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Mechanisms for Restraining and Deploying a 50-kW Solar Array*

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A 5000-ft² folding modular solar array, designed by The Boeing Company for the Jet Propulsion Laboratory, can generate approximately 50 kW of power, with an efficiency greater than 20 W/lb, for a Mars flyby mission. To adequately stow and deploy this large-area solar array during boost and space flight, new mechanism-system design using conventional (1967 technology) light-duty mechanisms has been developed. The design requirements and hardware descriptions used to restrain, release, and deploy this large array are discussed.

I. Introduction

As spacecraft become more sophisticated and are required to perform more tasks, electrical power needs increase rapidly. While the *Explorer I* satellite required just a few milliwatts to complete its mission, a hypothetical ion-propelled spacecraft system, which has been studied for a Mars mission in the 1970s, indicates power demands approaching 50 kW. A 5000-ft² folding modular solar array, designed by The Boeing Company, has the capability to generate approximately 50 kW of power,

with an efficiency greater than 20 W/lb, for a Mars flyby mission.

The spacecraft that would utilize the solar array would be boosted by a *Saturn IB/Centaur* launch vehicle, and the array would be deployed within 3.5 h following launch (see Fig. 1). The design environments include steady-state and transient load conditions: sinusoidal, random, and acoustic excitation and extreme temperature and thermal shock conditions. The array configuration (Fig. 2) maximizes the live cell area within the shroud envelope. Four identical panel assemblies are positioned symmetrically about the spacecraft longitudinal axis. A panel assembly consists of 13 separate subpanels, each

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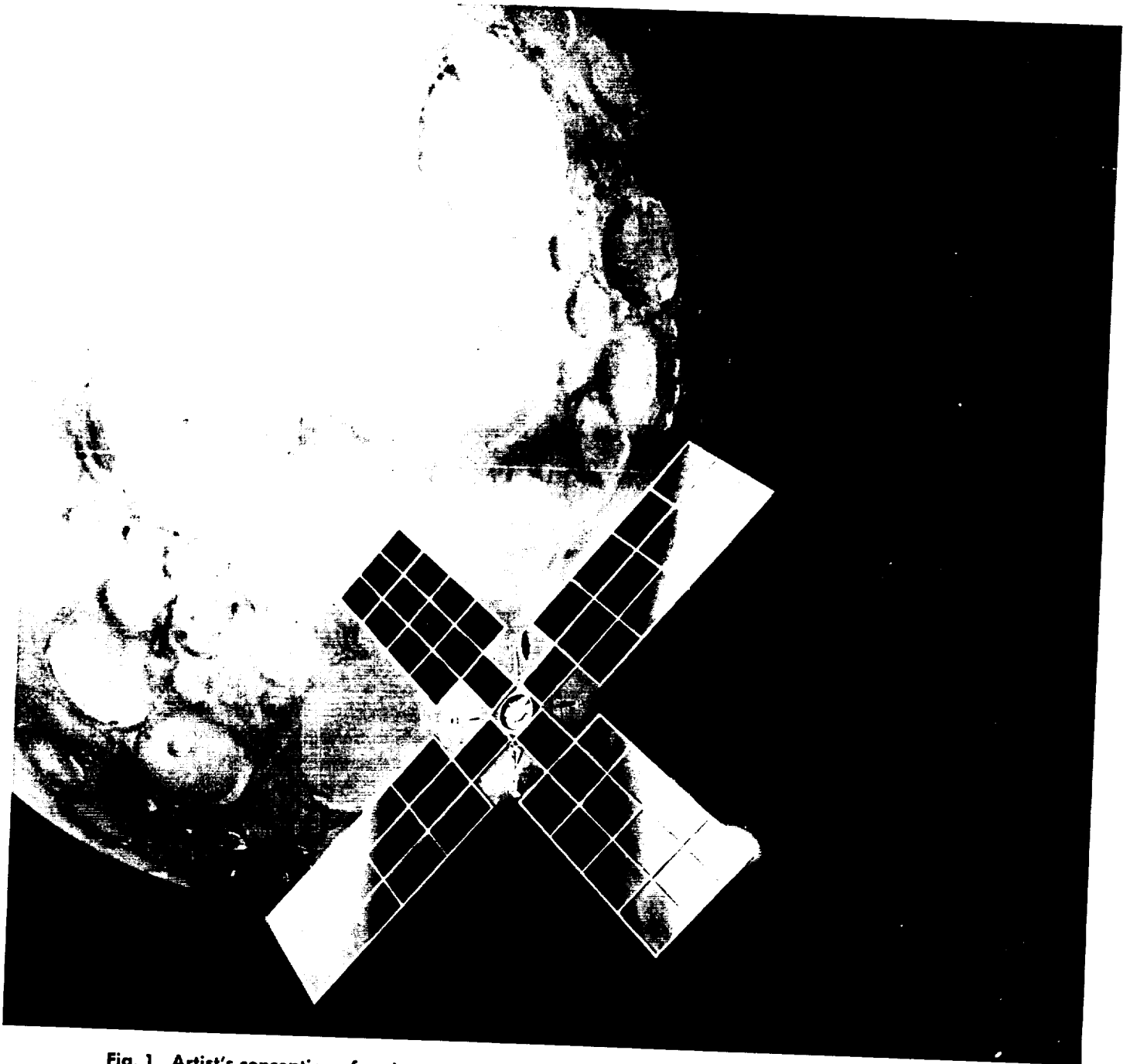


