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# FLEXIBLE SOLAR-ARRAY MECHANISM

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## ABSTRACT

One of the key elements of the flexible rolled-up solar array system is a mechanism to deploy, retract, and store the flexible solar-cell arrays. The selection of components, the design of the mechanism assembly, and the tests that were performed are discussed in this paper. During 6 months in orbit, all mission objectives were satisfied, and inflight performance has shown good correlation with preflight analyses and tests.

## INTRODUCTION

Several advanced space-technology experiments were placed in a circular orbit on October 17, 1971. One of these experiments was a flexible rolled-up solar array (FRUSA) (fig. 1). This unique, self-contained power system consisted of the following components.

1. A pair of drum-mounted, 4.88- by 1.68-meter (16 by 5-1/2 foot), extendible/retractable, flexible solar-cell arrays

2. An orientation mechanism and control that maintains the array in a sun-pointing attitude

3. A power conditioning and storage subsystem to provide regulated ac and dc voltages, to control battery charging, and to furnish housekeeping power before deployment and during eclipses

4. An instrumentation system to monitor structural, thermal, and system performance

The objectives of the FRUSA experiment were the following.

1. Demonstrate solar-array-assembly deployment and flexible-solar-cell-array extension and retraction in an orbital environment for a 1.5-kilowatt system

2. Demonstrate solar-array-assembly tracking and lockon performance in an orbital environment

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3. Demonstrate power-generation capability in an orbital environment for a period of up to 1 year

4. Verify dynamic behavior of the array system

5. Provide reference measurements with calibrated solar cells and modules

The subject of this paper is the development, qualification, and flight performance of the drum mechanism of the FRUSA system. The drum mechanism is a key unit used to deploy, retract, and store the flexible solar panels.

## DRUM-MECHANISM REQUIREMENTS

The drum mechanism is required to perform the following functions.

1. Store the solar arrays during the launch phase of the mission and during any retracted mode of operation

2. Extend and retract the solar-array panels in orbit

3. Provide equal tension across the width of the panel during extension and retraction and during fully extended operation

4. Transfer electrical power between the solar panels and the spacecraft

The mechanism must perform the functions in accordance with the following conditions.

1. Boost environment: 19.5g root mean square broadband random plus up to 8g sinusoidal

2. Flight dynamic environment: 0.1 g

3. Orbit environment: 1 year at 643.6 kilometers (400 miles) to synchronous altitude

4. Extension/retraction cycles
   In orbit: 10 cycles
   Ground test: 25 cycles

5. Array-storage-volume goal: 2 $ft^3$/kW

6. Power output: 1.5 kilowatts at synchronous altitude

7. Weight goal (including panel): 15.88 kg/kW (35 lb/kW)

## MECHANISM DESCRIPTION

The drum mechanism, shown with the solar panels in figure 2 and with the parts identified in figure 3, consists of several major elements. The elements include an extendible-boom-actuator unit, a boom-length-compensator mechanism, a storage-drum assembly, a panel-tension drive, and power- and data-transfer assemblies.

### Extendible-Boom-Actuator Unit

The boom-actuator unit, shown in figure 4 with a shortened torque tube, is a completely dry-lubricated device consisting of two actuators that store and form the 2.18-centimeter-diameter (0.86 inch diameter) stainless-steel Bi-Stem booms; a single 115-V ac, 400-hertz motor/gearhead to extend and retract booms; and an interconnecting torque tube between master and slave units to allow for a single motor drive unit.

Each of the four booms is approximately 4.88 meters (16 feet) long and deploys at a rate of approximately 1.27 cm/sec (0.5 in/sec). Microswitches are employed to indicate full extension or retraction. A strain-gage installation is built into one of the boom guidance assemblies to measure boom bending.

### Boom-Length-Compensator Mechanism

The boom-length-compensator mechanism (fig. 5) is used to ensure uniform tension on the solar panels in the event of uneven extension or retraction of the individual booms. This unevenness can develop because the extension rates of the individual booms are different (as a result of lost motion and friction within the actuator) or because each of the two panels extends to a different length (as a result of the dual-panel/single-drum design). Although the latter problem can be partially resolved by the use of different length booms on each side of the drum, exact compensation is difficult because of the variations in the effective thicknesses of the panel and cushion. The lost motion and friction variations within the cassettes could be corrected by sprocket drives, servo systems, and so forth. Because these approaches all involved complex modifications to existing flight-proven boom designs, the decision was made to compensate for the differences in boom lengths by designing a mechanism on the boom tips.

In the mechanism design, dry-lubricated ball bearings are used in the pulleys and rollers. A cobalt-alloy (Elgiloy or Havar) tape is used between the boom tips. Calibrated strain gages on the tape provide a direct readout of tension in the solar panels.

### Storage-Drum Assembly

A thin-wall magnesium cylinder, 20.32 centimeters (8 inches) in diameter and 177.80 centimeters (70 inches) long, is used for the storage drum. The end plates are a titanium/aluminum honeycomb structure.

The bearings used in the storage drum are as follows.

1. Type: angular contact
2. Material: 440C stainless steel
3. Bore: 5.8730 to 5.8738 centimeters (2.3122 to 2.3125 inches)
4. Lubrication: burnished molybdenum sulfide ($MoS_2$) plus Duroid 5813 retainer
5. Preload: 35.58 to 53.38 newtons (8 to 12 pounds)

The installation shown in figure 6 was designed to provide low torque operation over the expected temperature ranges, with temperature differentials between housing/shaft and inboard/outboard bearing pairs. Axial differential expansion is accommodated by allowing one pair of bearings complete axial freedom. In the case of differential temperatures between the inner and outer races of particular pairs, a combination of wavy washer springs and matched materials for housing, shaft, and bearings is used.

