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MILSTAR's FLEXIBLE SUBSTRATE SOLAR ARRAY--LESSONS LEARNED

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Editor's Note: The full text of this paper appears on page 235 of the Proceedings, but the figures were inadvertently left out. This document presents the paper in its entirety.

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ABSTRACT

MILSTAR's Flexible Substrate Solar Array (FSSA) is an evolutionary development of the lightweight, flexible substrate design pioneered at Lockheed during the seventies. Many of the features of the design are related to the Solar Array Flight Experiment (SAFE), flown on STS-41D in 1984. FSSA development has created a substantial technology base for future flexible substrate solar arrays such as the array for the Space Station Freedom. Lessons learned during the development of the FSSA can and should be applied to the Freedom array and other future flexible substrate designs.

INTRODUCTION

The FSSA is a large, lightweight, deployable solar array utilizing flexible substrate electrical panels, which are fan-folded when stowed (Fig. 1). When deployed, the array is 15.2 m long by 3.0 m wide (Fig. 2). Collectively, the solar cells, circuit paths, and Kapton® polyimide substrate is termed a blanket. The FSSA blanket has 69 active panels which contain solar cells, and an additional 7 spacer panels devoid of cells (inactive). Each panel is nominally 0.4 mm thick, and folded for stowage, the blanket stack is 2.5 cm thick.

The blanket stack is compressed between two foam and rubber lined honeycomb panels when stowed, to facilitate survival of the launch environment. Preload clamp and release action is produced by a multi-point preload/release mechanism. Upon preload release, the cover panel is rotated up and out of the blanket deployment path by two four-bar hinge mechanisms. Array deployment is then effected by a coilable-longeron Astro mast attached to the blanket by a spreader bar (upper tension bar). The mast pulls the panels out from the stowed stack as it extends. Orderly panel unfolding and alignment is assisted by three guidewires controlled by tensioning mechanisms. Near the end of the mast travel, the blanket is automatically tensioned by two mechanisms acting on a second spreader bar (lower tension bar).

DESIGN EVOLUTION

Initially, the design team studied a number of concepts for rigid and flexible substrate solar arrays. It became apparent that weight and volume requirements favored flexible substrate designs. The team was able to draw on LMSC's experience with the SAFE array as a model for the MILSTAR array. It should be

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noted that few of the MILSTAR array design team members had any direct experience working on the SAFE array. Primarily due to design requirement differences, but also due to this unfamiliarity, the FSSA did not start out as a replica of the SAFE design. Conceptually, both arrays fit approximately the same description, although most every mechanism has substantial differences in form and weight, if not function. The prime differences are in the ascent constraint structure, the preload/release mechanism, and the guidewire tensioning mechanism. The principal concern of the FSSA design team during the preliminary design phase was replicating a SAFE subsystem or mechanism with a lower weight. Although this tendency is natural in aerospace, it can narrow the design focus to the point that breakthroughs that eliminate, combine, or redefine functions are prevented.

Table 1 compares SAFE and FSSA specifications. The most obvious difference is size (SAFE is twice as long and one-third wider than FSSA), weight, (SAFE is 3.5 times heavier), and power (SAFE could have produced 3.1 times more power than FSSA if all panels were active). Thus, the FSSA is roughly one-third the size of SAFE. Improvements in photovoltaic cell technology are responsible for a 5.5% gain in power relative to area. Specific power-to-weight has improved 12%, reflecting not only better cells, but also the attention to detailed design to reduce weight for the FSSA.

Additional, critical differences apparent in Table 1 are the lack of a restow requirement for the FSSA, and the 10 year life requirement. The difference in deployed structural modes of the arrays is significantly affected by the 50% shorter coilable-longeron mast employed on the FSSA. However it is also influenced greatly by design differences reducing deployed tip mass. If all things were equal between the designs, the deployed modes of the array would increase in frequency by about 180% from the 50% reduction in length. Significantly, the FSSA has about 330% higher first- mode frequencies. During the development of the FSSA, the deployed array modal frequencies became a critical issue. Satellite Attitude Control System (ACS) simulations showed unacceptable structural response to control input, and redesign was required to raise the first bending modes about 10% in frequency.

As originally planned, MILSTAR was to use the STS with a Centaur upper stage to achieve High Earth Orbit (HEO). This was changed to the Titan IV (T-IV) with the Centaur after preliminary design of the FSSA was complete, as a consequence of the Challenger explosion. The effect of the change in ascent system on the array design turned out to be minimal, although structural analysis had to be repeated to verify margins. Generally, structural margins increased, although not enough to justify further paring of weight from the design. The peak dynamic loading on the blanket container system has been found to occur during Centaur engine shutdown, which is unaffected by STS or T-IV as the prime launch vehicle.

The heritage of several FSSA design features is apparent in Figure 3, depicting the SAFE array. It is more enlightening to discuss the differences between the two designs, and why they arose, than to describe the similarities. The FSSA blanket is smaller and substantially lighter than that of the SAFE (19% of SAFE's weight), thereby allowing the simplification of the containment structure from a deep-section strongback to 6.4-cm thick honeycomb cover and base panels. The deployable mast arrangement is similar, although the blanket container was relocated at the base of the mast with FSSA to reduce moment loading during ascent (the SAFE mast-to-blanket container configuration is driven by Shuttle cargo bay dimensions).