Fig. 1. Artist's conception of an ion-powered Mars flyby spacecraft utilizing a 5000-ft² solar array

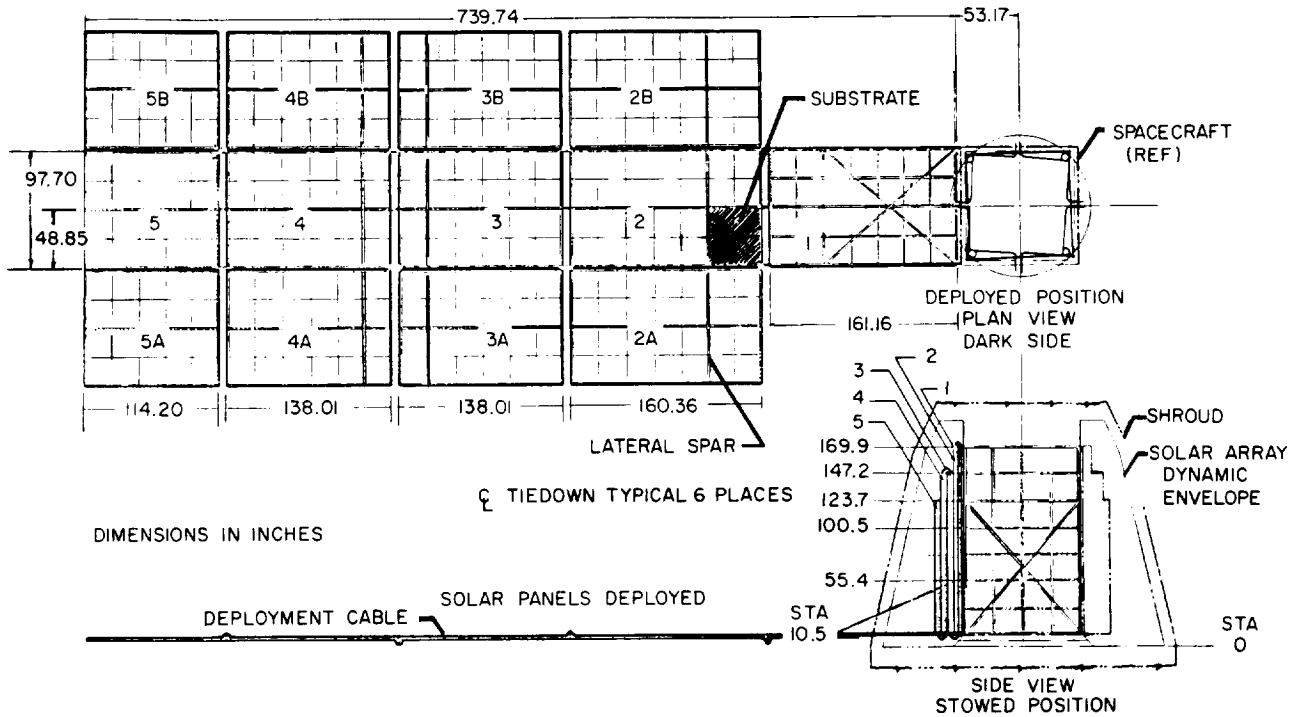


Fig. 2. Solar array, stowed and deployed

8 ft wide and varying in length from 9.5 to 13.5 ft. The first subpanel in each quadrant supplies 28 V power; all other panels supply 100 V power. When deployed, the array is firmly locked in a flat plane.

Beryllium is the primary structural material in the subpanel framework (Fig. 3) because of its excellent stiffness-to-weight ratio. Each framework consists of thin hot-formed beryllium channel and plate material bonded to form structural members. Adhesive bonding is used to eliminate possible stress risers that occur with mechanical fasteners. A diagonal matrix of 0.003- by 0.140-in. fiber glass tape is accurately positioned and bonded to the beryllium framework, providing a lightweight mounting surface for the solar cells. The tapes are pre-tensioned to increase substrate rigidity.

II. Boost Tiedown and Release System

The tiedown system allows the four panel assemblies to work together as a single structure during boost, increases the effective out-of-plane stiffness of each panel assembly, and reduces the loads inside the structure (Fig. 4). Mechanical release trains are used to minimize the number of pin-releases required for deployment.

To enhance its adaptability to different spacecraft configurations, the array-to-spacecraft interface is limited to a single array station plane. Three hinges per panel assembly transmit all boost loads from the array to the spacecraft and provide a hinge line for deployment. Each panel assembly is restrained from out-of-plane rotation about the hinge line during boost by linking it to its adjacent panel assemblies, which are inherently stiff in the in-plane direction; adjacent panel assemblies are joined by main tiedown fittings. To meet the boost phase frequency, envelope, strength, and weight environment, the 13 individual subpanels in each panel assembly act together as a type of "deep beam." A subpanel frame element is only 1.5 in. deep but may be as long as 13 ft.