## Panel-Tension Drive

A constant-torque Negator spring drive is used to provide tension on the panels during extension and retraction. The Negator spring is a coiled stainless-steel band wound on spools to produce a torque essentially constant over the entire travel range. However, because of the changing radii in the drum and Negator spools, the tape is modified by contouring. The contouring consists of varying the tape width with length to produce a slightly negative spring constant. Total two-panel tension provided by this drive arrangement over the entire travel and temperature range was 44.48 ± 11.12 newtons (10 ± 2.5 pounds).

## Panel-Cushion Takeup Drive

The cushion required to protect the solar cells in the stowed condition, particularly during launch, is made of embossed Kapton. The function of the cushion takeup is to roll up and store the cushion when the panels are deployed and to deploy the cushion between the two panels during the retraction cycle. The cushion tension provided by this drive is between 4.448 and 11.12 newtons (1 and 2.5 pounds).

The system chosen for this task is a Negator motor drive operating directly on the takeup reel, independent of the storage drum. As in the case of the panel-tension drive, this motor is a coiled metal band wound on spools to produce a torque essentially constant over the entire travel range. It was selected over a dc or ac motor and pulley drive for this function primarily because of its simplicity, low cost, low weight, and high reliability.

## Power- and Data-Transfer Assemblies

Transfer of power and data signals within the storage drum is accomplished by means of flexible flat cables. These cables employ copper conductors with $2.54 \times 10^{-5}$-meter (1 mil) Kapton insulation. Transition to conventional round wires is made at the hub of the drum to allow use of conventional connectors at the spacecraft interface. For the power cables, a printed circuit board is used as an interface with the panel-wiring bus (fig. 7). The data cable at the opposite end of the drum is soldered directly to the flat solar-panel conductors. The cables are wound up on the center spar of the drum when the panels are fully retracted. As the panels extend, the cables unwind and then rewind in the opposite direction. This feature permits shorter cable lengths and, therefore, lower power losses.

An extensive tradeoff study was performed to evaluate this system with respect to a slipring/brush arrangement. The final results of this study are summarized in table I.

# COMPONENT-EVALUATION TESTS

The component-evaluation phase of the program included functional and environmental tests of boom-actuator units; bearing, Negator, and flexible-cable installation; and the boom-length-compensator mechanism.

## Boom-Actuator Units

An engineering model of the boom actuator was subjected to the following series of functional and environmental tests.

1. Sinusoidal vibration tests
2. Thermal extension/retraction tests
3. Boom synchronization, straightness, alinement, and bending evaluation
4. Boom-bending instrumentation calibration

A single-boom breadboard model of the actuator unit was also built and subjected to a life-test program. This program consisted of 314 extensions and retractions under ambient conditions with simulated tip loading. The successful demonstration of 314 cycles represents a capability to perform 35 cycles (25 on ground and 10 in orbit) with a 90-percent confidence level.

## Bearing, Negator, and Flexible-Cable Development Tests

The development program on the drum bearings, panel-tension drive, flexible cable, and cushion reel drive was conducted in a dry-nitrogen environment and included the following conditions.

1. Drum bearings at room temperature and at 172.04° and 383.15° K (-150° and 230° F)

2. Drum bearings and simulated flexible flat cable at room temperature and at 172.04° and 383.15° K (-150° and 230° F)

3. Cushion reel drive at room temperature

4. Complete system (drum bearings, drum drive, cushion reel drive, and flexible cable) at room temperature and at 172.04° and 383.15° K (-150° and 230° F)

5. Drum bearings with inner-race temperature 2.78° to 16.67° K (5° to 30° F) higher than outer races

The test results indicated adequate margins for all components tested when operating in the expected thermal environment. The significant results and conclusions were as follows.

1. Drum-bearing torque levels for essentially uniform temperature distribution (no temperature gradients between inner and outer race) were $0.15 \times 10^6$, $0.25 \times 10^6$, and $0.31 \times 10^6$ dyne-cm (0.13, 0.22, and 0.27 in/lb) per pair for room temperature, 172.04° K (-150° F) and 383.15° K (230° F), respectively.

2. Drum-bearing torque for the expected 5° to 10° differential between inner and outer races was approximately $0.23 \times 10^6$ dyne-cm (0.20 in/lb) per pair. For $\Delta T$ = 16.67° K (30° F), the torque was $0.39 \times 10^6$ dyne-cm (0.35 in/lb), still within the allowable limit of $1.13 \times 10^6$ dyne-cm (1 in/lb).

3. Flexible-cable torque levels, based on a simulated cable with representative Kapton/copper, were estimated to be approximately $2.26 \times 10^6$ dyne-cm (2.0 in/lb), maximum. This includes two pairs of data cables and two pairs of power cables at 172.04° K (-150° F).

4. Cushion tension, provided by cushion reel drive, would be between 4.45 and 11.12 newtons (1.0 and 2.5 pounds). The larger value corresponds to the empty-reel condition, in which the largest tension is required for proper rollup of the cushion.

5. Drum Negators, when contoured to compensate for changing drum diameters, would provide total panel-tension levels (two panels) between approximately 35.38 and 35.58 newtons (8 and 12 pounds) (fig. 8). Based on panel rollup tests and the allowable boom loads, this range of panel tension was considered acceptable.

