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STRUCTURAL CONCEPTS FOR VERY LARGE (400-METER-DIAMETER) SOLAR CONCENTRATORS

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INTRODUCTION

Since the beginning of the space age in the late 1950's, there has been considerable interest in placing large structures in orbit. Most of the applications for these large structures are associated with the reflection of electromagnetic waves. Typical applications include communication antennas, a wide range of telescopes, and reflection of solar rays. Another application for large space structures involves platforms which are used as a common base for mounting many experiments or other devices which share utilities such as power and communications. The Space Station Freedom is an example of the latter category.

~~In this paper,~~ a general discussion of various types of large space structures is presented. A brief overview of the history of space structures is presented to provide insight into the current state-of-the art. Finally, the results of a structural study to assess the viability of very large solar concentrators are presented. These results include weight, stiffness, part count, and in-space construction time.

SPACE STRUCTURES HISTORY

In the 1960's, the only access to space was through the use of expendable launch vehicles. This required that all spacecraft be automatically deployed once in orbit. This requirement led to the development of novel and ingenious structures which could be packaged very compactly for launch, yet be deployed to very large dimensions. Perceived applications at that time included low frequency radio astronomy, solar sails for interplanetary propulsion and large flat surfaces for reflecting solar rays either for illumination purposes or to provide increased energy to solar collector farms (references 1, 2, 3, and 4). Requirements for these structures are discussed in reference 5.

During an energy crisis in the 1970's, attention was given to the possibility of collecting solar energy in space and microwaving it back to Earth. Such solar power systems were very large and required the use of reusable launch vehicles to reduce cost as well as to enable in-space construction. Thus a new class of space structures, commonly referred to as erectable structures were conceived to accommodate the construction of these very large systems. During the same time period, considerable interest developed in large (5 meter to 100 meter) low frequency communication antennas (references 6 and 7). This application was best served through the use of umbrella-like structures which could automatically deploy large parabolic mesh reflector surfaces.

In the 1980's, the Space Shuttle has enabled the practical consideration of astronauts constructing large structures in space. This capability opens the door to structures that are larger, more versatile, more accurate, and stiffer than could be accomplished through only the use of deployable structures. The Space Station Freedom support truss is an example where this new capability is being utilized to construct a structure with features which could not be accomplished by other means. This new capability for constructing structures in space has also led to the consideration of constructing large solar concentrators for use on the Space Station as well as constructing very precise and stiff segmented reflectors for large telescopes. (See figure 1.)

1960's
- **Small Deployables from ELV's (~ 20 meters)**
- **Extremely Large Deployable Membrane Surfaces (~ 1 - 2 km)**
  - **Solar Sails**
  - **Solar Reflectors**

1970's
- **Very Large Erectables**
  - **Solar Energy, Space-To-Earth Power Stations (~ 5 - 10 km)**
- **Deployable Mesh Reflectors (~ 5 - 100 m)**

1980's
- **Moderate Size Erectables**
  - **Space Station (~ 100 m)**
  - **Solar Concentrators (20 - 30 m)**
  - **Precision Segmented Reflectors (~ 10 - 40 m)**

Figure 1

LARGE SPACE STRUCTURES

Two major categories have been identified for large space structures, deployable and erectable. Figure 2 shows examples of truss structures of each type. The erectable truss shown is one that was developed for very large structures such as would be required for a solar power station. This particular truss was developed specifically to be rapidly assembled by astronauts in orbit and is presented in reference 8 and 9. These studies demonstrated that large erectable trusses could be assembled in space by astronauts at the rapid rate of one strut every 40 seconds.

The deployable truss shown is a tetrahedral geometry such as presented in references 10 and 11. This truss was built and tested at Langley Research Center. As can be seen in the figure, the truss packages very compactly, yet deploys into a deep truss. The truss shown was successfully deployed in a simulated 0-g test by free-fall dropping it in a vacuum chamber. Although this deployment test was successful, such structures have not been demonstrated in large multiple ring configurations. The lack of experience with the deployable trusses in large configurations is the primary barrier to the acceptance of this technology for space missions.

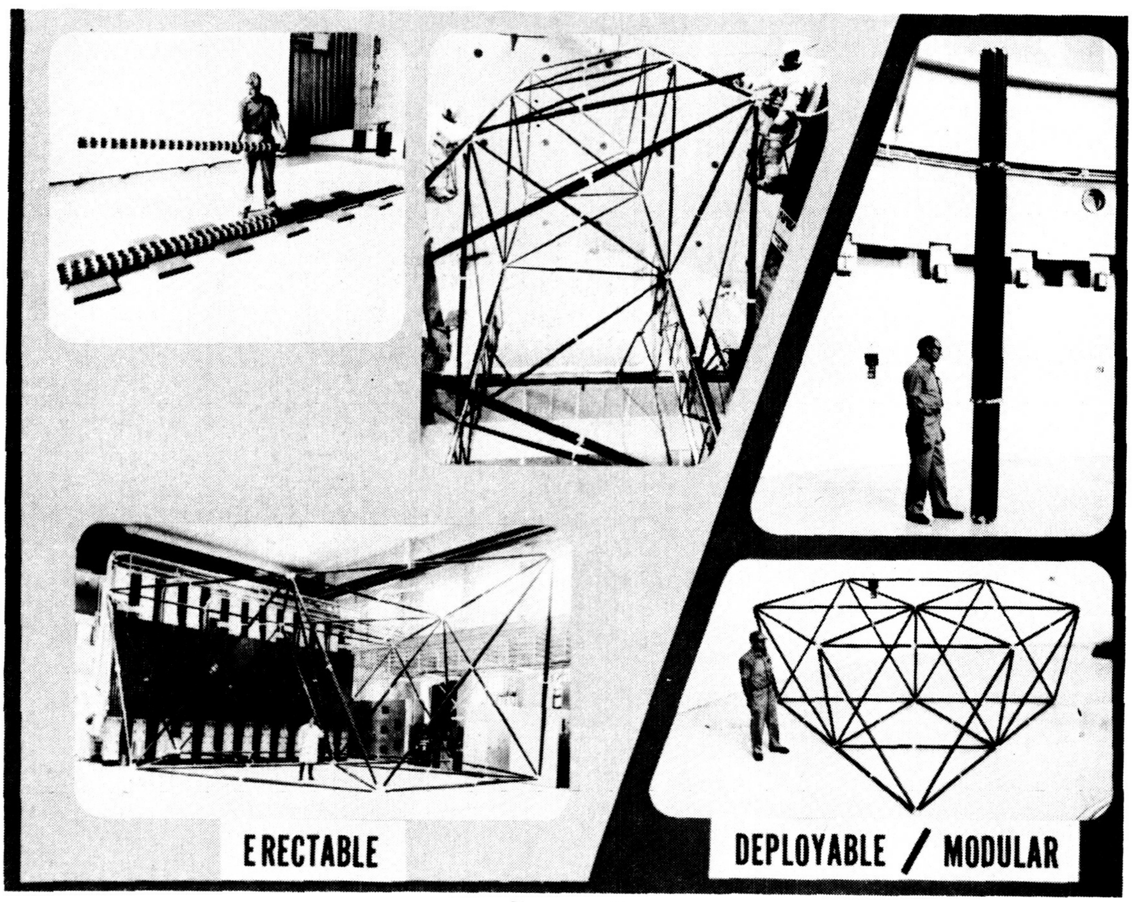


Figure 2

ERECTABLE LARGE SPACE STRUCTURES

Considerable experience has accrued over the past 10 years with erectable structures as indicated in figure 3. This experience has culminated in the development of the erectable backbone truss structure for the Space Station Freedom. Details of the research in erectable structures is presented in references 8 and 9, and in references 12 through 17. These references describe research on hardware design, development, and testing, on dynamic analysis, and on underwater simulated 0-g construction tests.