By comparison, the entire panel assembly stack is 23 in. deep. A minimum of six shear transfer points along each longitudinal spar member is necessary to satisfy strength and stiffness requirements. By increasing the number of shear transfer points from one per longitudinal spar member to six, the fundamental frequency of the array is increased from 8 to 22 Hz, the peak deflection is decreased by over 10 times, and the maximum internal bending moments in the spar members are decreased over two times without changing the spar cross-sectional properties.

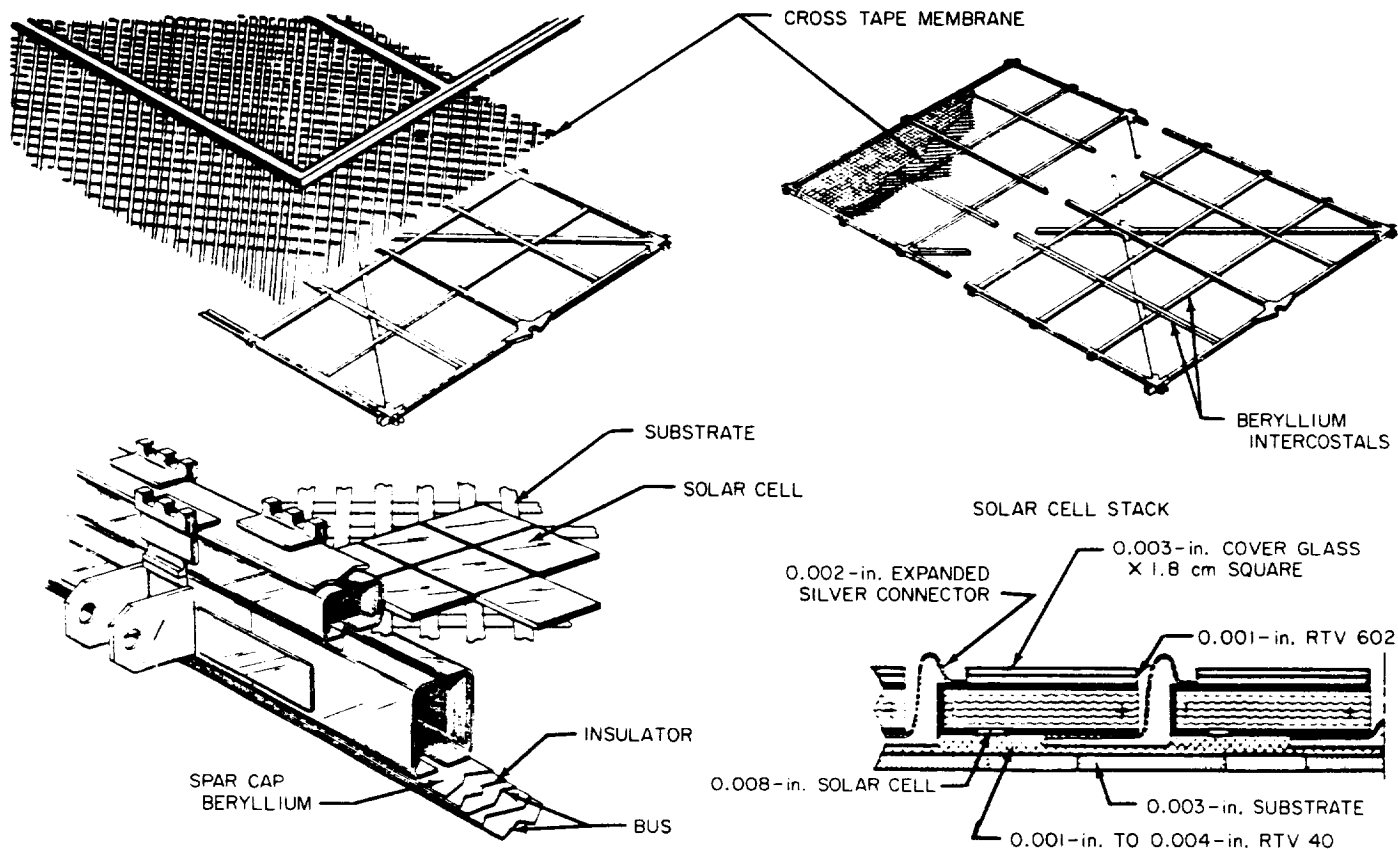


Fig. 3. Subpanel construction details

The net effect of using the tiedown and shear-tie system in this way is to make the individual subpanels work as an integrally stiffened panel assembly, where the individual panel assemblies work together as a more rigid unit basically independent of the spacecraft.