A contoured Negator was subjected to more than 4450 cycles at room temperature before a bending-fatigue failure occurred. This number of cycles represents a large margin over the 2500-cycle vendor guarantee and the 35-cycle (10 flight and 25 preflight ground test) life required for the experiment. Measurements made after approximately 4000 cycles revealed no apparent change in the Negator torque characteristics over a typical cycle. These measurements also verified that the contouring operation achieved the features desired.

### Boom-Length-Compensator Development Tests

The development test program on the boom-length-compensator devices was performed at room temperature and at 188.70° and 408.15° K (-120° and 275° F). Results of the tests indicated the maximum difference between the panel tension from one edge to the other was less than 4.45 newtons (1 pound). This value was considered well within the difference allowable for satisfactory rollup of the flexible arrays.

## ASSEMBLY ENGINEERING AND QUALIFICATION TESTS

Functional engineering tests of the drum mechanism with a solar panel were performed on a water-table-deployment installation (figs. 9 and 10). A total of 20 complete cycles were run with the following data and information obtained.

1. Motion-picture coverage at various locations to evaluate deployment characteristics of booms, panel, and so forth

2. Qualitative data on panel and cushion rollup features

3. Specific information on size, number of turns, and so forth, for panel drum and cushion reel

4. Operation of 400-hertz drive electronics with boom-actuator motor

5. Evaluation of water-table and float-insertion procedures

6. Static measurements of boom synchronization

The system operated well with no significant design changes required. The following were specific observations on the functional performance.

1. Boom synchronization appeared to be good, with less than ±5.08 centimeters (±2 inches) differential.

2. Cushion and panel windup was satisfactory, with only a small amount of lateral translation or "walking" noted during panel windup.

3. Float insertion and water-table operation was quite smooth, with only minor changes required in the table or procedure.

4. Operation of limit switches in boom-actuator unit was not proper, and redesign was initiated.

5. Booms had a tendency to self-extend approximately 15.24 centimeters (6 inches) after full retraction. To prevent a possible oscillatory mode, a slight modification in motor-drive electronics was incorporated.

The qualification model of the drum mechanisms was subjected to functional tests, solar thermal-vacuum tests, and the launch environments as indicated in table II. No major failures were observed during exposure to the environmental tests.

## FLIGHT TESTS

On the ninth vehicle orbit, the solar panels of the FRUSA system were deployed by the drum mechanism. Because array extension on the ground was influenced by the water-table/float system and gravity, this rollout provided the first real demonstration of the zero-g mechanical and dynamic performance of the drum-mechanism design. The accelerometers mounted on the boom tips recorded the data shown in table III during the extension. The start of the extension saturated the accelerometers with sensitive axes (u, w) in the plane of the panel. During rollout to the fully extended panel length of 4.88 meters (16 feet), the accelerations averaged approximately 15 to 30 milli-g peak. Termination of the rollout did not generate any noticeable dynamic excitation.

The duration of the initial panel extension was 294 seconds, which agrees with the extension periods measured on the water table in ground testing. Actuator-motor current levels also were approximately the same as ground-test values. The nominal tension in each of the panels as monitored by the strain gages on the boom-length-compensator mechanism was approximately 26.24 newtons (5.9 pounds). This value at full extension agrees with the nominal setting of the panel tension as defined by ground testing.

The accelerometer data, along with the boom-bending instrumentation, revealed a boom/panel system fundamental frequency of approximately 0.25 Hz and an effective damping factor of approximately 2 percent. Analytical prediction of the first mode frequency was 0.20 Hz. Analysis of flight data to this point indicates that the system is exceptionally stable. No significant dynamic interaction with the Agena control system has been noted for either the active gas or the gravity gradient modes of operation.

A total of 10 complete extensions and retractions had been performed successfully by the beginning of 1972. Several extension/retraction cycles were performed during eclipse conditions in which drum temperatures reach 233.15° K (-40° F) and the panel temperatures go as low as 188.70° K (-120° F). No measurable degradation in solar-panel power output was observed after the 10 cycles.

## CONCLUDING REMARKS

The successful operation of the drum mechanism on the flexible rolled-up solar array experiment aided in demonstrating the feasibility of the system. In addition, the agreement between analysis and ground tests and orbital dynamic performance enhances the confidence in the design approach and techniques for larger and more advanced power systems using this concept.

TABLE I. - COMPARISON OF SLIPRINGS AND FLEXIBLE CABLE

FOR 1500-WATT SYSTEM

| Parameter | Flexible cable | Slipring/brush arrangement | Difference |
|---|---|---|---|
| Weight | [a]0.15 kg (0.34 lb) | [a]0.68 kg (1.50 lb) | [a]-0.53 kg (-1.16 lb) |
| Reliability | Higher | Lower | -- |
| Voltage drop | .22 V | .11 V | +0.11 V |
| Power loss | 11.5 W (0.77 percent of total) | 5.75 W | +5.75 W |
| Torque about drum axis | Lower | Higher | -- |
| Growth factor | Equal | Equal | -- |

[a]Includes cells necessary to compensate for larger power loss.