The results of the highly successful ACCESS in-space construction experiment are presented in reference 18. This research has provided the basis for the reliable in-space construction of a wide class of large space truss structures. However, as will be discussed subsequently, there is a limit to the size of such structures that can be constructed by astronauts.

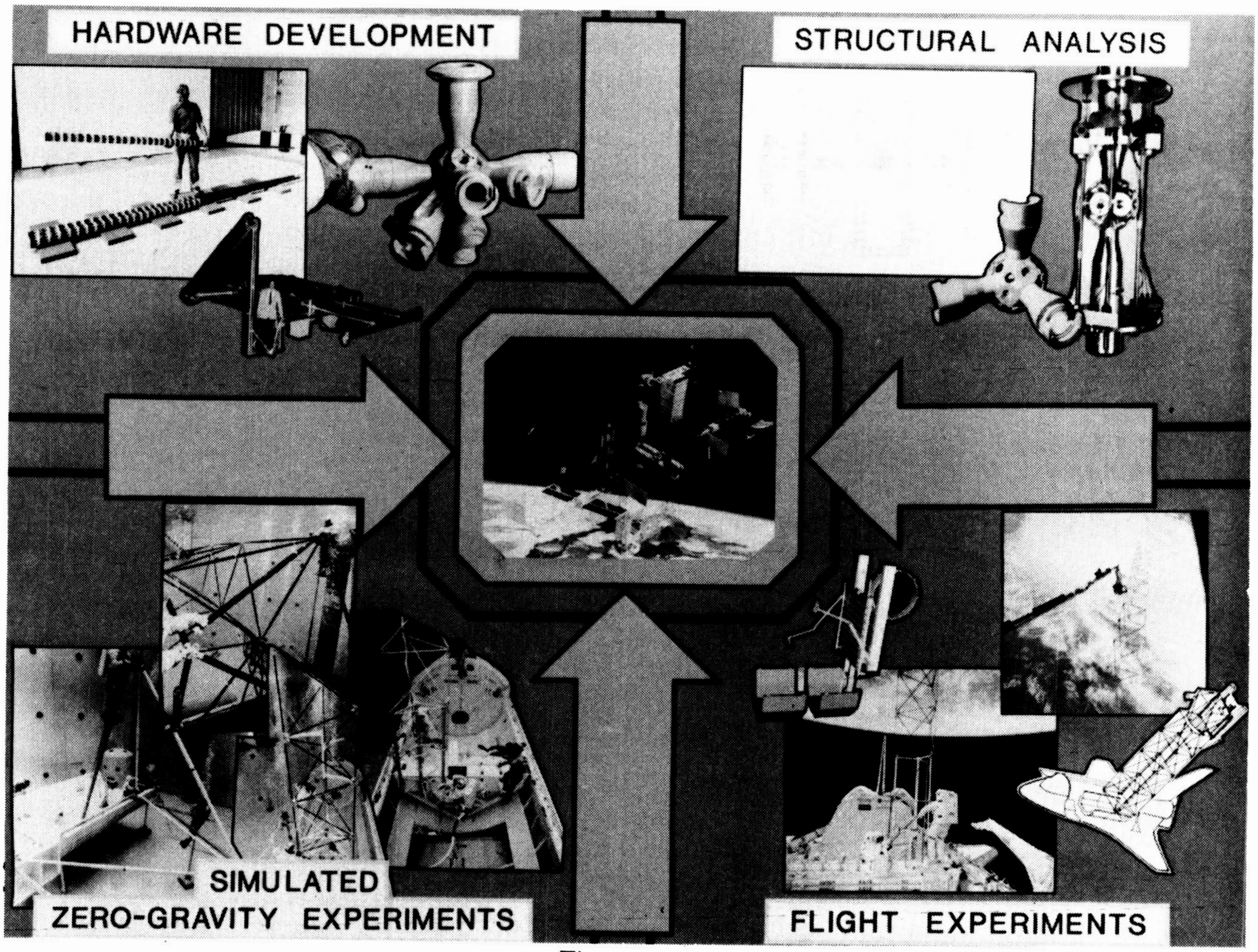


Figure 3

SPACE STATION MOBILE TRANSPORTER

Erectable structures offer great versatility in packaging for launch and the geometries of structures that can be constructed in space. However, these advantages are somewhat offset by the fact that structures must be assembled in space piece by piece. Experiments and studies over the past 10 years have shown that assembling structures piece by piece can be accomplished very efficiently if an appropriate construction aid is provided. One such construction aid was developed and demonstrated for very large space platforms and is shown in the upper center photograph of figure 2 (reference 9). This aid provided mobile foot restraints which could position astronauts for rapid assembly of the truss. A similar device was developed for the Space Station Freedom and is shown in figure 4. This aid, which is called the Mobile Transporter, has astronaut positioning arms on both sides of the truss and, in addition, is able to move over the truss. This transporter has been demonstrated in 1-g and in neutral-buoyancy-simulated 0-g tests (reference 18). The results of the tests showed that these structures could be assembled at the rate of 1 strut every 30 or 40 seconds. With such a construction rate, two astronauts could assemble about 500 struts per 6 hour EVA allowing some time for resting. This means that structures with only a few thousand struts will not represent a major construction challenge. For reference, the Space Station Freedom has about 600 struts. The major challenge in assembling a large space system is the installation and integration of all the utilities and subsystems. Again, however, the mobile transporter or assembly aid provides a mechanism for accomplishing the integration in an efficient and orderly fashion. For extremely large structures which may have hundreds of thousands of struts, it is likely that this assembly process will have to be automated to be practical.

