DESIGN, DEVELOPMENT AND MECHANIZATION OF A PRECISION DEPLOYABLE TRUSS WITH OPTIMIZED STRUCTURAL EFFICIENCY FOR SPACEBORNE APPLICATIONS

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ABSTRACT

The demand for large space platforms and antenna systems has identified the need for extremely long, stiff deployable booms. This need has prompted Lockheed Missiles and Space Company, under contract to the Jet Propulsion Laboratory, to develop the technology which could provide a space mast structure with a length in excess of the height of the Washington Monument. This structure will be capable of repeatable precision deployments in the space environment without external aids. The lightweight truss structure which also functions as a precision mechanism can be stowed within the Space Shuttle cargo bay. This paper will discuss the design, predicted performance and hardware development of this structure.

The structure, which will be described, is a unique application of a triangulated truss that successfully blends the mechanisms of a deployable structure with those of an efficient extended structure. Individual internal members are double tapered graphite-epoxy tubes for maximum strength/weight ratio and stowed efficiency. The longitudinal members are hinged at the mid point to achieve a simple mechanism joint which provides for a compact folding scheme. Precision alignment and alignment repeatability is provided by a unique prestressed joint design and pretensioned diagonal members which eliminate deadband. These features integrate into a truss system that exhibits a stiffness-per-unit-length ratio and a stowage efficiency unsurpassed by any currently available design approaches. The design synthesis and detailed design work will be presented for the structure in toto as well as the joint details and deployment devices. Also to be summarized are the fabrication and tests on selected critical members and joints, the performance projections based on a mathematical model in the form of parametric results, and a comparison of the theoretical and experimental component test results.

INTRODUCTION

The industrialization and colonization of space will require the establishment of truly large space structures in orbit. Though desirable, the on-orbit assembly and/or fabrication of such structures encounters severe economic and technological limitations for the near future. Thus, the need exists to begin the examination of this new technology through the development of reduced scale systems. Self-contained, deployable structures serving as an investigative foundation for later, more ambitious projects will fill this need. As an economic incentive, these systems should be useful in their own right, while serving as stepping stones toward higher goals.

The "focus mission" concept (Ref. 1) is an effort by NASA to sift the critical technologies required for various mission objectives and combine them into a hypothetical mission which will support their development. One of these critical technologies is the development of a class of large aperture antenna systems (see Figure 1). That model requires reflector apertures ranging from 30 to 300 meters in diameter, operating at radio frequencies from UHF to Ku-band. Lockheed Missiles and Space Company, Inc., under the sponsorship of the NASA/LSST Program, has initiated the development of a 55-meter offset wrap rib antenna demonstration project, scalable to 100 meters, that addresses these requirements (Ref. 2).

Concurrent with this effort, LMSC is proceeding with the development of a deployable feed support boom. As the 55/100-meter antenna system project is a hypothetical mission, no specific mechanical requirements for the boom have been identified. General requirements, however, may be derived from the expressed desires to incorporate specific features into the mission, stowage and weight limitations of the STS and the functional requirements for an antenna system of this size and frequency range. The boom is thus designed to: function with an S-band offset fed reflector up to 100 meters in diameter (possessing booms with a total length of 208 meters, and a positional accuracy of 6 mm between ends), be compatible with the shuttle envelope, and provide a re-stow capability. In addition, the boom will provide a definable stiffness at all phases of deployment and retraction, provide maximum stiffness within the allotted weight and envelope, and weigh no more than 227 kg (500 lbs). Its characteristics have the capability to be tailored to suit other potential uses such as ground-based mobile towers, solar panel support and solar sail booms, and as an elemental building block for large space platforms.

A review of the design synthesis and accompanying analysis is given in this paper.

DESIGN DESCRIPTION

Current deployable truss designs suitable for on-orbit use sacrifice many of their structural characteristics to achieve their deployable function. Recognizing that this mast must function primarily as a stable structure, the design synthesis began by selecting an efficient truss; then a means of mechanization was conceived that did not compromise the primary objective. The result is a feed support consisting of two dedicated subsystems: a folding mast structure and deployment cages containing the mechanisms which extend it.

Structural elements and mast configuration were driven by the need for an efficient truss. The selected arrangement is shown in Figure 2. As designed, the mast is a simple, three-sided, completely triangulated and preloaded truss. This system is an efficient structure wherein all loads are carried in tension or compression along load paths intersecting at node points. Doubly tapered tubes are used for the longerons and battens to achieve a maximum stiffness-to-weight ratio. Simple small-diameter tension rods serve as diagonal members. Pretensioning of these diagonals eliminates clearance in the longeron pivot bearings which ensures structural continuity and provides the majority of torsional stiffness.

The final mast configuration compatible with 55-meter reflector structural requirements is a 122-meter-long, 40-bay mast composed of 3.05-meter-long graphite-epoxy tubes with a 7.62-2.54-cm-diameter taper and a .528-mm wall thickness. Possessing a mass of 172 kg, it has a first mode natural frequency of .105 Hz and stows to a height of 3.32 meters.