Activation of the SAFE blanket preload/release is dependent upon mast motion, whereas the FSSA designers made this function independent. The FSSA design team realized that a weight savings could be achieved by eliminating the heavy cam and linkage rod preload system used on SAFE, as well as lightening the relatively rigid cover structure. The FSSA preload system is distributed to eight points, facilitating the use of a lighter, less rigid cover. Actuation is performed by two separate pyrotechnic pinpullers. Each pinpuller releases preload at one mechanism directly, and at three additional slaved mechanisms via cables and bellcranks. Figure 1 shows the eight preload/release mechanism locations. Figure 4 shows a single preload/release mechanism. Preload is applied by tensioning the rod between the blanket container base and cover using the adjustment nut. A stack of Belleville washers in the load path reduces the spring rate of the combined mechanism and blanket container to accommodate differential thermal growth in the system. Originally, preload was set by measuring a gap between the inner and outer Belleville guides. This feature did not provide the measurement accuracy and repeatability desired, however.

Preload is released by allowing the tension rod assembly to rotate 135 degrees about its longitudinal axis. The upper portion of the rod is attached to a cam roller bearing, which rides on a helically cut ramp section attached to the blanket cover. The tip of the rod is held by a cover bracket hole, which locates the cam roller on the ramp until release, and acts as a bearing during rod rotation. Preload in the tension rod induces a torque to rotate the rod via the helical ramp. This torque is resisted by a bellcrank at the bottom of the rod assembly. The crank is held in place by either a pinpuller toggle on the master unit, or a cable connected to the master crank on the slave units. On each set of four preload/release mechanisms, two captured coil springs provide additional tension on the cables to rotate the cranks and tension rods, and to keep them in the released position.

The SAFE designers were required to restow the solar array blanket, and could not effectively use pyrotechnic actuation to do so. Therefore, they developed a scheme which used the first few centimeters of mast motion to drive a four-bar linkage and cam system to apply and remove preload. This system clamped the cover and base at four locations. Although it is relatively heavy compared to the FSSA system, it has the advantages of restow capability and a reduced number of command and telemetry signals required to deploy the solar array.

During deployment of the mast, the blanket is controlled by guidewires, which constrain the blanket panels to deploy in a circumscribed plane. The guidewires pay out under uniform tension, controlled by guidewire tensioning mechanisms. The initial design of this mechanism was similar to the SAFE mechanism, consisting of a cable reel retarded by three negator spring reels. This mechanism allowed restowing the blanket, as dictated by early requirements. In addition, to ensure the proper motion of the blanket panels during restow, rigid panel frames and biasing springs along the panel hinge lines were also employed. The restow requirement was eliminated after systems analysis proved that battery recharge was not required until final orbit placement of the satellite. This change allowed simplification of the blanket, since frames and hinge springs are required to discipline the blanket only during restow, not during deployment. The guidewire mechanism is also simplified, since it is no longer required to reel in the cable during restow. A second design was developed, which uses a friction clutch to regulate cable pay out (Fig. 5). This design reduces weight from about 1.4 to 0.3 kg per mechanism. It also has the advantages of fewer moving parts and bearing surfaces.

When the solar array blanket nears full deployment, it is tensioned to remain flat by stretching it between two spreader bars. The lower spreader bar attaches to two cables, each of which is controlled by a blanket tension mechanism (Fig. 6). This mechanism is essentially the same as that used on the SAFE, and is also similar to the preliminary design of the guidewire tensioning mechanism, except that its range of cable travel is 0.6 m. The cable reel is centrally located, and four negator springs act on a drum integral with the reel. As previously mentioned, the SAFE design used three negator springs. The fourth negator spring was added when analysis determined that the blanket would not be properly tensioned if one spring failed out of three, but would if one of four failed.

The cover rotation hinge mechanism is a relative latecomer to the FSSA design. Originally, the FSSA, like the SAFE, deployed its cover with the mast tip; the cover acted as the upper tension bar. During development of the satellite ACS, the predicted modal frequencies of the deployed FSSA were found to be unacceptably close to a resonance condition. A crash redesign program was initiated to boost the first mode frequencies of the deployed array by about 10% in bending. Although some structural stiffening was performed, the major focus of this effort was the reduction of the deployed tip mass by leaving the cover behind with the blanket container base. A lightweight composite upper tension bar replaces the cover to tension the blanket. The cover is now hinged to the base by two four-bar rotation mechanisms (Fig. 7), which deploy it up 2.5 cm, and then rotate it away from the blanket deployment path. At this point the mechanisms lock up to eliminate any cover freeplay motion. One single and one dual helical torsion spring provide actuation torque for each hinge mechanism. All pivot points have dual or redundant bearing surfaces, since the pivot pins are floated through all linkage and mounting holes. Monoball bearings are used to eliminate alignment sensitivity, which causes binding.

ANALYSIS

Per standard Lockheed practice, analysis of the solar array design was performed by the design team, backed up by structures, thermal, and dynamics specialists from a central pool, not co-located with the designers. Structural analysis for the most part was straightforward, and traditional methods were used. Unfortunately, the blanket container preload pressure distribution, which is not readily analyzed without using finite element methods, was never analyzed except by traditional methods, with many assumptions. This led to a lot of guesswork with regard to the static load capabilities of the blanket containment system, and also with regard to scenarios that may induce cell cracks.

Perhaps the most interesting analysis performed is a dynamic simulation of the blanket deployment using the Automatic Dynamic Analysis of Mechanical Systems (ADAMS) code. The ADAMS model was used to explore sensitivity of the blanket deployment to variations in guidewire tension, guidewire friction, flat conductor cable torques, hinge joint friction, spacecraft inertial rates, and mast deployment rates. Due to limitations in computer capability, reduced models of ten and twenty panels were created to evaluate scaling to the full blanket. Each panel was modeled as a rigid body connected by a single-degree-of-freedom revolute joint to its neighbor. To account for panel flexibility and cable bending forces, torques were applied at the hinge joints. The mast was modeled as a single rigid body pivoting at its base, again with suitable torques to account for stiffness. The model predicted that deployment would be well regulated under all conditions, even under high satellite spin rates. Scaling up to the full blanket was ascertained by comparing the ten-panel model results to the twenty-panel results. Besides the model predictions, extensive testing of the SAFE on STS-41D provides high confidence that the similar FSSA will deploy under all required conditions at 0-G.

