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CARPINTERIA, CALIFORNIA

STUDY OF MEMBRANE REFLECTOR TECHNOLOGY
FINAL REPORT

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SECTION 1

INTRODUCTION

Very large reflective surfaces will be required by future spacecraft for such purposes as solar energy collection, antenna surfaces, thermal control, attitude and orbit control with solar pressure, and solar sailing. Metallized thin-film membranes have the potential of satisfying the requirements of most of these applications with minimum weight systems. Except for thermal control, each of these applications requires accurate surfaces whose performance can only be evaluated by including the supporting structure used to configure and maintain the reflector shape, including compensation for dimensional changes in the film material. The film thickness and associated weight is a major parameter in the design of these systems.

Astro Research Corporation has completed a study on membrane reflector technology for the Jet Propulsion Laboratory. The objective of this study was to identify and quantify the performance benefits in large membrane reflector systems which may be derived from an advancement of thin film and related structures technology. This technical note is the final report and summarizes the results of the study. Detailed technical discussions of various aspects of the study are included in several separate technical notes which have been referenced herein.

SECTION 2

SUMMARY

This study program was divided into three tasks. The first task required a survey of advanced space systems involving large collector/reflector surfaces for solar energy concentration, as well as for radio-frequency transmission, and the identification of the major characteristics and requirements of these membrane reflector structures. This task was completed and the results are summarized in Section 3.

The second, and largest, task of the study was to conduct a detailed evaluation of the potential benefits of advanced thin-film and related structures technology using the SOLARES free-flying solar-reflecting satellite concept as an example of a large membrane-reflector structural system. In accomplishing this task, Astro Research Corporation has examined the structural characteristics of thin-film reflector materials, developed a technique for supporting membranes with compensation for their dimensional changes, examined the reflector flatness requirements for the SOLARES mission, analyzed the behavior of polygon-shaped film segments, established the external loads on free-flying reflector surfaces, and created a baseline design for a reflector satellite.

The third task consisted of establishing parametric relationships applicable to large reflector systems and arriving at conclusions on the benefits of further advancement in thin-film and related structures technology, including recommendations as to specific developmental areas. In this respect, the study has shown that the total weight of reflector and structure can always be reduced through the use of thinner films. Our baseline reflector

assumed 2-μm Kapton film, similar to that developed in 1977 for the solar sailing program. Any further reduction in film density would reduce the total weight and improve the accuracy of the reflector performance by reducing lateral loadings on the reflector, due to control accelerations. Recommendations are included in this report regarding other aspects of thin films, such as local irregularities in flatness.

SECTION 3

ADVANCED SPACE SYSTEMS SURVEY

The results of a systems survey of potential missions where large-area reflectors will be required have been previously reported in ARC-TN-1062, "Summary of Advanced Space Systems Survey, Large Membrane Structures," 23 June 1978. The survey identified five categories of applications for large reflector surfaces. A sixth category, using solar pressure on reflectors for attitude and/or orbit control, is included here:

- Concentrating solar radiation
  - on the Earth (SOLARES, Lunetta, Soletta)
  - to operate heat engines in space
  - on photovoltaic arrays in space
- Supporting large photovoltaic arrays
- Forming large-diameter optics
- Solar sailing
- Precision radio frequency reflectors
- Attitude and/or orbit control by solar pressure

Thermal control surfaces have not been included since they generally do not have precision shape requirements that require membrane-type support.

The approximate dimensional characteristics of these reflector systems, as envisioned prior to this study, are shown in Table I. Note that only the engineers studying the solar-reflecting satellites were aware of the thin-film technology work associated with solar sailing studies completed in 1977. ARC-TN-1062 lists reference sources for the material in this table.

SECTION 4

STRUCTURAL CHARACTERISTICS OF THIN-FILM REFLECTOR MATERIALS

Thin metallized polymer films have a common characteristic of very low weight per unit area and negligible bending stiffness. In addition, when exposed to the space environment, they are subject to substantial dimensional changes (±1 percent) due primarily to temperature changes. Dimensions are also affected by exposure to radiation and by long-term tension loading. Compared to these dimensional effects, the films appear elastically rigid under the low tension loadings required in reflector designs.

The above characteristics result in two requirements on membrane reflector designs. First, in the absence of surface pressures or body forces, wrinkle-free reflector surfaces can be formed only by providing an isotropic tension in flat-film segments. Curved surfaces, if desired, can be created by providing an appropriate surface pressure distribution or simulated by combining a number of flat facets at varying angles. Second, the supporting structure must provide some means of compensating for substantial dimensional changes in the film while maintaining the film under tension. Failure to satisfy these requirements will result in wrinkles or overloading of the film.

A flat mirror is desirable for the solar-reflecting satellite mission and as a result tension must be maintained on the reflecting film to limit curvatures caused by surface pressures and body-force effects associated with the satellite's trajectory. Solar pressure, aerodynamic drag, gravity-gradient forces, and control loads associated with pointing the reflector towards ground targets will act on the membrane of this type of satellite. The strength and stability of the film in the space environment must be sufficient to avoid failure or excessive creep under applied tension during the life of the mission. The latter requirement is the more significant one.

It is a requirement of the solar-reflecting satellite that the film material has a flat specular, reflecting surface. It was observed, during studies on solar-sail designs, that very thin metallized films are subject to embossing as a result of the manufacturing processes and subsequent handling. The effect of these local imperfections will reduce the reflector's efficiency. Most reflective measurements on these films were restricted to very small areas with the film held flat. Future testing should be made with macroscopic areas, and with the film subject to varying isotropic tensions in the range of those anticipated for the mission.

SECTION 5

THE SUPPORT OF THIN-FILM MEMBRANES IN SPACE

The first technical problem investigated in this study was the challenge of providing a support structure to hold thin films under tension while compensating for dimensional changes in the film. Even if inelastic effects such as long-term creep or shrinkage could be eliminated, polymer films have high temperature coefficients of expansion compared to materials which might be used in the support structure. Furthermore, these coefficients often vary between the width and length directions in a roll of film as a result of the manufacturing processes. As a result, there will always be differential changes between the support structure and the film as orbital variations in the angle between the reflector and the sun line cause temperature changes. The largest difference will occur when the reflector experiences temporary shadowing by the earth, since the reflector may be nearly normal to the sun's illumination just before and after occultation.

In order to fully compensate for dimensional changes in the film, and minimize the possibility of wrinkles and excessive deflections from a flat-mirror condition, the support system for the film must allow for relative changes in both directions everywhere along the edge of the film. A concept which achieves this result is illustrated in Figures 1 through 4. This design concept, which will be referred to as the "film facet design" applies to film surfaces formed from any regular polygon of M-sides. The design is explained in detail in ARC-TN-1067, "The Support of Large-Area Thin Films Without Wrinkles," 21 November 1978.

Each boundary of the reflector facets is supported by an edge tendon as illustrated in Figure 1. Each tendon is enclosed in a bias-mesh hem which is bonded to the film and allows the film to slide along the tendon with a minimum of resistance. The shape of the hemmed film edge forms a long arc so that tension applied to the tendon results in a uniform tension applied continuously along the edge of the film. For a given tension applied to the film, the tension required in the tendon, and the resulting load on the supporting structure, is in proportion to the radius of the edge arc. Deep arcs minimize these loads, but also reduce the reflecting area as compared with straight sides. This effect is a very important one in the design of a triangular reflecting satellite.

The expansion compensator used at each corner is illustrated in Figures 2 and 3. This device compensates for changes in the film size by allowing the tendon intersection location to move while maintaining tension in the edge tendon and the film. The spring, or constant force device, specification depends on the number of sides of the film panel, which establishes the corner angle, and the required tendon tension. The collar sheave, which is mounted to the support structure through the spring, has rollers to minimize friction. A model has been constructed of this corner compensator along with the corner of a large film panel. Tests on this model demonstrated that the device performs as desired.

Flat-film facet panels can be constructed with any integral number of sides using tendons along each side and expansion compensators at each corner. In addition, large triangular or hexagonal reflectors can be constructed using an array of smaller triangular facets. A reflector built in this manner has the characteristics of reinforcing the effective strength of the basic film.

This reinforcing scheme may be of significance in applications of very thin films where local reinforcement of the film by the incorporation of a mesh is not acceptable because local differential expansions create surface irregularities. Both of these concepts are illustrated in Figure 4.

SECTION 6

FLATNESS REQUIREMENTS FOR A SOLAR-REFLECTING SATELLITE

The optimum reflector shape and finish for a SOLARES-type orbiting solar-reflecting satellite is a perfectly flat, specular reflecting surface like that of a flat mirror. Since each low-earth orbiting satellite illuminates a fixed location on the ground, it must rotate in respect to the sun line; and as a result a concave concentrating curvature cannot be taken advantage of. Any deviation from a perfectly flat condition, caused by lateral load-induced curvatures or local irregularities in the film surface, will cause dispersion of the light reflected by the surface.