TRUSS MECHANIZATION

The design requirements for mechanization were as follows:

- deployment must be automatic and reversible,
- hinges, joints, etc. must have no detrimental effects on extended rigidity,
- mast, reflector and support equipment must stow within STS cargo bay envelope

These requirements were met by incorporating a center joint and pivoting end fittings for each longeron and flexible diagonal members. These features allow the mast to stow as shown in Figure 3. The longerons fold outside the battens while the diagonals stow inside, providing a stowage ratio in excess of 30:1 (55-meter design).

LONGERON CENTER JOINT

The longeron center joint is designed to meet the requirements of low weight, zero deadband, and positive locking at full extension. In addition, it provides a force to aid the deployment of the longeron.

The joint consists of a number of short links connected to fittings attached to the longeron halves. Figure 4 shows the joint in various stages of deployment. The center link pivots about the longeron centerline, facilitating the side-by-side folding of the longeron while avoiding the length extension impacts of a side hinge. As the two halves are allowed to rotate for mast extension, the four-bar linkage formed by the center link, control arm, and end fittings controls the motion of the joint; when fully open the two toggle links extend and lock the joint into position with sufficient preload to eliminate deadband for the orbital loadings.

The locking force is provided by a torsion spring located at the pivot point of one of the toggle links. Due to its placement and the kinematics of the joint, the direction of the resultant force changes during operation. Figure 5 graphs typical values for the moment about the longeron center during joint operation and compares them to predicted values. The positive values denote a moment acting to extend the longeron, while negative values denote a force acting to stow the longeron. The motion is limited by a stop slightly before the toggle links are allowed to reach full extension. This forces them into compression, which in turn causes a tension load in the two center links. This preload eliminates backlash caused by bearing clearances.

A model of the joint is shown in Figure 6. Aluminum was used for ease of manufacture, availability and cost. For flight use titanium or chopped graphite fiber-reinforced plastic materials will be used.

END JOINTS

The longeron end joints are simple clevis connections as shown in Figure 7. The bearing clearances in this joint are eliminated by the tension in the diagonals.

DIAGONALS

The diagonal tension members are designed as several layers of unidirectional graphite/epoxy fibers having a rectangular cross section, typically 1.5 x 5 mm. They are formed with a curve along their length which, when the mast is stowed, causes the diagonals to lie inside the truss, avoiding potential interference with the longerons or deployment mechanism.

EXTENSION/RETRACTION MECHANISM

The mast extension sequence is illustrated in Figure 8. The stowed mast is held in the deployment cages which are functionally divided into two compartments, one for handling the stowed mast and one for extending the bays. The stowed mast is slowly raised toward the forming compartment; the mechanism in the forming compartment lifts a single batten assembly and extends the longerons and diagonals of one bay until the bay is fully formed. The process is repeated at the rate of approximately 1 bay every 2 minutes until the complete mast is fully formed. These steps are reversed to retract the mast. A simplified schematic of the device is pictured in Figure 9 which illustrates the high/low speed drive arrangement and the function of the gear boxes, driver and belts. Not shown are torque tubes interconnecting the drive motors to enhance redundancy and assure speed synchronization. A unique longeron forms the right angle bend in the mast. A significant design feature of the deployment mechanization is that, during deployment, loads are transmitted through the deployed mast sections into the upper deployment cage and around the deploying sections. This feature assures a predictable structural stiffness throughout the entire deployment operation.

Additional considerations were given to the transfer of ascent loads and subsystem interfacing. The cages function as chassis to which the various spacecraft subsystems are mounted and serve to transfer spacecraft loads to the boost vehicle. Loads to the orbiter are transferred through an adaptor ring. Figure 10 shows a complete spacecraft (55-meter configuration) stowed in the orbiter bay.

ADDITIONAL MODELING AND DEVELOPMENT

A full-scale demonstration longeron was constructed of T-300 autoclave-cured graphite epoxy on an aluminum mandrel. Fiber layup of the tube shown in Figure 11 is 0/45/45/0 degrees. This layup represents a compromise between the desires for a low thermal expansion coefficient (CTE = 4.0 x 10^{-6}/°C along the longitudinal axis), adequate torsional stiffness (G = 11 GPA), and a reduction in the probability of microscopic crack propagation due to differences in the ply orientation angle. End fittings and the center joint were bonded in place on a fixture that ensured a precision alignment between ends and a dimensional exactness of the overall part.

As a complement to the ongoing design layout work, a mathematical model of the truss was produced to predict the structural and mass properties of the truss. This model can also be used for both parametric and point design case studies. Functioning as a design tool, such analysis allows member sizing and optimization consistent with design goals and physical constraints.

Figures 12 and 13 are examples of the parametric data generated. They represent the cantilever bending stiffness and mast weight, respectively, as a function of the mast geometry and material thickness.

CONCLUSIONS

Preliminary design and development work at Lockheed Missiles and Space Company, Inc. has resulted in a deployable mast concept which meets the weight, size and stability requirements for a feed support structure for offset antennas up to 100 meters in diameter. A triangulated truss configuration, the use of tapered tubes which exhibit a high strength-to-weight ratio, and low CTE graphite-epoxy material provide an efficient, lightweight and stable truss suitable for an antenna feed support. A low stowage ratio of 30:1 is achieved through a unique preloaded hinge located at the center of each longeron and an autonomous deployment cage with a drive mechanism. Initial analysis and proof of concept hardware have validated the basic mechanism and design assumptions and provided a basis for further investigation. The concept can readily accept variations in member size and thus lends itself to optimization for other potential uses where a stiff, lightweight deployable truss is needed.