TEST PROGRAM

As proof of concept, a mechanical development unit containing all mechanisms (except for the cover rotation hinges) was built near Critical Design Review. This development array contains a few panels using solar cells, but has glass cell simulators on all remaining panels. The development unit was tested in ambient conditions to simulate deployment in 0-G by a horizontal deployment fixture based on the SAFE ground test fixture (refs. 3 and 4). This fixture consists of a track supporting the mast from below, and a set of tracks suspending the blanket panels and tension bar(s) (or the cover) from above (Fig. 8). The mast is supported on carts traveling on the lower track, spaced at intervals of about 3 m. Low friction roller bearings minimize cart resistance to mast motion in the deployment direction, and Thompson linear bearings incorporated into each cart allow the mast a degree of freedom across the track. Each blanket panel is individually counterweighted. The counterweight and suspension system allows each blanket panel to move in the mast deployment direction, while following the motion of the panel CG as it moves inward toward the mast, to a final position along the inner hinge line. The blanket panels are necessarily suspended above their CG, midway between their hinge lines, and the deployed blanket is tensioned along a line that coincides with the hinges closest to the mast (every other hinge). A small range of vertical motion is also accommodated by this blanket suspension system. The panel thickness is the most complicating factor to the blanket suspension system design. Because panel counterweights only 0.4 mm thick are impractical, and because it is desirable to use roller bearings on the track carriages suspending the panels, a stacked arrangement of carriage tracks and counterweights allows the test equipment to have reasonable thickness.

Several problems related to the horizontal deployment test equipment have occurred during testing, due to weaknesses in the original design. During one of the first development tests, the suspension wire supporting the 10-kg cover broke, causing a chain-reaction domino effect to propagate down the blanket. Several panels ended up on the floor of the test facility. After this incident, the cover support wire was increased in size and changed from single-strand music wire to braided cable to avoid a future mishap. However, the remaining suspension wires continue to plague the test fixture with fatigue-related breakage, and are now in the process of being converted to heavier gage braided cable as well. The main problem with the music wire cables occurs at their end fittings, which have small radius bends, inducing low-cycle fatigue failure. Revised end termination designs for the braided wire cable have ball end fittings, or relatively large-radius cable loops to eliminate these problems.

Ambient testing of the FSSA development unit proved that the basic design was sound. One of the most important test results was the discovery of panel-to-panel sticking, caused by assembly adhesive on the backside of the panels. Because of this, manufacturing and handling procedures were successfully revised to eliminate such problems on flight panels, by scrupulous attention to cleanliness during bonding operations.

Additional testing with the development hardware exposed it to the ascent acoustic environment, the release pyroshock environment, and ascent quasi-static loads. No anomalies occurred during the first two tests, proving that the foam and rubber insulation in the blanket container performed as intended. The quasi-static load testing of the blanket container did result in unexpected behavior, however. In order to properly load the stowed blanket in the preloaded container, the entire assembly was placed on a centrifuge, oriented such that the centrifuge arm was along the resultant load vector for the worst-case peak load condition. Before maximum load was reached, the blanket panels slipped relative to one another, and the cover also shifted (Figure 9). Experimentation found that the cover required lateral restraint, and preload was raised from an initial value of 9.3 kN to 13.4 kN to avoid slippage. Panel slippage while stowed and preloaded is a concern, since it can cause cell cracking. The centrifuge testing also found inadequacies in the preload setting/measurement method.

Several changes are incorporated into the flight FSSA units as a result of the development test program. The deployed mode requirement change easily caused the most modifications and additions to the design. The most significant changes include: cover rotation hinge mechanisms added; lightweight upper tension bar added; fourth negator spring added to blanket tension mechanism; longeron lockup cams added to mast to avoid reliance on microswitches for deployment termination (deployment is shut off by a timer); blanket cover lateral restraint added; preload on blanket increased; strain gage load cells added to tension rods to measure preload in lieu of mechanical measurement. Several other minor changes have been made to some mechanisms, such as an improved coil spring containment cage on the preload/release mechanism cables, and modifications to the pinpuller toggles and bellcranks to eliminate impact damage caused by repeated ground test.

DESIGN ASSESSMENT

The principal improvements to flexible substrate solar-array design exhibited by the FSSA are:

1. Increased specific power-to-weight ratio by 12% relative to SAFE (5.5% due to cell technology improvements).

2. Increased first bending mode frequencies by 330% relative to SAFE (approximately 150% increase per given length).

3. Increased qualified life expectancy to 10 years from several weeks.

Many lessons have been learned during the design and testing of the FSSA. A summary of these includes:

DO's:

1. Establish written test requirements and a test plan as early as possible.

2. Devote sufficient resources to thoroughly prove 0-G deployment test equipment works, and that it is robustly designed with fail-safe features or high structural margins.

3. Minimize deployed mass at the deployed end of the array or mast (leave the cover at the base).

4. Create a finite-element model of blanket container preload distribution.

5. Perform development acoustic and shock testing as appropriate to establish minimum acceptable blanket preload to survive these environments.

6. Consider pretesting cell assemblies by uniformly preloading prior to incorporation in the blanket. This will eliminate or reduce cell cracking caused by cell assemblies with residual stresses.

7. Insist on high cleanliness standards during panel bonding, especially when the process involves cutting film adhesives, to avoid panel sticking.

8. Use electro-mechanical measurement of preload when it is critical. Ensure adequate strain reliefs are provided for connection wires.

9. Maximize spreader bar stiffness in the deployment plane, and perform analysis to ensure acceptably low deflection to avoid panel warping or wrinkling.