The shear ties provide load continuity between subpanels, both in a shearing and a normal direction. The shear teeth fitting minimizes localized loading effects into the beryllium spar members, thus improving the overall structural capability. The shear teeth are machined from 6Al-4V titanium plate with a multiple-tooth cutter to minimize the additive tolerance between mating parts. The teeth are bonded to the subpanels, but may be adjusted dimensionally along three axes. A preload at each shear-tie location maintains positive contact between mating shear teeth during critical loading conditions and is applied by three types of cable assemblies (Fig. 4): the circumferential cable, the corner cables, and the center tie cables. Additionally, release train cables run along each inboard edge of a panel assembly parallel to the longitudinal axis of the spacecraft and release the tiedown system on signal. In addition to these cable

assemblies, there are various fittings in the boost tiedown and release system that transfer loads between adjacent panel assemblies, serve as the termination point for the tiedown cables, transmit the component of cable loads inward into the panel stack, and react the center tie preloads.

The materials used for the system include stainless steel control cables for all external tiedown cables, organic Nomex cables for all center spar ties, and 7075-T6 aluminum for all fittings. Hard-anodize and molybdenum disulfide are used for bearing surfaces.

Rigging procedures require that center tie cables are installed and pre-tensioned initially, followed by installation and pre-tensioning of the outer cables in a predefined order to minimize wracking of the panel assembly. Rigging tests will be made to establish an optimum sequence to obtain the desired preloads in all cables. The mechanics of operation for the boost tiedown and release system during the rigging, operation, and release phases of the mission are examined and verified by ground tests as the overall program progresses.

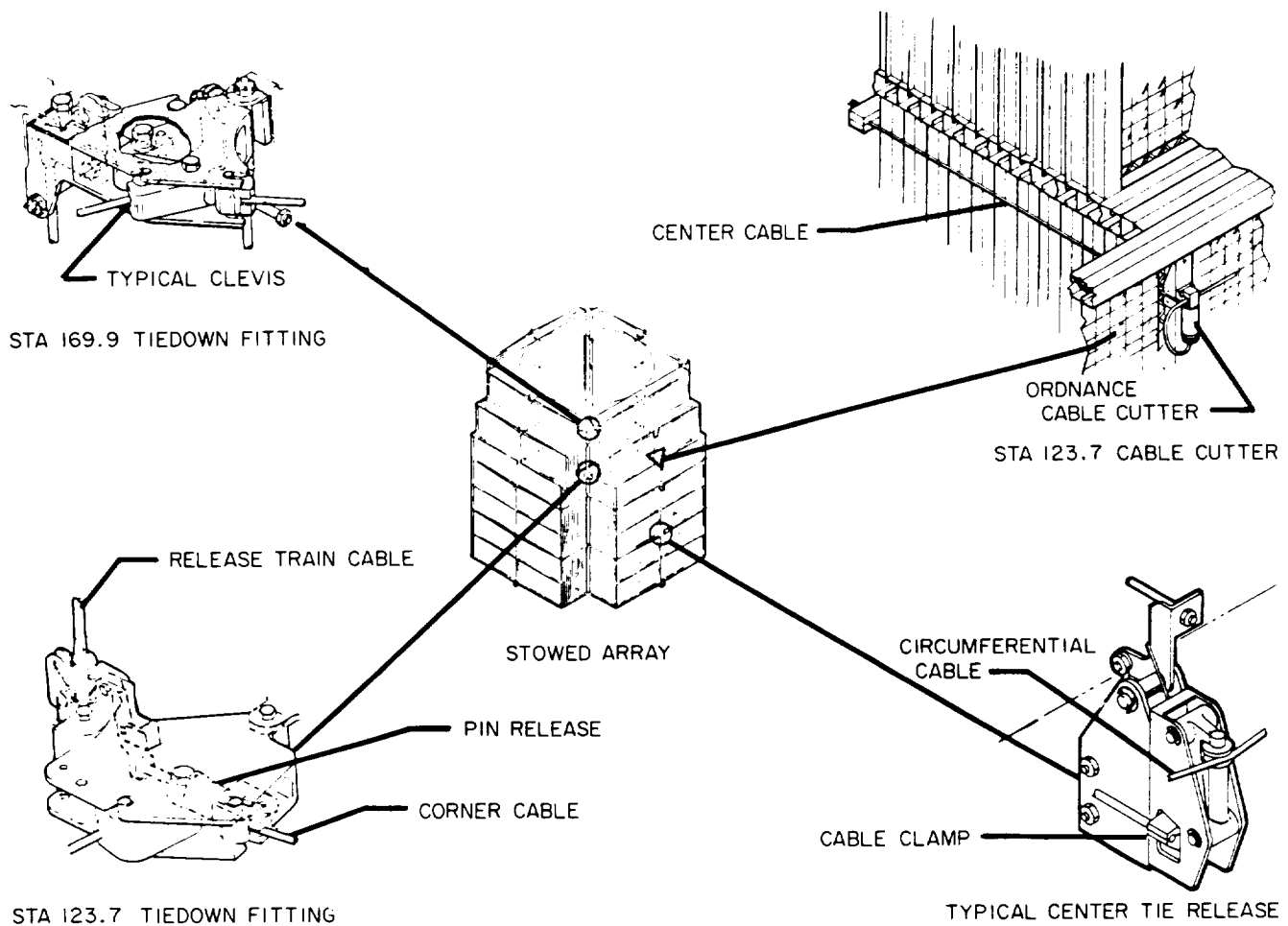


Fig. 4. Boost tiedown and release system

In a typical mission profile, the nose shroud is discarded before the final-stage burn. After burnout, when all significant boost loads have ceased to exist, the tiedown releasing sequence is initiated. An ordnance pin-release mechanism at each of the four major fittings is detonated, setting off a series of mechanical motions throughout the release train system. (The ordnance pin-releases selected are identical to those previously qualified on the *Lunar Orbiter* program.) All cables are released and discarded except for a single center tie cable that is retained on each of the four panel assemblies to prevent premature deployment. All significant stored strain energy is dissipated before panel deployment.