REFERENCES

(1) Freeland, R. E. and Campbell, T. G.; Deployable Antenna Technology Development for the Large Space Systems Technology Program; AIAA/NASA Conference on Advanced Technology for Future Space Systems, Hampton, VA, May 8 - 10, 1979, NASA CP-2118.

(2) Wade, W. D. and McKean, V. C.; The Technology Development Methodology for a Class of Large Diameter Spaceborne Deployable Antennas; 15th Aerospace Mechanisms Symposium, Huntsville, AL, May 14 - 15, 1981, NASA CP-2181.

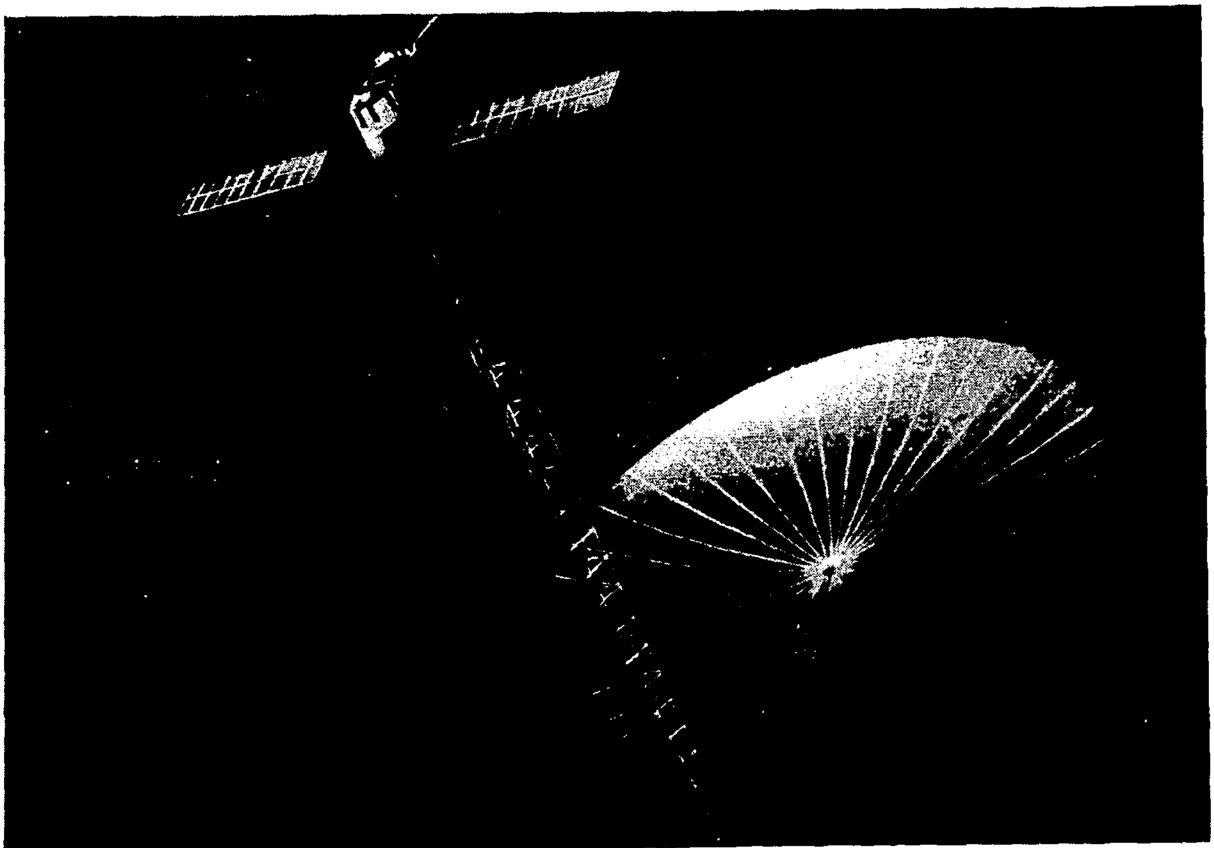

FIGURE 1. PARABOLIC WRAP RIB REFLECTOR WITH OFFSET FEED SUPPORT MAST

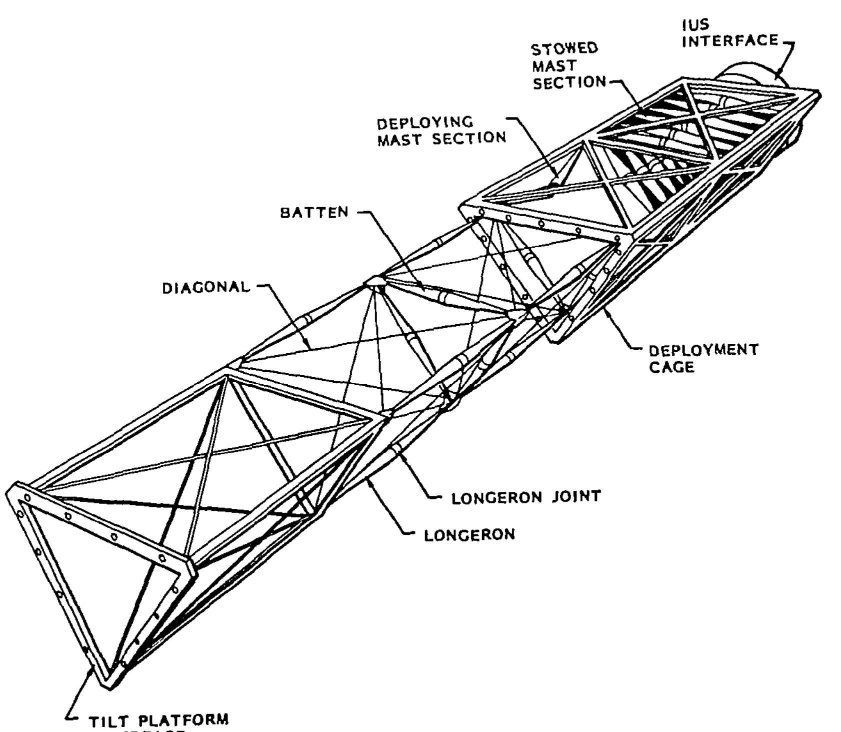

FIGURE 2. PARTIALLY DEPLOYED MAST
(DEPLOYMENT CAGES ASSURE A DEFINABLE LOAD PATH DURING MAST DEPLOYMENT)

