately 80 pounds, heavier loads are within the capability of present designs.

4. COMMUNICATION SATELLITES

The Echo I communication satellite extended the use of the plastic balloon from the stratosphere into space orbit. Echo I was an inflatable sphere 100-foot in diameter made of 1/2-mil metalized Mylar. The aluminum thickness on this sphere was approximately 2,500 angstroms, or equivalent to approximately 4 pounds of aluminum on the entire surface of the 100-foot diameter sphere (Figure 7).

Before launching, 10 pounds of benzoic acid and 20 pounds of anthraquinone were inserted into the deflated sphere. The balloon was then folded accordion fashion and placed inside a 26.5-inch diameter magnesium container which carried this sphere into orbit. Two minutes after the payload was injected into orbit the magnesium container was separated by an explosive charge and the benzoic acid expanded to inflate the Echo I sphere into a spherical shape. The antraquinone provided a progressive subliming inflation material to keep the sphere inflated for approximately seven days, even though micrometeorite punctures of approximately 0.5 square inch per day were expected.

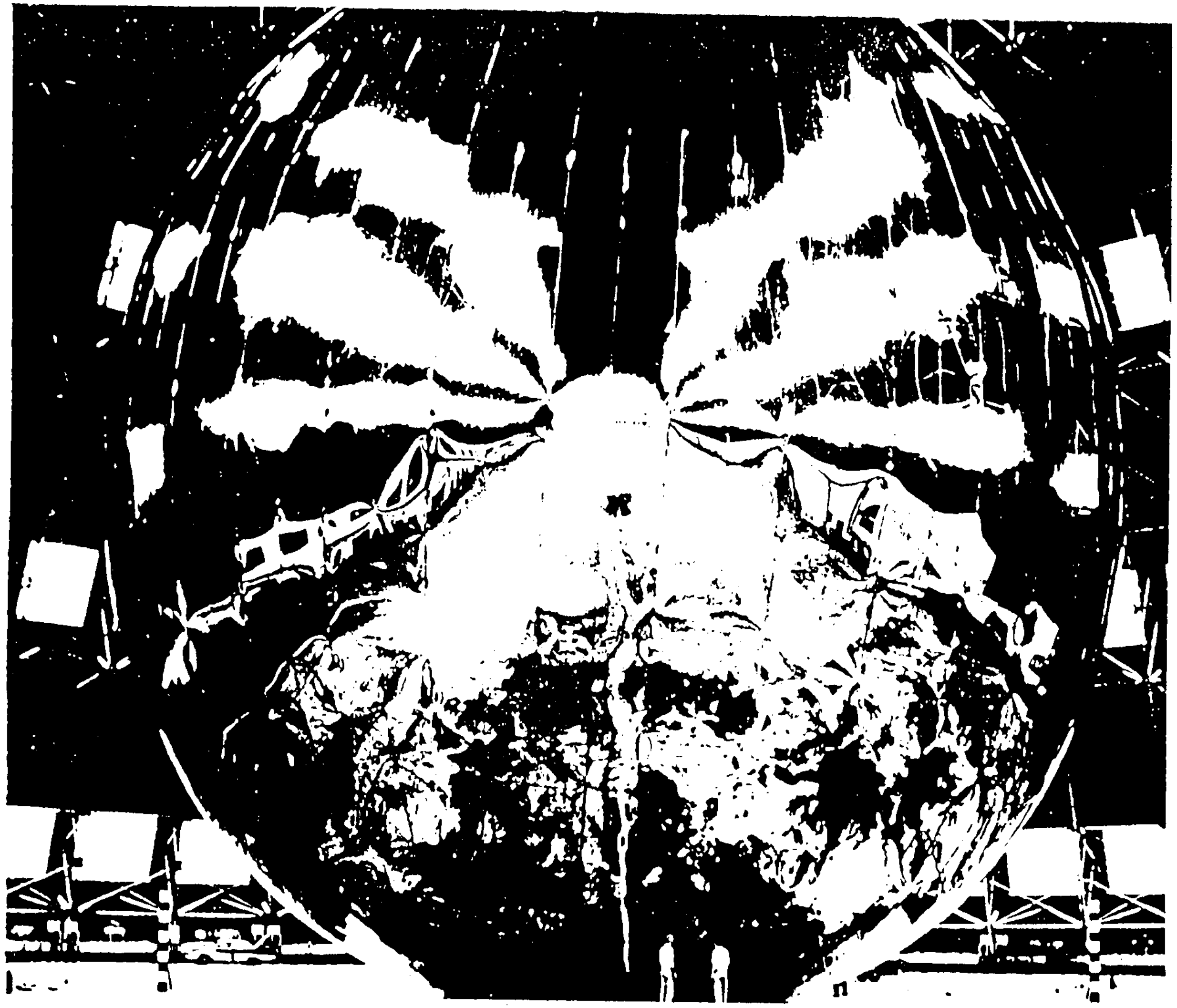

Figure 7. Static Inflation Test Echo I. Sphere, 100-ft diameter, of .0005-in. thick metalized Mylar and sealed with Schjel-Bond 301.

Echo I has performed well as a communication satellite research tool. It is believed that the skin of the Echo has become somewhat wrinkled due to the effect of the deforming forces of solar pressure, electrostatic drag, and micrometeorite punctures. However, the satellite is still being used for communication experiments after three years in orbit.

As a result of the success achieved with Echo I, a program was undertaken to develop the 135-foot diameter Echo II or A-12 sphere designed to have twice the cross-sectional area of the Echo I and to be rigid enough to withstand the deforming forces of space. Again the problem which faced the balloon designer was finding a material which 1) was exceedingly light weight, 2) could be packaged in a minimum space, and 3) then deployed and rigidized in space. The result of this study was a seven-layer material approximately 3/4-mil thick (Figure 8). This material is basically a lamination of 0.00018 inch thick aluminum foil on both sides of 0.00035 inch thick Mylar. In order to control the inflation material (acetamide) and keep the temperature of the sphere within that which the acquisition beacons would operate, it was necessary to thermal balance treat the inside and outside surface of this material. Alodine 401-45, an inorganic chemical treatment of the aluminum, was used to increase the emmissivity of the outside surface from 0.02 to 0.18. The inside surface of the sphere was coated with a carbon black to increase the heat transfer from one side to the other thereby helping to control the temperature gradients and reduce hot spots.