10. Be aware that MoS_2 coatings have a coefficient of friction dependent upon humidity. Variations are on an order of magnitude between ambient and vacuum conditions.

DON'T's:

1. Do not rely on preload and friction to hold a blanket stack in place during ascent; use a positive mechanical load path such as pins, skewers, or interlocking sections. A reduction in applied pressure from 9.7 kPa to 1.2 kPa (a factor of 8) should be possible if this is done.

2. Avoid overly complex electronic test consoles; if a simple power supply with polarity and on/off control suffices, use it.

3. Avoid using notch-sensitive materials as threaded fasteners (the original tension rod cam roller bearing screw was 440C CRES, and broke at the root of the first thread).

4. Do not apply MoS_2 coatings to both surfaces of a sliding/mating pair, or a higher coefficient of friction will result than if only one surface is coated (this occurred in the tension-rod Belleville washer stack).

5. Do not allow inexperienced engineers to design spacecraft mechanisms without sufficient supervision and design review (many details of the preload/release mechanism have required changes, due to the designer's lack of experience and insufficient review).

CONCLUSION

The flight FSSA has successfully been qualified in static load (centrifuge) and acoustic environmental testing. As this paper is written, qualification for pyroshock and thermal-vacuum conditions is forthcoming. Improvements to the reliability and ruggedness of the simulated 0-G blanket suspension system of the horizontal test equipment also are being made. Completion of the qualification program is anticipated by mid-1992.

ACKNOWLEDGEMENTS

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TABLE 1: SAFE AND FSSA SPECIFICATIONS

SPECIFICATION		SAFE	FSSA
POWER (BOL)		13,300 *	4300
WEIGHT (kg)		304.5	88.2
SIZE (m)		30.9 x 4.0	15.2 x 3.0
SHAPE		FLAT, RECTANGULAR	FLAT, RECTANGULAR
TOT. CELL AREA (m^2)		124	38
WATTS/M^2		107.3	113.2
WATTS/KG		43.7	48.8
PANELS PER S/A		84	69 active + 7 inactive
SUBSTRATE		FLEX, POLYIMIDE	FLEX, POLYIMIDE
CIRCUIT CONSTRUCTION		PRINTED	PRINTED
CELL CONSTRUCTION		SILICON	SILICON
CELL SIZE (cm)		2 x 4, 5.9 x 5.9	7.1 x 7.1
MAST		ABLE	ASTRO
DEPLOYED 1st MODES (Hz)	out-of-plane	0.0375	0.162
	in-plane	0.0405	0.200
	torsion	0.0577	0.391
LIFE		2 WEEKS	10 YEARS
ASCENT SYSTEM		STS	(STS/CENTAUR originally) T-IV/CENTAUR
RESTOW REQUIREMENT		YES	(YES originally) NO
DESIGN/TEST STANDARD		NASA/MSFC	MIL-STD-1540B
FAILURE TOLERANCE CRITERIA		1 FAULT/STS JETTISON	1 FAULT

* Theoretical Value. SAFE did not carry a full complement of solar cells.