In the case of a perfectly flat solar reflector, the size of the sun's image on the ground is governed by the apparent solar angle, the height of the satellite's orbit, and to a lesser extent by the reflector's size. In order to establish a criteria limiting deviations from a flat condition, calculations were performed to establish the amount of light which would be dispersed by a curved or wrinkled reflector outside the image of a perfectly flat reflector. These calculations are included in ARC-TN-1072, "Structural Design of Free-Flying Solar-Reflecting Satellites," unpublished at this date. One set of calculations was performed for the spherical distortion typical of a uniform lateral force acting over the area of a circular membrane. A second set of calculations was completed for a random gradient distribution. It is of interest to note that for an energy loss (beam widening) of less than 20 percent, there is very little difference between these two cases when the root-mean-square gradient values of each are compared, as shown on Figure 5.

Since it was not obvious that spherical curvature was a good approximation for the distortion of a tension-tendon-supported polygon, such a triangle, under the same loading; a technique was developed for computing these deflections, with variations in the number of sides and in the curvature of the edges. This work is reported in ARC-TN-1070, "Deflection of a Membrane with Tension-Tendon-Supported Edges," 17 November 1978. The results of the analysis show that the maximum gradient, which occurs at the center of each film edge, is only a few percent larger than that of a circular membrane when the arc radius of the edge tendon is small. For a triangular membrane with nearly straight edges, the maximum gradient at each edge center increases to a value 17 percent larger than that of the gradient along the circumference of a circular membrane. The difference between the rms radient values is smaller. It appears that the spherical curvature results can be used as an approximation for the polygon reflectors in preliminary studies.

For baseline design calculations, an rms gradient of 0.00071 radians, corresponding to an edge gradient of 0.001 radians for a spherically curved circular membrane, has been selected. This corresponds to an energy loss, or beam spread, of approximately 16 percent of the illumination. This is a reasonable starting point, since this loss is comparable with other inefficiencies such as the lack of perfect specular surface reflectivity and errors in pointing the satellite.

It is apparent that the structural weight of the reflector can be optimized by fixing the amount of energy falling within the ground target area and comparing large reflector surfaces (designed with moderate curvatures) with smaller reflectors (designed with less allowable curvature). Flatter surfaces require higher tensions and structural loads, but are more efficient. Total system weight is influenced both by size and by loads. Eventually, all other considerations being equal, the required reflector size and flatness should be selected by this type of optimization.

SECTION 7

EXTERNAL LOADS ON FREE-FLYING REFLECTOR SURFACES

Spacecraft are subjected to a number of external loads which depend on their trajectory, dynamic maneuvers, distance from the sun, distance from the earth, and orientation. The reflective surfaces of a free-flying satellite in earth orbit will experience forces due to solar radiation pressure, aerodynamic drag, gravity-gradient effects, and control acceleration. Solar pressure and atmospheric drag result in relatively uniform pressures on the film which depend on orientation. Body forces due to gravity gradients and control accelerations associated with the mission cause forces which are dependent on both orientation and the distance from the spacecraft's center of mass. The magnitudes of these forces are calculated and discussed in ARC-TN-1072, "Structural Design of Free-Flying Solar-Reflecting Satellites." The maximum laterial loads which result from these effects are shown in Figure 6 as equivalent pressures where the control loads are characteristic of the SOLARES mission.

Solar pressure forces are largest, approximately 1×10^{-5} N/m^2, when the reflector directly faces the sun and they decrease as the cosine squared of the angle away from this orientation. This pressure is applied at nearly full value on a solar-reflecting satellite when it is at its most efficient point of operation.

Aerodynamic pressures, due to interaction with the plasma and the reflector surface, decrease rapidly with increasing orbital altitude. This effect is smaller than that caused by solar pressure for altitudes above 700 km, and it is larger for altitudes below 700 km.

Orbiting reflector surfaces will experience gravity-gradient forces, when the surfaces are not parallel to the orbit trajectory, due to the combined effect of the change in gravitational force and the centrifugal force at points distant from the center of gravity. The equivalent pressure resulting from this effect depends on both the distance from the center of gravity, the mass per unit area of the reflector film, and the orientation. Very thin films, with their low mass per unit area, minimize gravity-gradient effects. Note that for a value of the parameter $m_a r$ of 1 kg/m, which would apply to a location 250 meters from the center of gravity in a film which weighs 0.004 kg/m^2, the maximum gravity-gradient effect is less than all of the other forces. However, for larger satellites or heavier reflectors, the gravity-gradient forces are significant.

Control loads are present in solar-reflecting satellites, such as required for the SOLARES concept, since the spacecraft angular attitude must be continually changed to keep the beam pointed at the ground-based target. The required accelerations depend on the orbit selected and are higher for low-altitude orbits. The equivalent pressure is again dependent on the parameter $m_a r$, since these angular accelerations occur about the center of gravity, and the force is proportional to the mass being accelerated. Since the angular acceleration rates depend on the location of the satellite in its trajectory, the equivalent pressures are shown as a band for two values of $m_a r$ in Figure 6. These forces, due to control dynamics, dominate all other effects at lower altitudes. At approximately 3000 km, the highest value of this loading for $m_a r = 1$ kg/m^2 drops to the same level as the solar radiation pressure.

In order to minimize the weight of a SOLARES-type of solar-reflecting spacecraft, it is essential to keep the loads associated with control accelerations down to the same level as the solar pressure. Since the orbit determines the rates of angular acceleration, the parameter $m_a r$ must be minimized to a value which decreases with the orbit altitude. In order to have large, efficient reflectors at lower altitudes, the film weight per unit area must be minimized. For example, to operate a 1000-m-diameter reflector at an altitude of 3000 km a film density of 0.003 kg/m^2, corresponding to a thickness of approximately 1.4 μm, is desired. At lower altitudes either the film thickness or the reflector size would have to be reduced from these values.

SECTION 8

BASELINE STRUCTURAL DESIGN OF A REFLECTING SATELLITE

The procedure followed to establish a baseline design for a reflector satellite was as follows:

1. Determine the required reflector flatness.
2. Determine the external loads acting on the membrane.
3. Determine how much membrane tension is necessary to maintain its shape within the required flatness while subjected to the external loads.
4. Design a statically stable, minimum-weight structure to apply the required tension.

Note that this approach has not taken into account other concerns such as dynamic interactions between the structure and the control system. It is hoped that the accuracy requirements will be stringent enough that this incomplete "static" procedure will provide a valid basis for establishing the effects of film thickness on the structural design.

The required reflector flatness has been examined in Section 6. A maximum rms gradient of 0.00071, corresponding to a 0.001 radian edge gradient for a spherical deflection, was selected for the baseline design. As previously discussed, this amount of surface distortion causes an energy loss of approximately 16 percent.

The external loads on an orbiting reflector have been summarized in Section 7. For the baseline design, an average total pressure loading on the film of 1×10^{-5} N/m^2 was selected for a 1000-m-diameter reflector with a 2-μm film thickness (4 g/m^2) orbiting at a 4000-km altitude.

The film tension required to limit the edge gradient to 0.001 radians, while subject to a pressure $p = 1 \times 10^{-5}$ N/m^2, can be computed for a circular membrane of diameter D, using the following formula which is discussed in ARC-TN-1070:

$$N = \frac{pD}{4(\text{grad } \overline{w})_e}$$

For a baseline reflector diameter of 1000-m, the above equation results in a film tension of 2.5 N/m. Figure 7 shows the film tension required to maintain this degree of flatness in different sizes of reflectors. The resulting stress in a 2-µm-thick film is shown in the same figure.

The design of support structures to apply the required film tension is treated in detail as part of ARC-TN-1072. The resulting baseline design is a nearly circular reflector configuration similar to the illustration in Figure 8, except that the rim is divided into 80 segments. Preliminary examination of a triangular configuration, such as illustrated in Figure 9, showed that the supporting structure would be excessively heavy for large (kilometer) sized satellites. This triangular configuration would be efficient for an application needing reflectors in the 100-m range.

The nearly circular reflector satellite configuration packages and deploys in a manner similar to the segmented-rim structure illustrated in Figure 10. The film material is stored by wrapping it in pleated gores around the center body to form a cylindrical launch payload. An Astromast center hub column collapses in length to store inside the folded rim segments. Front and back carbon-composite stay tapes are stored on reels at each end of the center column. Furthermore, the diameter of the packaged spacecraft is further reduced by using externally stiffened expandable truss columns for each of the rim segments. This type of weight-efficient column stores to a very small diameter as illustrated in Figure 11. ARC-TN-1065, "Design of an Externally Stiffened Truss Column," 9 August 1978, describes the design and analysis of this new type of deployable column, which has been modeled and tested at Astro Research Corporation.

The design of each component of the baseline spacecraft structure is described in ARC-TN-1072. Reasonable attempts were made to optimize the length of the rim element, and hence the number of tension stays, for minimum total structure mass. Safety factors, when applicable, were included in the design of each component. A conservative area density of 4 g/m^2 was assumed for the 2-μm metallized Kapton film which has a basic area density of approximately 3.2 g/m^2. The additional $0.88/m^2$ generously provides for seams, rip stops, and thicker coatings. The calculated masses for the reflector film and components of the spacecraft structure are tabulated on Table II. Other spacecraft systems, such as the control system, are not shown. The baseline design has a total reflector mass of 3142 kg and structure mass of 2738 kg. The average area density of the total is 7.5 g/m^2 based on the reflector area of 785,000 m^2.