TABLE III. - DRUM-MECHANISM EXTENSION DYNAMICS

| Acceleration sensing axis | Peak accelerations, milli-g | | |
| --- | --- | --- | --- |
| | Start of extension | During extension | End of extension |
| U direction | (Saturated) | 59.1 | 18.3 |
| V direction | 70.4 | 32.2 | 23.5 |
| W direction | (Saturated) | 27.0 | 13.9 |

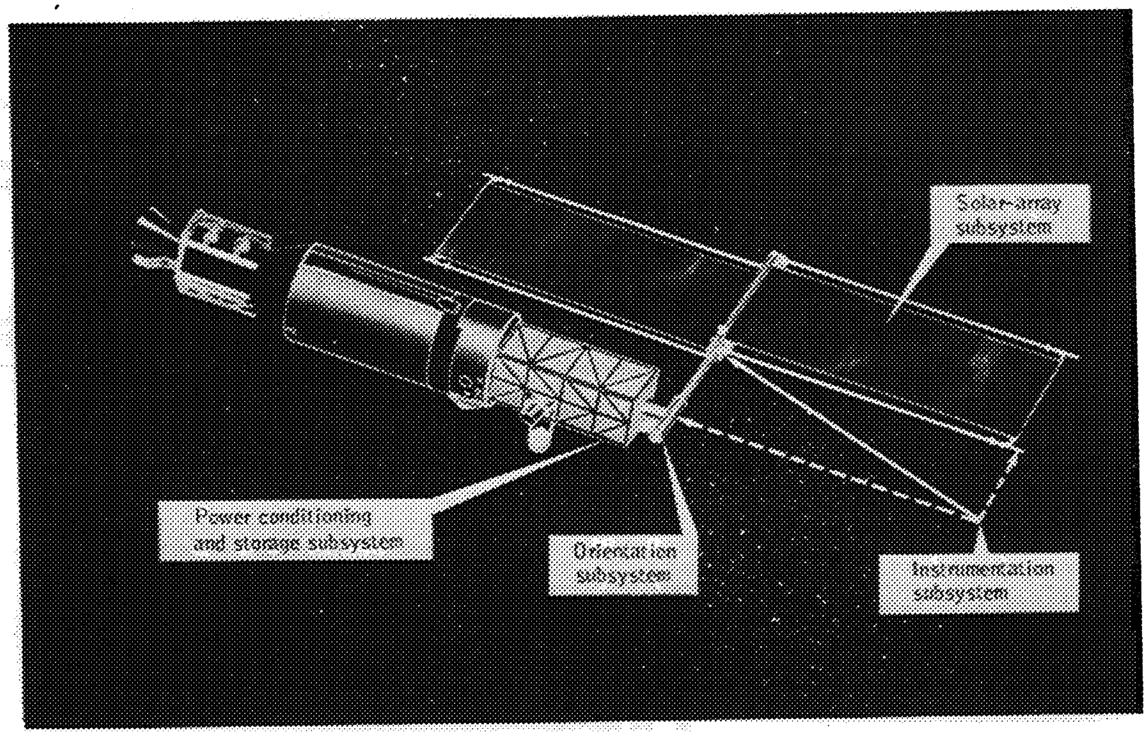


Figure 1. - The FRUSA system.

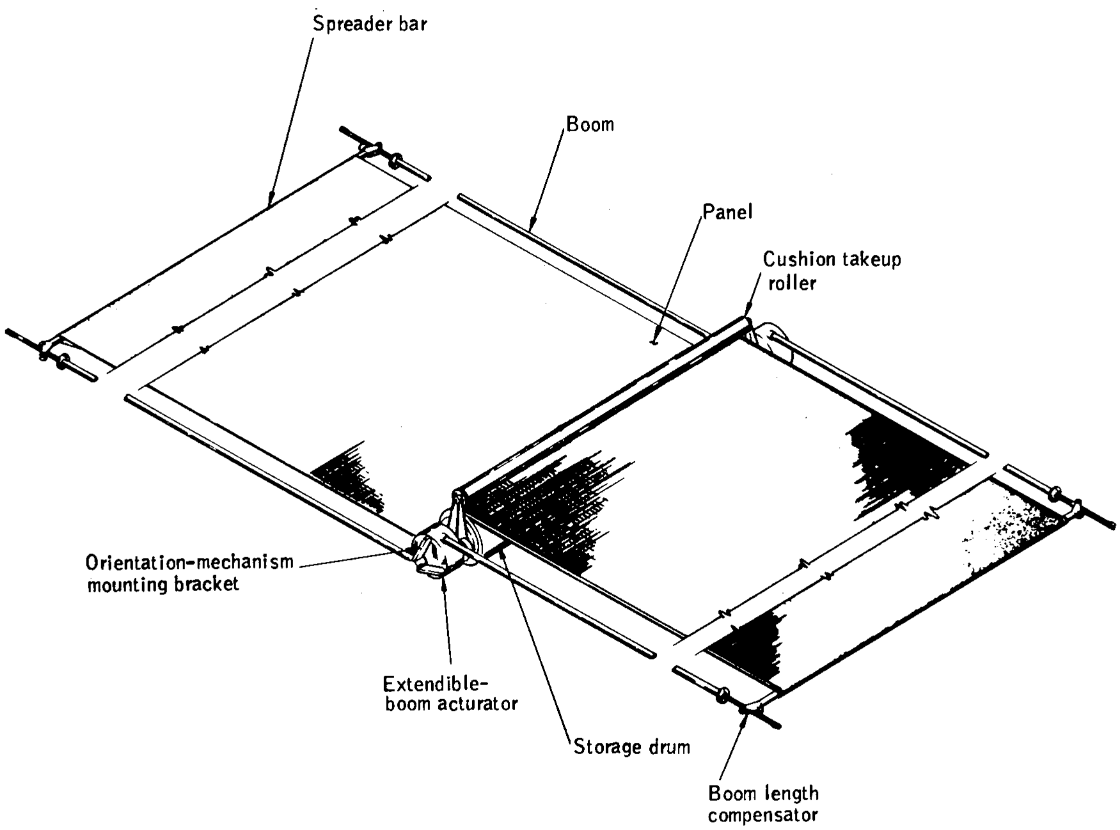


Figure 2. - Drum mechanism and solar panels.