SPACE STATION TRUSS ASSEMBLY WITH MOBILE TRANSPORTER DEMONSTRATED IN 1-G TESTS

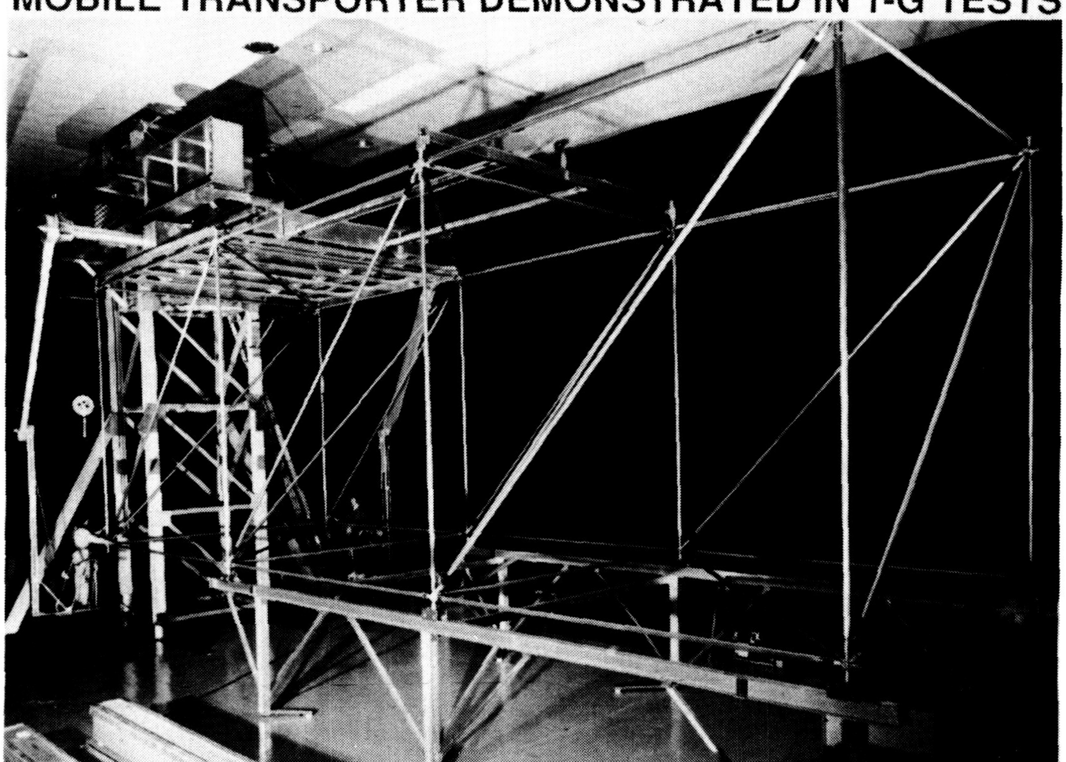


Figure 4

REFLECTOR ANTENNA CONCEPTS

Figure 5 shows three concepts for deployable reflector antennas. The state-of-the-art of these and other deployable antennas is presented in reference 19. Because of the delicate nature of the mesh surfaces of such antennas, it is highly desirable to have these systems prebuilt on the ground and automatically deployed in orbit.
An alternate approach for achieving very large antennas is to deploy modules and assemble them in space (reference 20).

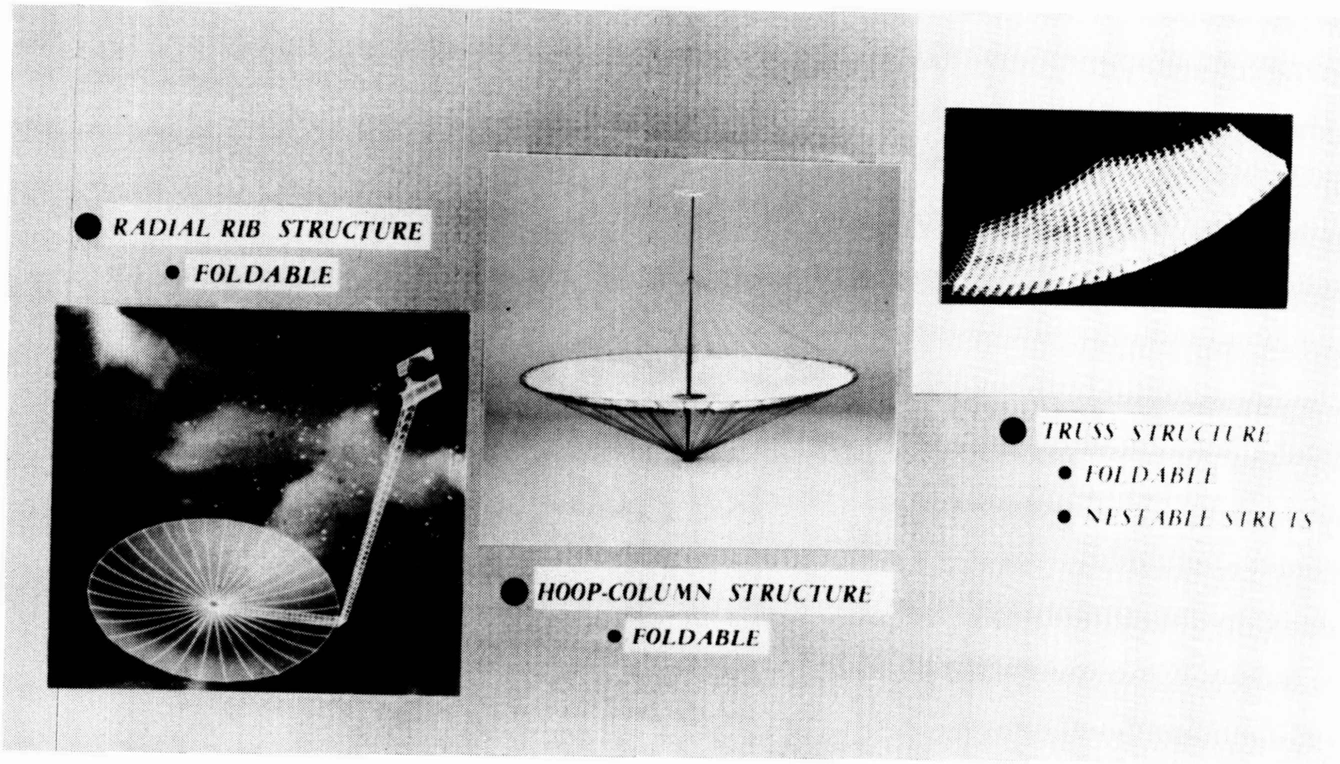


Figure 5

ONE KILOMETER FLAT SOLAR COLLECTOR

In the past, large orbiting flat solar reflectors have been considered for applications such as illuminating cities, extending growing seasons, and increasing power to solar collector farms (references 2 and 3). A sketch of a one kilometer version of such a reflector is shown in figure 6. This particular concept is well suited for deployable structures. This concept consists of a central telescoping mast and an outer deployable torus which is laterally supported by guy wires. As can be seen in the figure, the flat membrane is stretched inside the torus to form the reflecting surface. There are no major technical barriers to achieving this type of reflector. The deployable torus would require the most development. Areal density for these structures would be quite low (on the order of 0.1 kg per square meter).