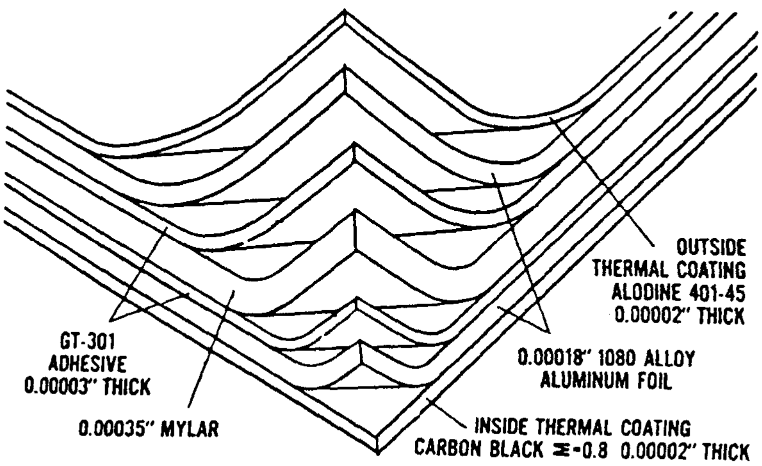

Figure 8. Echo II Lamination

In Echo I the Mylar exhibits a memory to the folds generated in packing the sphere into the canister. In the Echo II material these folds are removed when the sphere is deployed and the skin stressed to the yield point of the aluminum foil. The aluminum, being dead soft and having a higher modulus than the plastic, maintains and rigidizes the spherical surface. The stress-strain characteristics of this lamination are shown in Figure 9. As can be seen by this curve, the material must be stressed to approximately 4, 500 psi to reach the yield point of the composite laminate. However, through model tests it was determined that a stress of 2, 000 psi would remove the wrinkles in sufficient degree to satisfy the reflection requirements of the Echo experiments.

This seven-layer lamination was calculated to be approximately 50 times more rigid than the Echo I satellite, even taking into account that the measured rigidity falls to approximately one-third that computed for this material, based on the bulk modulus of the components. A number of testing techniques were used in evaluation of the rigidity of this material including taper or deflection tests, diaphragm tests, hemispherical deflection tests, and cylinder compression tests. Testing of a material of this type is not easy, since small wrinkles or imperfections in the surface being measured often exceeded the thickness of the material and therefore influenced the results. The cylinder test, however, appeared to give the most consistent results and was considered a standard for evaluation of materials (Figures 10 and 11) . The discrepancy in rigidity observed from these tests was believed to be from the aluminum foil. The ability to produce an aluminum sheet 54 inches wide to a thickness of 0. 00018 inch is a significant advancement. It is believed that small pin holes and imperfections in the rolled sheet accounted for this discrepancy in the modulus. It was impossible to run strain curves on the aluminum itself as the samples tended to tear well before reaching the yield point of the aluminum.

The Echo II satellite has completed all of its qualifying tests and is presently ready for shooting into orbit early next year. Figure 12 shows the Echo II satellite during static inflation tests at Weeksville, North Carolina.

Concurrent with the work on Echo II, the Schjeldahl Company has been engaged in advanced materials for space inflatables. One of these programs with NASA has resulted in the development of a lighter weight, rigidizable material for larger passive communication reflectors. Studies conducted by NASA have shown that, for an operation communication satellite network, a 425-foot diameter sphere will be required to give adequate band width for one television channel.

The feasibility portion of this materials study has been completed and prototype spheres are now under evaluation. This material, like Echo II, is a lamination of plastic and aluminum (Figure 13). The plastic in this case is biaxially oriented polypropylene with a tensile strength of 30, 000 psi in both directions and a density of 0. 92. Polypropylene was chosen because of its high strength-to-weight ratio