SECTION 9

CONCLUSIONS

Since the tension required for a fixed normal loading on the film to maintain a specified flatness is independent of the film thickness, the structure weight is also independent of film thickness for a fixed reflector size, required film flatness, and lateral loading. The total mass of reflector film and structure will, therefore, decrease with decreasing film thickness. This effect is shown in Figure 12. However, a reduction of film area density will reduce control loads at any given orbital altitude. As a result, the structure weight of a 1000-m-diameter reflector can be reduced, for the same 4000-km orbital altitude, if the film density is lower than 4 g/m^2. Alternately, this reflector and the baseline structure could operate at orbits below a 4000-km altitude with a lighter film resulting in the same lateral loading.

A parametric study was conducted to establish the variation of the structural mass fraction (the ratio of structure mass to the reflector film mass) with reflector size for a fixed reflector accuracy, film thickness, and lateral loading. The results are shown in Figure 13 and indicate that small reflectors are the most efficient, but that very large reflectors still require less structure weight than payload weight for 4 g/m^2 films. The development of thinner films would cause a significant reduction in total weight for all sizes of the reflector spacecraft. Since lower weight films would also reduce the loads due to control maneuvers, the structure weight might also be reduced.

This study has shown that 2-μm and thinner films can be used to construct lightweight reflecting spacecraft. Improvements in thin-film technology would help by:

- Reducing the large environmental strains characteristic of existing films
- Reducing the stress required to flatten the films
- Improving long-term stability of films
- Lowering the elastic modulus of thin films

This study illustrates the need of further development of both thin-film technology and structural design techniques for membrane reflectors of all sizes.

TABLE I. CHARACTERISTICS OF SMALLEST ELEMENT OF LARGE MEMBRANE REFLECTORS

APPLICATION	SHAPE	LARGEST DIMENSION (m)	AREA (m^2)	FILM THICKNESS (μm)	FILM AREA DENSITY (gms/m^2)
Solar-Reflecting Free-Flying Satellites such as SOLARES	Triangular	1400	1×10^6	2.7	4.2
	Circular	1130	1×10^6	2.7	4.2
Thermal SPS	Hexagonal	40	1×10^3	7.6	11.2
Photovoltaic SPS Concentrator C.R. = 2	Rectangular	600	3×10^5	25.0	36.0
Photovoltaic SPS Cell Blanket	Square	660	4.3×10^5	25.0	36.0
Large Optics	Round	610	4.7×10^5	Undefined	Undefined
Heliogyro Blade	Rectangular	15	1×10^2	2.3	3.6
Precision rf Reflectors	Paraboloid	Up to 3000	Undefined	Undefined	Undefined
Attitude or Orbit-Control Surfaces	Various	Undefined	Undefined	Minimum	Undefined

TABLE II. WEIGHT SUMMARY OF BASELINE DESIGN FOR A 1000-m-DIAMETER REFLECTOR AND STRUCTURE

Item	MASS (kg)
Structural Components	
Edge tendons, 80	12
Corner compensators, 80	307
Rim segments, 80	1299
Front and back stays, 160	478
Astromast hub column, 500m	231
Center body	210
Mechanisms	201
Structure Total	2738
Reflector Membrane ($4\ g/m^2$)	
$A = 785{,}400 m^2$	3142
TOTAL	5880

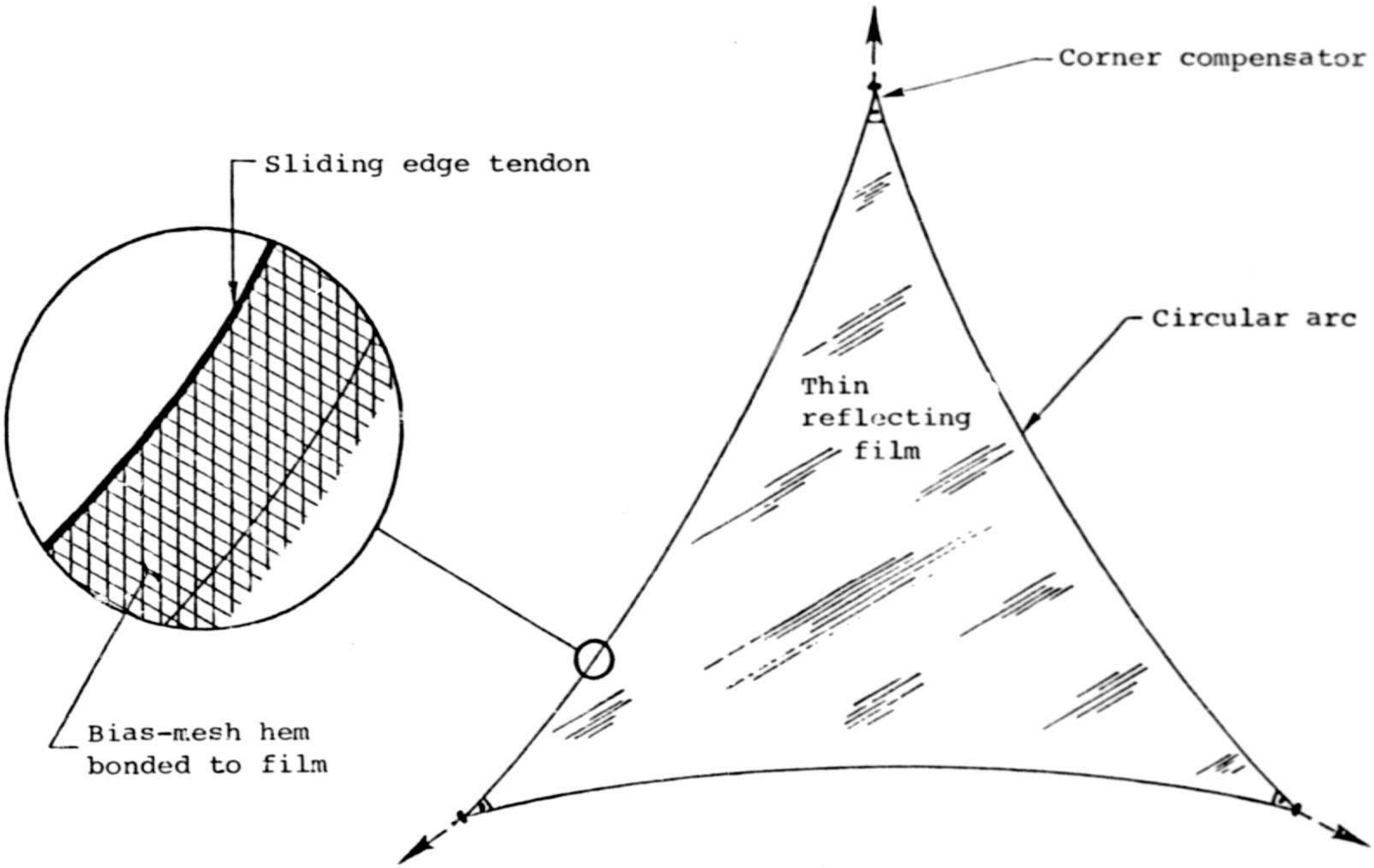

Figure 1. Triangular reflector facet design.