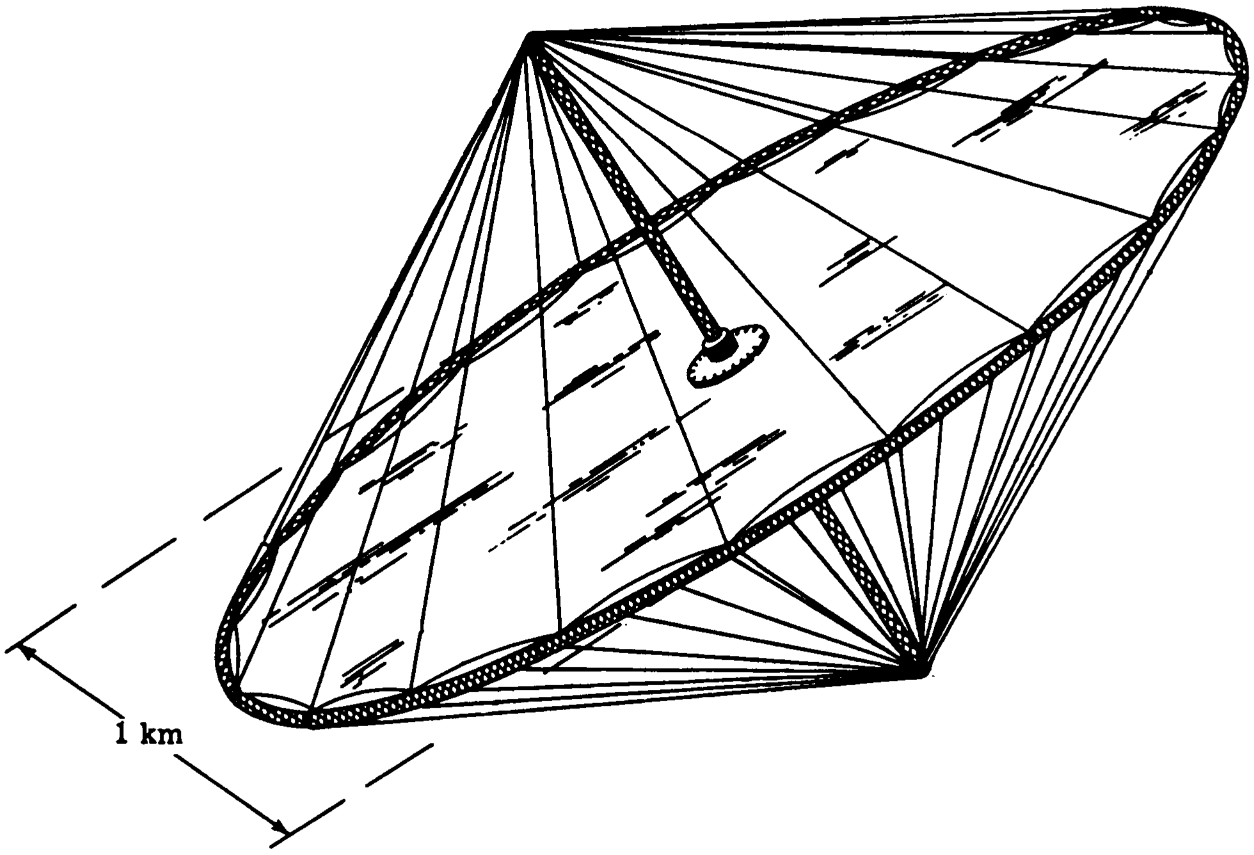


Figure 6

POSSIBLE MEMBRANE SHAPES

As shown in figure 6, stretched membranes result in very lightweight reflectors, thus, making them attractive for space applications. However, high performance solar concentrators require a dish-like shaped doubly curved surface to focus the solar rays. The equation which governs the equilibrium of a membrane is presented in figure 7 for two possible cases. The first case considered is one in which the membrane is loaded with a lateral pressure. In this case the loading is equilibrated by inplane loads as shown at the lower left hand side of the figure. Since a membrane has no bending stiffness the inplane loads must be positive or equal to zero. Experiments in the past have shown that a membrane surface must be stretched to eliminate wrinkles and develop a high performance reflecting surface. Thus for a membrane to achieve high quality dish-like shape, it must be loaded with a lateral pressure. This is difficult to achieve in space, however, in a subsequent section inflatable concentrators are discussed. The second case considered is one in which there is no lateral pressure. In this case there are two possible ways to satisfy the equilibrium equation. Either the membrane is flat (both radii are infinite), or one radius is positive and the other is negative. The later case results in a saddle shaped membrane as shown in the lower right. In subsequent figures, solar concentrator concepts which utilize these different membrane shapes will be discussed.

General Membrane Equation

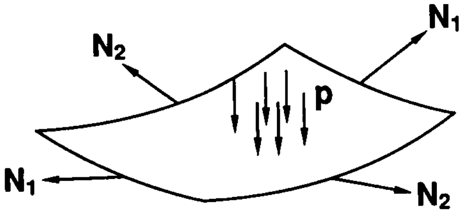
$$\frac{N_1}{R_1} + \frac{N_2}{R_2} = p$$

For an Unwrinkled Membrane

N_1 & $N_2 > 0$

For a Dish Shaped Membrane

R_1 & $R_2 > 0$

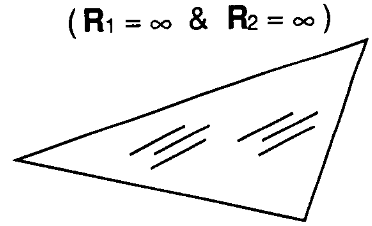


Zero Pressure Membrane Equation

$$\frac{N_1}{R_1} + \frac{N_2}{R_2} = 0$$

Thus Either

$(R_1 = \infty \;\&\; R_2 = \infty)$



Or, $R_1 = -R_2 \dfrac{N_1}{N_2}$

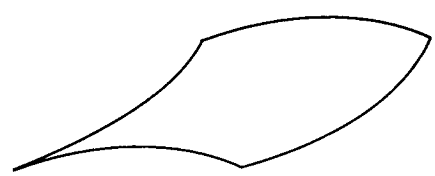


Figure 7

DOUBLY CURVED MESH REFLECTORS

Doubly curved mesh reflectors have proven to be quite valuable for low frequency radio communications applications as discussed in reference 18. An example of one mesh reflector concept is shown in figure 8. This concept is known as the hoop column antenna and is discussed in detail in reference 21. The hoop column antenna is very similar to the flat reflector shown in figure 6. The major difference being that the reflector surface is pulled into a doubly curved shape by many radial catenary-like cords. The resulting doubly curved surface is composed of numerous radial sectors, each of which is saddle shaped as discussed in figure 7. Such a locally saddled surface has been shown to be adequate for radio antennas where rms surface errors control the performance. This type of membrane shaping system is not suited for solar concentrators for two reasons. First, locally pillowed surfaces have large local slope errors which produce unsatisfactory scattering of the solar rays. Second, the membrane films required to reflect solar rays are not as forgiving as double knit meshes in forming a wrinkle-free doubly curved surface.