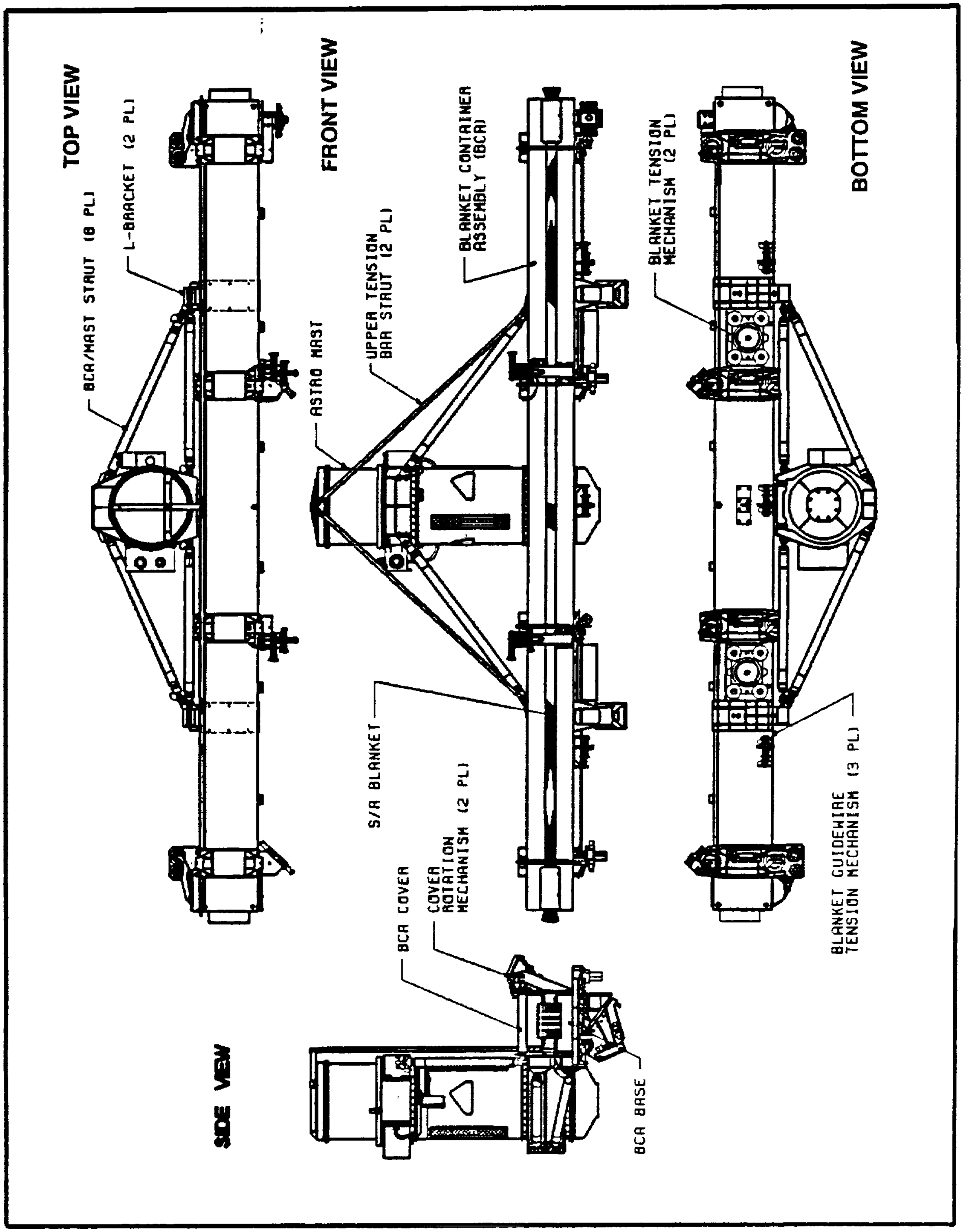


FIGURE 1: FSSA, STOWED CONFIGURATION

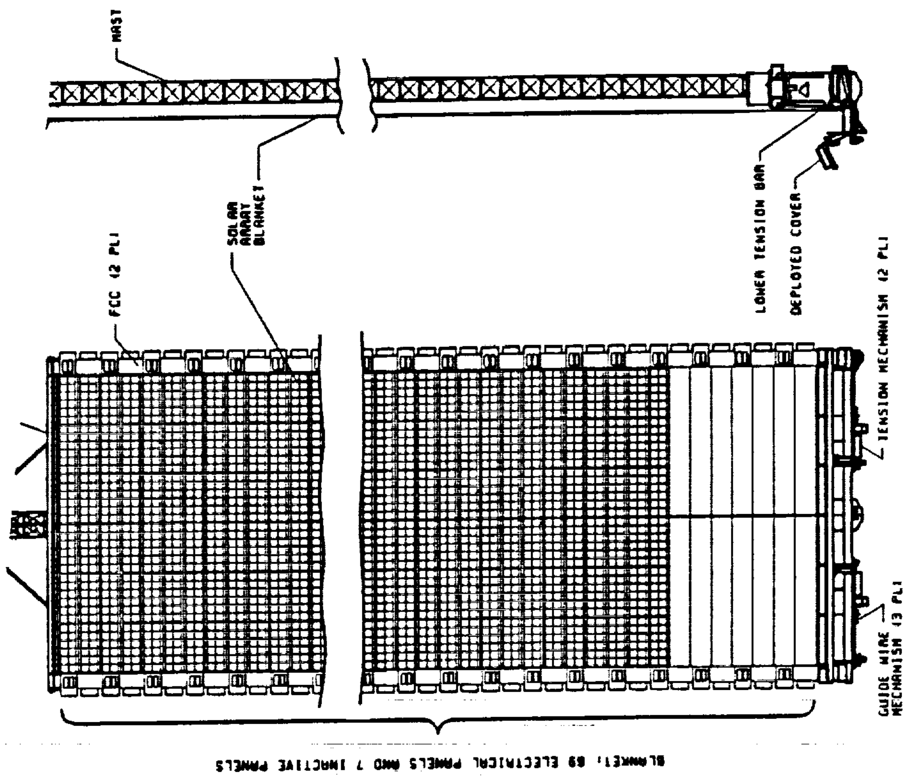


FIGURE 2: FSSA, DEPLOYED CONFIGURATION

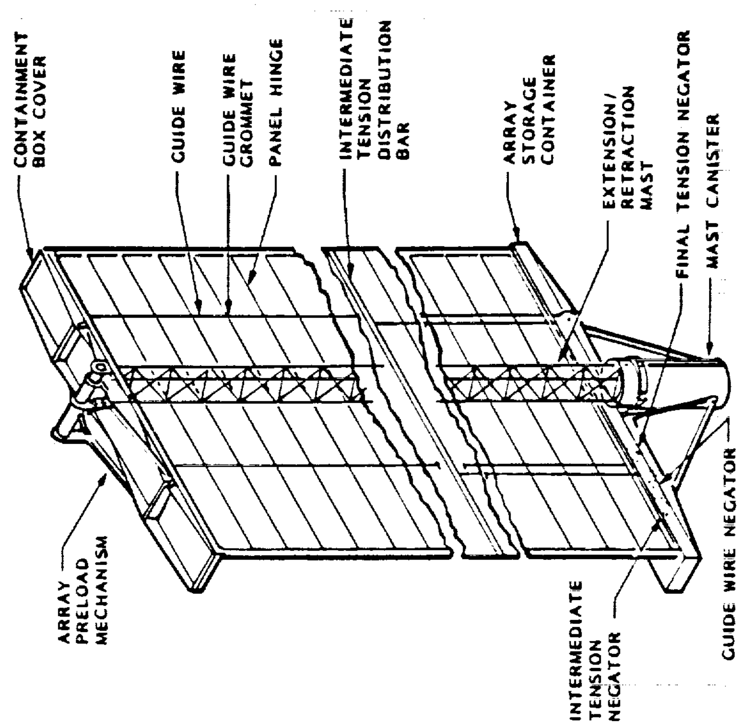