III. Panel Deployment

The main panels are deployed sequentially by an electric-motor-driven cable drum (Fig. 5). Four cable drum motor units mounted inside the spacecraft provide

a primary drive for each panel assembly. The cabling is rigged to make opposite panel motors operationally redundant, thus ensuring symmetrical deployment of each panel assembly pair even if one motor and cable drum assembly fails. Deployment velocity is controlled by the cable drum speed. On each main subpanel a control quadrant converts cable tension to hinge moment and controls the deployment sequence using a geneva drive mechanism to keep the panel stack secure until the adjacent inboard subpanels are open.

When the spacecraft is properly oriented, cable cutters sever the remaining center tie cables and release the panels for deployment. Power is supplied concurrently to the four deployment motor-cable drum assemblies. As the cable is drawn in, each panel assembly rotates 90 deg from the spacecraft centerline until a diagonal strut extends fully. Cam action on the center hinge unlatches the outboard 12-subpanel stack from the inboard panel, allowing deployment to continue. The subpanel stack

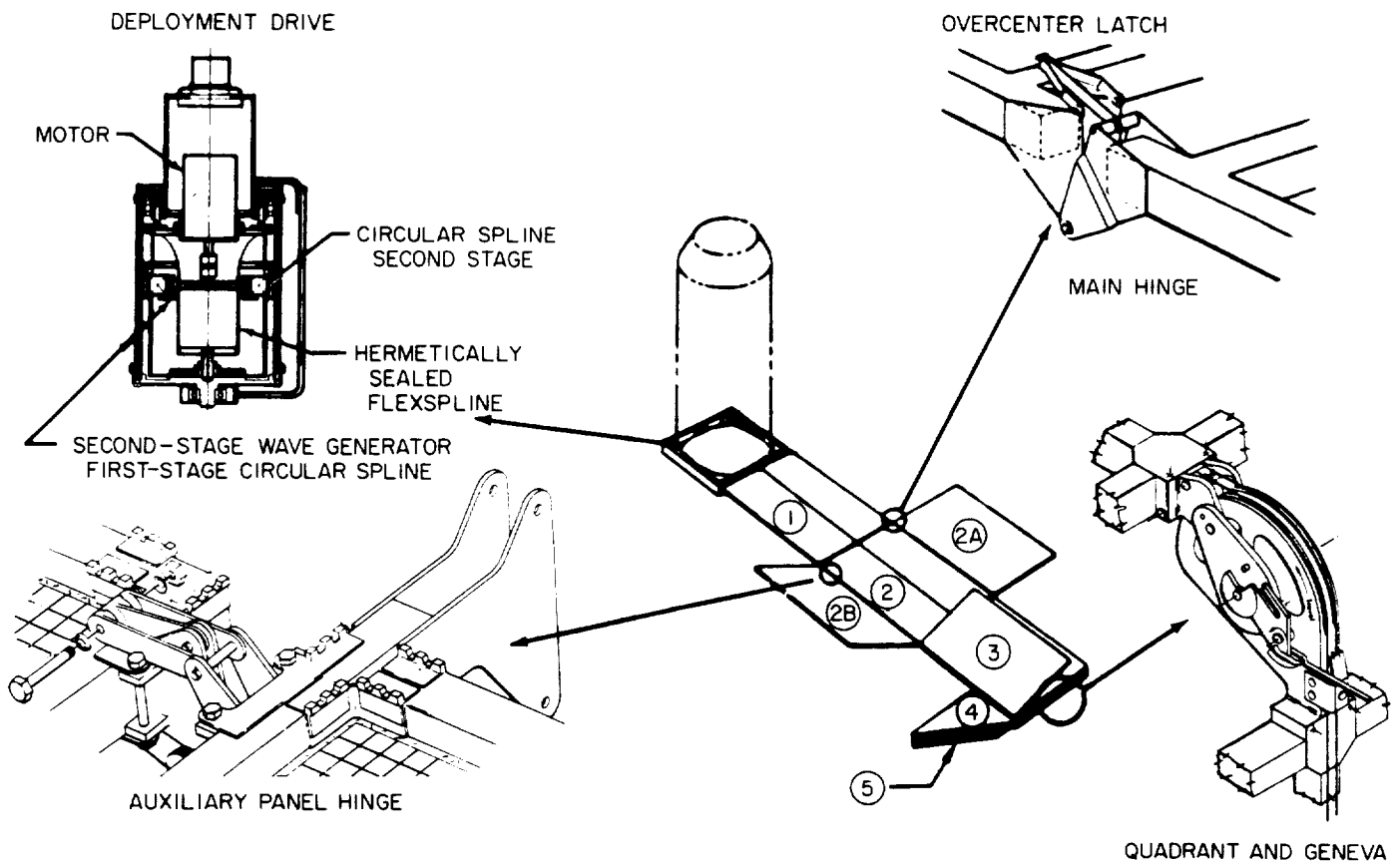


Fig. 5. Mechanisms and deployment sequence

rotates through 180 deg, at which time a four-bar linkage, integrated within the main hinges, snaps over center to securely latch Panel 2 to Panel 1 in a flat plane.