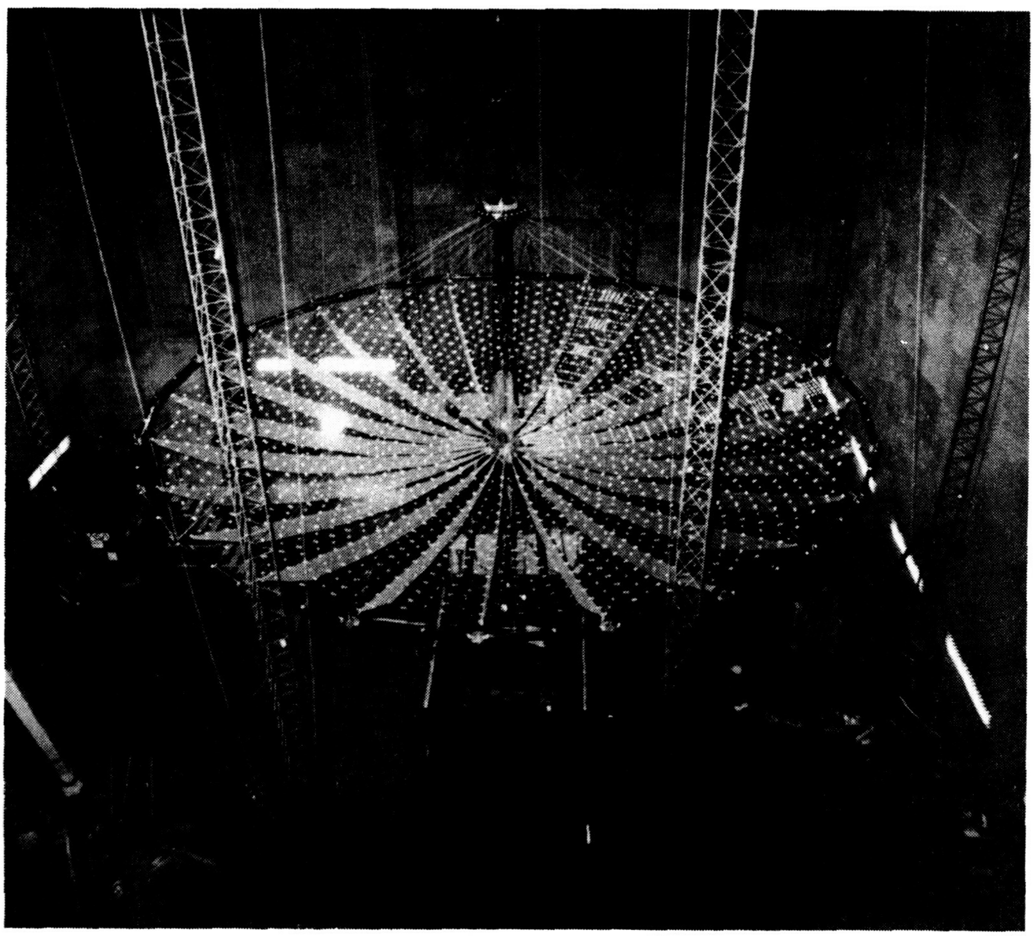


Figure 8

INFLATABLE SOLAR CONCENTRATOR

Inflatable solar concentrators have been under consideration for many years. Until recently, inflatable reflectors where not given serious consideration due to pressure leakage through micrometeoroid penetrations of the membrane film surface. However, in reference 22 it has been shown that for very large diameter concentrators (> 100 meters), the required inflation pressures are so low that leakage is very small. Thus, inflatable reflectors are legitimate contenders for the large solar concentrators. Figure 9 shows an artist concept of an inflatable concentrator. The concentrator is lenticular in shape with a clear membrane forming the front of the lens and a pressurized torus at the intersection of the front and rear surfaces to maintain radial equilibrium. Weight curves are presented in reference 21 for large inflatable solar concentrators and the results show that this concept is extremely lightweight. There are two main problems that remain unresolved with inflatable solar concentrators. First, the thin film surfaces must be formed from several meter-wide strips of thin plastic films. The seams between strips represent discontinuities in the film which results in local wrinkles which degrade reflector performance. Increasing pressure to remove these wrinkles, results in heavier concentrators. Second, the thin films used for these reflectors are some form of plastic, all of which have very high coefficients of thermal expansion. This high coefficient of thermal expansion inhibits making a stable, high precision solar concentrator. Although the inflatable concept has some drawbacks, it is clearly worth continued research because of the potentially low resultant weight.

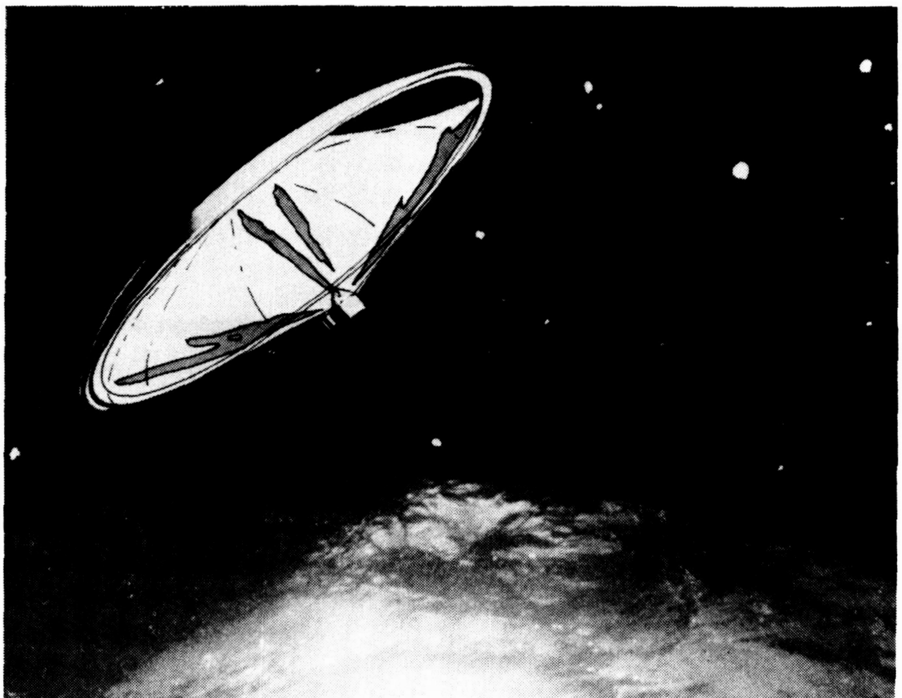


Figure 9

SOLAR DYNAMIC CONCENTRATOR

A solar dynamic power system is currently being considered for a growth version of Space Station Freedom. The concentrator required for this application is about 18 meters in diameter and is discussed in detail in reference 23. A photograph of a partly assembled concentrator in shown in figure 10. The concentrator is formed from 4-meter-diameter hexagonal panels. These hexagonal panels were sized to fit in the Space Shuttle cargo bay for launch. Once in orbit, the panels would be assembled by astronauts to form the 18-meter-diameter reflector. This approach is limited to small (about 20 meters) concentrators because of the low inherent stiffness of the resulting thin configuration. However, this approach could prove to be of value for larger concentrators by providing numerous subreflectors to be mounted on a very large support truss.