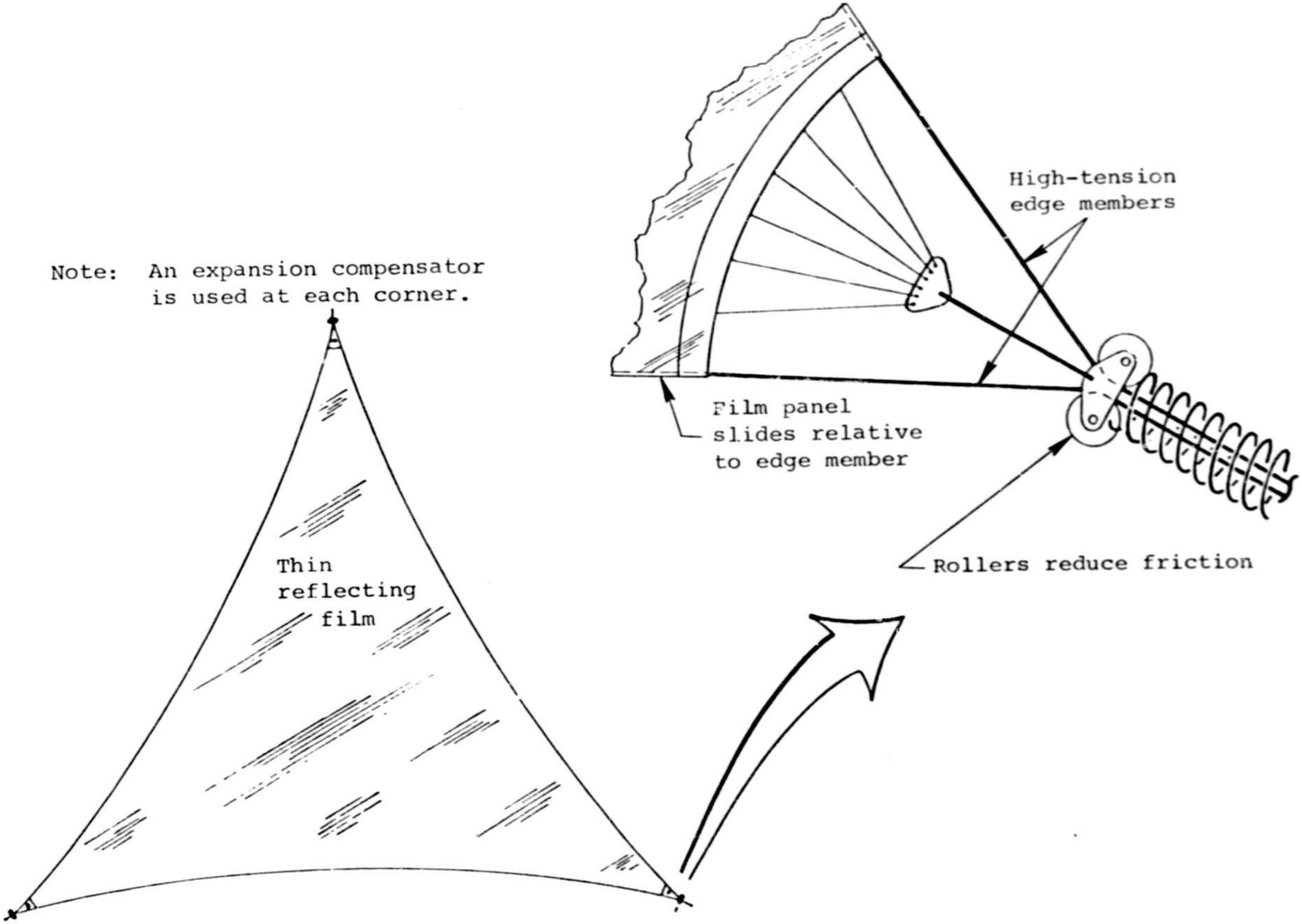

Figure 2. Corner compensator details.

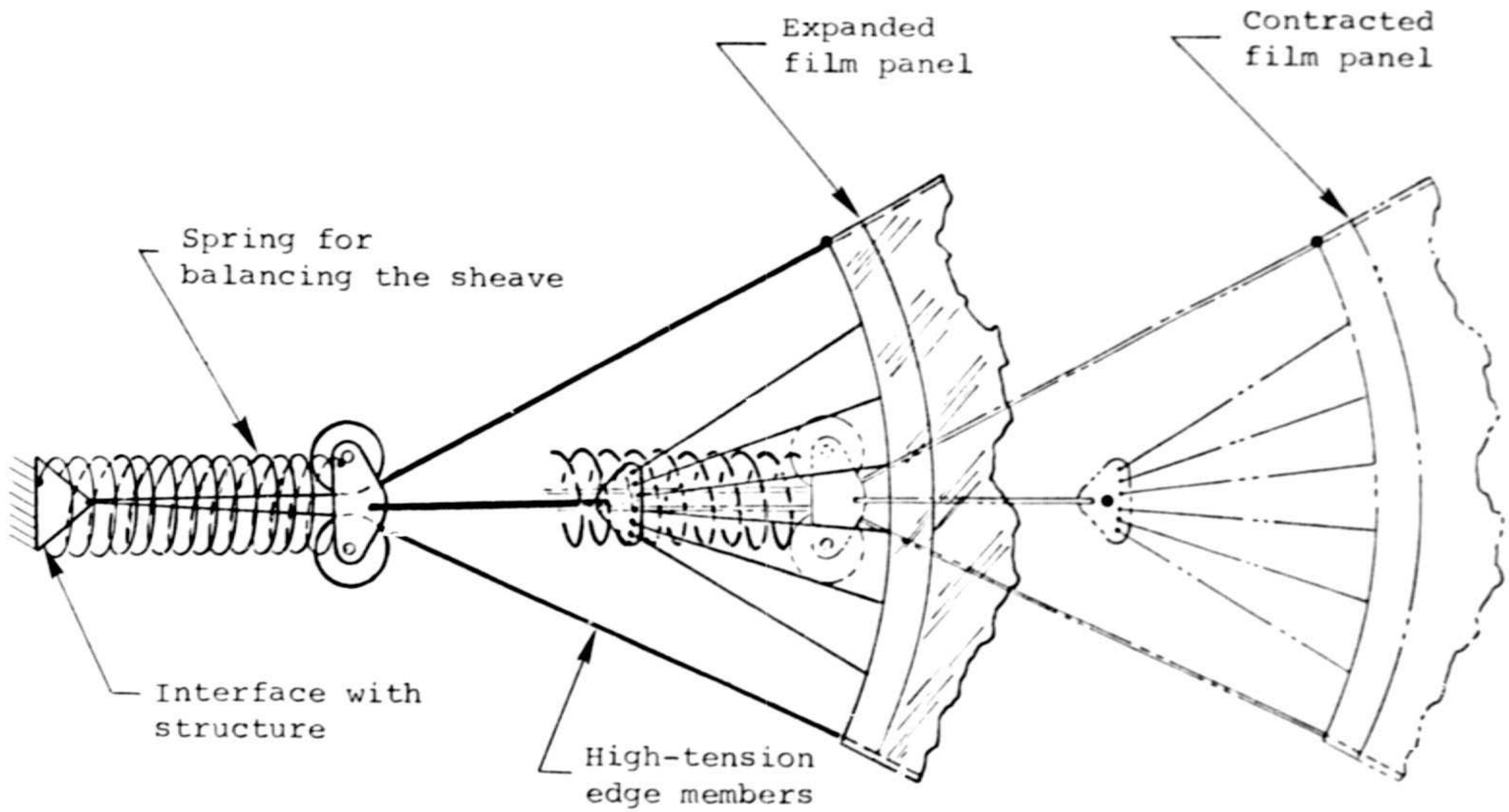

Figure 3. Expansion compensator.

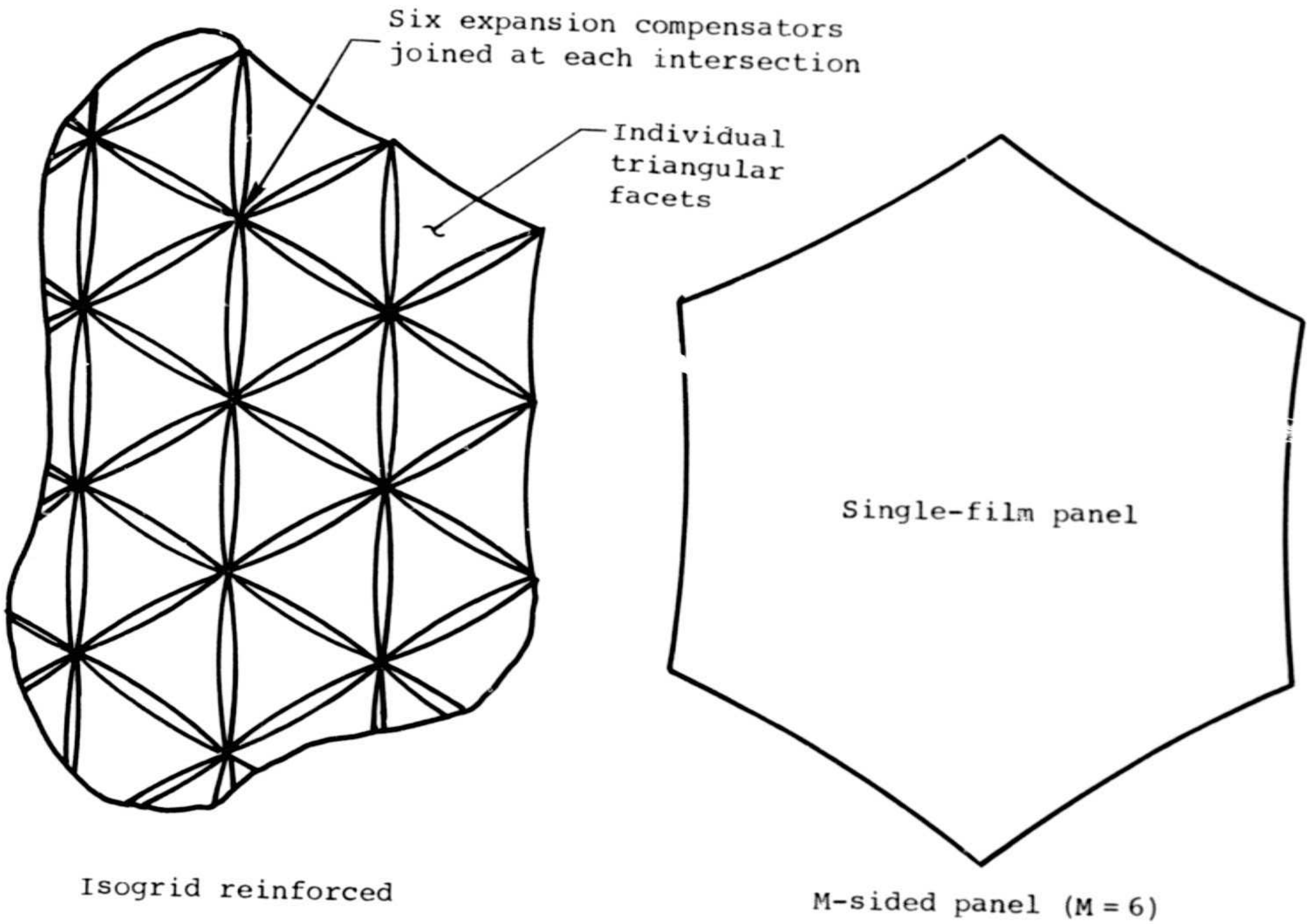

Figure 4. Film panel types.