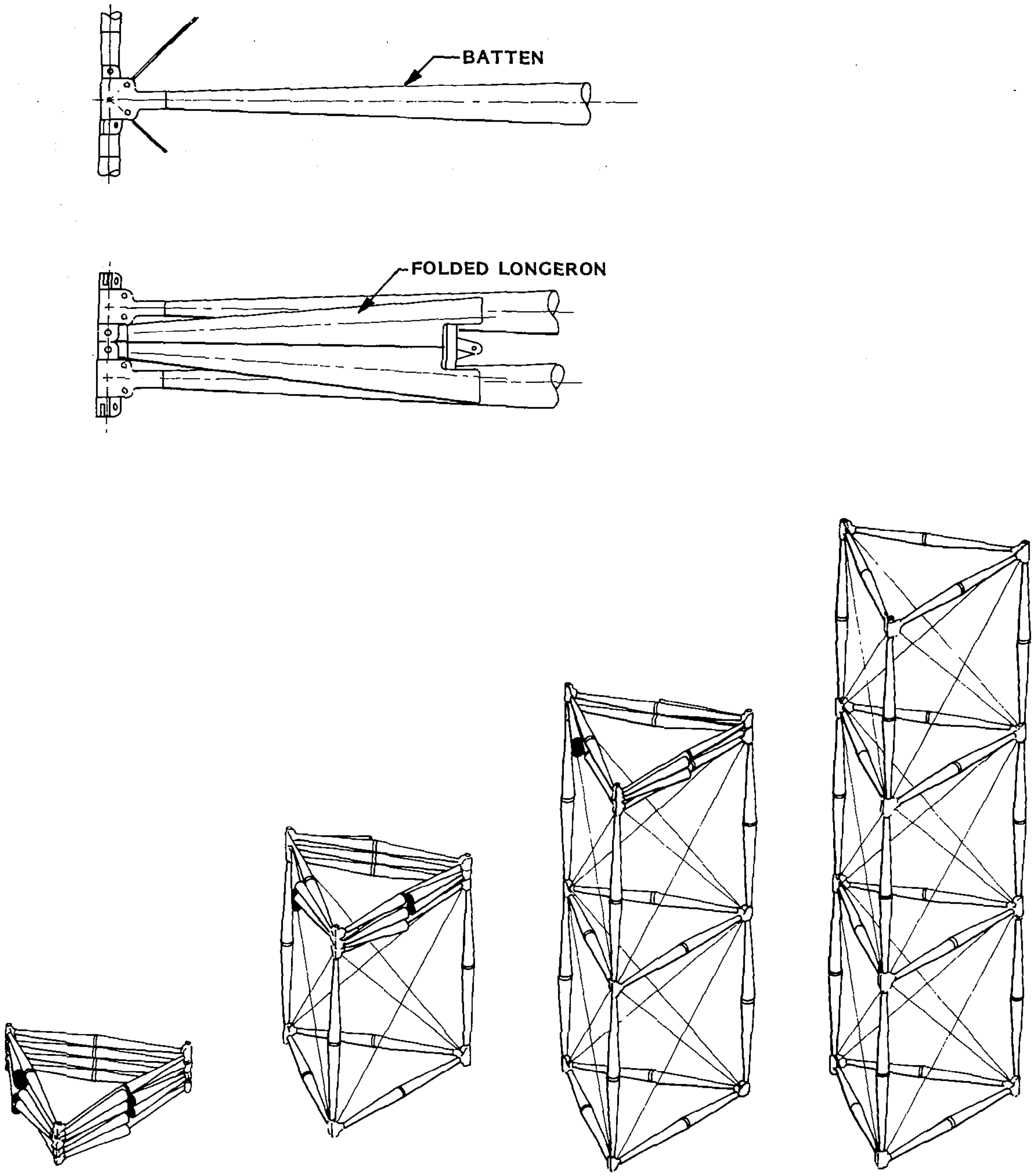

FIGURE 3. STRUCTURAL ELEMENT STACKING CONFIGURATION

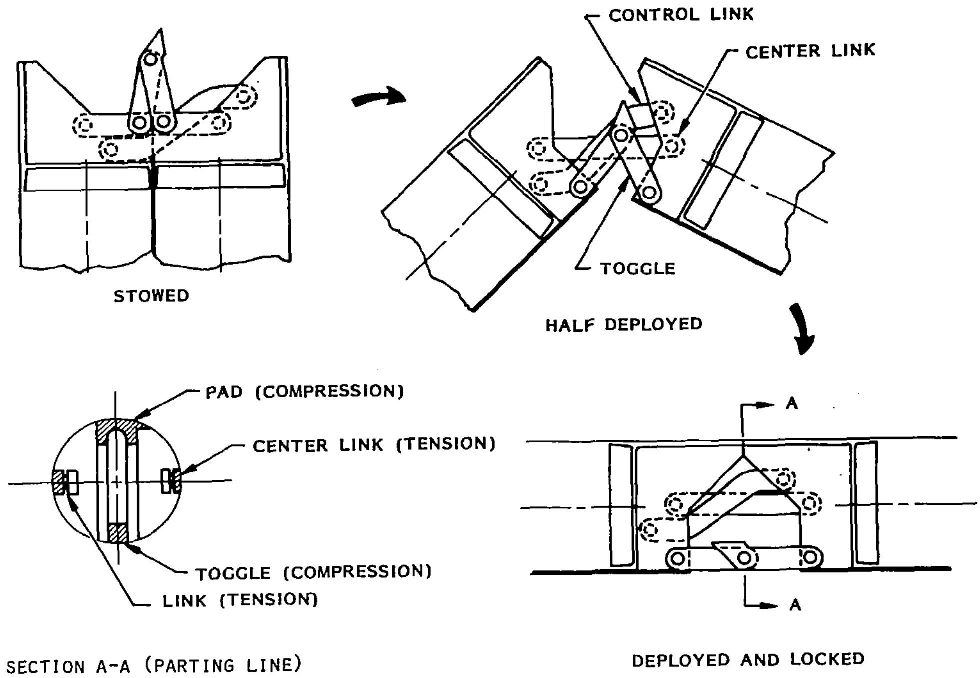

FIGURE 4. LONGERON CENTER JOINT SCHEMATIC

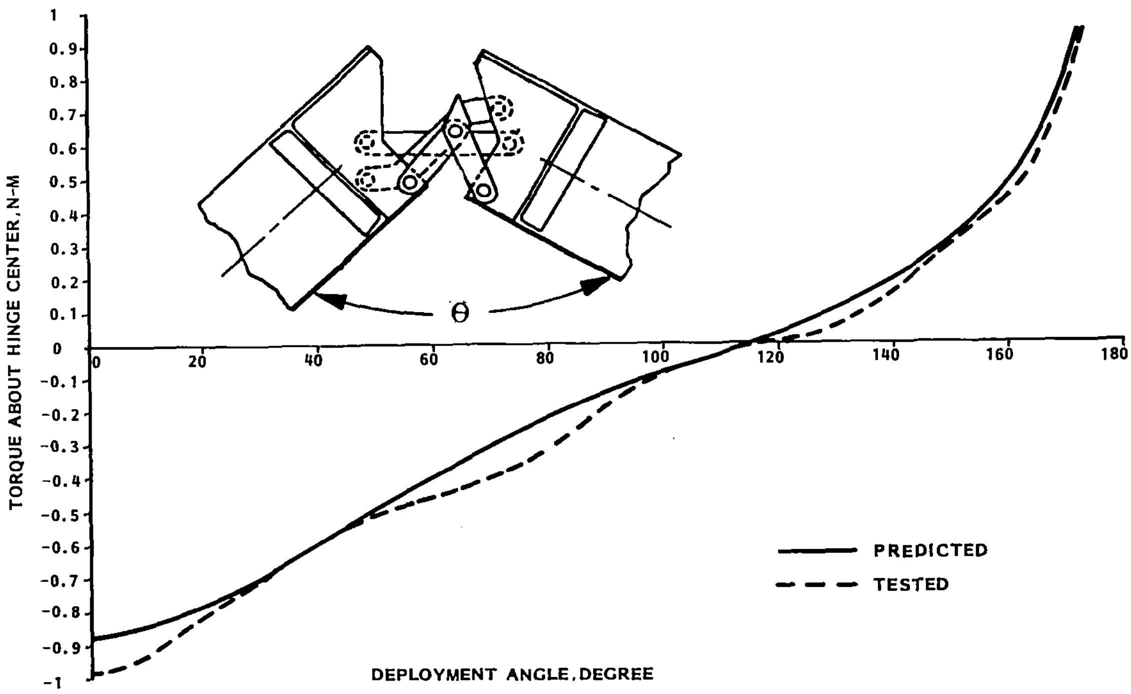

FIGURE 5. TORQUE ABOUT HINGE CENTER VS DEPLOYMENT ANGLE