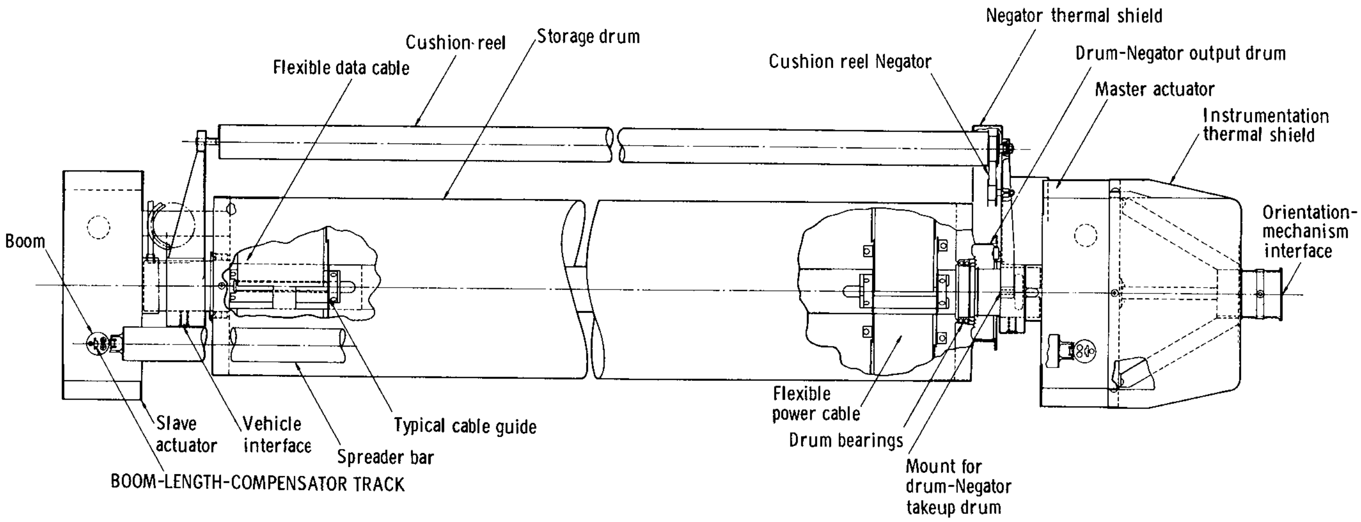


Figure 3. - Drum-mechanism details.