As the second subpanel reaches the full open position, the control-quadrant geneva rotates to release the out-board 9-panel stack. The sequence continues through successive 180-deg unfolding maneuvers until all main panels are deployed. Runaway deployment is prevented and passive damping provided by resistive torsion springs inside each main panel hinge assembly.

Each main subpanel four-bar linkage latch connects to a pin, which, when withdrawn from a fairlead in the end of the auxiliary A and B panels, allows each to deploy independently about its hinge axis. The deployment energy is supplied by a torsion spring in each hinge. Light-duty four-bar overcenter linkage latches lock the auxiliary subpanels in a flat plane. The angular velocity at latching is limited by a rotary viscous damper on each auxiliary subpanel. The dampers provide a damping ratio of 12 in.-lb/rad/s. Since the dampers are not temperature-compensated, thermal-control coatings are applied to

prevent excessively high temperatures. High-temperature operation causes a reduction in the damping capability, allowing excessive closing velocities at latching. Dampers exposed to deep space during the 3.5-h coast period are not protected from reduced temperatures. A warming period is required, after the main panels are deployed, before the oil flows freely within the damper passages. The dampers have sun exposure over 50% of their surface once the spacecraft locks on the sun and the main panels are deployed. If the spacecraft tumbles during coast, cooling of dampers is reduced.

IV. Deployment Design Details

The motor-cable drum assembly is composed of a 1/250-hp electric motor with a speed of 9700 rpm under load. The motor drives a 2.75:1 smooth ball bearing planetary reduction. The sun ring forms the wave generator for a middle-stage harmonic drive reducer with a ratio of 72:1. The output of the middle reducer is the wave generator of the third-stage harmonic drive with reduction of 140:1 for a total reduction of about 37,700:1.

The third stage output directly drives the cable drum, which is the outside housing for the motor and reducing train. The effective pitch diameter of the cable on the drum is 2.46 in.; the drum revolves at 0.259 rpm, providing a cable speed of 0.033 in./s. The motor, the planetary reduction, and the middle-stage wave generator are hermetically sealed, and the third-stage reduction has a rotary seal. Four drive units, each weighing 2.50 lb, are used. Batteries in the spacecraft electrical subsystem supply 28 V electric power. Space is provided within the spacecraft to route deployment cables and mount the motor-cable drum units.

The deployment cable used is 1/16-in.-diameter Monel, coated with molybdenum disulfide (MoS_2) dry-film lubricant, and has a breaking strength of 304 lb. It becomes a spring of reducing stiffness as deployment progresses to panel stacks of decreasing mass moment of inertia (803 slug ft² initially and 92 slug ft² for Subpanels 5, 5A, and 5B).

The control quadrants are made from aluminum alloy and provide an effective moment arm of 2.88 in. The cable groove is coated with MoS_2 , preventing adherence of the cable to the quadrant. The cable is retained on the quadrant by a Negator under a hoop tension load. As the quadrant and outboard panel stack rotate, the Negator spring is rolled onto a ball bearing take-up spool. These ball bearings, for space vacuum service, are stainless races and balls with a Teflon ball separator that deposits a minute quantity of Teflon to the rotating balls for lubrication and prevents vacuum welding.

The hinges between the spacecraft and the panel stack are the only ones that must withstand boost burnout loads. Outboard hinges support the deployed panels only under spacecraft maneuvers, ion engine thrust, and the panel loads introduced as they latch in place during deployment. Outboard hinges are made of simple flat aluminum plates riveted to mounting plates bonded on the outboard beryllium spars. Each hinge-half forms one leg of a four-bar linkage overcenter latch with pin joints. Bearing surfaces are prepared by first hard-anodizing the hole area and grinding to size. A baked-on coating of MoS_2 dry-film lubricant is then applied. The use of pin joints for latching eliminates sliding and mating surfaces, and backlash is limited to a tolerance buildup of the pin joints. Drilling of one hole on final assembly of the latch ensures perfect alignment. Striker plates, shear pins, and other precision-fitted parts are eliminated.

Auxiliary subpanel hinges use the same hard-anodize and dry-film pin bearings. Auxiliary subpanel deployment drive is provided by torsion springs. In the deployed state, the bending moment between panels is carried across the hinge as a couple between the hinge pin and the overcenter latch pins.

The diagonal strut between the spacecraft and the first subpanel maintains the angle between the spacecraft and the solar array. It also is a panel deployment lock. The strut is made up of four articulated links that stow nested together between the panel assembly and the spacecraft. As the panel deploys, two links straighten to form a tension-compression member maintaining angular control. Two smaller links lock the rotary joint in exact alignment so that no eccentric column buckling exists.