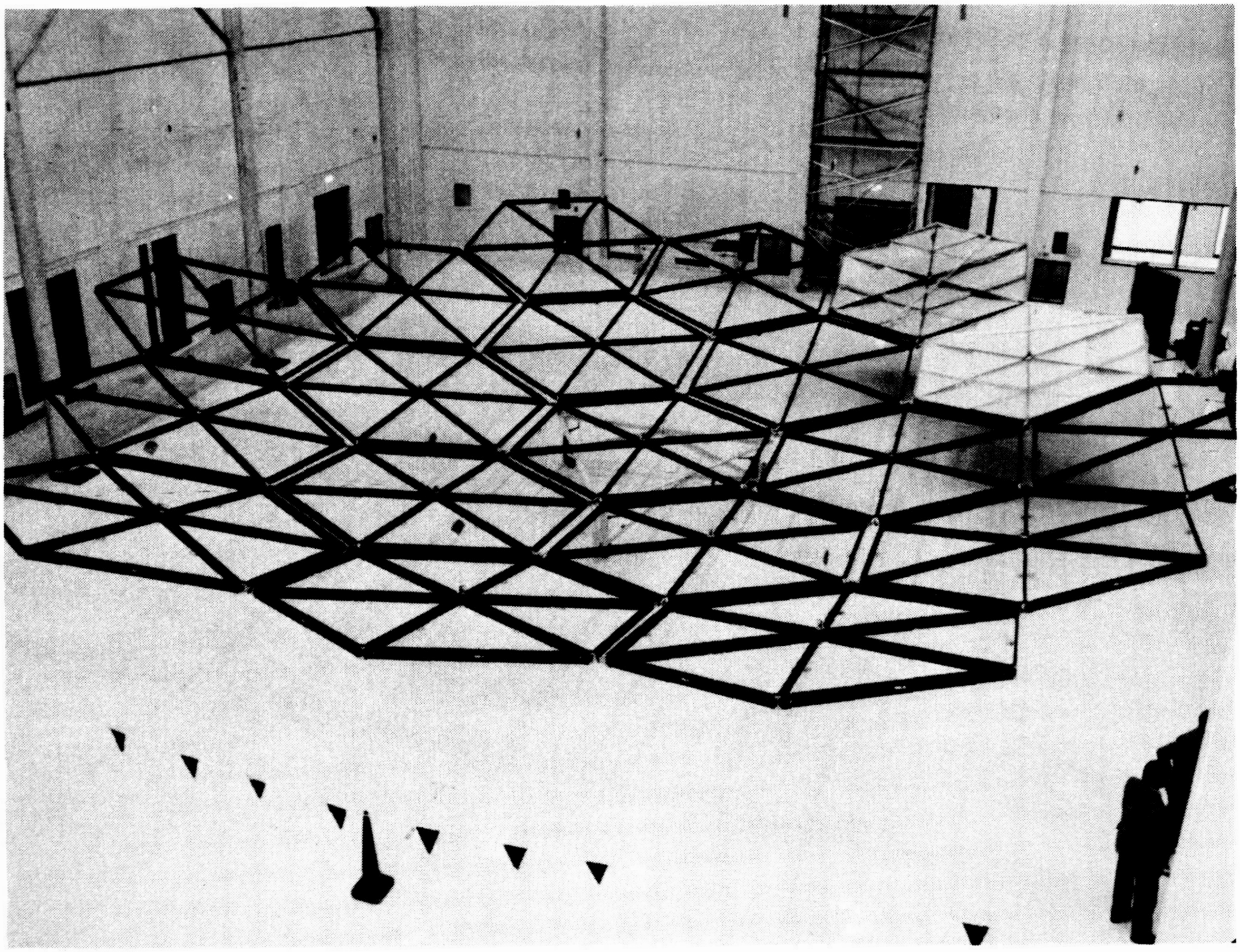


Figure 10

TRUSS SOLAR CONCENTRATOR

It is well known that trusses form very stiff, lightweight structures for many applications. In order to assess their applicability to large solar concentrators, the truss/concentrator configuration shown in figure 11 was studied. In this concept, a flat triangular membrane facet is stretched between the intersections of three struts on the truss surface to form the concentrator. In order to reduce part count and to minimize truss mass, the individual truss struts should be as long as possible. However, the size of the membrane flats is dictated by the concentration ratio desired. If the sun's rays were exactly parallel, each facet could be no larger than the receiving collector. However, since the sun's rays are not exactly parallel, there must be a correction for that fact which makes each flat slightly smaller. The details of this correction are presented in reference 24. To assess the applicability of trusses to very large solar concentrators, a 400-meter-diameter concentrator is presented in the next figure.