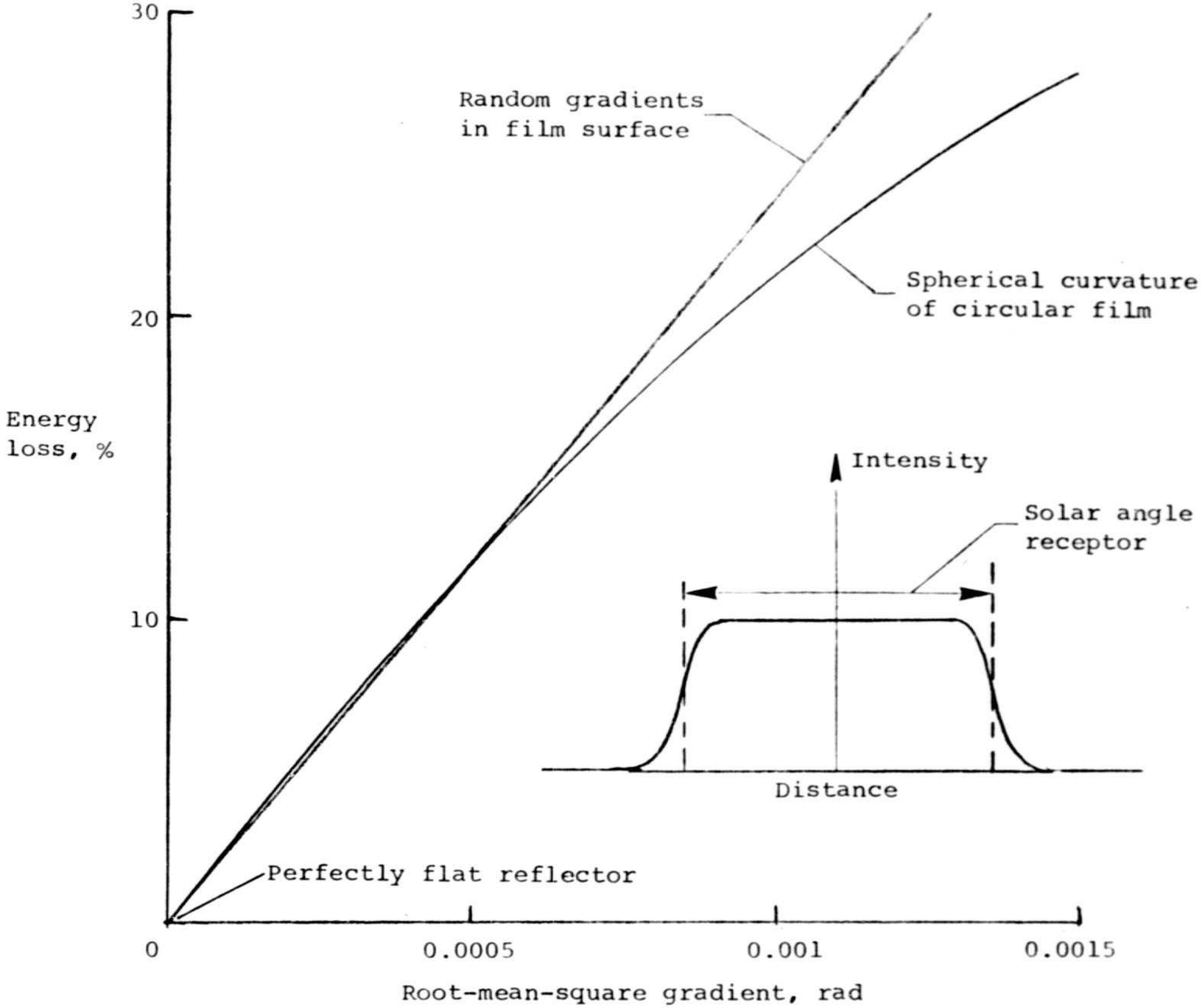

Figure 5. Effect of local gradients on beam spreading.

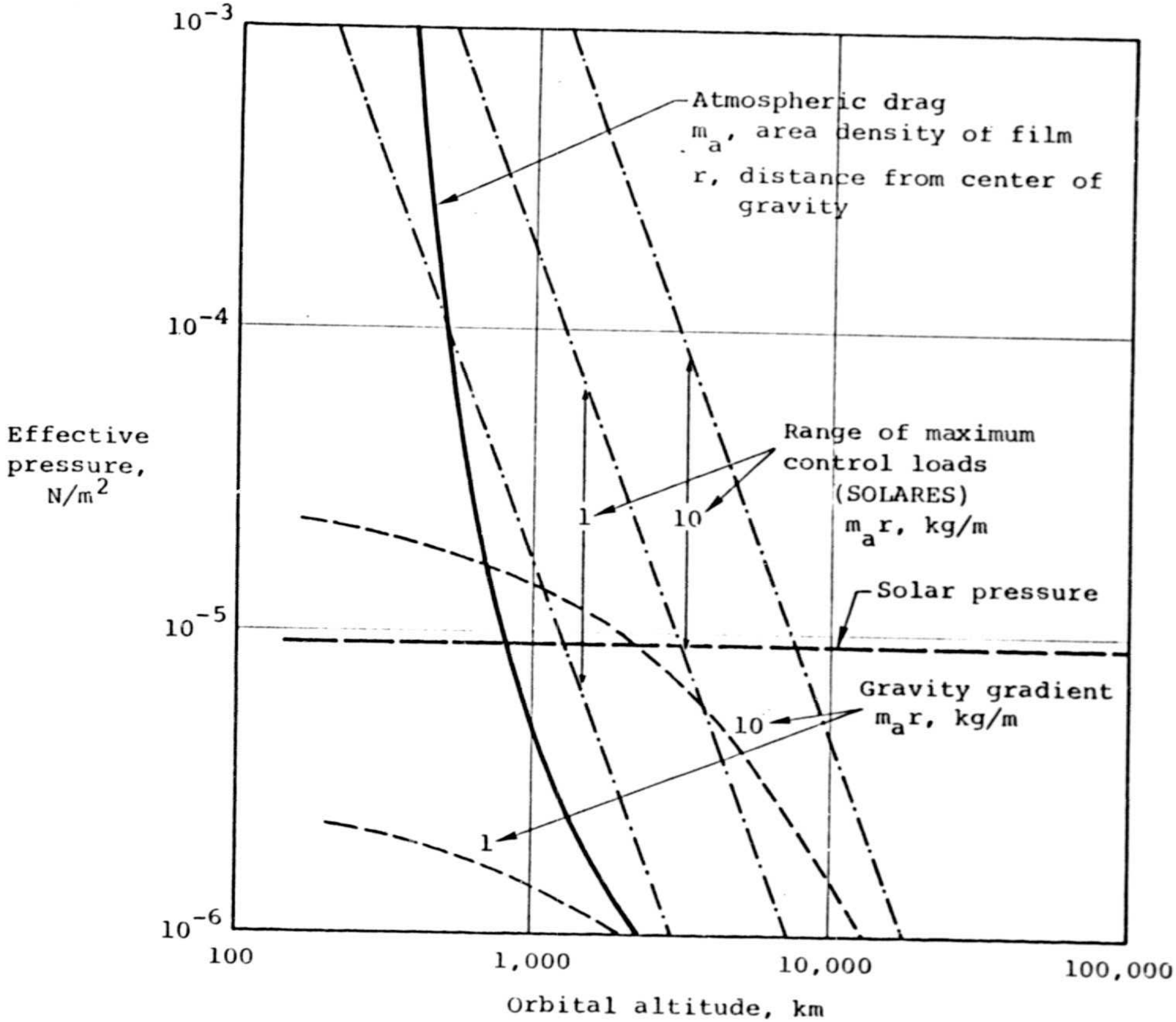

Figure 6. Maximum lateral loads on reflecting films at different orbital altitudes.