Four types of springs are used on this design: Negator springs as cable guards; compression springs as ice breakers (to provide a short-stroke high-impulse force); torsion springs as main panel resistance springs, auxiliary panel deployment drive springs, overcenter latch springs, and diagonal strut springs; and curved washer springs on the overcenter latch and on the diagonal strut pins.

V. Test Program

Testing of the array in an earth gravity field has been identified as a complex problem. The fully deployed structure, intended exclusively for space operation, hardly supports its own weight in the 1-g environment. Each subpanel must be completely supported independent of the adjacent subpanel and without putting excessive forces on the hinges. The supporting equipment must introduce a minimum resistance to deployment when driven with the panel deployment drive system, to minimize the influence of the equipment on the array characteristics and to avoid masking the attainment of system objectives. Deployment data and hard vacuum operation are obtained using prototype mechanisms mounted to small aluminum frames. Friction, latching, frame deflection, and performance tests are completed before the test article is inserted in a vacuum chamber. Hinge centerlines are positioned vertically to minimize gravity effects.

Full-size main subpanel deployment requires a fixture that fully supports the subpanels and minimizes operating friction (see Fig. 6). The fixture uses an overhead suspension system to support the deployed subpanels, simulating 0-g conditions, while the undeployed subpanels are carried on an air-bearing sled that follows a

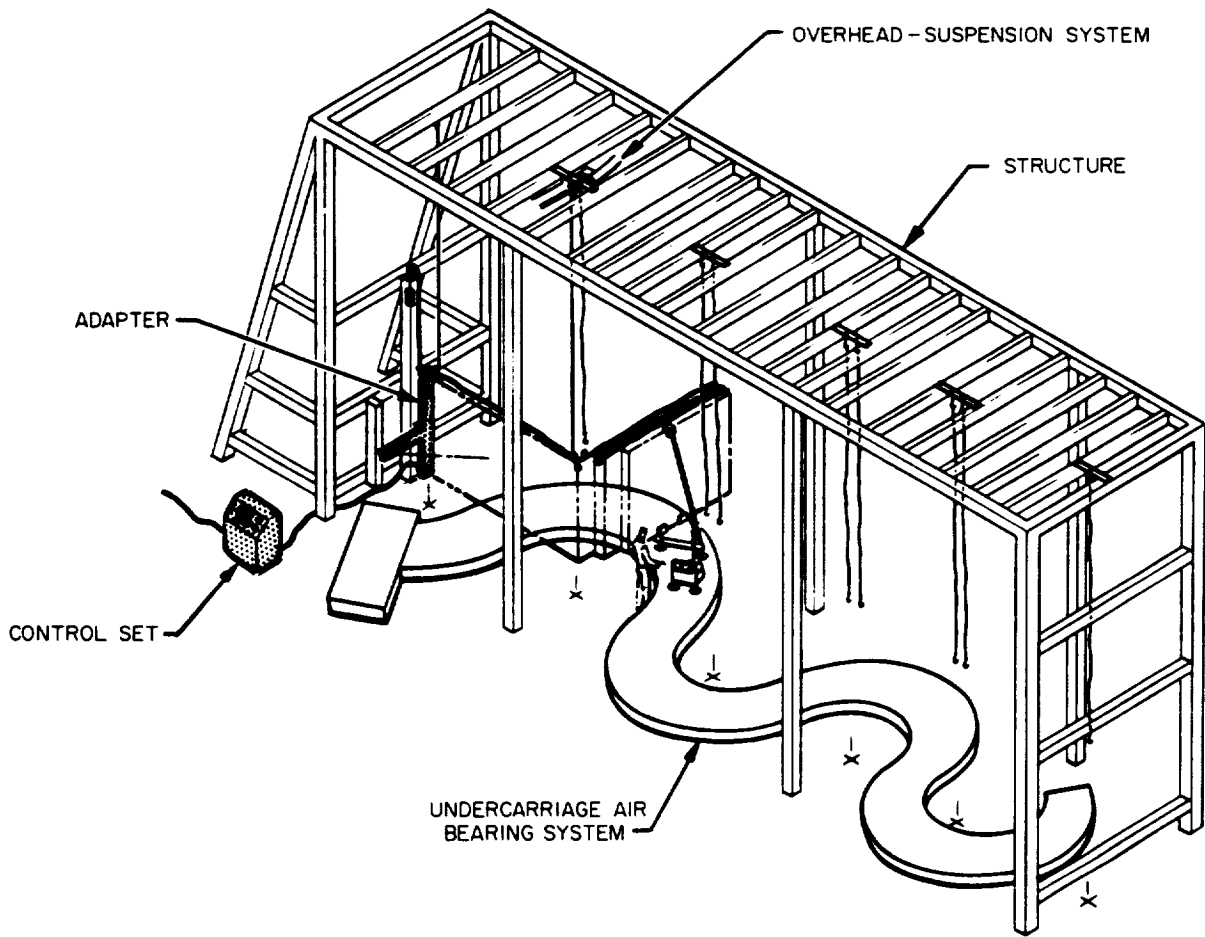


Fig. 6. Artist's drawing of the air-bearing track and overhead support used to provide the 0-g environment for the array during the deployment test. The air-bearing sled and air supply tender are also shown