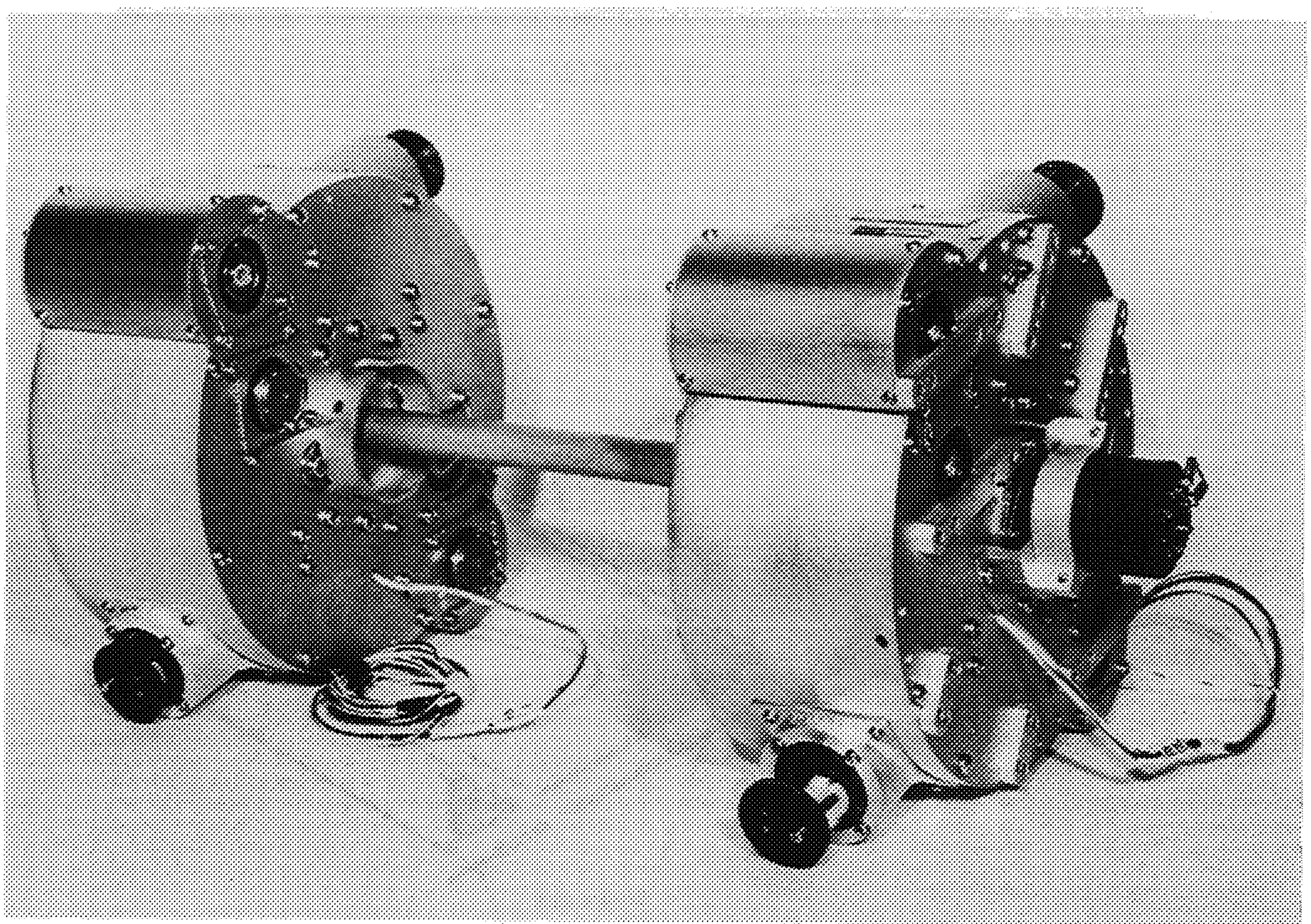

Figure 4. - Extendible-boom-actuator unit.

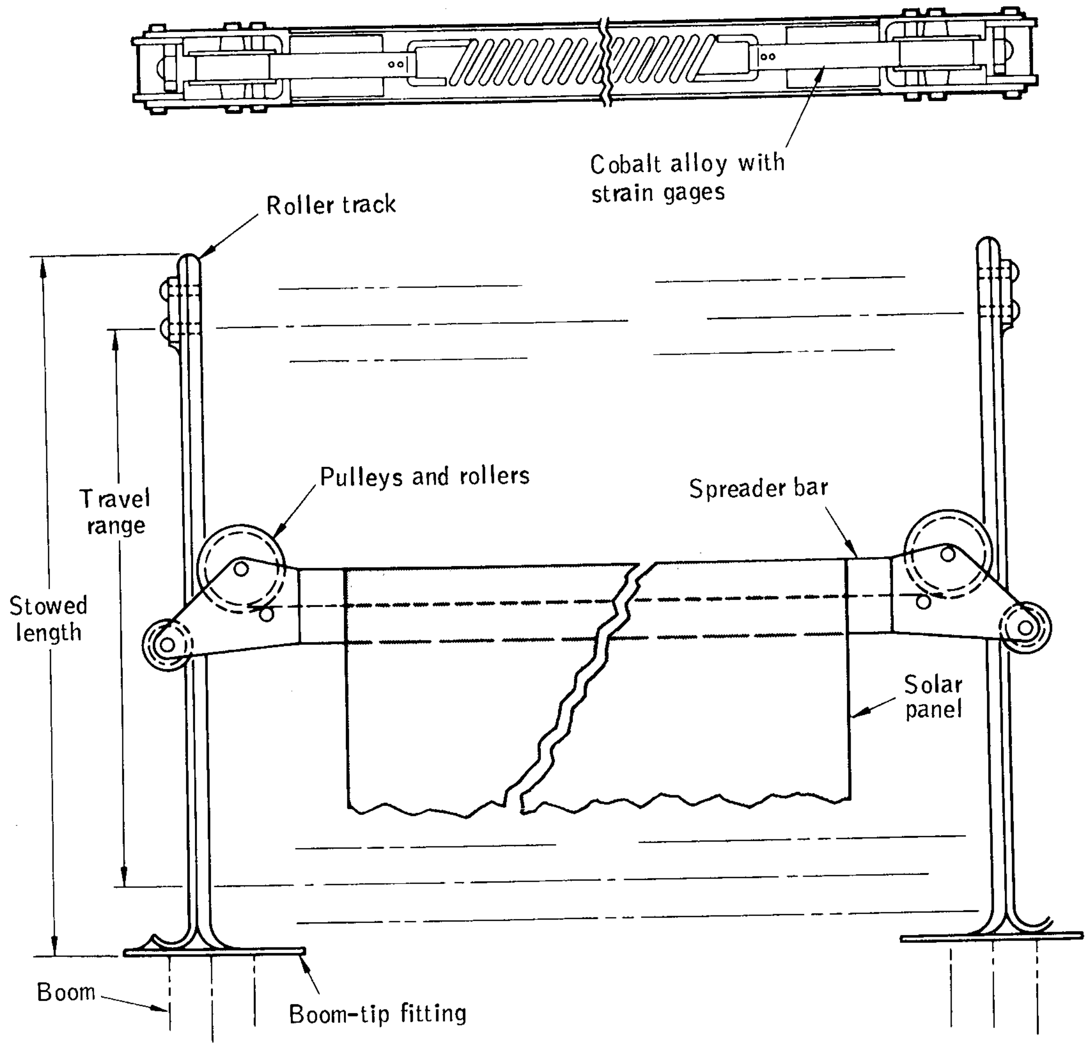


Figure 5. - Boom-length compensator.

