Project

ABLE

FINAL REPORT (U)

Contract NAS8-20668

Volume I - SUMMARY

Prepared for George C. Marshall Space Flight Center by

GOODYEAR AEROSPACE CORPORATION AKRON, OHIO

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GOODYEAR AEROSPACE CORPORATION

AKRON 15, OHIO

PROJECT ABLE

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CONFIDENTIAL

FOREWORD

Goodyear Aerospace Corporation's final report for Project ABLE consists of two volumes plus an addendum to Volume II as follows:

Volume I - Summary (Confidential)
Volume II - Technical (Confidential)
Volume II - Technical - Addendum I (Secret)

Volume II Addendum I which contains Section V Paragraph 4 "Attitude-Sensing Systems" and carries a Secret classification has been put under separate cover so that the major portion of Volume II could maintain a Confidential classification.

The work reported was done under Contract NAS8-20668 for George C. Marshall Space Flight Center, Huntsville, Alabama.

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SECTION I - INTRODUCTION

1. SCOPE

Goodyear Aerospace Corporation conducted a three-month study to assist in establishing the technical feasibility of a flat solar-reflector operating in earth orbit. The reflector satellite system requirements were determined through orbital, illumination, and control analyses performed within certain guidelines established by NASA. Preliminary concepts were generated, and through supporting materials, structural, thermal, control, manufacturing, packaging, and deployment analyses, a conceptual design and a research, development, test, and engineering (RDT &E) plan were evolved for a 2100-ft-diameter reflector. This 2100-ft-diameter reflector would give an illumination level on the ground slightly in excess of a full moon, providing a specular reflectance coefficient equivalent to 0.8 on a flat mirror could be maintained.

In addition, Goodyear Aerospace provided Boeing, Westinghouse, and Grumman, who had systems contracts on Project ABLE, with assistance in the areas of materials, structures, packaging, and deployment. This assistance was provided through technical meetings at Goodyear's plant in Akron in which data and reports were given to the systems contractors.

The guidelines established at the start of the program confined Goodyear's effort to satellites having reflector diameters of 1500 to 3000 ft that would operate in synchronous orbits. After the midterm presentation at NASA Headquarters 11 October 1966, the contracting officer's representative requested that Goodyear Aerospace consider reflector diameters in the 400- to 750-ft range that would result in illumination levels of 0.1 to 0.2 of full moon. Also, about this time, it became apparent that higher reflector-membrane stress levels might be required.

Inasmuch as less than three weeks of technical effort remained in the program, these factors were not completely resolved; for example, it was not possible to develop a conceptual design and RDT & D plan for the smaller-diameter reflectors. However, to the extent possible, smaller reflectors were investigated and tests were conducted for gross evaluation of the effects of membrane tension on the local waviness of aluminized Kapton film and correspondingly its reflective characteristics. Since the required membrane tensions were not yet established, the analysis made to upgrade the large reflector designs necessarily incorporated higher membrane-tension loads independent of the test results. For the reflectors in the 400- to 750-ft range, parametric data were generated using membrane tension as a parameter and structural concepts including extendible radial member approaches utilizing "hard" structures that become much more attractive with the smaller sizes.

2, OBJECTIVES

The objectives as established by the Project ABLE work statement were:

1. Conduct feasibility study of a large orbiting solar reflector to illuminate a specific ground area continuously during nighttime
2. Determine the attainable intensity and area of ground illumination
3. Create a conceptual design of the most promising concept
4. Select materials for the reflector
5. Develop manufacturing, packaging, and unfolding techniques
6. Create an RDT & E program that will make possible an operational reflector in the shortest possible time

3. INITIAL GUIDELINES

The guidelines provided at the start of the study were:

1. Synchronous orbital altitude
2. Reflector surface areas equivalent to 1500- to 3000-ft diameters
3. Saturn V launch vehicle
4. Satellite weight in orbit of 45,000 lb or greater
5. Technologies compatible with late 1968 or early 1969 launch date
6. Minimum operating life time of 6 months with 12 months desired
7. Packaging envelope in spacecraft LEM adapter with Apollo nose fairing
8. Reflector structure and configuration compatible with control loads and optical requirements
9. Maximum effective utilization of existing modified or planned materials and hardware

SECTION II - SUMMARY

1. GENERAL

The reflector system requirements as determined from the guidelines and orbital and illumination analyses served as the basis for orientation and control studies, preliminary concept generation, and materials selection. The preliminary concepts were evaluated and the promising ones refined through additional structural analysis, thermal analysis and manufacturing considerations to arrive at the final conceptual design for which the RDT & E plan was developed.

This design consists of a 2100-ft-diameter reflector with a wire-grid tube truss of triangular cross section serving as the peripheral ring structure for the reflector membrane support. The reflector packaged size is compatible with stowage in the Saturn LEM adapter section and the launch weight is well within the payload capability of the Saturn V The reflector membrane is aluminized Kapton, which was selected for its high radiation resistance characteristics and good structural properties over the operational temperature range.

The decision as to the design for basis of the RDT & E plan was made without benefit of results of tests conducted during the last two weeks of the program, wherein the required stress level in the membrane to provide the desired local flatness and reflective characteristics was determined. Unfortunately, this required stress level is higher than can be accommodated with the wire-grid truss. On the basis of these higher membrane stress requirements, the pressurized torus approach would have to be implemented for reflectors in the 2000-ft-diameter class. Studies of reflector concepts in the 400- to 750-ft-diameter range indicate that the wire-grid tube truss and the pressurized torus, along with "hard" structure arrangements utilizing a flex tube ring, lazy-tong trusses, telescoping tubes, and bowstring concepts are applicable and could provide the necessary tensioning loads.

2. ORBITAL ANALYSIS

As the result of the orbital analysis for synchronous altitude, a stable elliptic orbit was selected to minimize station-keeping fuel. With this stable orbit, the perigee point remains on the earth-sun line throughout the year and both the orbital eccentricity and the period remain essentially constant. A point at 15 deg north latitude was selected as the center of the ground illumination. A comparison of stable elliptic orbits with an initially circular orbit is shown in Figure 1. Solar pressure forces will cause the eccentricity of the initially circular orbit to build up to a maximum of 0.43 after 200 days. This large eccentricity change would reduce the ground illumination to less than half the initial intensity level and increase the spot diameter illuminated on the ground by 50 percent. In addition, the period of this

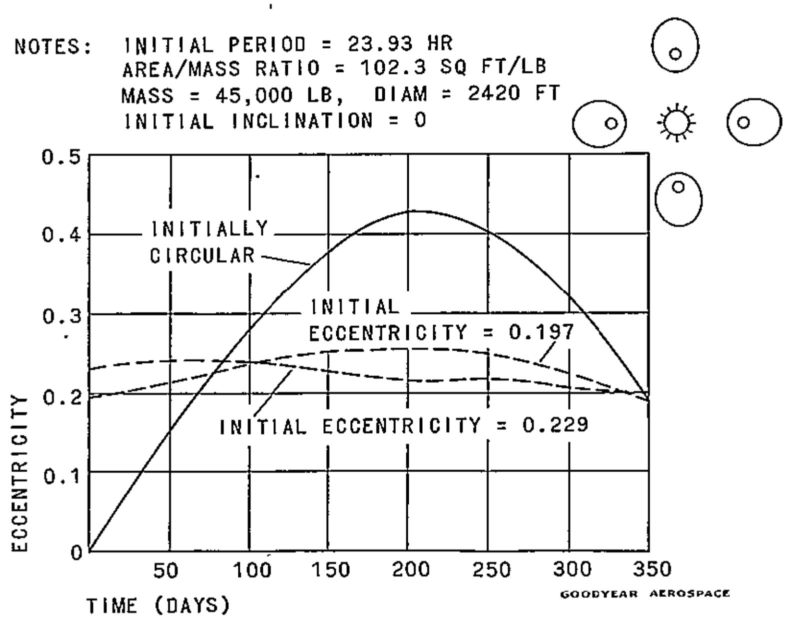


Figure 1 - Comparison of Stable Elliptic and Initially Circular Orbits

initially circular orbit would be changing so that the satellite would require fuel to maintain a period consistent with earth rotation.

The analysis presented in Figure 1 considered a rotary pitch motion of the orbiting reflector in which the average pitch rate would be 7.5 deg per hour. Therefore, in one day the reflector would rotate through 180 deg and on the following day the opposite side of the reflector would be oriented toward the sun, thus requiring a two-sided reflector. A sketch of this rotary pitch motion is shown in Figure 2 along with an oscillatory pitch motion. The oscillatory pitch motion is identical to the rotary during nighttime. However, during daytime, the attitude would be rotated from its 6 a.m. position to the 6 p.m. position by keeping the same side toward the sun. Thus, the oscillatory pitch motion will permit the use of a single-sided reflector that may significantly reduce thermal problems, particularly for radial member arrangements where the structure can be located on the shadow side and be kept at nearly constant temperature.