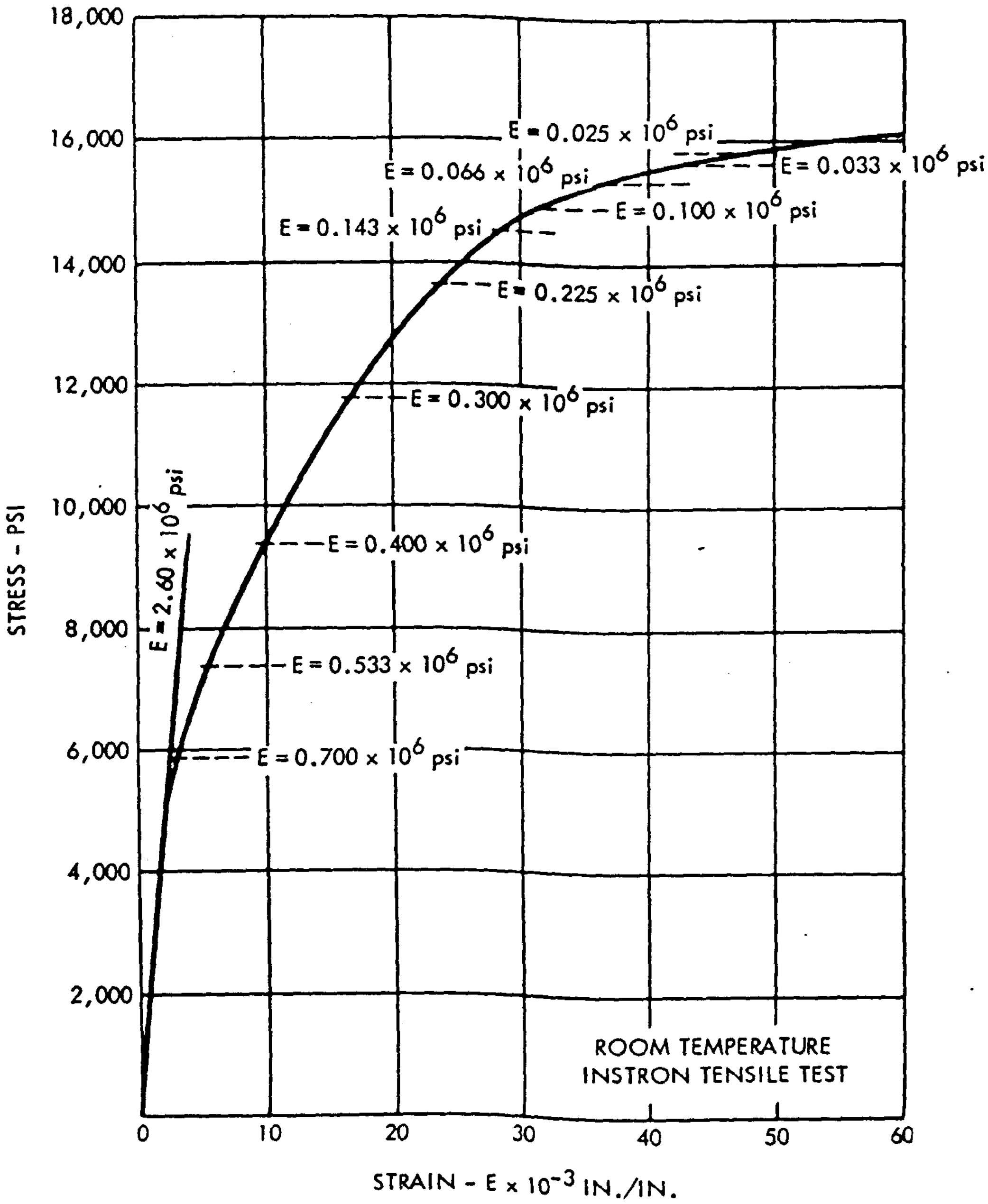

Figure 9. Stress-Strain Curve for X-15 Laminate

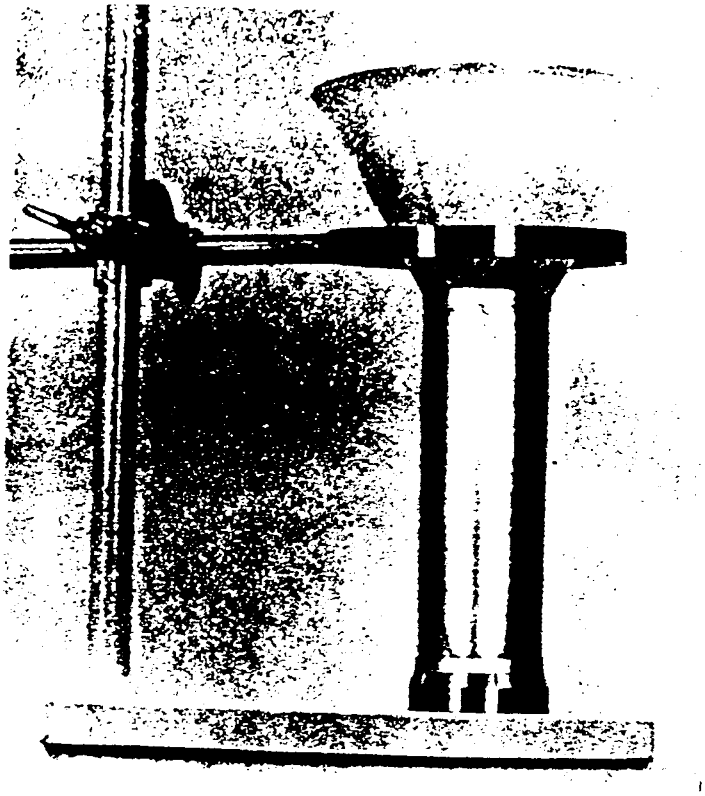

Figure 10. Cylinder Compression Test

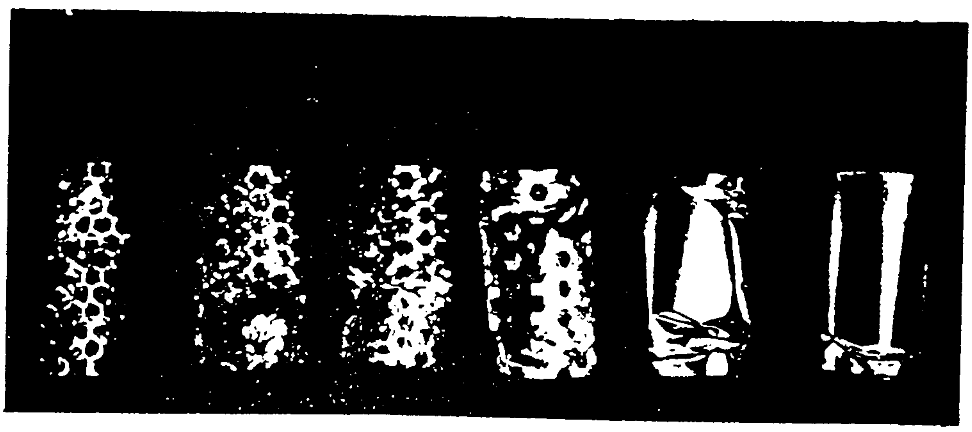

Figure 11. Pictorial Results of Cylinder Compression Test

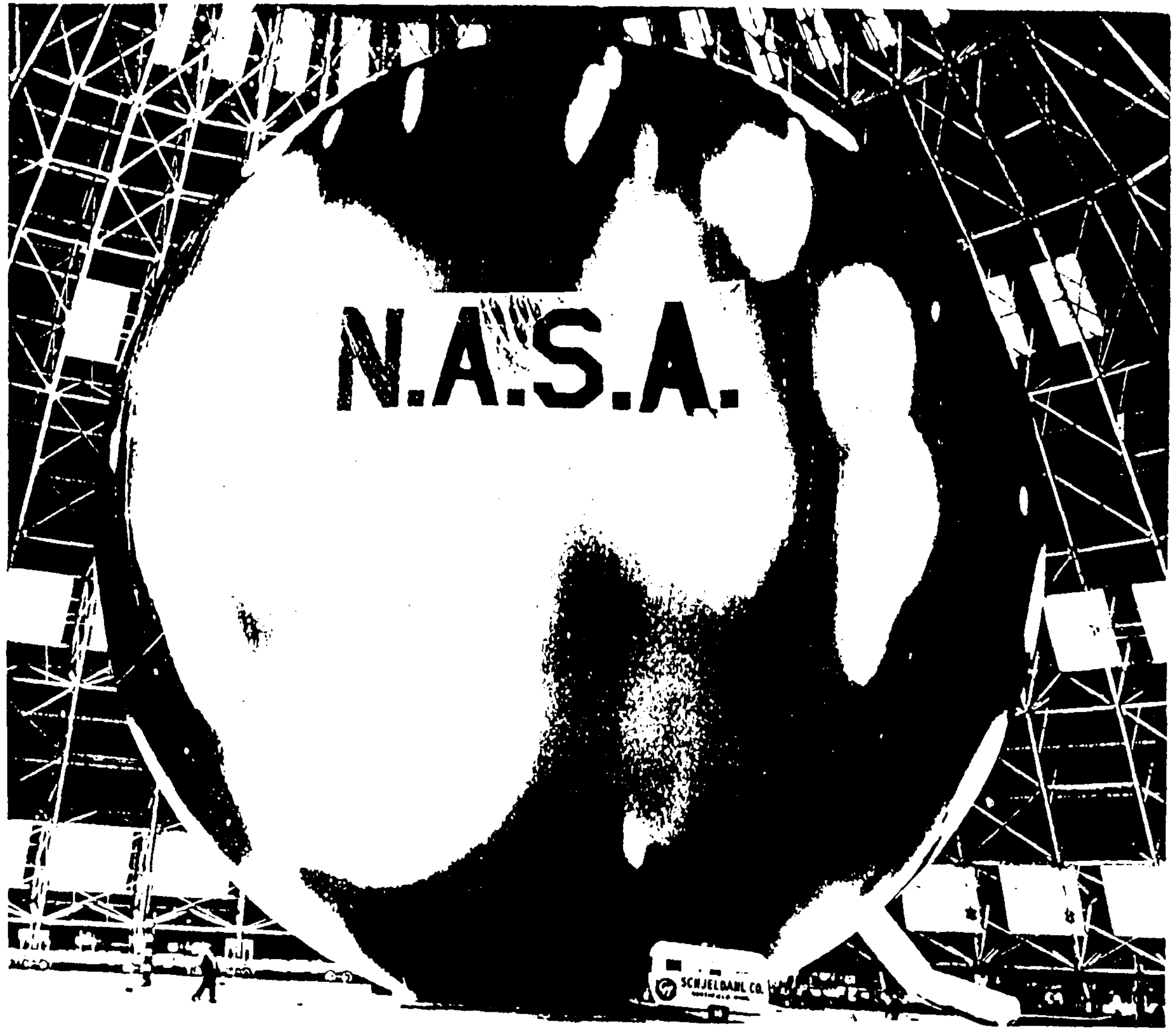

Figure 12. Static Inflation Test Echo II. Sphere, 135-ft diameter, of .00018-in. thick aluminum foil on both sides of .00035-in. thick Mylar bonded with Schjel-Bond 301.

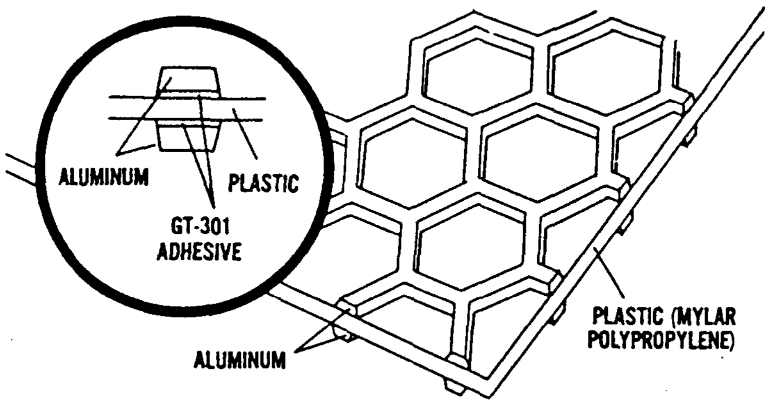

Figure 13. Advanced Material for Rigidized Communication Satellites

and its resistance to discoloration in a space environment. The aluminum in this case is milled out in a hex pattern to 1) reduce the satellite weight, and 2) allow 90 percent of the solar energy (1.3×10^{-9} psi) to pass through the satellite and therefore reduce the required rigidity.

Further study to reduce the weight of these communication satellites is presently under study. One technique employs a lenticular shape reflector which is oriented by means of gravitational gradients (Figure 14). This system has a potential of reducing the weight of a given reflector by as much as 40 percent. Also by using solar reflective and absorbing coatings and passing a current through the torus it would be possible to change the orientation of the reflector when it is not in use. This can be used as a station keeping function or it might be used to move the satellite into a higher orbit.

Each of these balloon applications has been made possible by 1) availability of a wide range of packaging materials in this country and 2) a decided effort by the balloon engineer to make use of the materials or combination of materials he has at hand. As I said earlier, first establish the design requirements, temperature, strength, tear, permeability, and so on, then choose the material which best meets these requirements. If one does not exist, do not be afraid to combine or modify these materials to give the desired results. This may be contrasted with the approach of designing the system around a material.

It is not possible here to go into all of the new materials developed or being developed for inflatables. I will therefore list only a few of the programs in existence or being considered for inflatables.

1. ROBIN - A one-meter diameter sphere containing an octahedral corner reflector which is ejected from a rocket nosecone at 250,000 feet and used to determine meteorological parameters from 250,000 feet down to 100,000 feet.