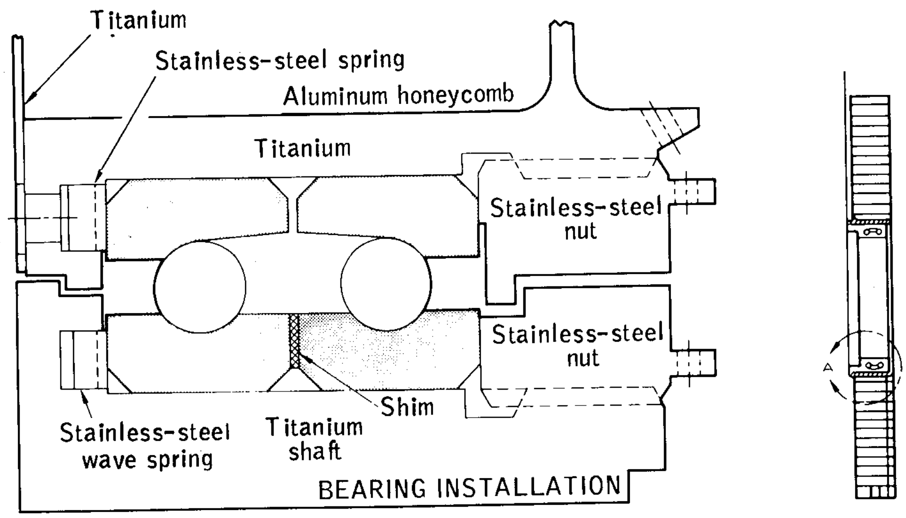


Figure 6. - Drum end plate and bearing installation.

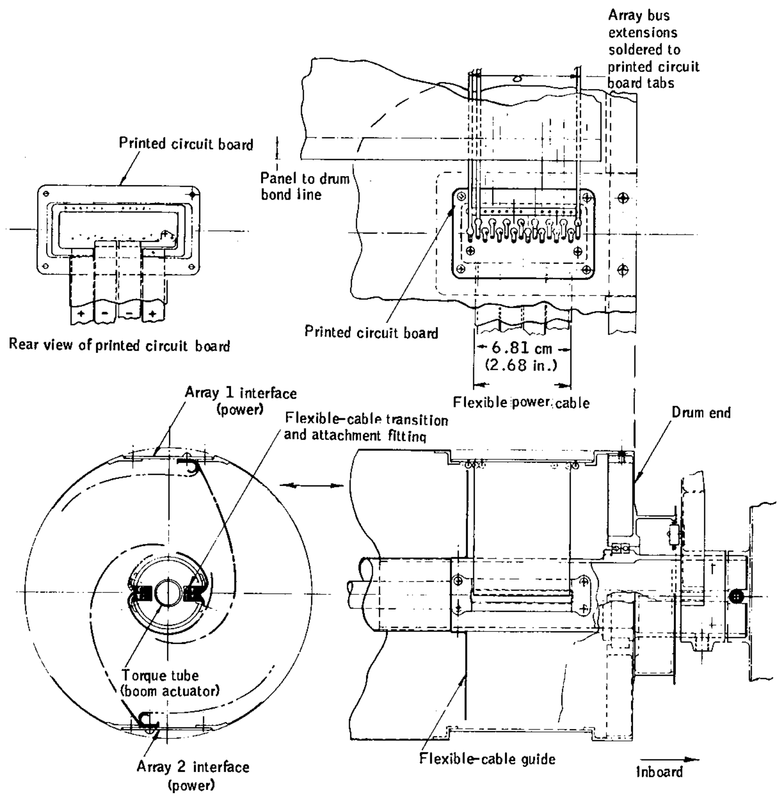


Figure 7. - Flexible-power-cable arrangement.

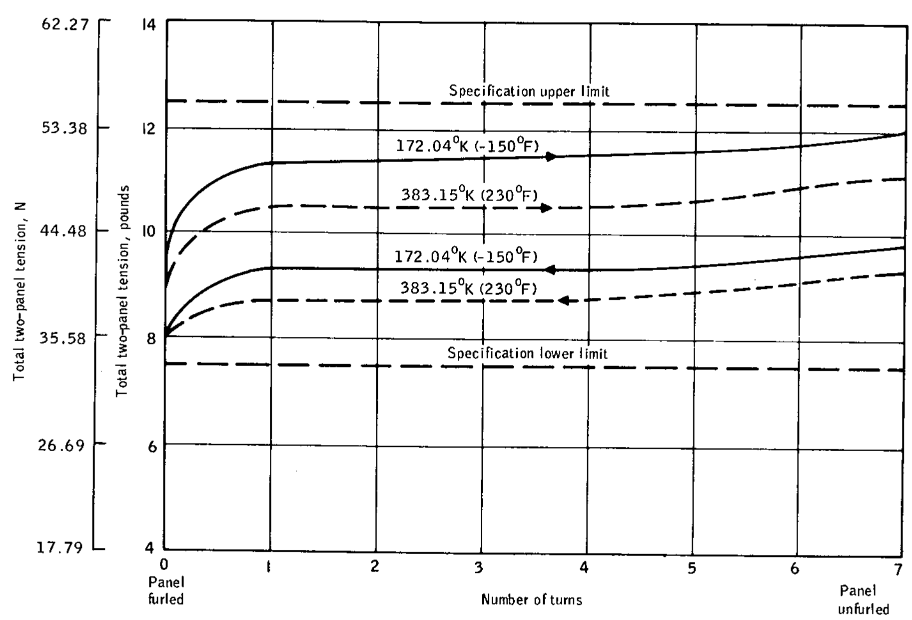


Figure 8. - Estimated average two-panel tension based on development test data.