The control logic utilized in establishing the oscillatory motion through the daylight portion of the orbit would switch to the oscillatory mode when the illuminated point on the earth is 90 deg from the earth-sun line and switch to the reflecting mode 12 hr later. This logic would cause asymmetries in the switching points relative to the major axis of the orbit since switching times are independent of satellite position. The asymmetries, in turn, would tend to increase the period perturbations that caused them. However for an eccentricity close to that required for a stable elliptic orbit, the effects of these asymmetries were minimized and an essentially stable orbit was attained (see Figure 2). With the control logic used, a total Δv of approximately 20 fps would be required to maintain the period of the orbit constant for one year operation. With fuel having a specific impluse of 100, this would require a fuel weight of 0.7 percent of the satellite gross weight for station keeping. However, with a change in the control logic utilized during the daylight portion of the

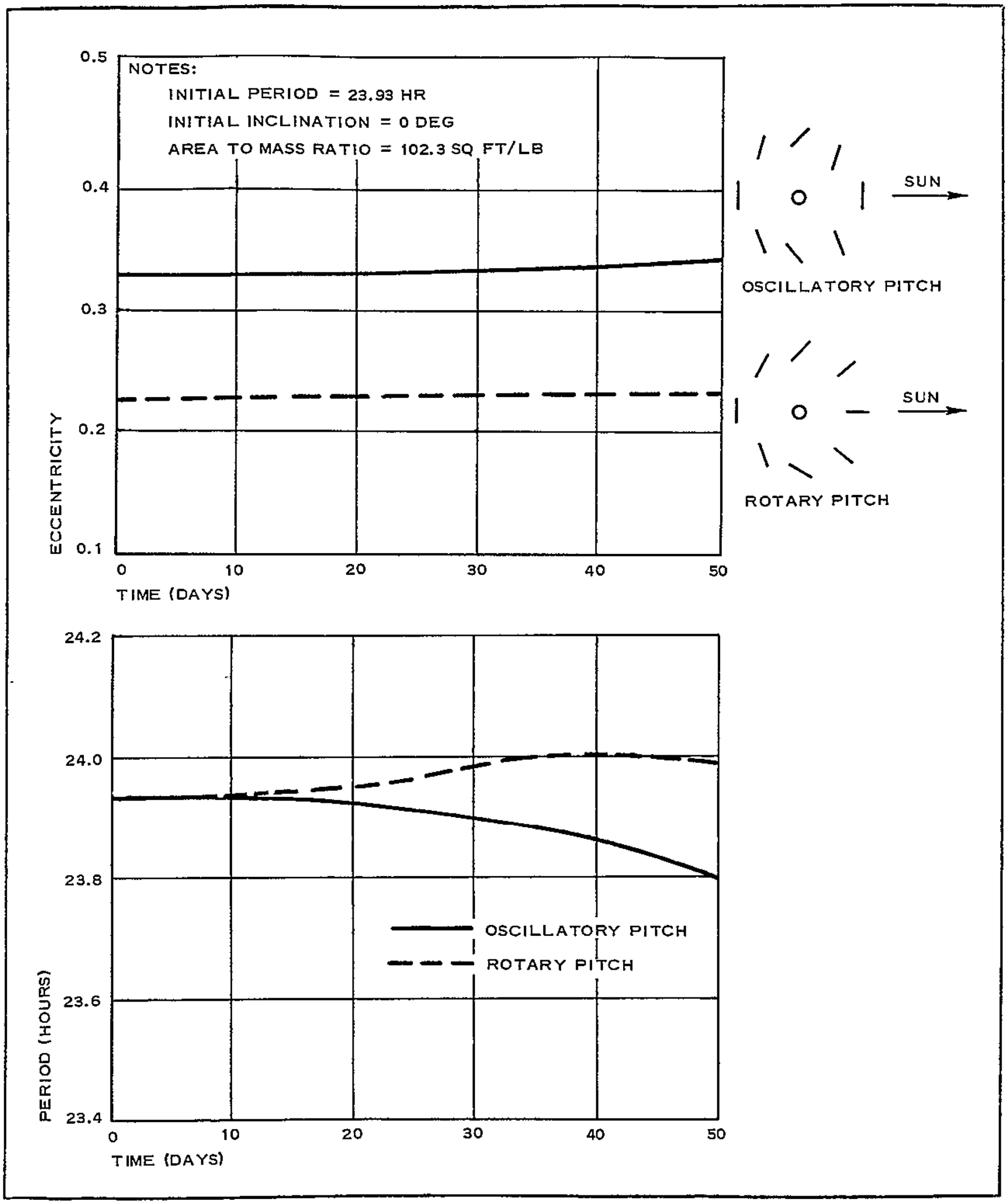


Figure 2 - Comparison of Oscillatory and Rotary Pitch Motions

orbit, it should be possible to reduce this station-keeping fuel requirement to a negligible value. The new control logic would consist of switching between the daytime and nighttime modes as a function of true anomaly rather than target position. As can be seen from Figure 2, the eccentricity for the stable orbit for the oscillatory pitch mode would be approximately 50 percent greater than for the rotary pitch mode, which would require a two-sided reflector.

Analysis showed that an equatorial orbit will result in a total loss of illumination of 40 hr in one year due to earth eclipse as compared with almost 2 hr each night, or 720 hr per year, for an ecliptic orbit. The change in orbital inclination of approximately 5 deg during a year's operation is well within the steering capability of the reflector. The reflector orientation accelerations in pitch and roll would be extremely small, the maximum being on the order of a degree per hour squared.

3. ILLUMINATION ANALYSIS

The illumination analysis determined the illumination intensity and the ground diameter illuminated as a function of reflector size in a circular synchronous orbit and included the effects of mirror center deflections. Correction factors to account for changes in altitude, reflection coefficient, and incidence angle were also determined. Typical illumination and ground coverage with a 2100-ft-diameter reflector is shown in Figure 3 for a synchronous orbit with an eccentricity of 0.165. The illumination will vary from a minimum of about 1.25 times that of a full moon at midnight when the reflector is farthest from the earth to a maximum of 1.75 times that of a full moon at 6 a.m. and 6 p.m. The diameter of the illuminated ground area is a function of the distance from the ground and will vary from a maximum of 220 naut mi at midnight to 190 naut mi at 6 a.m. and 6 p.m.

Preliminary tests on local reflector-flatness variation indicated that approximately 100 psi will be required in the 1-mil aluminized Kapton

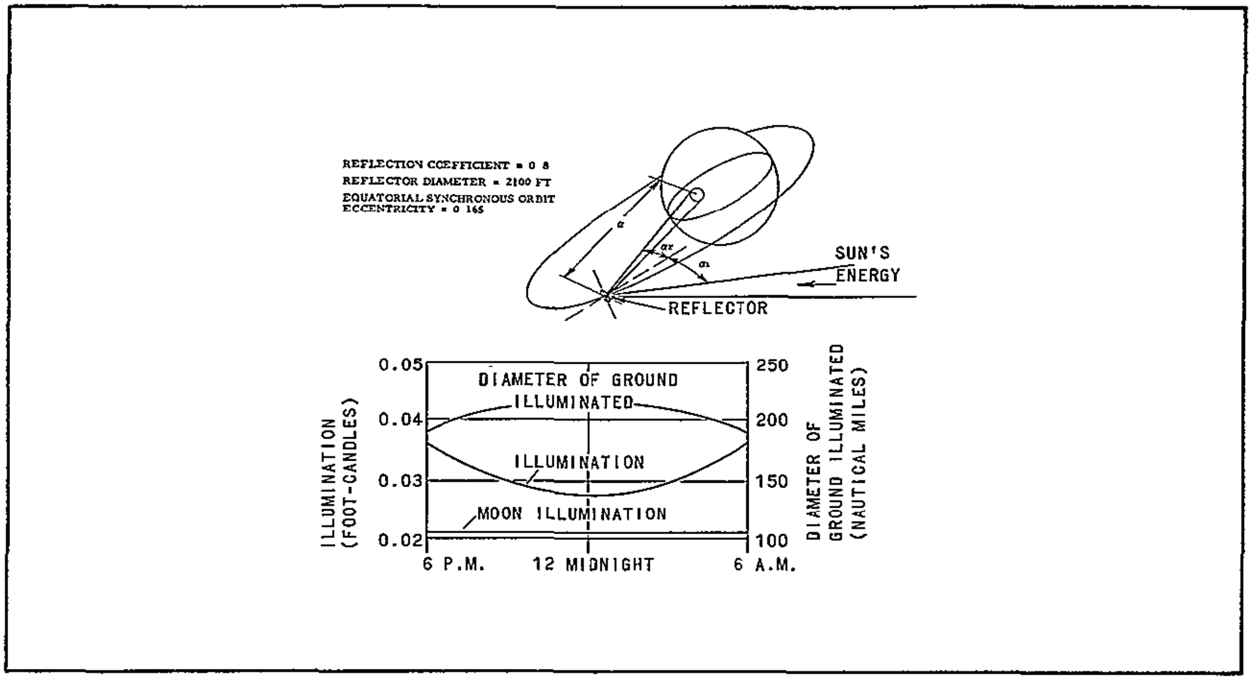


Figure 3 - Typical Illumination with 2100-Ft-Diameter Reflector

film and approximately 300 psi in the 0.5-mil film to provide the desired reflectance characteristics. Since thicker membranes provide acceptable flatness with lower stress levels, a tradeoff exists between membrane thickness or weight and structure weight.