Baseline Parameters

- 2-μm-thick metallized film with seams ($4\ g/m^2$)
- $1 \times 10^{-5}\ N/m^2$ lateral loading
- 0.001 rad edge gradient, spherical curvature

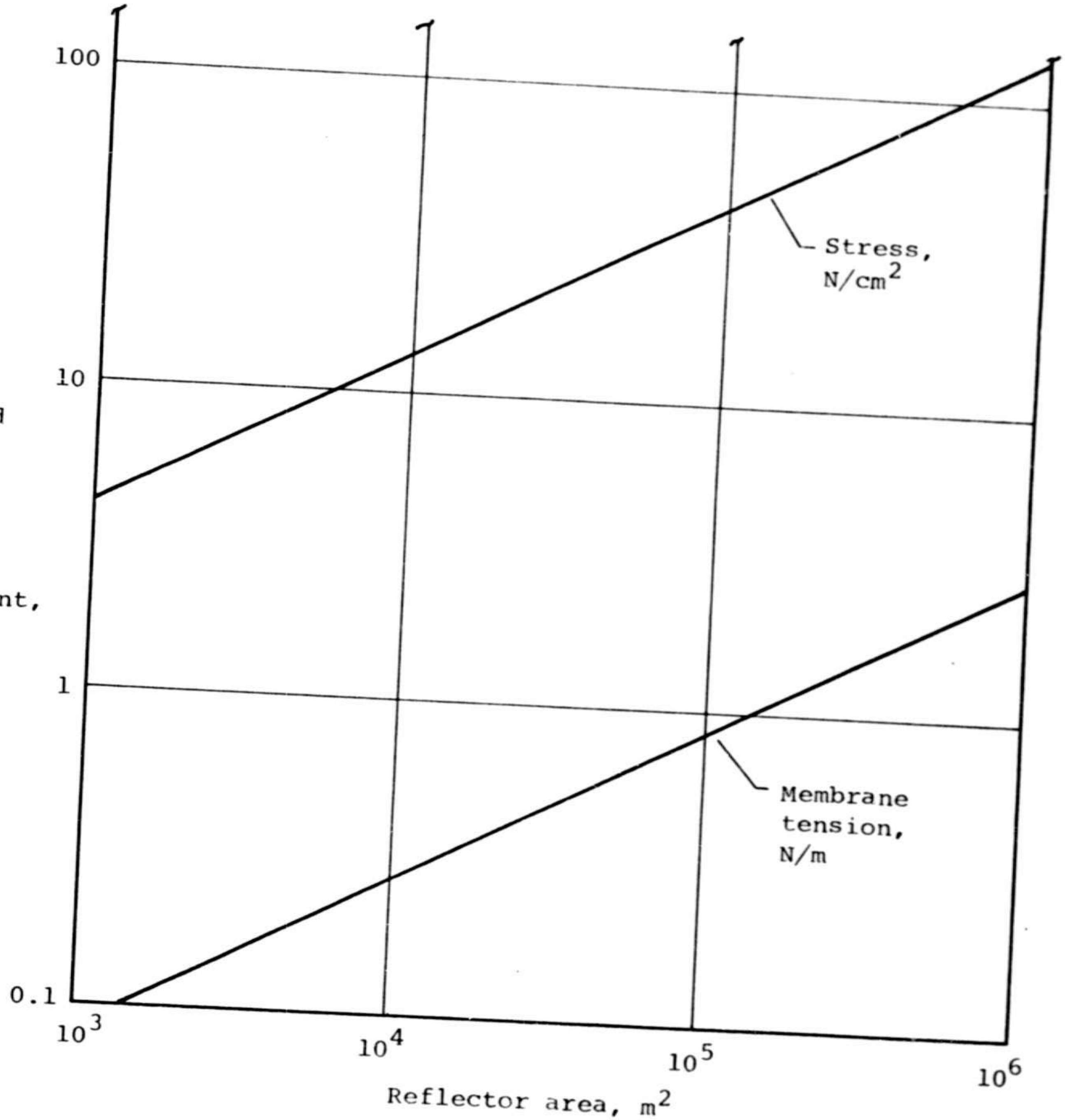

Figure 7. Film tension required to limit spill-over energy loss to 16 percent.

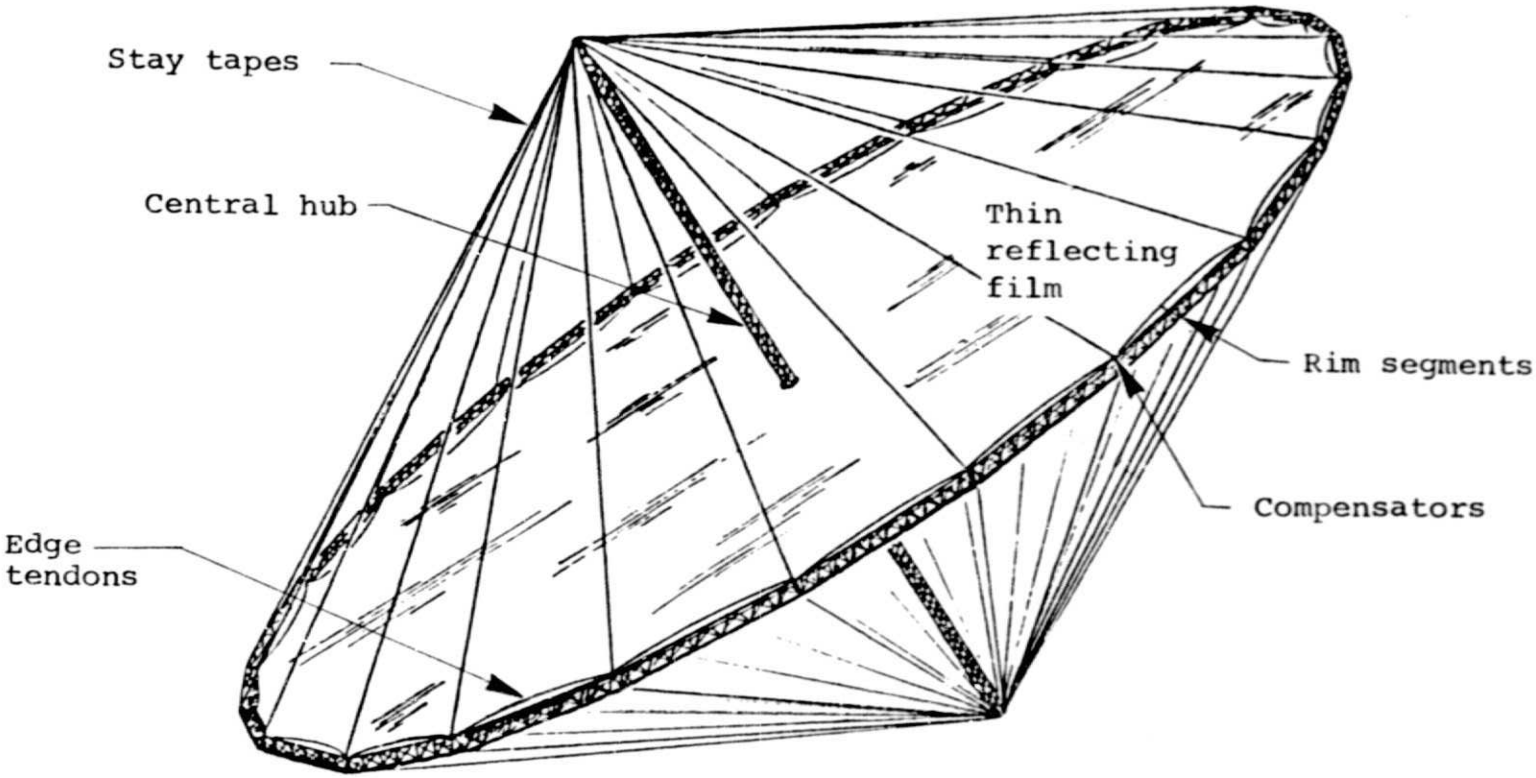

Figure 8. Reflector satellite nearly-circular configuration.