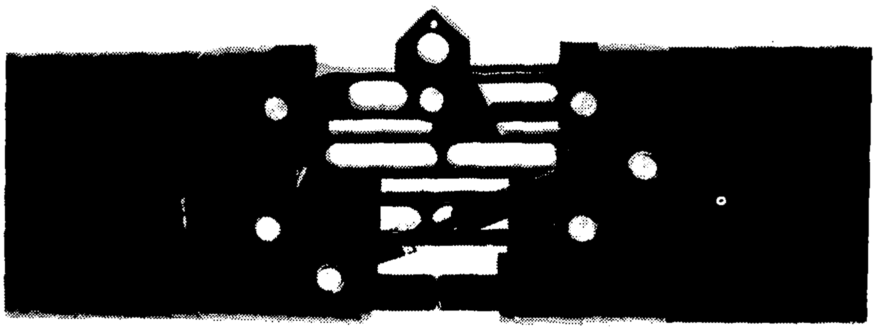

FIGURE 6. LONGERON JOINT-A PRELOADED, OVER-THE-CENTER LATCH THAT IS SELF-LOCKING AND EXHIBITS NO DEADBAND

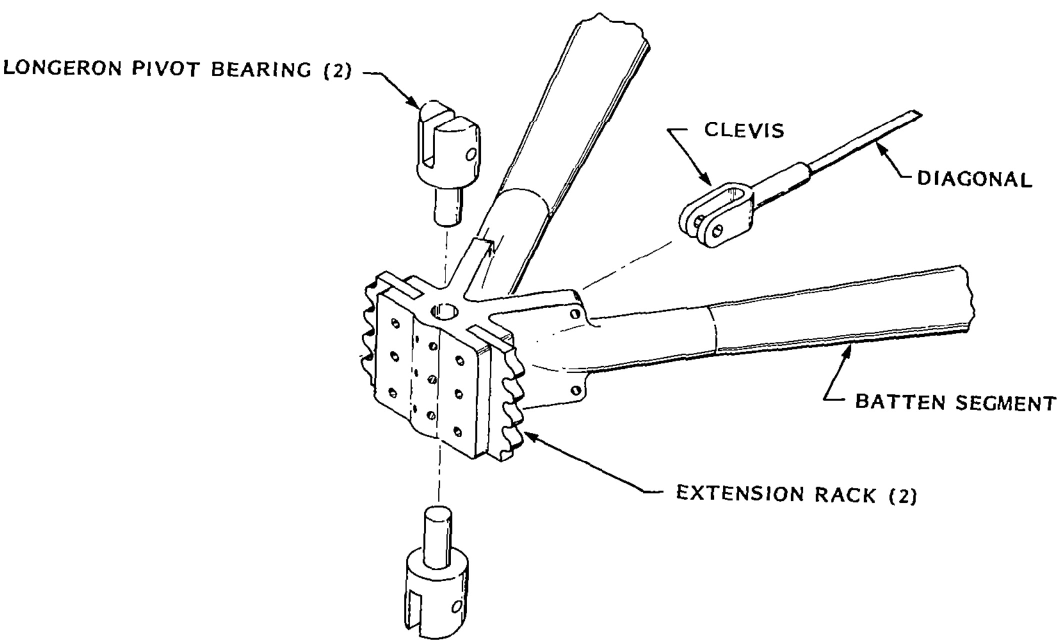

FIGURE 7. TRUSS CORNER-JOINT
(ALL LOADS INTERSECT AT CORNER NODE POINTS.)