4. ATTITUDE CONTROL SYSTEM

The basic control system concept shown in Figure 4 will provide an acceptable attitude-control capability. Precision roll and pitch-attitude control is provided. The crude yaw-control system is not shown. Attitude sensing is provided relative to two lines of sight, that to the sun and that to the center of the ground area to be illuminated. Information content from the sensing system is sufficient to provide a full three-axis attitude-control capability but with reduced accuracy about the yaw axis when the line-of-sight to the ground is relatively close to the line-of-sight to the sun. This will be the situation existing near the midnight position in orbit. However,

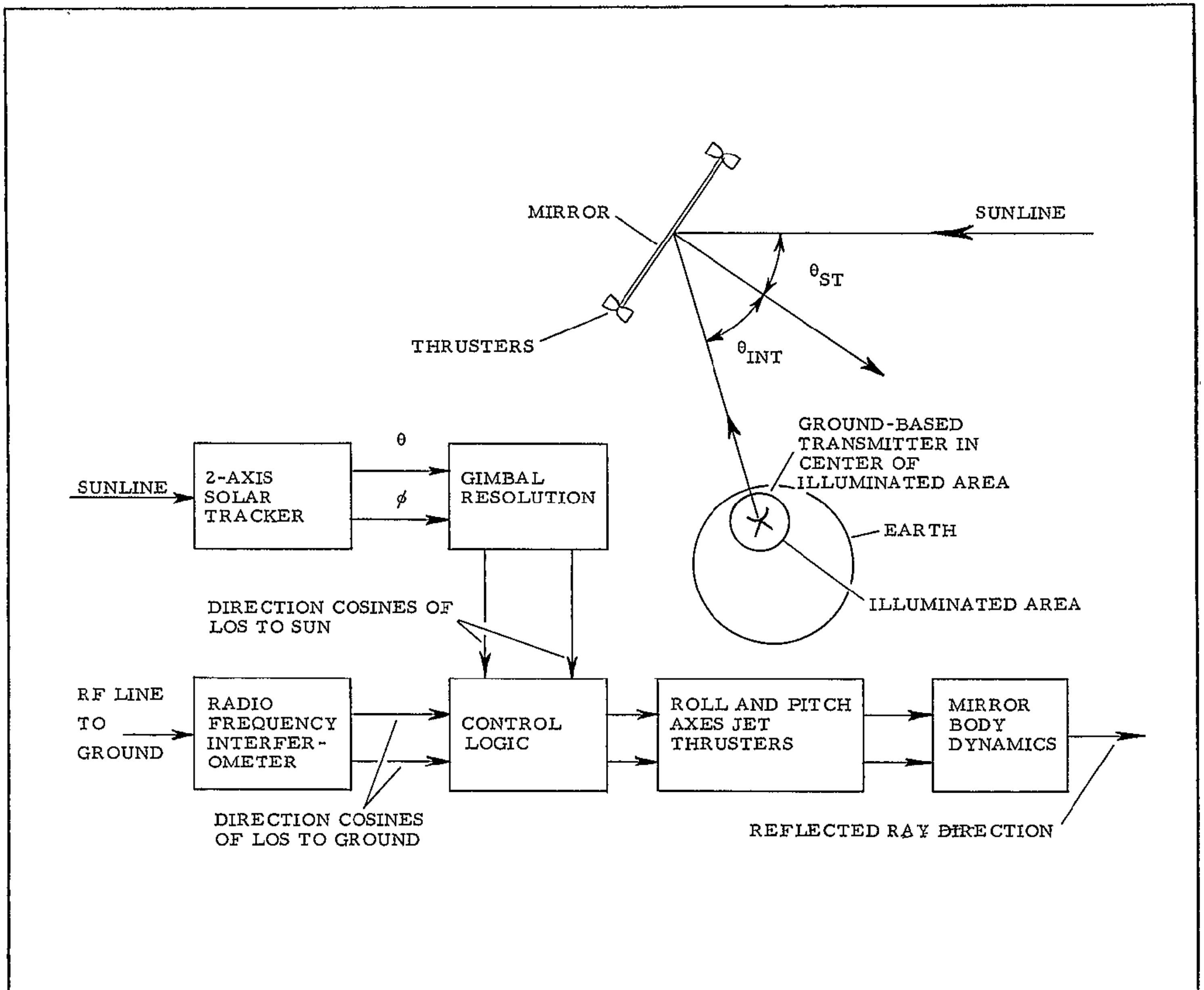


Figure 4 - Basic Attitude-Control System Concept

pointing accuracy will not be degraded to any significant extent at the midnight position because the accuracy essentially is determined by the accuracy of roll and pitch control.

The line-of-sight to the sun may be sensed by a two-axis gimballed solar tracker whose gimbal axes may be used to derive the pitch and roll axes direction cosines of this line-of-sight by means of resolvers on the gimbal axes. The line-of-sight to the ground, where the illumination is to be directed, may be sensed by radio frequency methods using either frequency modulation or interferometer techniques. The control logic is relatively straightforward. In each axis, the direction cosine of the line-of-sight to the ground is compared with the direction cosine of the line-of-sight to the sun and the difference serves as an attitude-error signal. For damping purposes, pseudo rate signals may be determined by differentiation of the error signals. Because of the slow tracking rates and accelerations, sample data methods may be employed. Analysis shows that obtaining an attitude sample once every 3 min will be adequate for control purposes. Thus, long integration times and/or low-pass filtering may be used in the radio-frequency attitude-sensing methods as well as reduced operating duty cycles in the sensing devices.

Various types of attitude-control jets are available in the levels of 10^{-1} to 10^{-3} lb of thrust. Both hydrazine monopropellant and subliming solid rocket motors were considered. The slow speed of response required in the control system permits very low limit-cycle rates on firing of the jets.

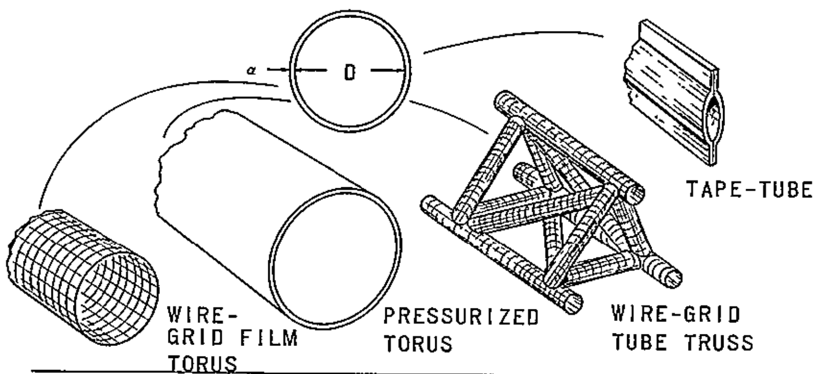
When the RF attitude sensor must operate despite enemy countermeasures, the satellite-to-ground radio-frequency links must have some form of redundancy over the unsecured system to achieve immunity. The number of vital RF paths must be minimized and maximum use made of the available time per attitude determination. Then an optimum security system may be determined by a tradeoff of the following system parameters: (1) transmitter power, (2) redundant paths including multifrequency, multiground site approaches, (3) antenna gain and directivity, (4) spread spectrum (a form of frequency diversity), (5) supervisory control from a high-power station in a secure area, and (6) coding of pulsed transmissions. The threat model, mission requirements, and attitude-system parameters should be considered in a future study to determine the optimum security system.

5. LARGE-DIAMETER REFLECTOR CONCEPTS

For investigation of reflectors in the 1500- to 3000-ft-diameter range, a 2250-ft-diameter was established for a baseline design. Initial effort included evaluation of equal-inertia, three-dimensional versus planar-surface configurations. Although the equal inertia configuration did result in some fuel savings, past Goodyear Aerospace work on lenticular satellite configurations indicated that the weight to provide out-of-plane booms and tip masses would significantly exceed the weight of fuel saved. Therefore, continued investigation was limited to planar surface configurations. Centrifugally tensioned structures were investigated briefly and discarded because the tension required to produce structural integrity would result in spin rates that would require excessive amounts of fuel to precess the momentum vector and correspondingly the satellite during steering.

Comparison of planar surface geometries utilizing a peripheral ring or radial members (4, 6, and 8 members) with tip catenaries for support of the reflector membrane indicated that the peripheral ring results in the lowest compression load in the members. This minimum load is approached with an eight-radial member arrangement. However, the total length of the eight members is almost twice the length of the peripheral ring circumference. Therefore, the major effort was concentrated on peripheral ring concepts.

A comparison of these concepts is shown in Figure 5. The tape-tube ring consists of two strips of aluminum or beryllium-copper formed as shown



TORUS CONFIGURATION	D (FT)	A (FT)	MATERIALS WEIGHT (LB)	INFLATION SYSTEM WEIGHT (LB)	TORUS STRUCTURE WEIGHT (LB)*	0 35-MIL KAPTON MEMBRANE STRESS (PSI)
WIRE GRID FILM TORUS	2,250	17.0	16,000	2,350	18,350	10
PRESSURIZED TORUS	2,250	66 0	8,800	2,400	11,200	150
WIRE GRID TUBE TRUSS	2,000	58 0	10,600	1,900	12,500	50
TAPE TUBE	2,250	6 5	41,500		.	10

*REFLECTOR WEIGHT NOT INCLUDED (0 35-MIL KAPTON REFLECTOR ALUMINIZED 1500 A) ON EACH SIDE WEIGHS 11,100 LB FOR 2250-FT DIAMETER

Figure 5 - Comparison of Peripheral Ring Concepts

and joined at the edges. This section can be flattened without yielding the material and could be packaged by rolling on a drum. However, the weight of this tape-tube, even to accommodate a stress in the membrane of only 10 psi, would be extremely high and therefore this construction was not given further consideration for the large-diameter reflectors. The wire-grid film torus consists of small-diameter aluminum wires running longitudinally and circumferentially between two layers of film.