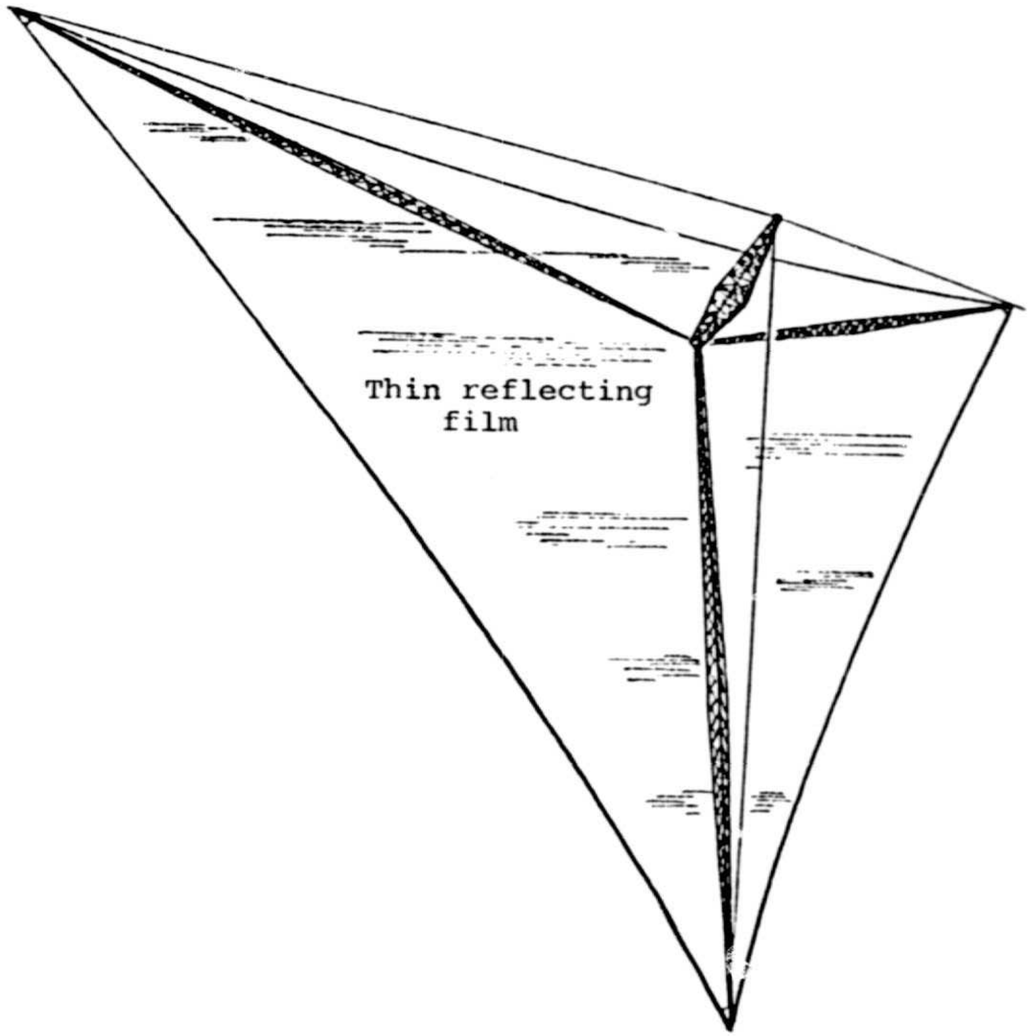

Figure 9. Reflector satellite triangular configuration.

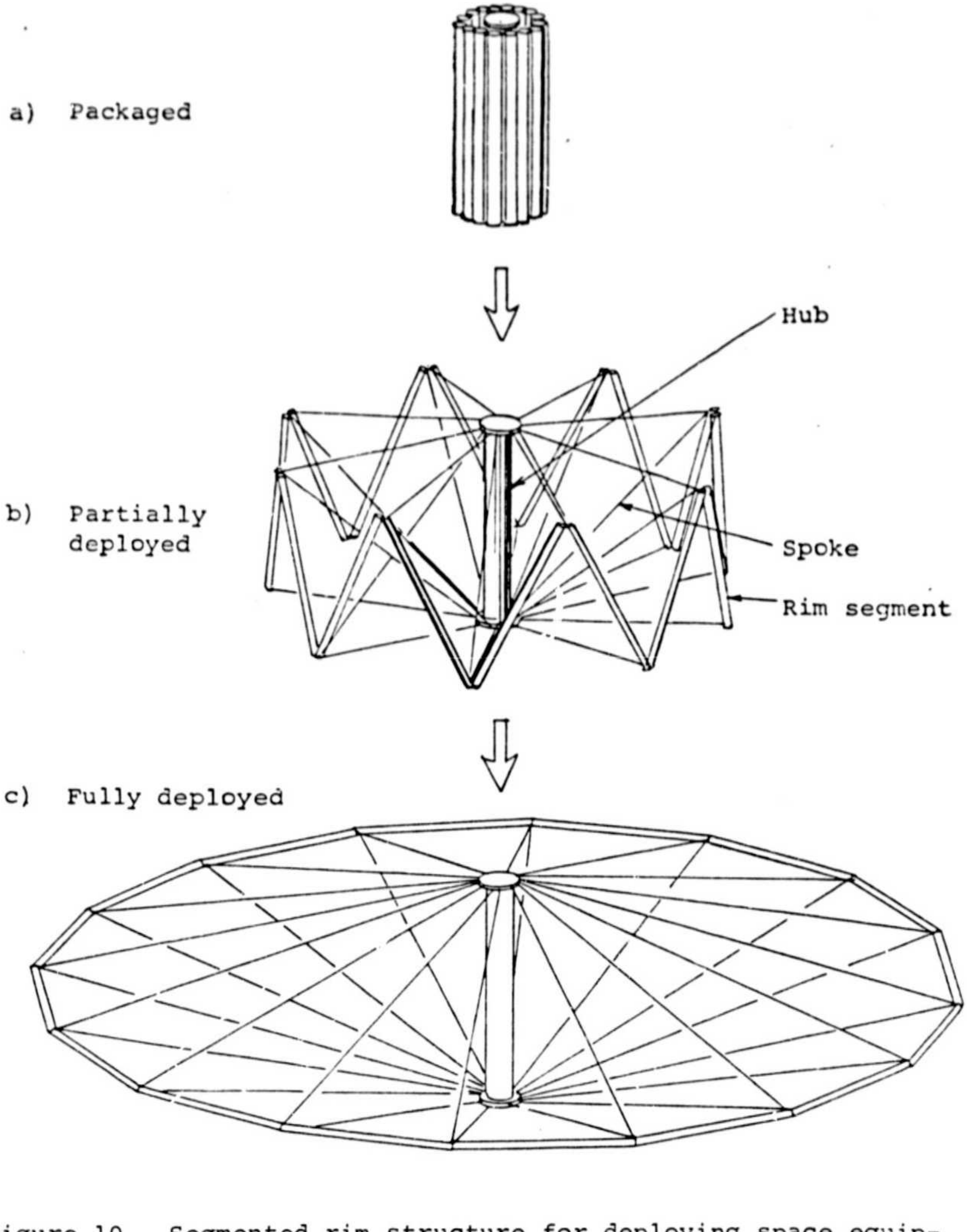

Figure 10. Segmented rim structure for deploying space equipment. (This Astro figure was published in NASA CR-2347, "Spoked Wheels to Deploy Large Surfaces in Space - Weight Estimates for Solar Arrays.")

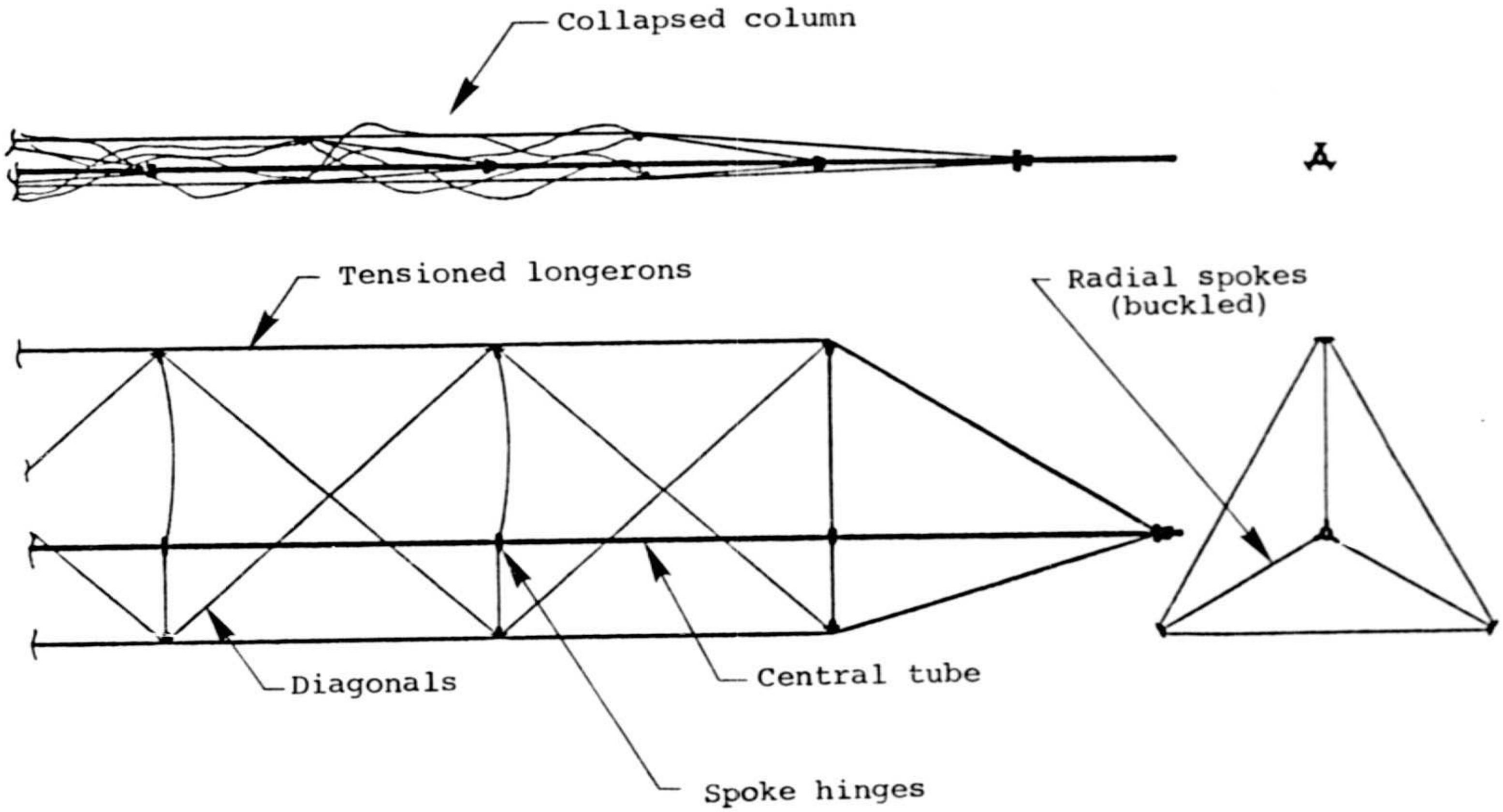

Figure 11. Design and packaging of an externally stiffened expandable truss column.