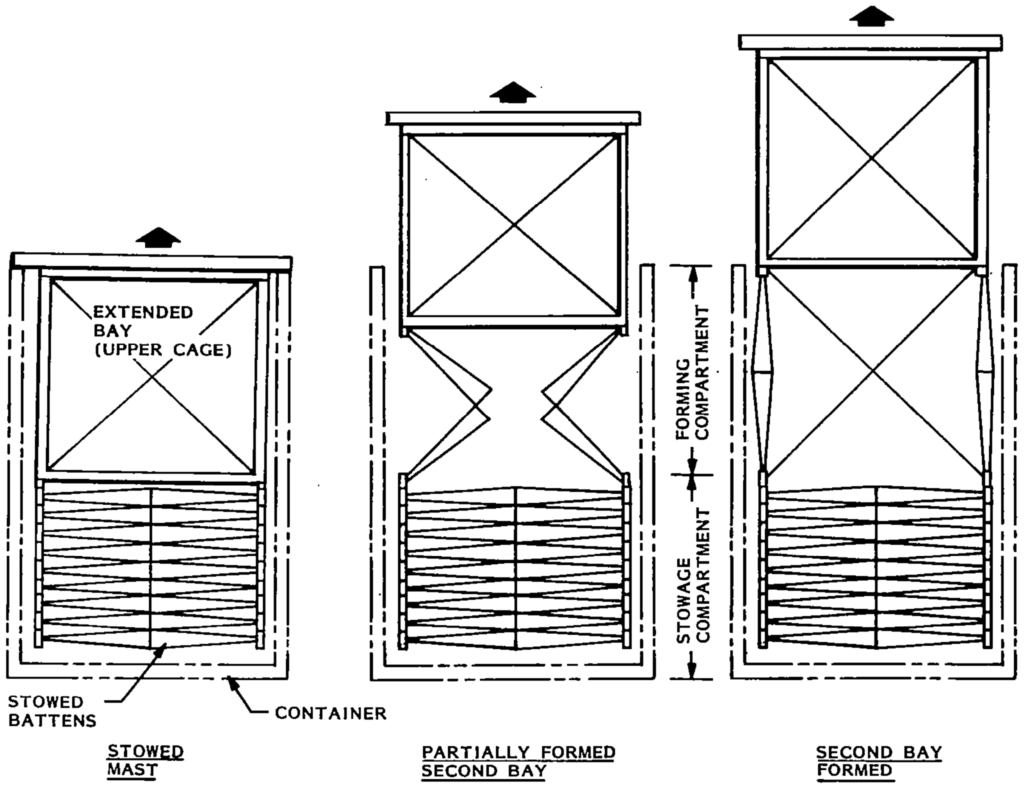

FIGURE 8. EXTENSION/RETRACTION PRINCIPLE

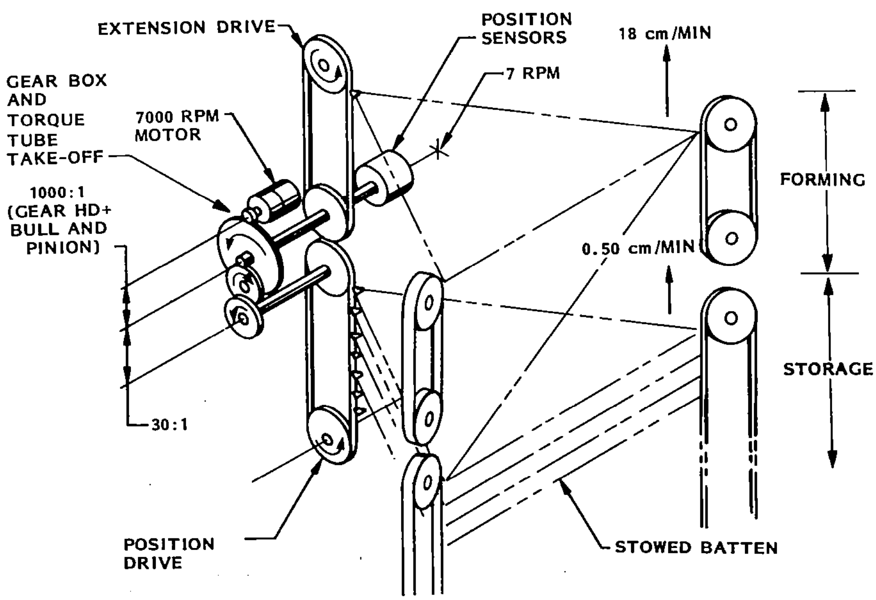

FIGURE 9. EXTENSION/RETRACTION DRIVE MECHANISM

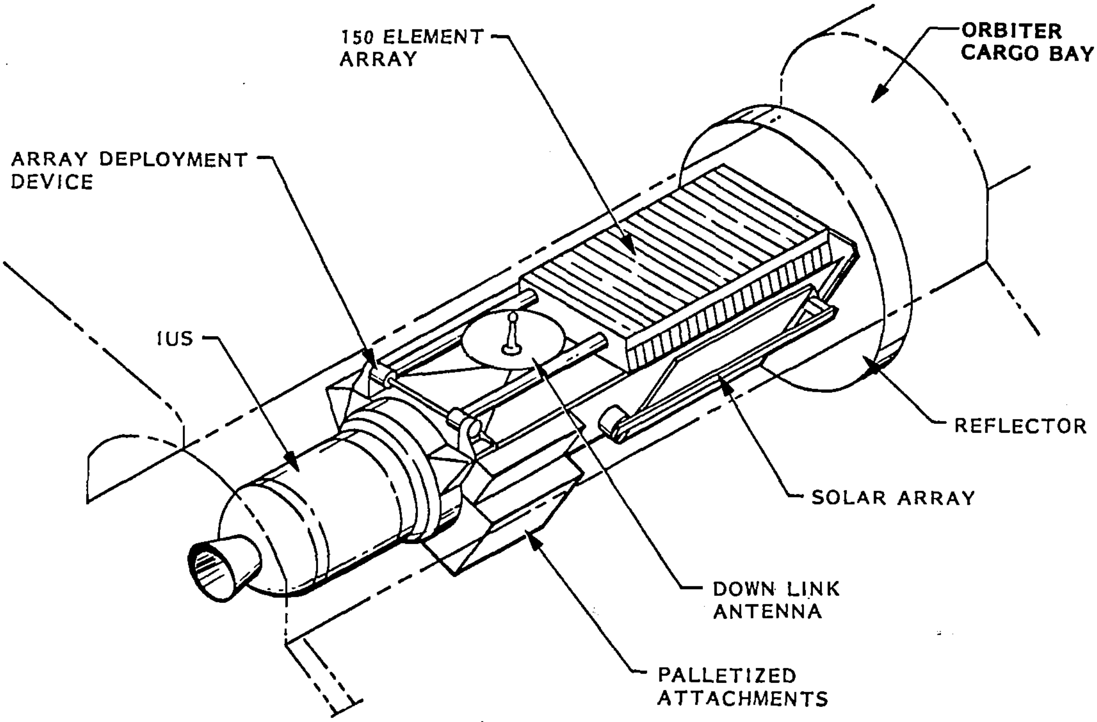