The wire-grid film structure can be flattened and folded to provide an efficient packaging arrangement. Upon deployment, pressurization gas would be introduced into the torus with the film acting as a pressure bladder. The wires would be straigtened and rigidized to their originally fabricated shape. The pressurization gas then would be vented and the structural integrity would be maintained by the rigidized aluminum wires with the film contributing shear stiffness. The wire-grid film torus proved to be heavier than the wire-grid film truss or the pressurized torus so it was also eliminated.

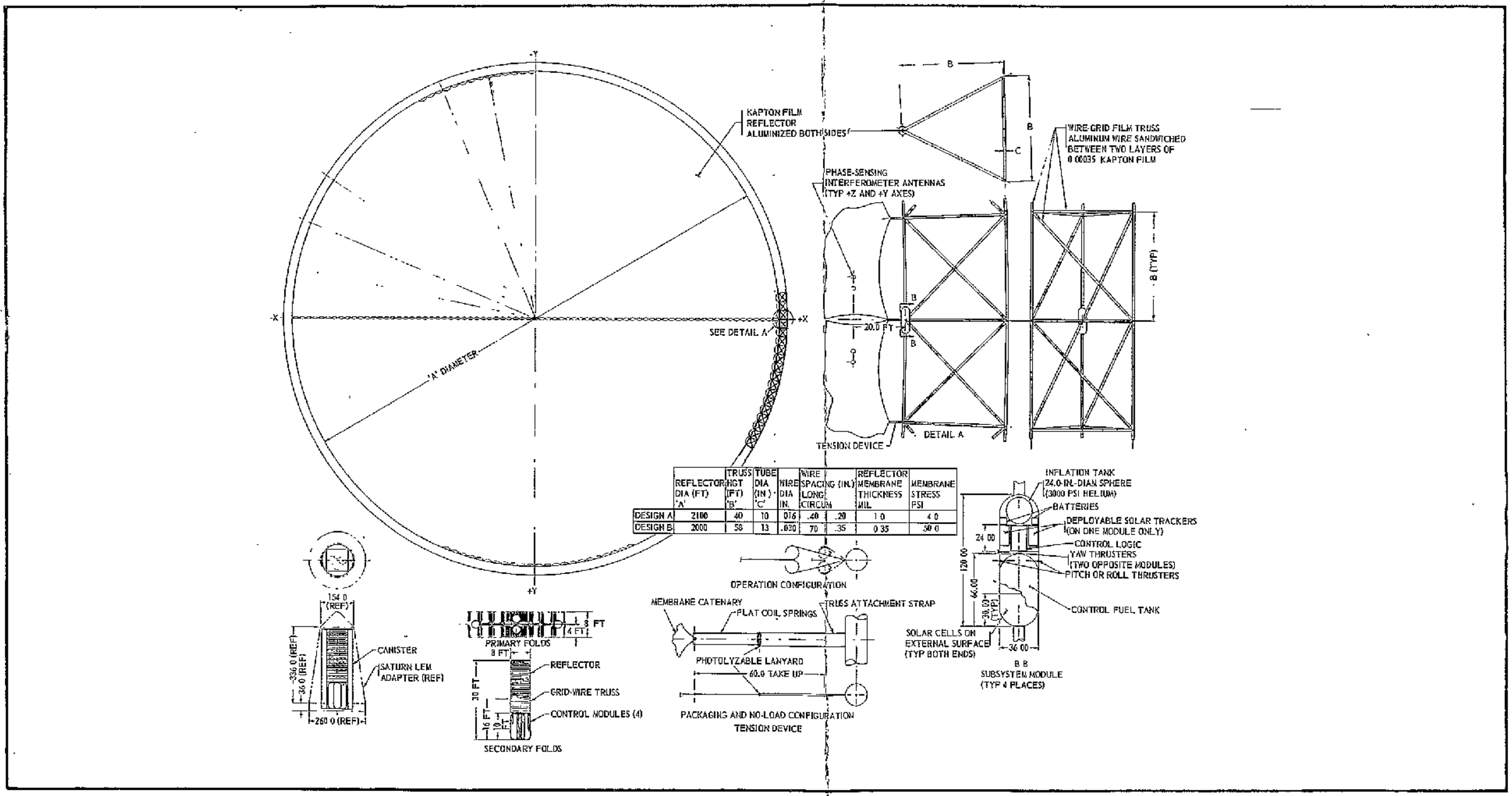
The remaining two concepts of the pressurized torus and the wire-grid film tube truss were then analyzed for higher stresses in the membrane after it was learned that such stresses might be required to remove the local waviness of the aluminized Kapton film and provide the desired reflective characteristics. The wire-grid tube truss, with the reflector diameter reduced to 2000 ft, can accommodate a stress of 50 psi in the 0.35-mil Kapton reflector membrane. The limitation of the wire-grid truss is 0.03-in.-diameter aluminum wire, which is considered a maximum for efficient packaging, and a longitudinal wire spacing-to-diameter ratio of 20, which is the minimum that will provide a good bond between the film layers.

The pressurized torus concept was analyzed for a stress of 150 psi in the 0.35-mil Kapton reflector membrane. This configuration is capable of accommodating higher membrane stresses by increasing the diameter of the film torus.

The decision on the final concept for development of the RDT & E program had to be made without benefit of the tests conducted during the final two weeks of the program to determine the membrane stress required in the aluminized Kapton film to provide acceptable reflective characteristics. Therefore, the wire-grid film tube truss was selected because it did not require permanent pressurization and the development and demonstration of a micrometeoroid-damage self-sealing technique The reflectance tests indicated higher reflector-membrane stresses than can be accommodated with the wire-grid tube truss. On the basis of these tests, the pressurized torus would be the preferred concept for the large-diameter reflector. However, time and funding limitations did not permit the generation of an RDT & E program based upon this concept.

The wire-grid tube truss peripheral-ring structure to support the reflector membrane is shown in Detail A of Figure 6. Two designs are shown: Design A, which was utilized for the development of the RDT & E program, and Design B, which reflects a structure with a higher membrane-stress capability. The appropriate dimensions for each design are shown on the table in this illustration. Subsystems modules shown in Section B-B located on orthogonal axes contain components of the attitude control, inflation, and power systems. The membrane is attached to the structure at the truss joints with a series of tension devices. These devices, consisting of flat coil springs placed back to back, are restrained in the fully extended position bya photolyzable lanyard. This will permit the structure to be deployed with essentially no load on the structure since the membrane would be slack. After deployment and rigidization of the structure, the photolyzable lanyard would weaken and break under the action of sun's ultraviolet rays, allowing the springs to coil and tension the membrane. The tension device, in conjunction with its counterpart on the opposite side of the reflector, would provide constant tension over 10 ft of travel, which will accommodate dimensional differences in the membrane and the structure arising from manufacturing tolerances, differential thermal expansions, fold effects, etc. The reflector would be packaged in a cylindrical canister within the Saturn LEM adapter section. Reflector weights are well within the capability of the Saturn V launch vehicle.

The pressurized torus concept shown in Figure 7 utilizes Kapton film for the torus structure as well as the reflector, thereby eliminating thermal expansion problems associated with dissimilar materials. The 66-ft-diameter figure "8" torus cross section is designed for 150 psi stress in the 0.35-mil Kapton membrane and provides a passive system for handling manufacturing tolerances and thermal distortions. This section principle follows that of a cylinder, which, having knife-edge forces applied, reaches the point where resistance remains nearly constant. Thus, with the 66-ft-diameter, it is possible for the reflector tension to remain relatively constant with variations in the overall torus diameter up to 30 ft. To account for circumferential manufacturing tolerances, pressurized adjustment panels as shown in Section C-C of Figure 7 are provided.



	REFLECTOR DIA (FT) 'A'	TRUSS HGT (FT) 'B'	TUBE DIA (IN.) 'C'	WIRE DIA IN.	WIRE SPACING (IN.) LONG	CIRCUM	REFLECTOR MEMBRANE THICKNESS MIL	MEMBRANE STRESS PSI
DESIGN A	2100	40	10	.016	.40	.20	1.0	4.0
DESIGN B	2000	58	13	.030	.70	.35	0.35	50.0