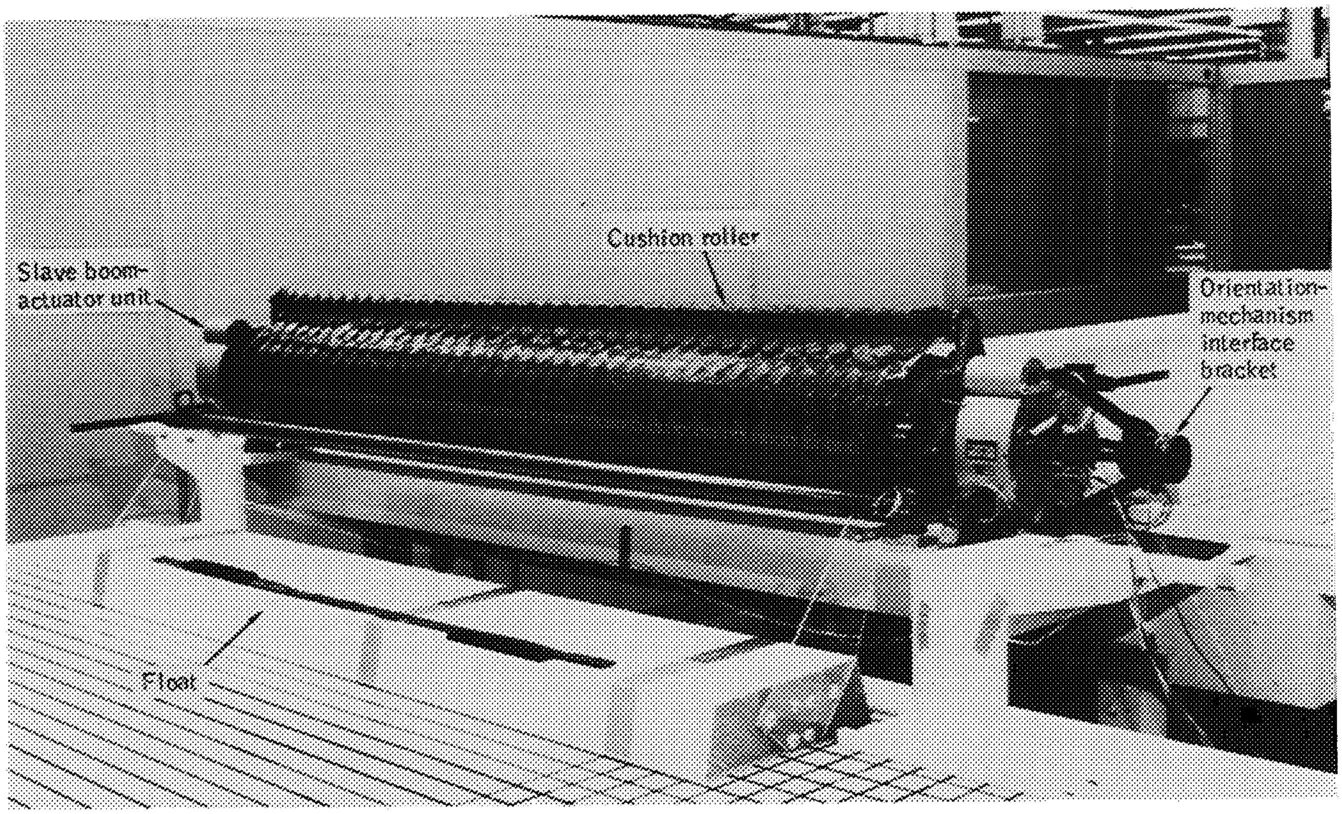


Figure 9. - Drum mechanism and panels mounted on water table for engineering tests.

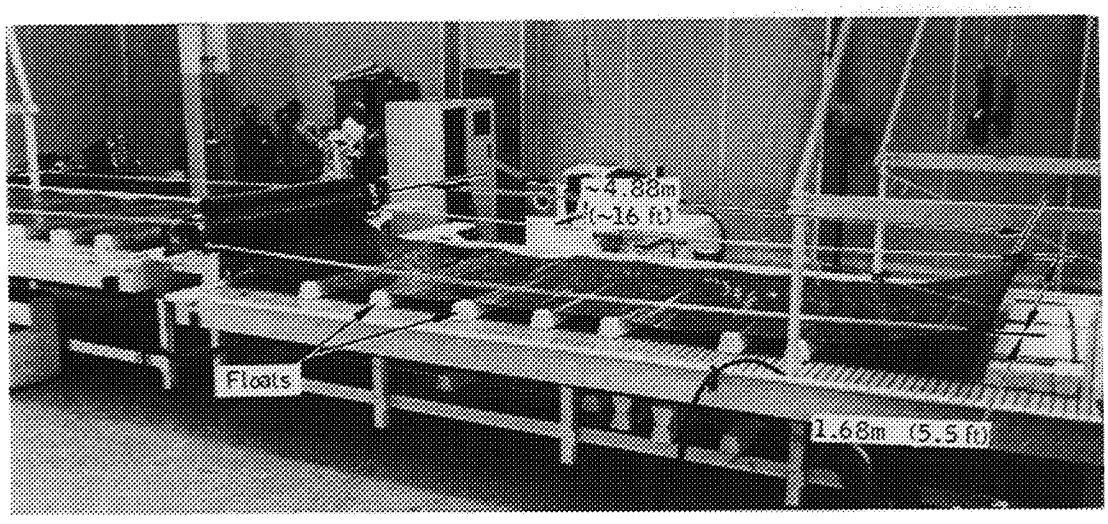


Figure 10. - Drum mechanism and panels deployed on water table.