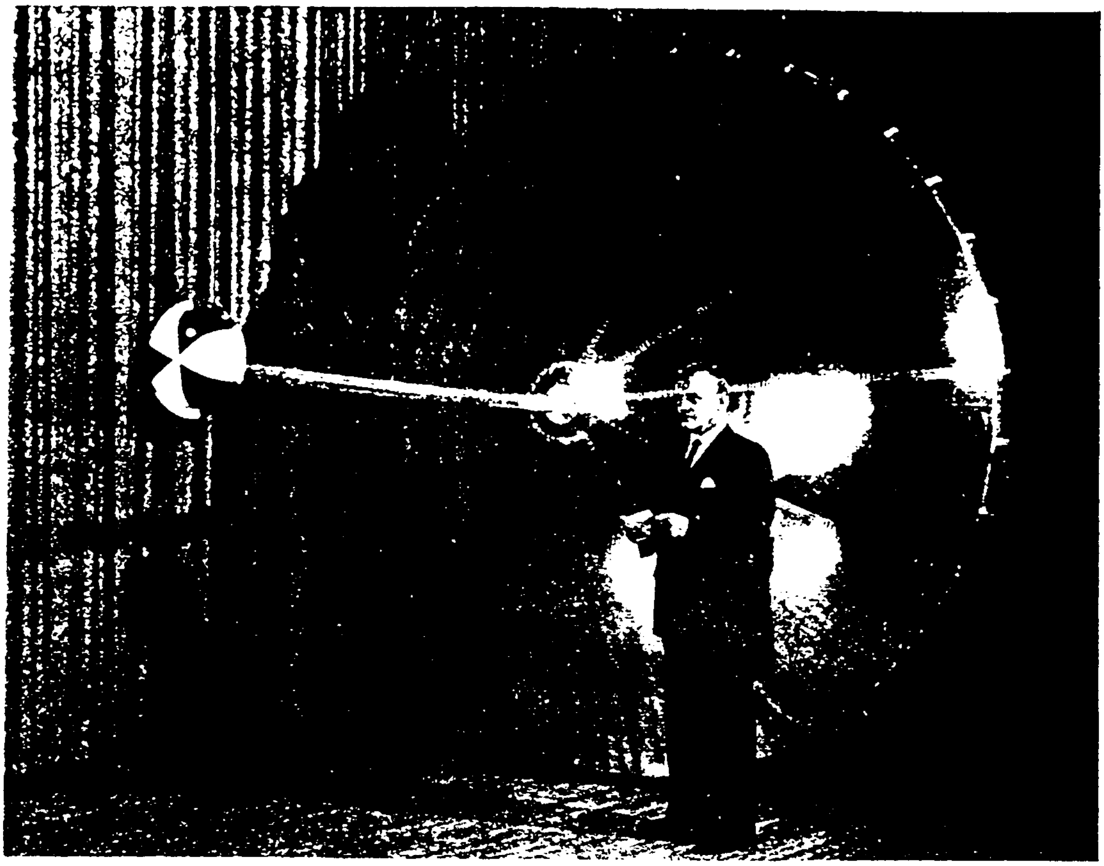

Figure 14. Lenticular Shaped Reflector

2. Targets or decoys which are carried aloft in a rocket nosecone and then ejected and inflated (Figures 15 and 16). The canisters, inflation mechanisms, deployment, and inflatables used in these programs have been thoroughly evaluated and in some cases are presently in production. These systems use either RF reflective materials with a plain plastic backing or systems which will rigidize when erected in space.

3. Antennas - Space inflatable antennas are another ideal application for inflatables. (Figure 17) The ability to pack these inflatables in a minimum space and their light weight requiring a minimum torque moment to orient, are important factors.

4. Solar Concentrators and Solar Cell Arrays - Some work on inflatable solar concentrators has been done although the main problem still is obtaining high efficiency. To date we have achieved approximately 50 percent efficiency from an inflatable and rigidizable concentrator. Inflatable mattresses can also be used to deploy and serve as a rigid mounting for solar cell panels.