Figure 6 - Wire-Grid Tube Truss Concept

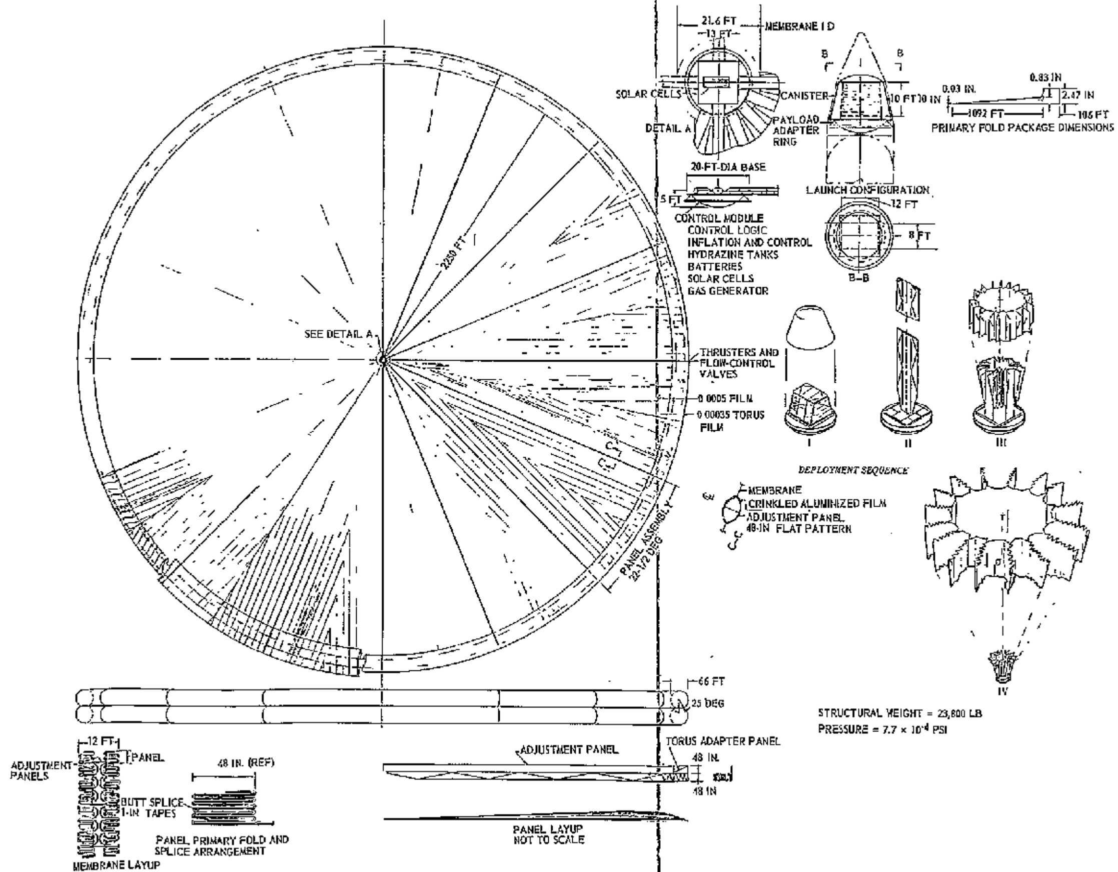


Figure 7 - Pressurized Torus Concept

19-A

19-B

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The torus and adjustment panel pressurization of 0.00077 psi would be provided by vaporized hydrazine. The micrometeoroid-damage sealing technique would consist of carbon particles in the 150-micron-diameter range dusted on the inside of the film torus during fabrication. Equal weights per cubic feet of gas and particles appear to be the optimum ratio of mixture. For one year of operation, 182 lb of mixture would be required for initial inflation, 576 lb of gas would be lost through the holes before the carbon particles would contact and plug the holes, and 1624 lb would be lost through the holes too large to seal with the particles. The pressurization gas also would provide the thrust for attitude control. For this concept, a test program is required to demonstrate the micrometeoriod-damage self-sealing technique.

6. INVESTIGATION OF SMALLER-DIAMETER REFLECTOR CONCEPTS

a. Choice of Diameter

Following the midterm presentation on the project held at NASA Headquarters 11 October 1966, the contracting officer's representative requested that Goodyear Aerospace consider the possibility of looking into reflector diameters in the 400- to 750-ft range. The reason for this change was that the prime potential use of the reflector could be accomplished with illumination levels of 0.1 to 0.2 of full-moon illumination. Based on illumination data for larger reflectors at synchronous altitude, a diameter of 700 ft would provide a moon-equivalent illumination of 0.24 at zero incidence angle and 0.17 at an incidence angle of 45 deg. Therefore, where specific designs were worked out, this 700-ft diameter was used. Inasmuch as less than three weeks of technical effort remained in the program, it was not possible to develop a conceptual design and RDT & E plan for the smaller diameters. However, parametric data were generated for the wire-grid truss and pressurized torus with the stress in the 0.35-mil Kapton reflector membrane used as a parameter. In addition to the pressurized torus and wire-grid truss approaches, the peripheral-ring concept utilizing a "flex" tube ring becomes practical for the smaller size reflectors. Radial members approaches also are attractive for smaller-diameter reflectors, since member lengths are much shorter and larger member depth-to-length ratios can be obtained within the package constraints. The flex-tube ring concept and radial member concepts using lazy-tong trusses and telescoping tube trusses are discussed in the following paragraphs.

b. Pressurized Torus and Wire-Grid Truss Ring Concepts

The results of the parametric analysis for the pressurized torus and the wire-grid truss ring are presented in Figure 8. For a 700-ft-diameter pressurized torus with a stress of 500 psi in the 0.35-mil Kapton reflector membrane, the weight of the torus and reflector would be 3500 lb. If higher membrane stresses are required, they can be accommodated by increasing the torus diameter. For the wire-grid truss ring, the dotted line on Figure 8 represents a limitation based on 30-mil-diameter aluminum wire with a spacing-to-diameter ratio of 20. A maximum membrane stress of 200 psi is indicated for a 700-ft-diameter reflector. All designs below the dotted line represent practical designs. The weight of a 700-ft-diameter reflector using wire-grid structure and including the inflation system weight would be 4000 lb.

c. Flex-Tube Ring Concept

The flex-tube ring concept shown in Figure 9 uses two 0.015-in. beryllium-copper strips formed as shown in Section A-A and joined at the edges. The section can be flattened without exceeding the yield stress in the material, and rolled upon a drum for packaging. Four of these members (one for each quadrant) form the ring structure to support the reflector membrane. One end of each of the flex tubes would be attached to the subsystem module as shown in the "rim packaging" sketch on Figure 9, and the opposite end of each member would

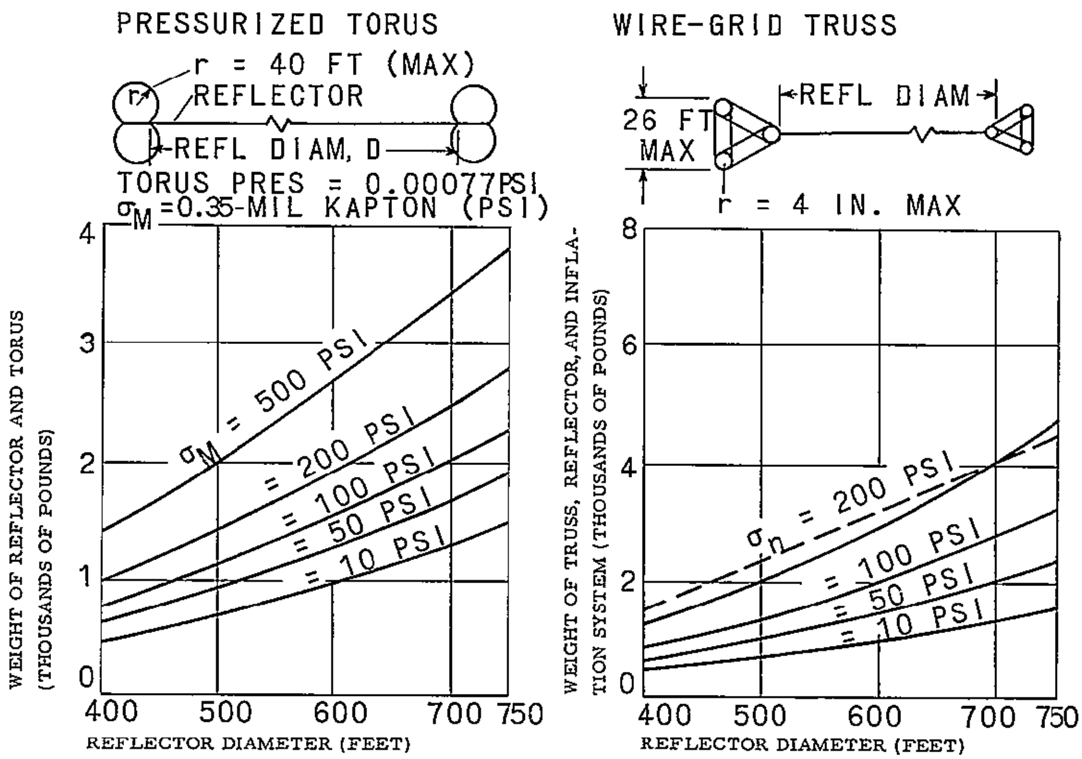


Figure 8 - Pressurized Torus and Wire-Grid Tube Truss Weights for 400- to 750-Ft-Diameter Reflectors

be attached to a storage drum that also would contain subsystem components. The flex tubes could be flattened and rolled on the storage drums, actually cone frustums that would permit the flex tubes to remain in a plane as they are wound the drum.

For deployment, brakes extending from the drums would control the unfurling of the flex tubes, which would extend as shown in Figure 9. With a 700-ft-diameter reflector, the weight of the flex-tube structure for accommodating a stress of 500 psi in the 0.35-mil Kapton membrane would be 19,400 lb exclusive of the drum and deployment braking system.