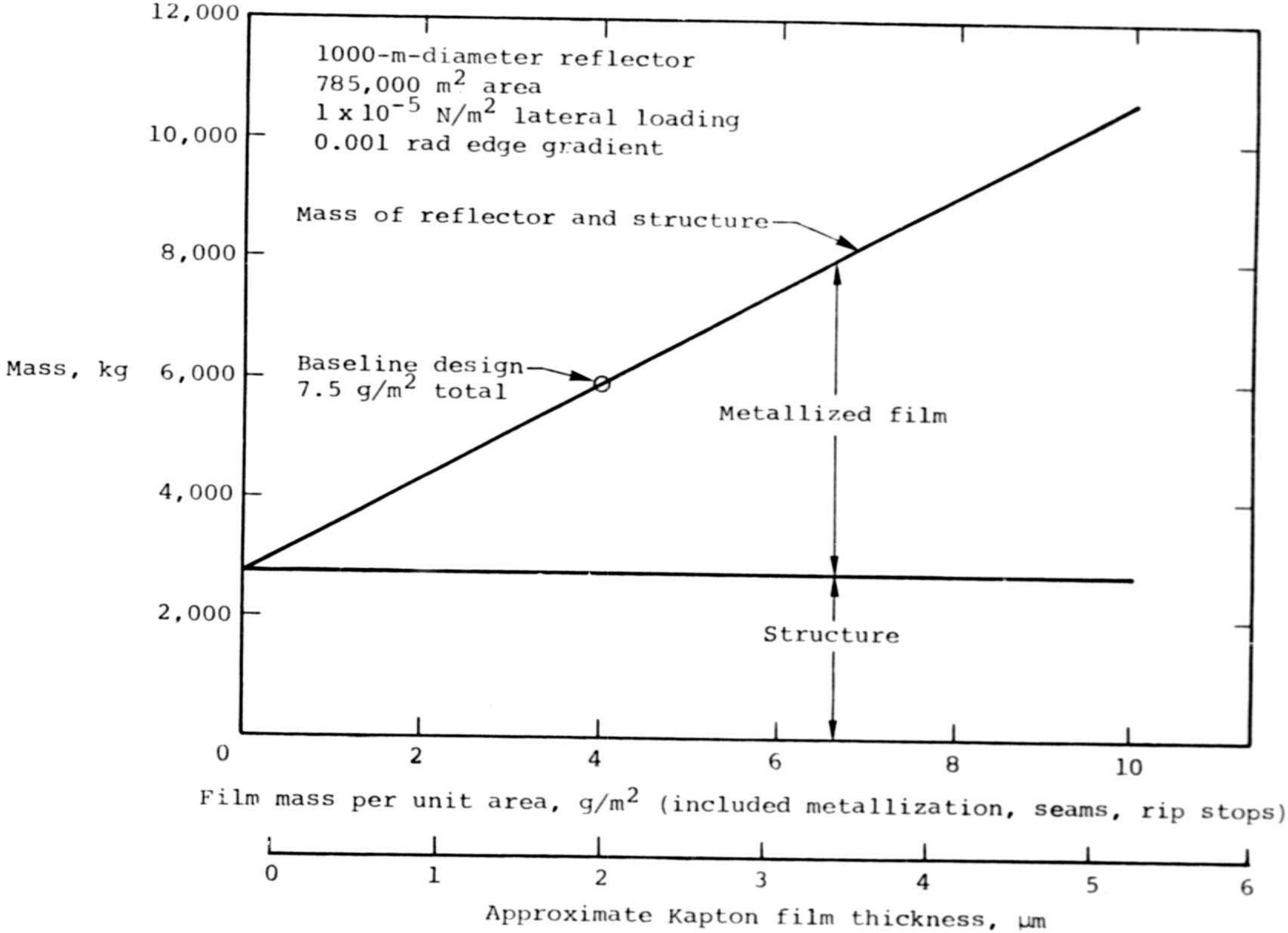

Figure 12. Variation of structure and reflector mass with film thickness (mass) for a 1000-m circular satellite.

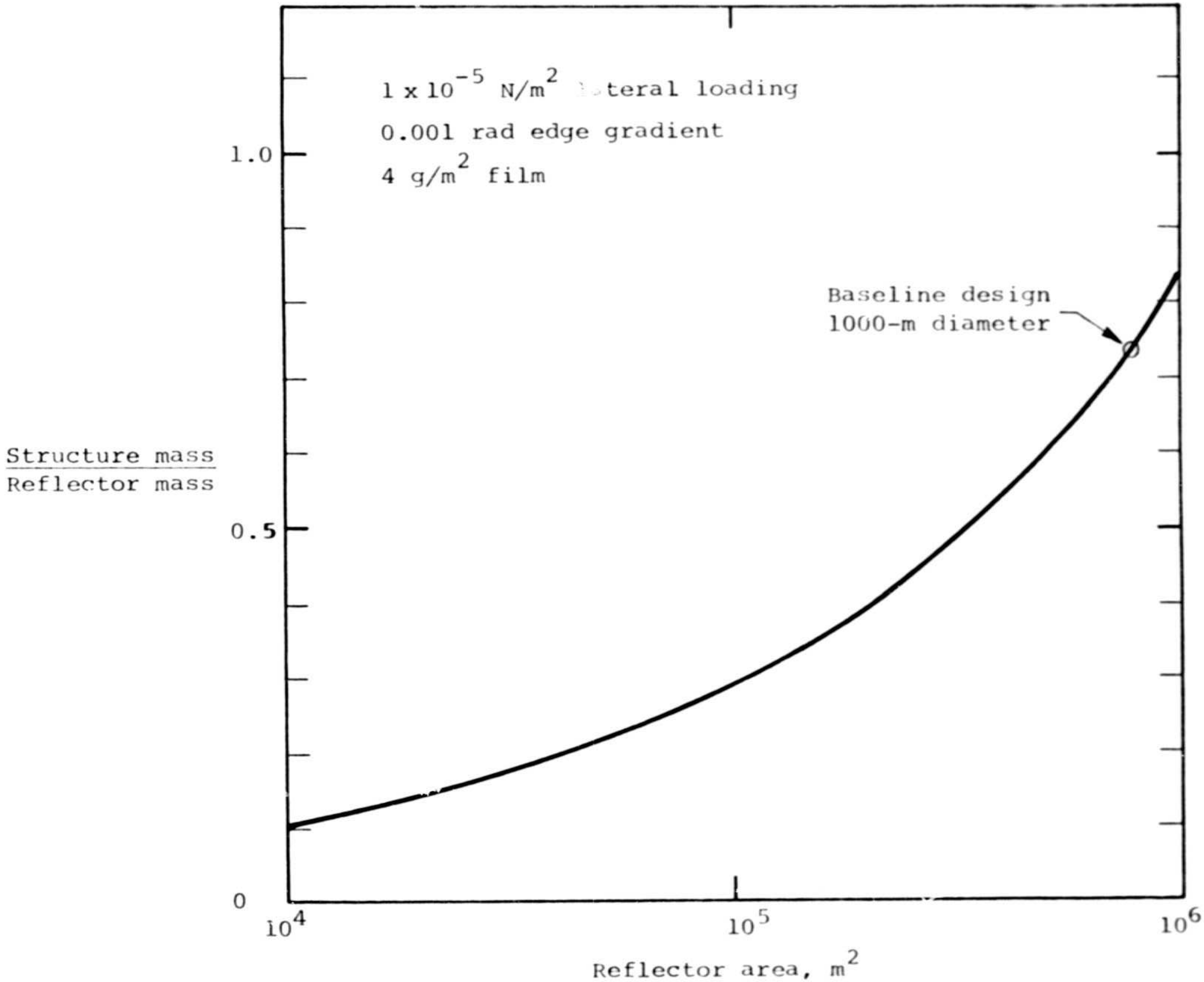

Figure 13. Structural mass fraction for circular reflector satellite.