FIGURE 10. SPACECRAFT IN STOWED CONFIGURATION

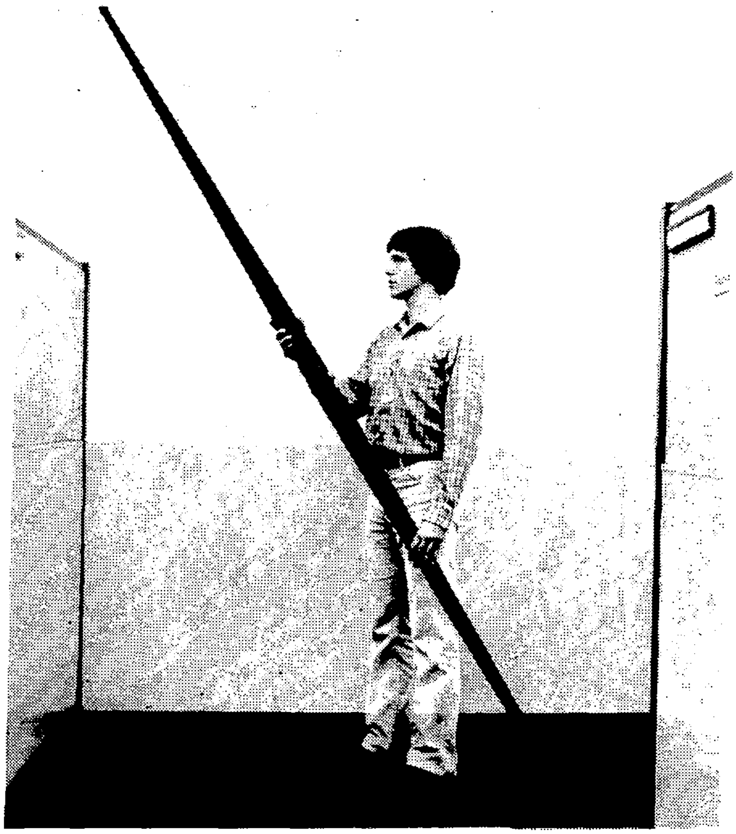

FIGURE 11. TAPERED GRAPHITE TUBES OFFERING HIGH STRENGTH AND LOW WEIGHT

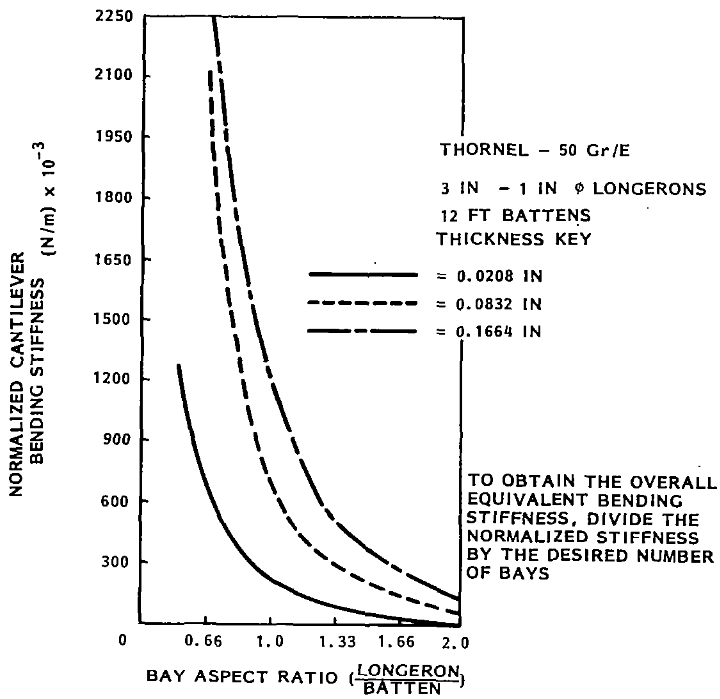

FIGURE 12. EFFECT OF MATERIAL THICKNESS AND ASPECT RATIO