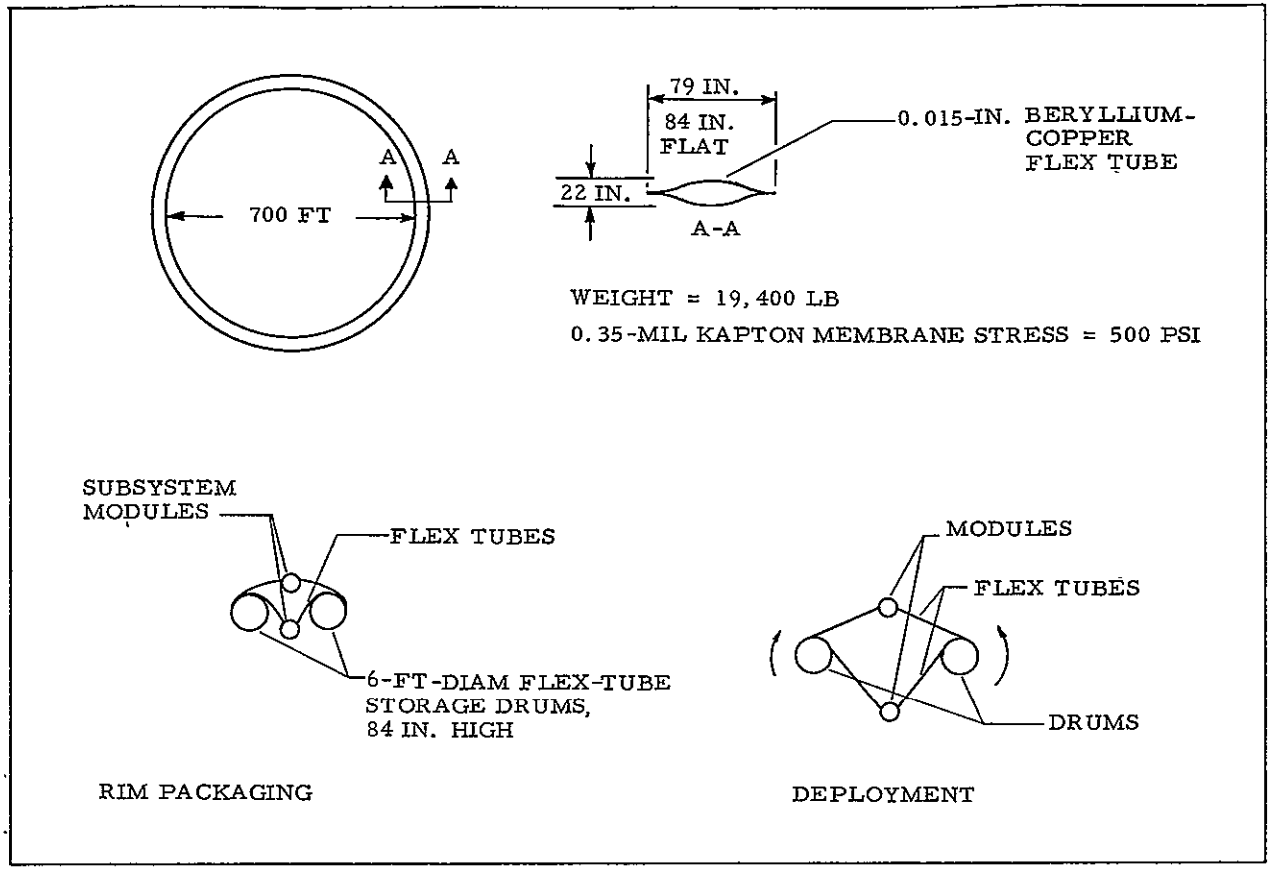
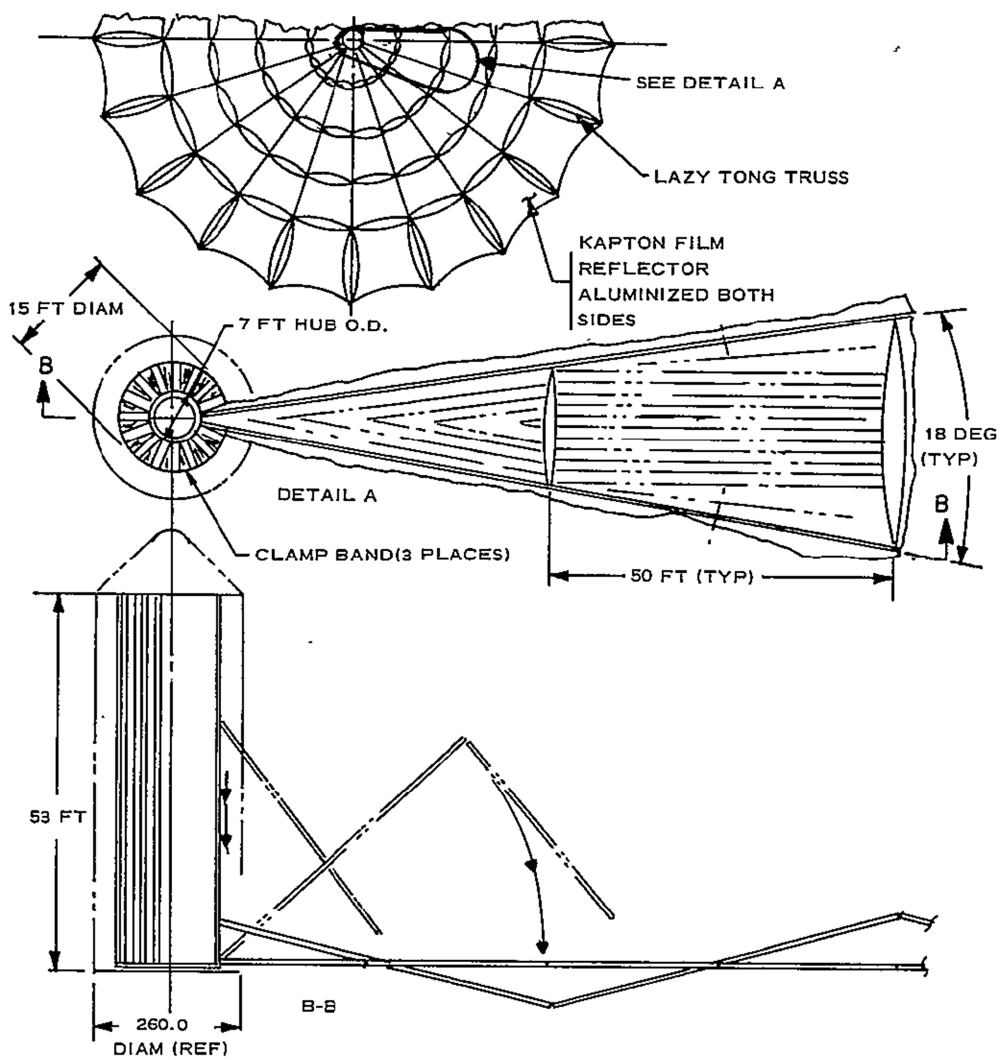


Figure 9 - Flex-Tube Ring Concept

d. Lazy-Tong Truss Concept

The lazy-tong truss concept shown in Figure 10 consists of 20 trusses equally spaced about a 7-ft-diameter structural hub. Each truss is made up of seven sections or bays approximately 50 ft long The actuating column (approximately 53 ft long) of each section is sandwiched between two 50-ft reflector-film supporting columns and pinned at the midpoint. The ends of the columns are attached to the adjacent sections with hinges.

The advantages of the lazy-tong truss arrangement are a positive deployment system similar to that utilized on the Pegasus satellite, and a simpler fabrication technique for the membrane since it is made up of smaller panels. Since the maximum membrane width between the



EQUIVALENT DIAMETER (FT)	MEMBER DEPTH (IN.)	STRUCTURE WEIGHT (LB)	0 35 MIL KAPTON MEMBRANE STRESS (PSI)
700	6	31,800	150
700	9	52,900	500
700	12	39,300	500

Figure 10 - Lazy-Tong Truss Concept

trusses would be 110 ft, it would be possible to tension and check out the individual membrane bays on the ground. Deployment of individual trusses could also be ground checked. The weights of three different designs of the lazy tong are shown in Figure 10.

e. Telescoping-Tube Truss Concept

The telescoping-tube truss concept shown in Figure 11 consists of six equilateral, triangular trusses extending out radially from the hub. Each complete truss has 15 equal sections or bays. The aluminized reflector film is attached by catenaries to the outermost section of the trusses to form a hexagon planform. The reflector is equivalent to a 700-ft-diameter disk.

In the packaged configuration, the reflector would form a cylindrical shape 12.5 ft in diameter and 41 ft long, which is compatible with the existing Saturn-Apollo profile. The reflector film would be packaged in a canister at the lower end of the hub. After separation of the packaged reflector from the spacecraft, deployment would begin with release of the clamp bands and ejection of the canister. The truss members then would be extended to their maximum length, either with a ball-screw or cable and pulley arrangement. By means of an electrical drive mechanism in the hub, the six trusses would be rotated 90 deg to unfurl the reflector membrane into a flat plane. This arrangement is particularly applicable to a single-sided reflector in which the structure could be kept on the shadow side and an essentially constant structure temperature maintained.