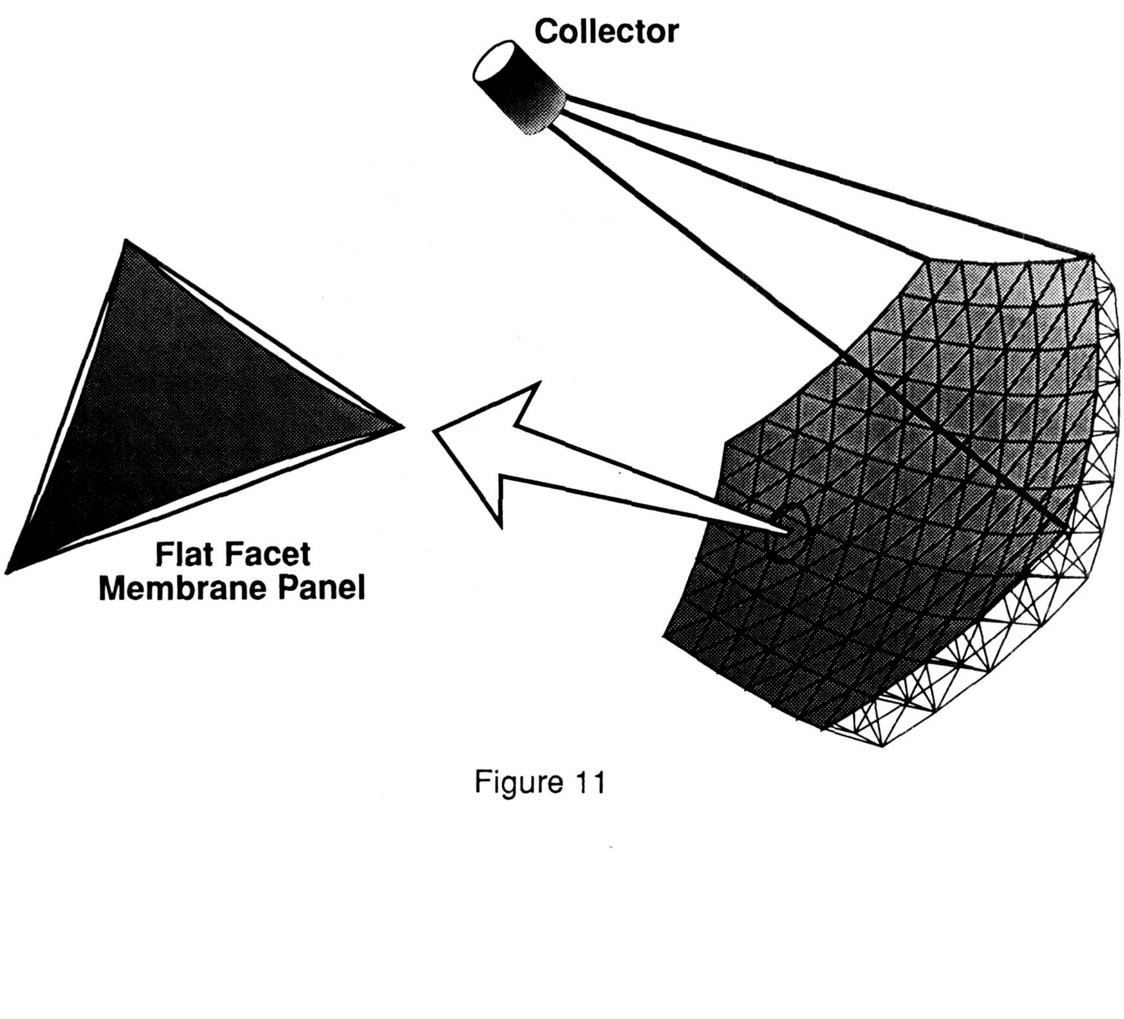


Figure 11

400-METER FACETED SOLAR CONCENTRATOR

Figure 12 shows a flat projected sketch of a 400-meter effective diameter, faceted solar concentrator. The concentration ratio selected for this point design was 2000 to 1. This results in a maximum flat facet size of 5 meters as determined from reference 24. A typical facet is shown in the upper right with an astronaut for comparison. As indicated in the figure, this geometry would require 18,000 triangular facets and 52,000 struts. The next two figures show the weight and assembly time for such large solar concentrators.

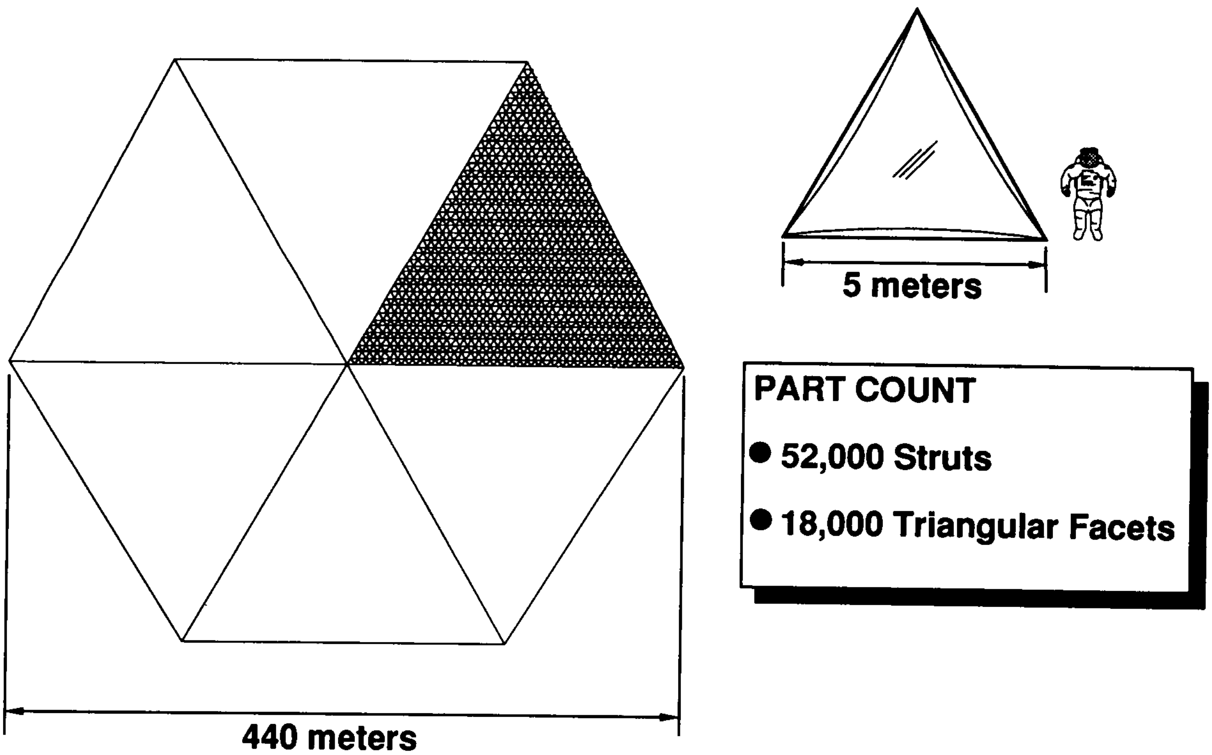


Figure 12

WEIGHT OF LARGE SOLAR CONCENTRATORS

In figure 13 the weight of flat faceted truss and inflatable concentrators is presented. The circular symbol at the upper right of the figure indicates the weight of the 400 meter concentrator shown in the previous figure. For these weight calculations the membrane facets were 0.25 mil kapton and the struts were 1.2 inches in diameter, 0.015-inch-thick walled graphite/epoxy tubes. A factor of two was applied to the total strut weight to account for truss joints. As can be seen in the figure, the truss concentrator weighs about 75,000 lbs. as compared to about 8,000 lbs. for the inflatable. The shaded lines are included to provide a means for comparison with other concepts. For example the flat solar reflectors of reference 3 have an areal density of about 0.1 kg/m^2. This was the areal density chosen for a system level study of solar concentrators in reference 25. Although the flat solar reflectors are very lightweight, there is no known means for adapting this concept into a high performance reflecting concentrator. Thus, at this time it appears that the choices for large solar concentrators are the relatively heavy truss type or the very lightweight inflatable. The truss type concentrator, although heavy, has the advantage of being technically straightforward to develop. The inflatable, although lightweight, has the disadvantages of wrinkles from the seams, high coefficient of thermal expansion and low natural frequencies. Further development work is required on both concepts before a rational selection can be made.