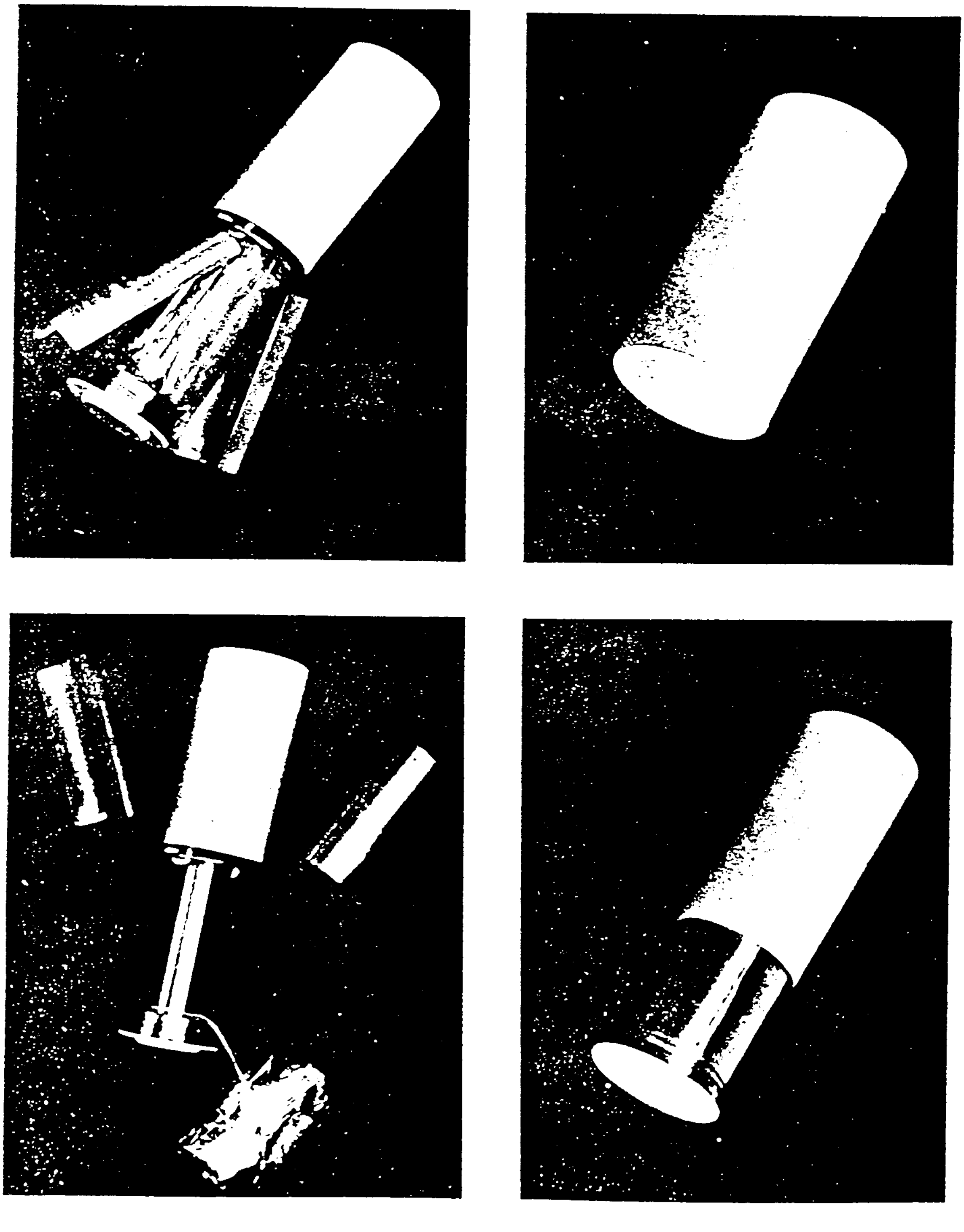

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Figure 16. Space Inflatables

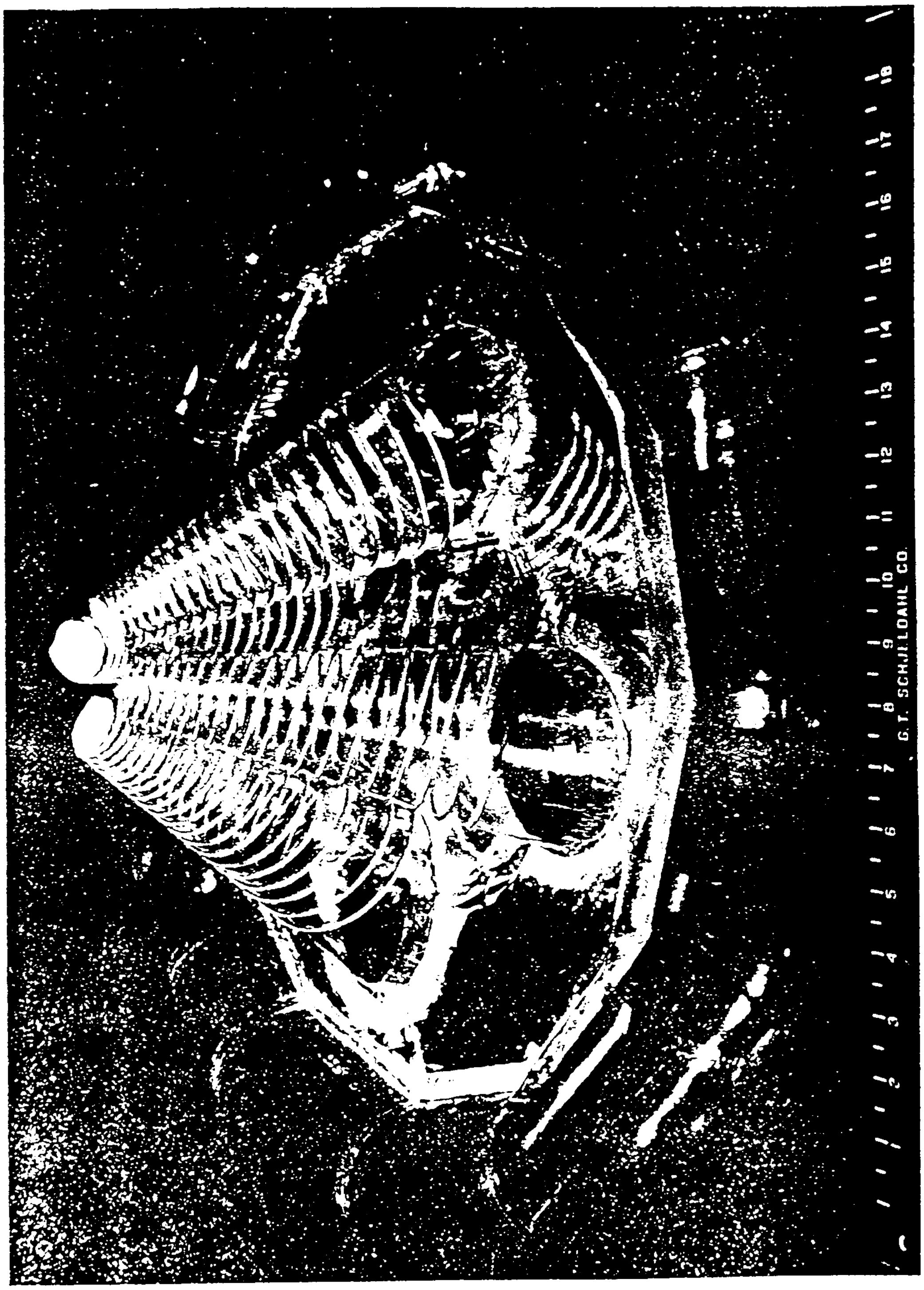

Figure 17. Space Inflatable Antenna

5. Solar Sails - These are another application for light weight inflatable devices. Large surface areas containing reflective and absorbing coatings can be used for station keeping, orientation, or as a true solar sail for propelling an object through space.

6. Re-Entry Devices - A considerable amount of work has been done on inflatable type re-entry devices. These include the Ballute which is a spherical shaped drag device and the Regallo Wing which is a steerable parachute type glider for re-entry of space vehicles. Many other types of re-entry devices are being considered which make use of the inflatable concept. One of the more interesting is a nosecone or umbrella shaped device which cradles a man re-entering from space. This device would work similar to a parachute. If a man had a malfunction of his space vehicle he could eject himself, inflate the cone shaped re-entry device and return safely to earth. Most of these devices require extremely high temperature resistant materials. The most successful have been metal fabrics impregnated with silicone compounds. H-film, a new product of DuPont which has a service temperature exceeding 800 F, is also being considered for some of these applications.