The membrane could be tensioned in two ways. In the first method, shown in Figure 11, the truss members would be maintained in a plane and the membrane would be attached to constant-tension devices installed at the end of each truss member to accommodate dimensional changes in the membrane and structure arising from manufacturing tolerances, differential thermal expansions, etc. With this arrangement, the truss member weight designed for a safety factor of 2

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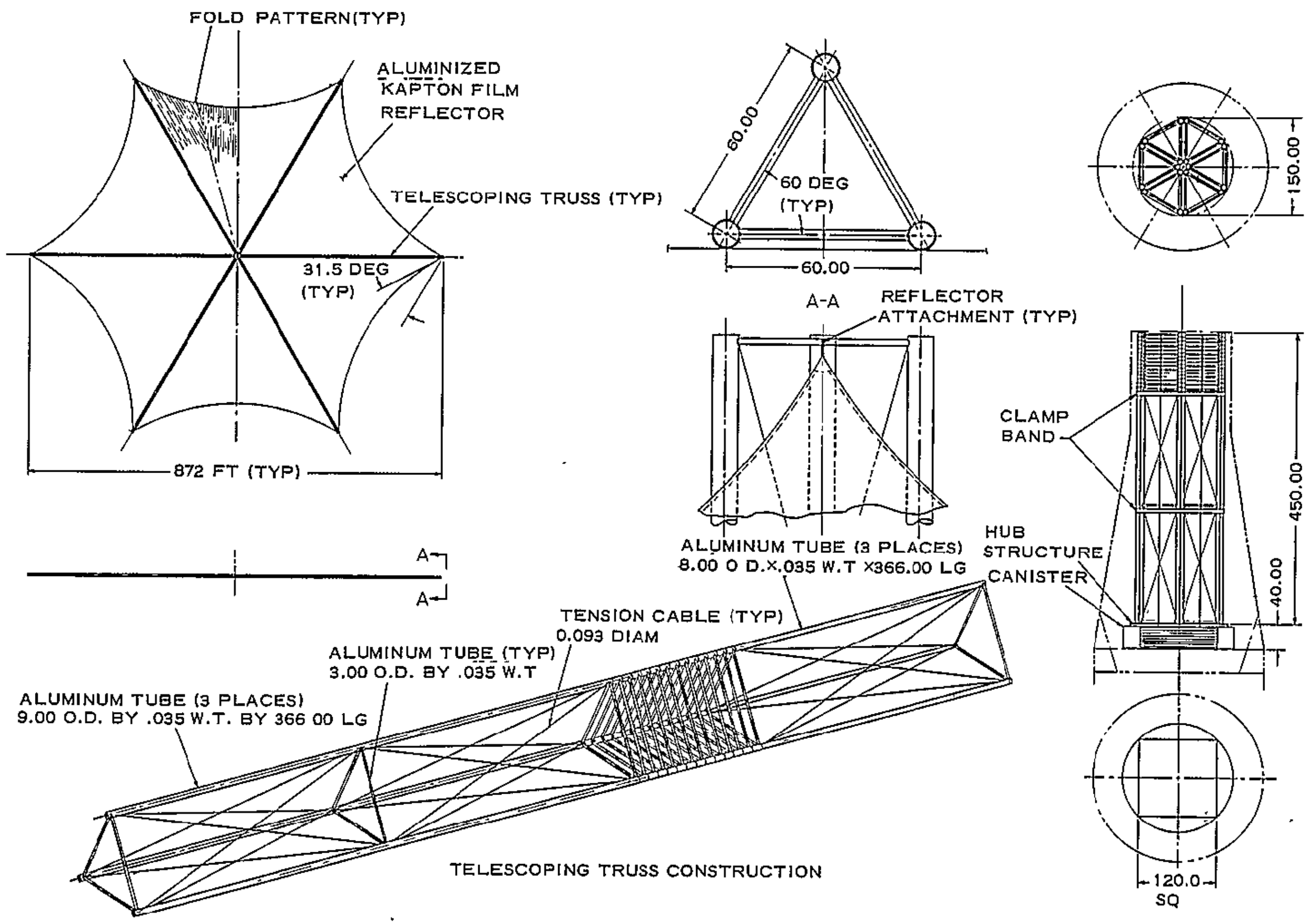

Figure 11 - Telescoping-Tube Truss Concept

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would be 22,000 lb for a stress level of 500 psi in the 0.35-mil Kapton reflector. The second method of tensioning the membrane is the bowstring concept.

f. Bowstring Concept

An alternate method of regulating the membrane tension, which will result in a lighter weight structure and provide a means of tensioning the membrane, is the bowstring approach shown in Figure 12. Construction details of the truss and the packaging arrangement would be the same as for the telescoping truss. With this concept, the structure again would be located on the shadow side of the membrane and the truss members would be designed to be approximately 5 ft longer than the radius of the membrane. This shorter membrane length would cause the truss members, instead of lying in a plane, to bow and displace the truss hub 50 ft from the plane of the membrane. Analysis of thermal conditions for the oscillatory pitch mode with the structure on the shadow side indicates that the membrane stress will remain constant and the membrane will shorten by 10.5 in. With the truss hub initially displaced 50 ft from the plane of the membrane, this membrane shortening with only a fraction of a pound change in membrane tension, will increase the bow in the truss members so that the hub will be 63.75 ft from the plane of the membrane. Thus, for this concept, the truss members would act as the tensioning devices for accommodating temperature differentials of structure and membrane.

The truss weight for this concept with 500 psi stress in the 0.35-mil Kapton reflector membrane would be 11,300 lb. Since the hub of the truss would be displaced from the plane of the reflector membrane, the center of mass and the center of pressure would not coincide and solar pressure forces would produce torques that must be reacted with control thrust. Preliminary estimates indicate that for a center-of-mass displacement of 25 ft from the reflector plane, approximately 700 lb of fuel having a specific impulse of 50 sec would be

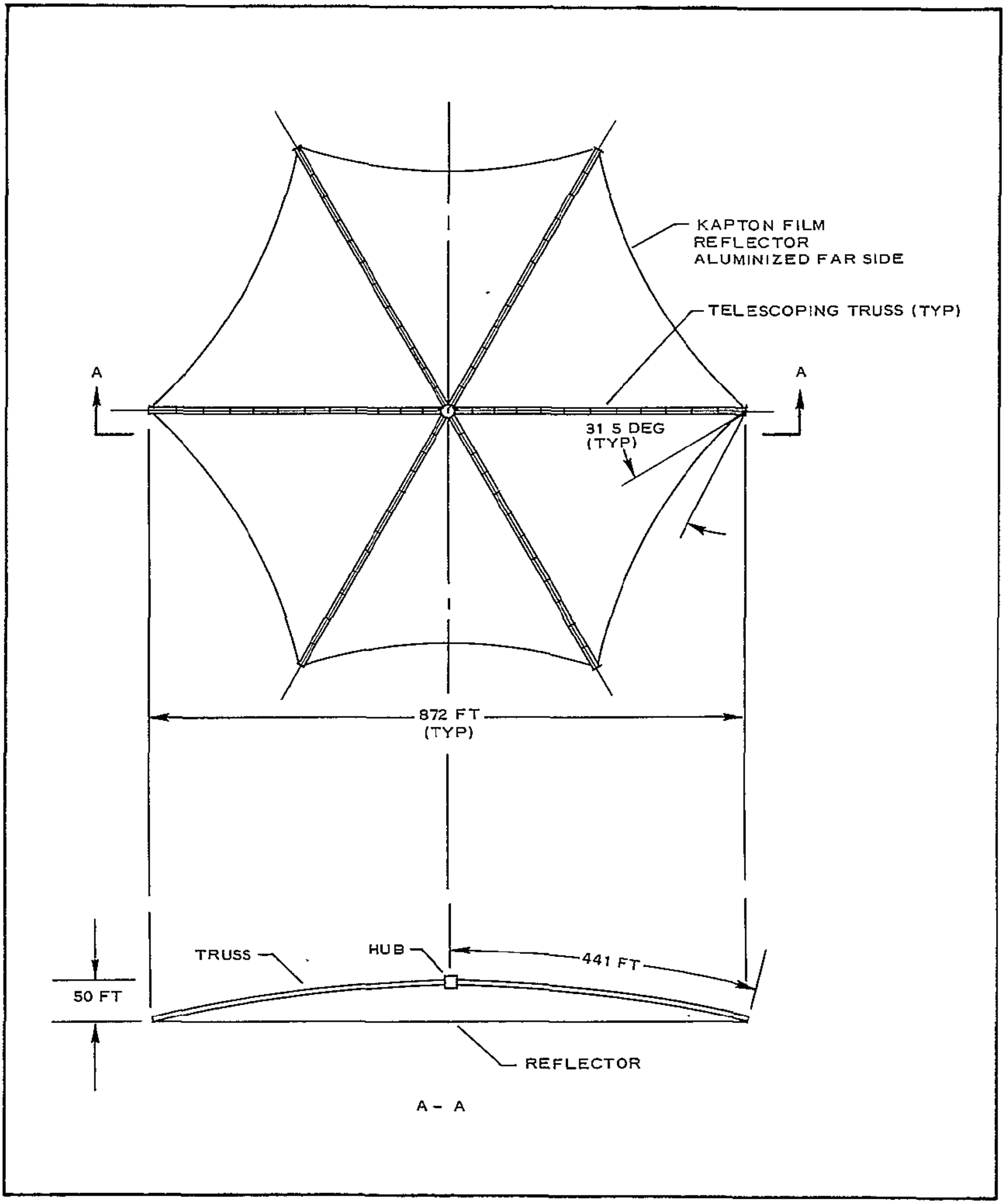

Figure 12 - Bowstring Concept

required for one-year operation. While this fuel weight is significant, the savings in structural weight of about 10,000 lb over the telescoping truss arrangement in which the members remain in a plane makes the bowstring approach even more attractive.