FIGURE 3: SAFE WING ASSEMBLY

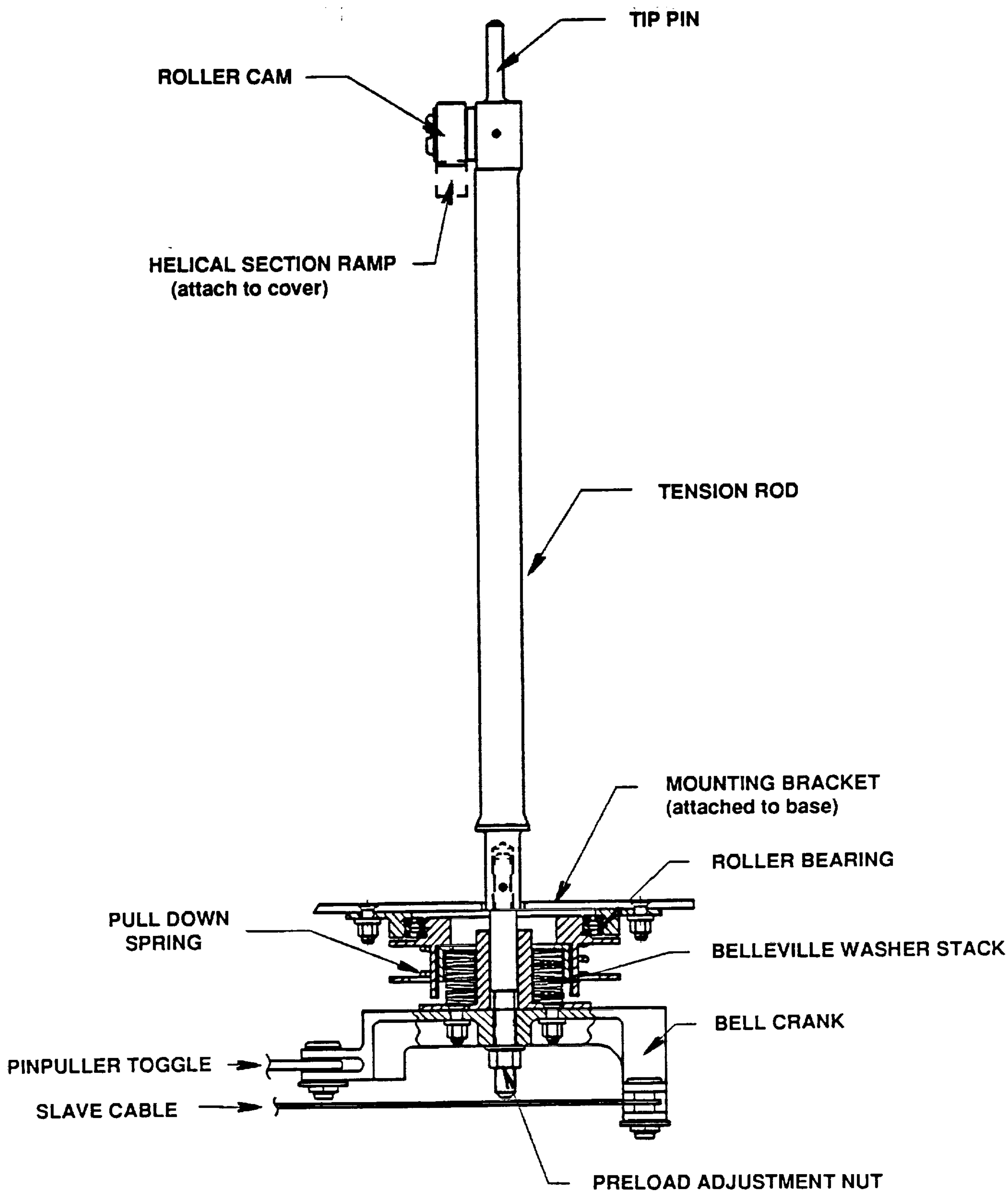


FIGURE 4: PRELOAD/RELEASE MECHANISM

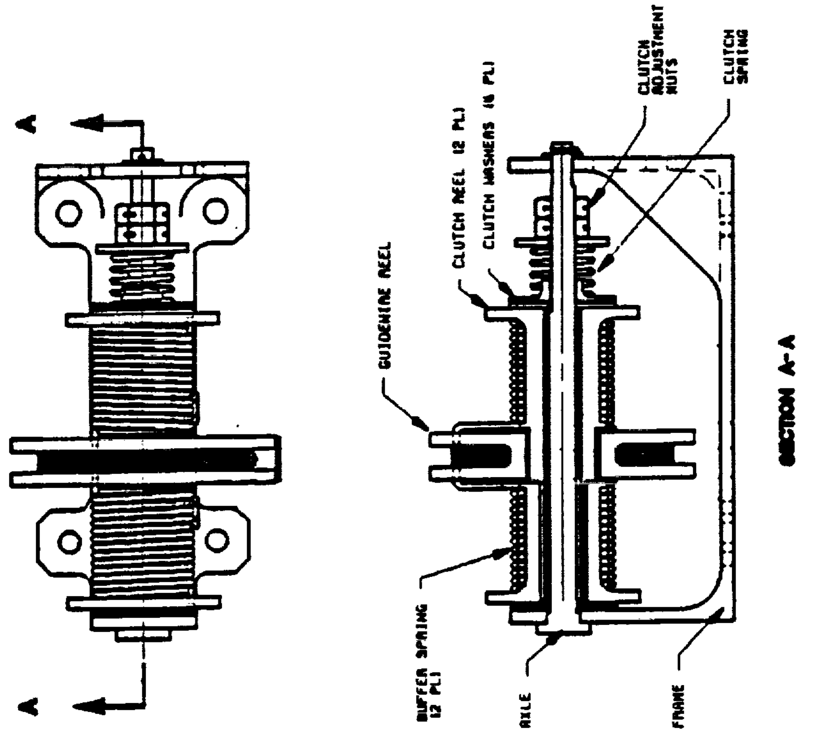


FIGURE 5: GUIDEWIRE TENSION MECHANISM