7. Manned-Space Station (Figures 18, 19, and 20) - This series of pictures demonstrates one concept for the use of inflatables in connection with an orbiting space station. Materials for such an application are not available today, however, a good deal of effort is now being placed on their development. The advantages of this concept are obvious. First, inflatables are lighter weight and capable of being packaged in a minimum space, and, secondly, they can be deployed in space without having astronauts exposed to the space environment in bolting, welding, or fastening sections of the space station together.

Inflatables are playing a bigger role today than ever. Through new materials, I am sure we will see an even greater expansion in this field in the years to come.

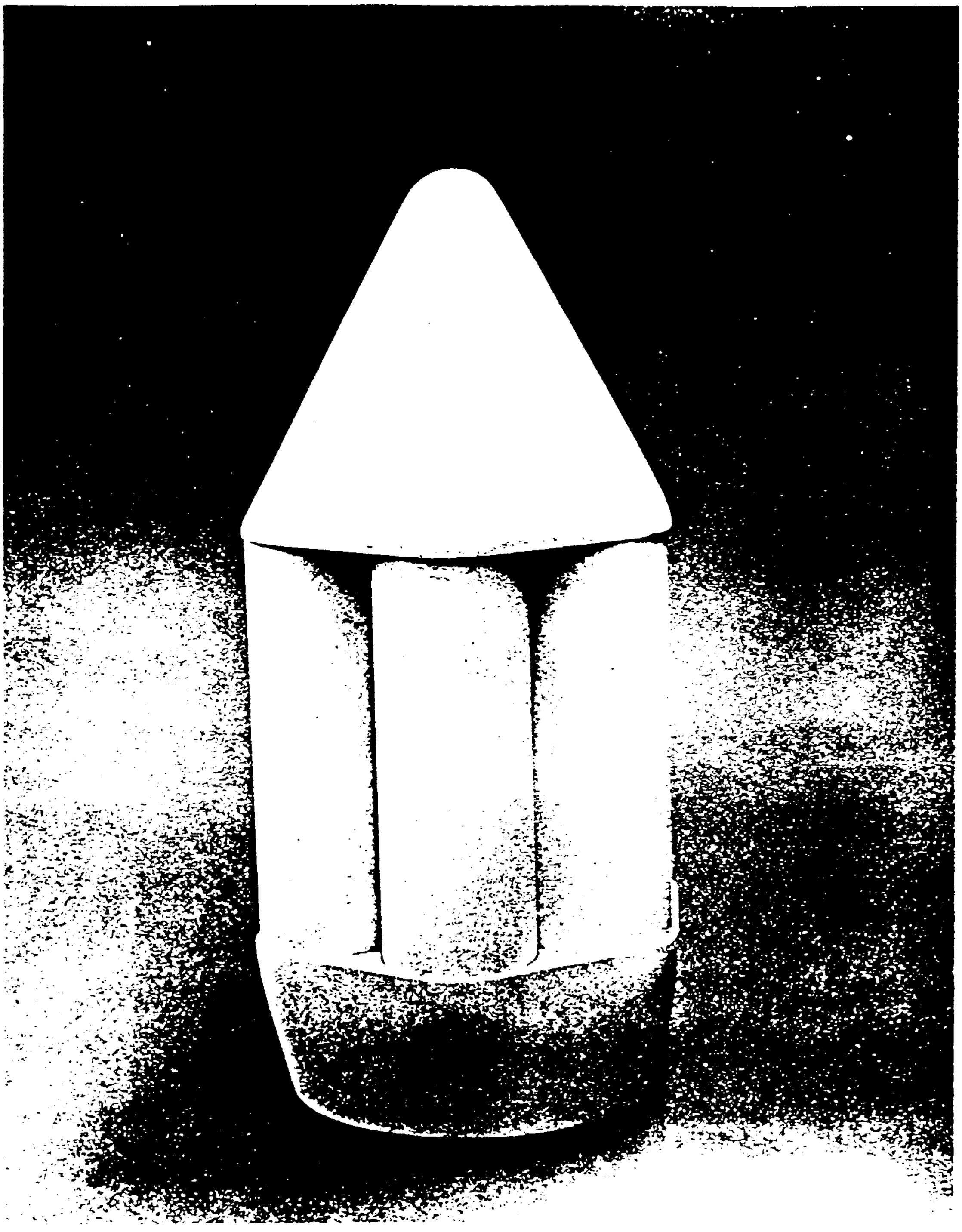

Figure [illegible] The Erectable Space Station in Folded [illegible] be Mounted on the Nose of a Launching Booster