7. RESEARCH, DEVELOPMENT, TEST, AND ENGINEERING PROGRAM

The research, development, test, and engineering (RDT & E) program plan is based on the final concept for a 2100-ft-diameter reflector using a wire-grid tube truss for the peripheral ring structure. A realistic schedule as shown in Figure 13 can be established. It is built upon a total elapsed time of 32 months from the time of go-ahead for the for the RDT & E phase until launch. Included is a six-month period for payload integration, transportation to the launch site, and prelaunch assembly and checkout operations.

The estimated costs required to produce the 2100-ft-diameter wire-grid peripheral-ring reflector system are as follows:

I	Design and analysis	$ 4,071,000
II	Testing	5,678,400
III	Tooling and special equipment	448,000
IV	Manufacturing	42,794,900
V	Facilities	1,474,600
VI	Launch operations	2,101,900
	Total	$56,568,800

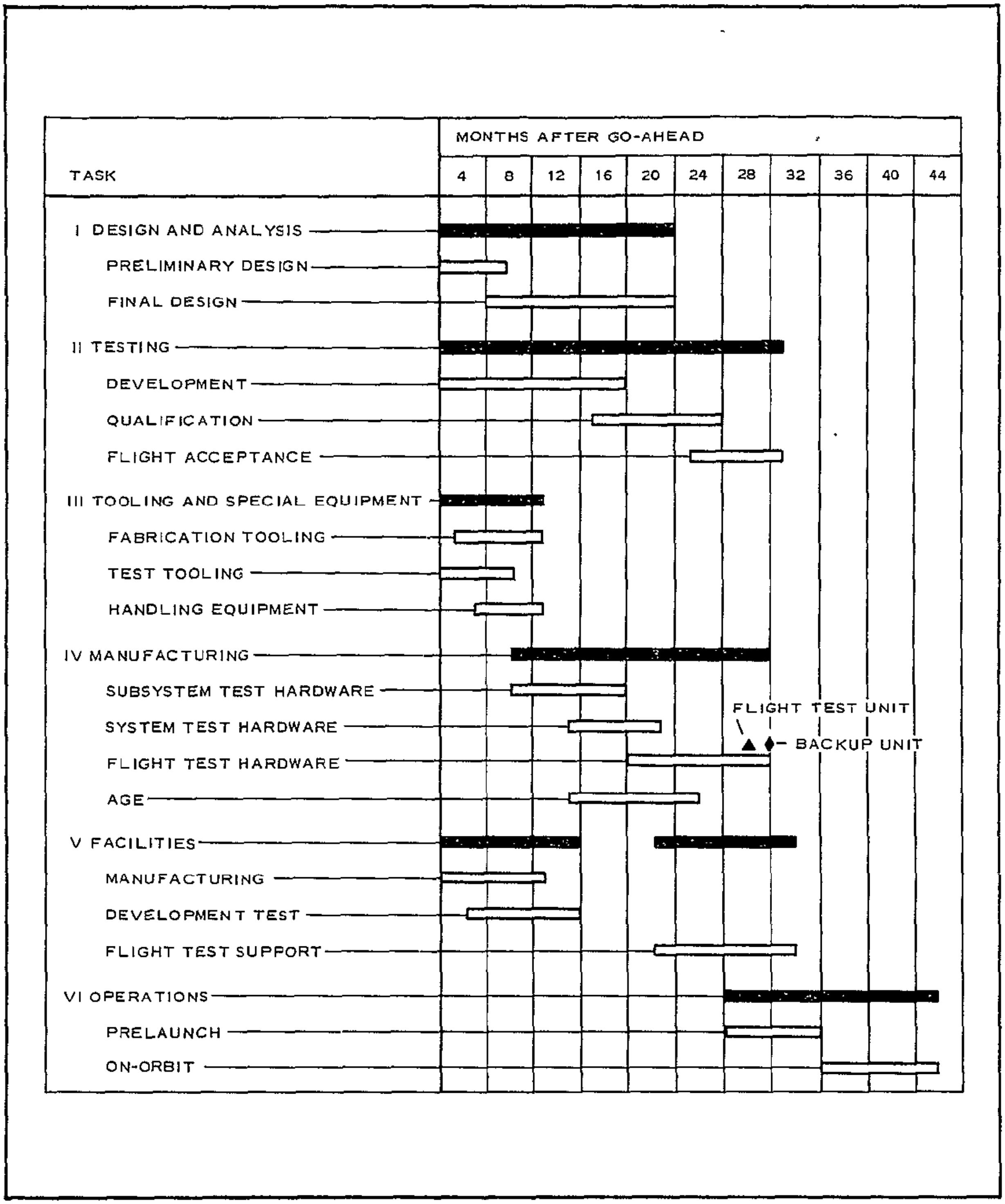

Figure 13 - RDT & E Program Schedule

SECTION III - CONCULSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

As a result of the three-month feasibility study, it is concluded that:

1. The reflector material should be aluminized Kapton film.

2. Stable elliptical orbits, which minimize station-keeping fuel requirements, are attainable for both the rotary and oscillatory pitch modes of reflector operation. While eccentricities will be approximately 50 percent greater for the oscillatory pitch and ground illumination levels somewhat reduced, the advantage of alleviating thermal-control problems by having one side of the reflector always in the direction of the sun indicates that the oscillatory pitch would probably be the desired mode of operation. To finalize this conclusion, additional design analysis will be required.

3. The launch weight and size envelopes appear to be adequate for the reflector sizes considered.

4. The attitude-control requirements can be met with various stabilization systems consisting of different combinations of attitude-error sensors and thrusters. Three rather distinct concepts have been presented, any one of which is feasible for the stabilization. Additional tradeoff studies are required to determine the optimum stabilization system.

5. Security of the data links and attitude sensors may be maintained in spite of countermeasures.

6. The propellant weight for the attitude-control system to operate the satellite for one year will be on the order of 10 percent or less of the total payload weight.

7. The power requirements (principally dictated by the attitude control system) are low and can be met with solar cells and batteries.

8. Preliminary tests indicate that local reflector-flatness variation will require approximately 100 psi in 1-mil aluminized Kapton film and approximately 300 psi in 1/2-mil aluminized Kapton film for acceptable reflective characteristics. Since the 100 psi in the 1-mil Kapton represents a load of 0.1 lb/in. that the structure must accommodate as compared with a load of 0.15 lb/in. with the 0.5-mil Kapton stressed to 300 psi, a tradeoff exists between the membrane thickness and weight and the membrane supporting structure weight. Additional tests aimed at providing better methods of tensioning the membrane at the lower stress levels should be performed to serve as basis for future structure-membrane weight tradeoff investigations.

9. For 2000-ft-diameter reflectors, the pressurized torus concept is the most applicable because it is capable of handling the loads resulting from higher membrane stresses. For this size reflector, the

wire-grid tube truss concept is limited to a stress of 50 psi in the 0.35-mil Kapton membrane.

10. The RDT & E program, developed on the basis of a 2100-ft-diameter reflector and a peripheral ring structure consisting of a wire-grid tube truss, would require 32 months from program go-ahead to launch and would cost approximately 56 million dollars.

11. For reflectors in the 400- to 750-ft-diameter range, the following approaches are applicable:

    Peripheral ring concepts

    1) Wire-grid truss
    2) Pressurized torus
    3) Flex-tube ring

    Radial member concepts

    1) Lazy-tong truss
    2) Telescoping-tube truss with radial members lying in a plane
    3) Bowstring with telescoping-tube truss members bowed by the tension load from the reflector membrane

12. Tensioning devices or techniques are required for compensating for differences in the dimensions of the reflector and the structure resulting from manufacturing tolerances, differential thermal expansions of the reflector and structure, effective membrane shrinkage due to folds, and initial shrinkage of the membrane and creep.

13. More detailed analysis of the total system is required following a specific definition of the desired illumination characteristics.

2. RECOMMENDATIONS

The three-month study program has resulted in a wealth of useful design information for continuing orbital reflector program effort. Inasmuch as the program did not include an operational analysis, it was not possible to define the desired illumination characteristics. Therefore, for the continuing program effort, specifications on the desired illumination characteristics need to be provided. With this information, it is recommended that the following effort be conducted:

1. Continue oscillatory-pitch motion analysis utilizing an upgraded control logic for the daylight portion of the orbit
2. Investigate processes for improving the flatness of the Kapton film
3. Upgrade tests and analysis for determining the membrane-reflectance characteristics and the required stress levels for the Kapton film
4. Conduct tests and analysis of Kapton-film creep characteristics under the design stress levels and thermal environment conditions
5. Continue design and analysis effort on reflector concepts: (1) for 2000-ft-diameter pressurized torus design, develop and evaluate tests for micrometeoroid-damage automatic repair concept; (2) for ≈700-ft peripheral-ring or radial member designs or ≈2000-ft-diameter pressurized torus design: (a) conduct more-detailed structural analysis of packaging (launch), deployment, and operational loads and deflections; (b) perform more-detailed structure-thermal analysis; (c) upgrade definition and solution of dimensional control problem; (d) conduct

more-detailed analysis of control system, including offset illumination, structure dynamic effects, boresighting calibration techniques, and error budget; (e) define power system arrangement; and (f) establish more-detailed facility implementation, fabrication, and testing requirements and plans.

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