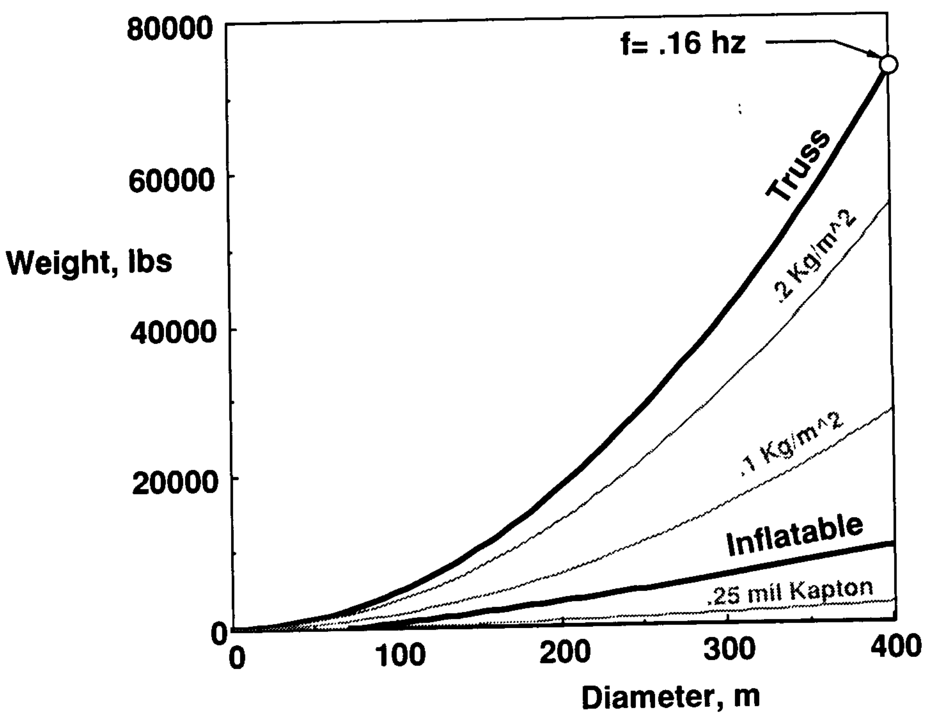


Figure 13

PART COUNT AND ASSEMBLY TIME FOR LARGE TRUSS SOLAR CONCENTRATORS

Figure 14 shows the number of struts and corresponding assembly time for truss solar concentrators. As can be seen, a 400-meter-diameter concentrator would require over 400 hours of assembly time at the rate of 0.5 minutes per strut. This would correspond to astronauts working 72 6-hour EVA's to complete the construction. This is probably not a feasible approach for constructing these large reflectors. The alternate approach for assembling the erectable concentrator is through the use of robots. The use of robotic construction on such a large scale is currently being studied; however, the feasibility of such an approach has not yet been determined. Deployable truss structures have been studied in the 10- to 20-meter-diameter range, however, this very large scale has not been given serious consideration. Again, much development work would be required to establish feasibility.

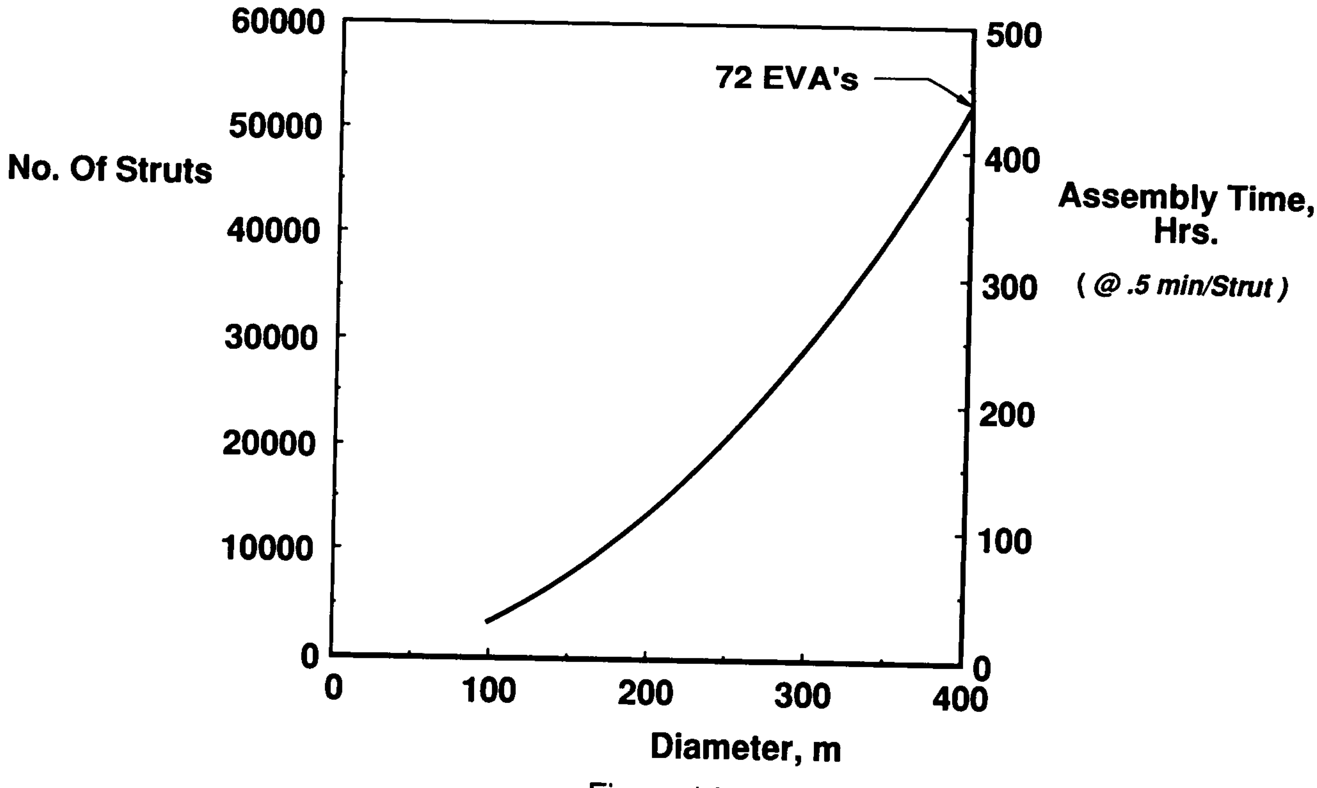


Figure 14

CONCLUDING REMARKS

In this paper an overview was given of large space structures technology and an assessment was made of the applicability of various structural concepts to very large solar concentrators and is summarized in figure 15. There does not appear to be any technical barrier to developing very large ultra-lightweight deployable membrane surfaces such as solar sails or flat reflectors. However, achieving very large high performance solar concentrators for space applications is a challenge. For all the structural concepts considered for large solar concentrators, each one had several major perceived disadvantages that need to be resolved. The major conclusion of the current study was that several years of development would be required on a couple of selected structural concepts before a feasible approach could be identified for very large (400-meter-class) solar concentrators.

- **Large Ultra-Lightweight Deployable Membrane Surfaces Appear Achievable For Applications Such As Solar Sails Or Flat Solar Reflectors**

- **For Large Solar Concentrators Several Years Of Research And Development Required Before A Satisfactory Concept Can Be Identified**

Figure 15

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