curved track made of cast aluminum sections. Each section has an epoxy coating and is machined flat to within ± 0.0005 in. in 10 in. On installation, the sections are leveled to ± 0.003 in. The air-bearing gap varies between 0.0008 and 0.0013 in., depending on the load when supplied with 15 to 20 psig air. The sled air is supplied from a tender which contains its own pressure vessel and regulator to eliminate drag, which an air hose from a ground supply would cause. Tests, using mass and balance simulated aluminum main subpanels, have shown that the

solar panel deployment mechanisms are adequate to drive the ground equipment as well as the deploying subpanels.

Auxiliary subpanel tests use a fixture that mounts a main subpanel and its contiguous auxiliaries with the hinge pin centerline vertical. Mechanical bearings rather than air bearings are used to overcome gravity loads. An artist's conception of the subpanel test fixture is shown in Fig. 7.

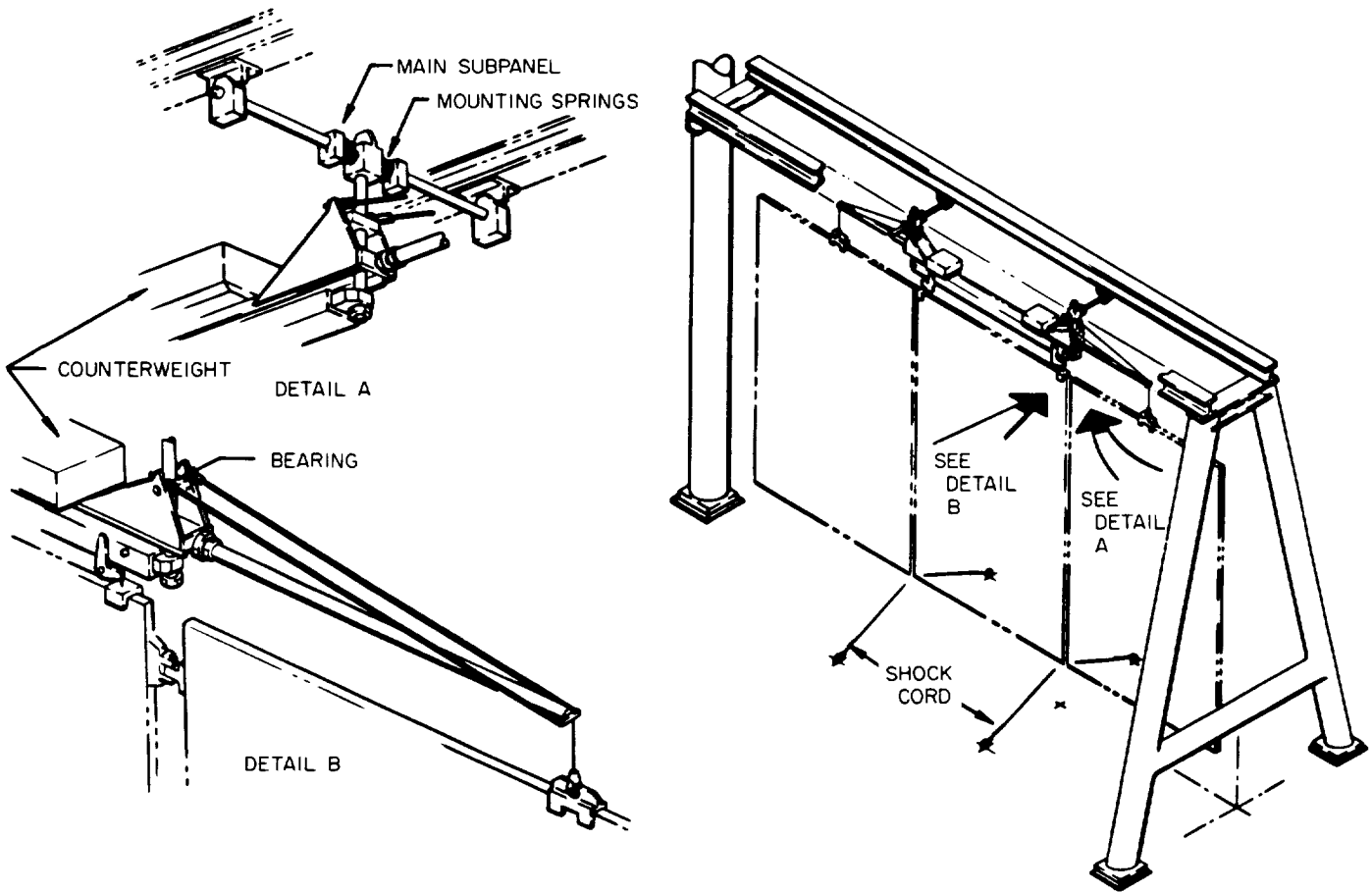


Fig. 7. Artist's drawing of the overhead support system providing for a 0-g auxiliary panel deployment environment