ON NORMALIZED BENDING STIFFNESS (NORMALIZED TO BAY LENGTH)

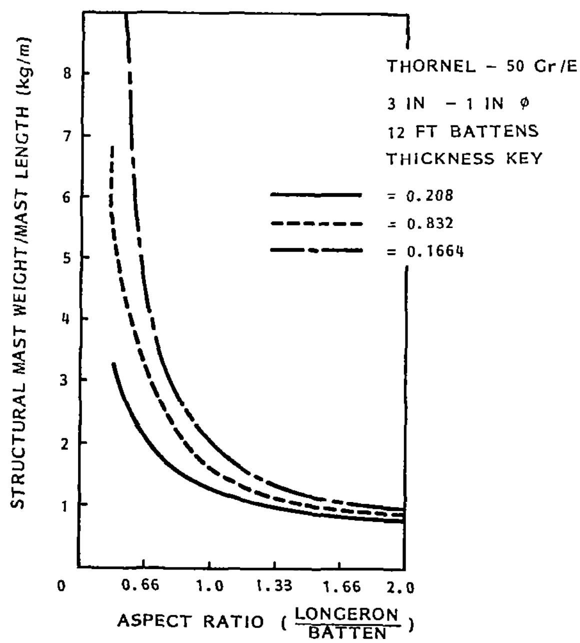

FIGURE 13. EFFECT OF MATERIAL THICKNESS AND ASPECT RATIO ON MAST STRUCTURAL WEIGHT

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