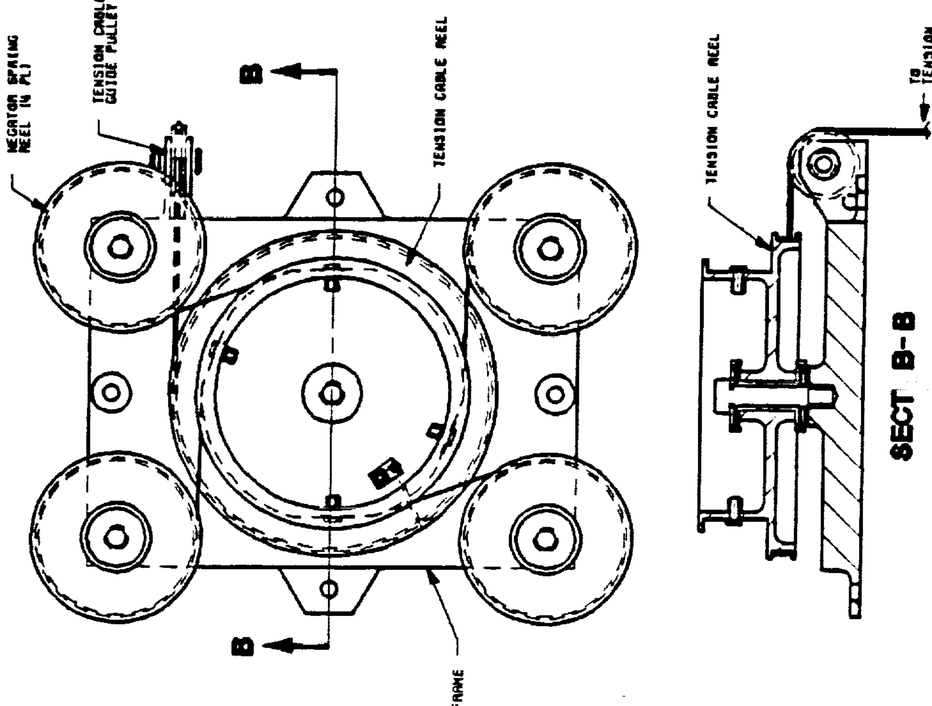


FIGURE 6: BLANKET TENSION MECHANISM

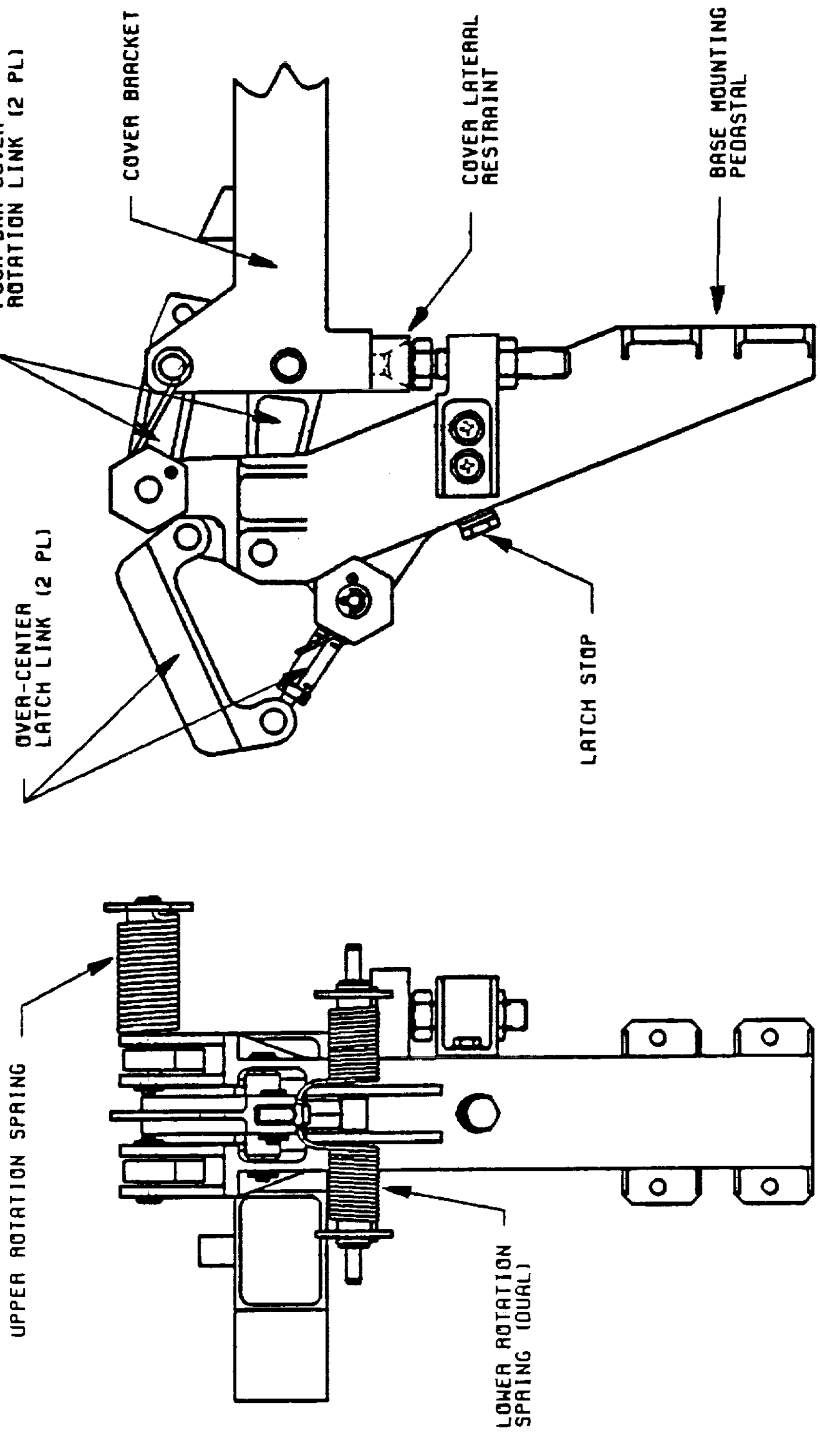


FIGURE 7: COVER ROTATION MECHANISM

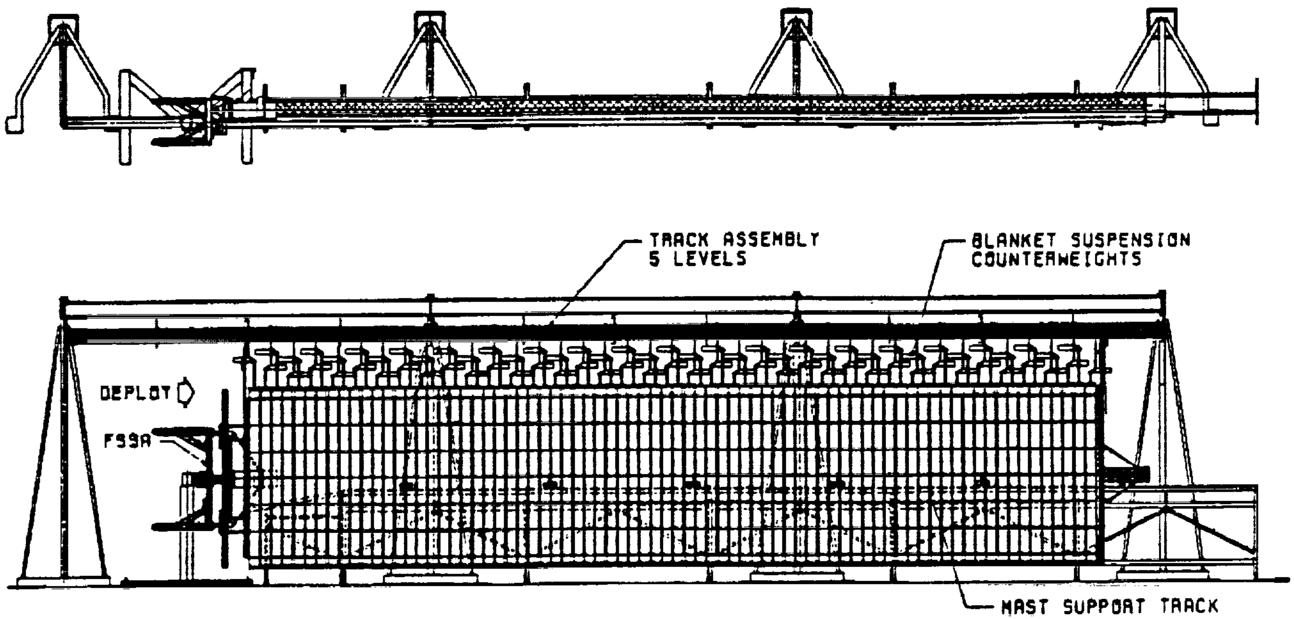
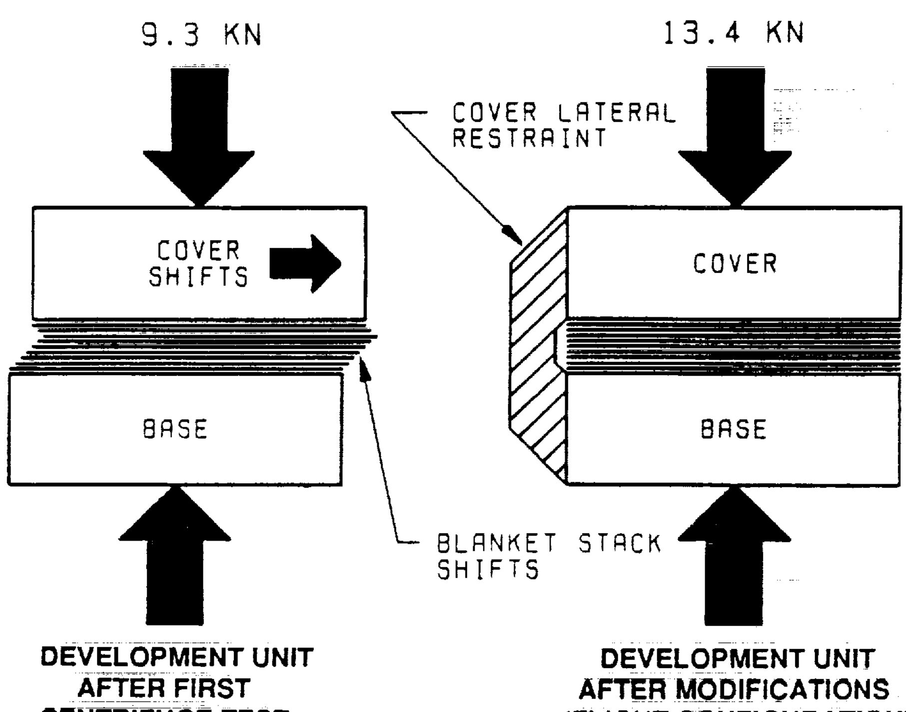


FIGURE 8: HORIZONTAL DEPLOYMENT GROUND TEST FIXTURE



DEVELOPMENT UNIT AFTER FIRST CENTRIFUGE TEST

DEVELOPMENT UNIT AFTER MODIFICATIONS (FLIGHT CONFIGURATION)

FIGURE 9: BLANKET PANEL SLIPPAGE