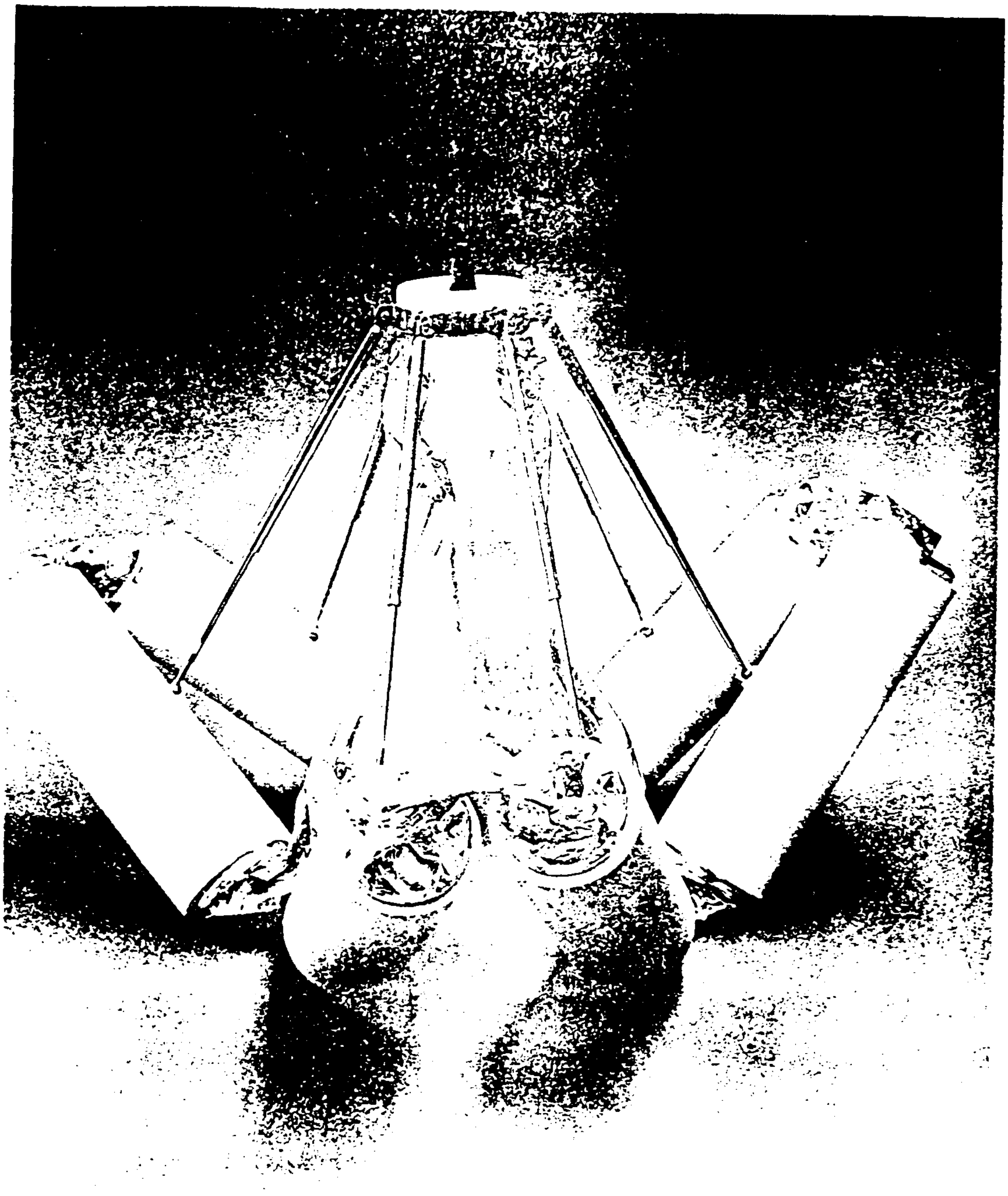

Figure 19. Space Station Is Shown About Half-Erected

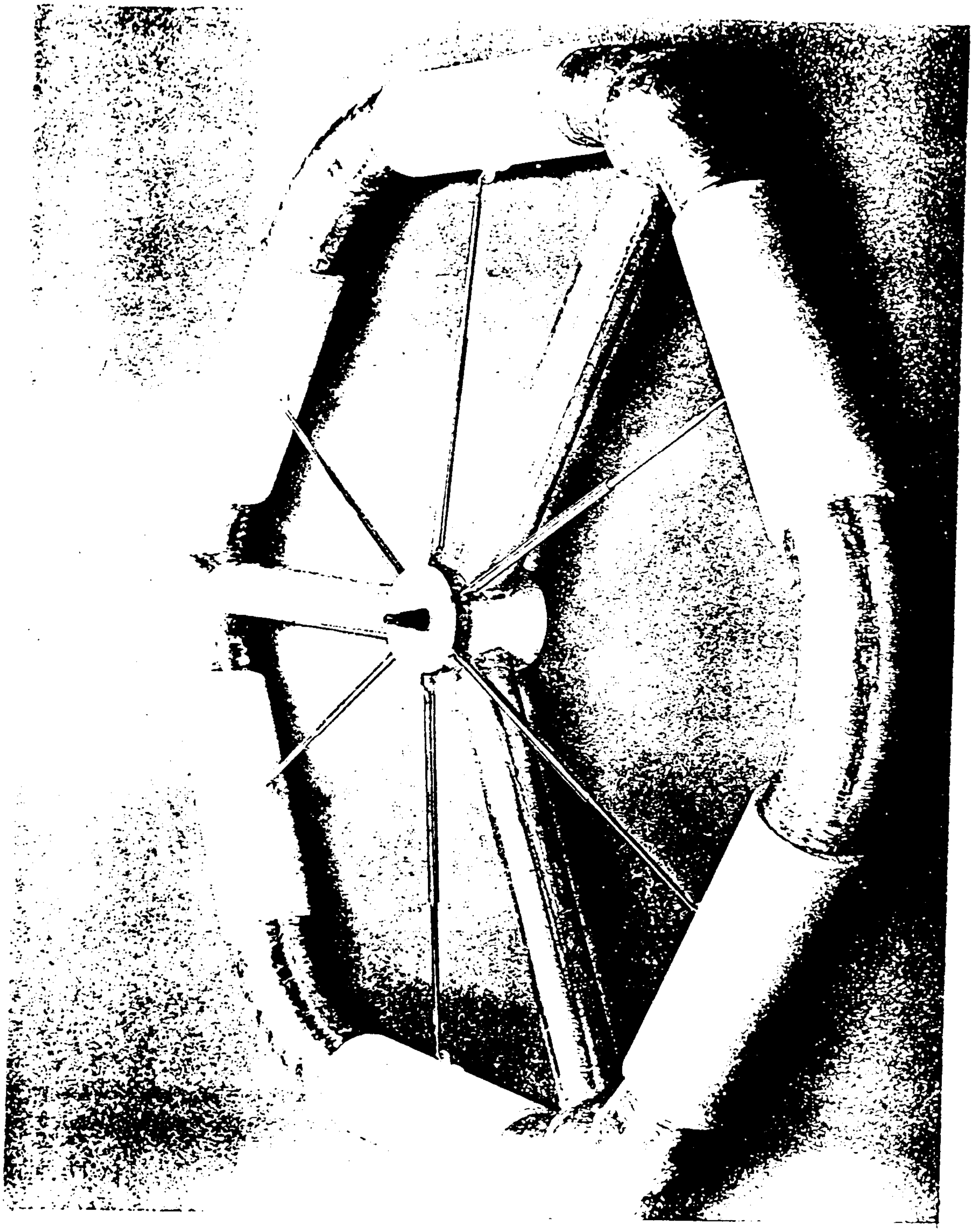

Figure 20. View of the Completely Erected Space Station