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CONCEPTUAL DESIGN AND STRUCTURAL MODEL OF A 560-WATT THIN-FILM SOLAR-CELL ARRAY

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16. Abstract

A structural model of a cadmium sulfide thin-film solar-cell array was constructed with a deployment structure weight of 0.12 lb/sq ft (0.59 kg/m^2) of panel area and a projected power output of from 15.5 to 19.4 W/lb (34.2 to 42.7 W/kg) using available CdS solar cells. The rollout, nonretractable array used a 40-ft (12.2-m) long storable boom as the basic structural element. The boom stiffness was tested using two simple mechanical suspensions.

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SUMMARY

A structural model of a cadmium sulfide thin-film solar-cell array was constructed. To deploy and support the active array area of 188 square feet (17.5 m^2) required a structural weight, less solar-cell panels, of 22.7 pounds (10.3 kg) or 0.12 pound per square foot (0.59 kg/m^2). The complete rollout, nonretractable array would have an initial air mass zero, 60° C output of 560 watts or 15.5 watts per pound (34.2 W/kg) using present average production cells. If the best present production cells could be used, the array output would be about 700 watts or 19.4 watts per pound (42.7 W/kg). The lowest natural frequency of the array (transverse vibration) was estimated to be 0.09 hertz and the deployable boom used to support the array had a column load capacity almost three times the required value.

INTRODUCTION

Past work at the Lewis Research Center has demonstrated the feasibility of fabricating large area solar arrays using cadmium sulfide (CdS) thin-film solar cells (ref. 1). In reference 1, Brandhorst and Spakowski concluded that to produce a $\widetilde{20}$ watt per pound (44.1 W/kg) power system using available thin-film cells would require an array extension mechanism weight of less than 0.14 pound per square foot (0.68 kg/m^2). During 1967, the Lewis array effort was expanded to develop a conceptual design and model of a flight-type thin-film solar array with the purpose of defining the actual mechanism weight required for such an array. The project was also expected to define other important problem areas of thin-film array design and provide experience in testing large, flexible array segments on the ground.

It was decided to develop a concept for a 500-watt array which would constitute one-half of a nominal 1000-watt-array system (see fig. 1). The Agena space vehicle was

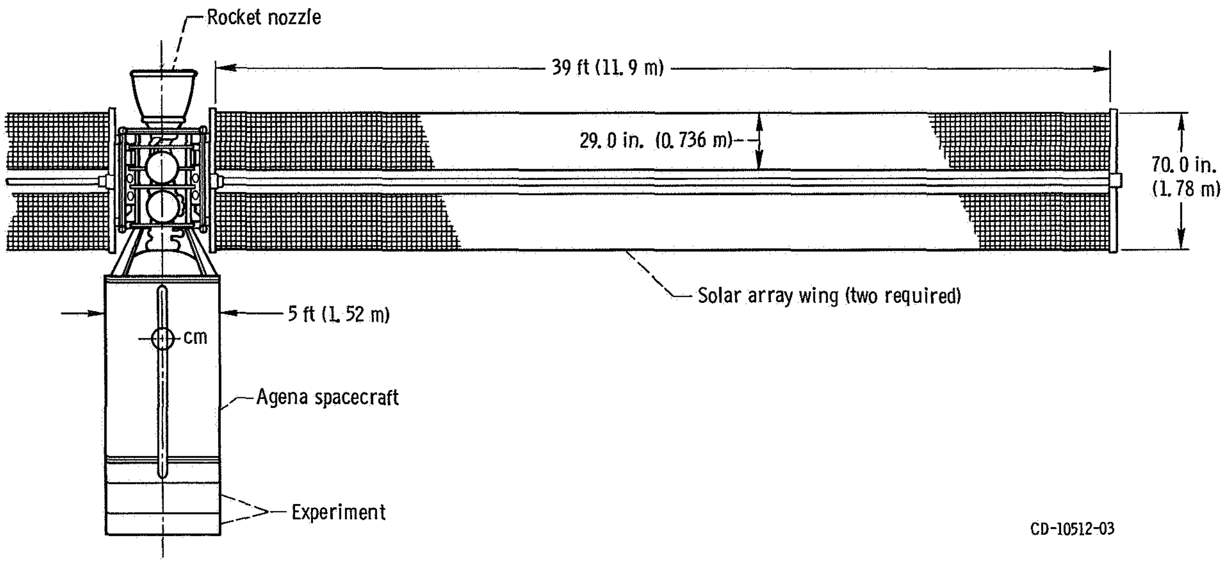

Figure 1. - 1000-Watt, thin-film cadmium sulfide solar-cell array (500 W per wing).

used as a guide to establish general ground rules for the model array but no exhaustive effort was made to define and solve the many vehicle-array interface problems that would be encountered in flight. The work concentrated on the structural problems of array design with only minimum consideration of electrical requirements.

This report first surveys the general design constraints used to define the array configuration. The resulting structural design and model are then described and some structural characteristics are presented.

GENERAL DESIGN BASIS

The mission base for the array design was the SERT II (Space Electric Rocket Test) flight test, which is planned to demonstrate the operating life and operational feasibility of ion thrusters. The SERT system consists of a thruster, a 1.5-kilowatt silicon solar-cell array, power conditioning, propellant storage and feed, and a control system. The Agena vehicle serves both as a second-stage (Thor first-stage) launch vehicle and as the orbital spacecraft for the mission. The launch vehicle will inject the spacecraft, from the Western Test Range, into a near polar circular orbit of 500 nautical miles (926 km) altitude. Gravity gradient stabilization will provide attitude control of two axes and control moment gyros will provide control of the third axis and damping for all axes. Cold gas attitude control thrusters will also be used.

The SERT mission characteristics were used essentially as a design tool to help make the thin-film CdS array design as realistic as feasible for the limited effort involved. In general, only light treatment was given to the complex area of array-vehicle interface. Various mission peculiar characteristics of the spacecraft influenced the array design as follows:

(1) Since the mission required no array orientation relative to the spacecraft, the array was designed for a simple static mount to the Agena aft equipment rack.

(2) The problem of transferring electrical power across a rotating joint was circumvented by mounting the storage roller on the outboard end of the deployment boom which permitted the inboard end of the array with electrical connections to be statically fixed to the vehicle end of the structure.

(3) The SERT II mission is characterized by a low orbital acceleration level which permitted the highly flexible array structure to be designed for deployment only, with no provision for retraction during orbital spacecraft maneuvers.

The photovoltaic cell used as a basis for this array design is a commercially available 3- by 3-inch (0.076- by 0.076-m) CdS cell (see ref. 1). Modules of 25 cells each were made. Figure 2 shows one such module in a flat position and another module rolled into a small cylinder to illustrate its roll storage capability. Details of the fabrication and testing of these modules are presented in reference 2 and will not be discussed here. However, table I summarizes the array-related module characteristics used to estimate the model array performance.

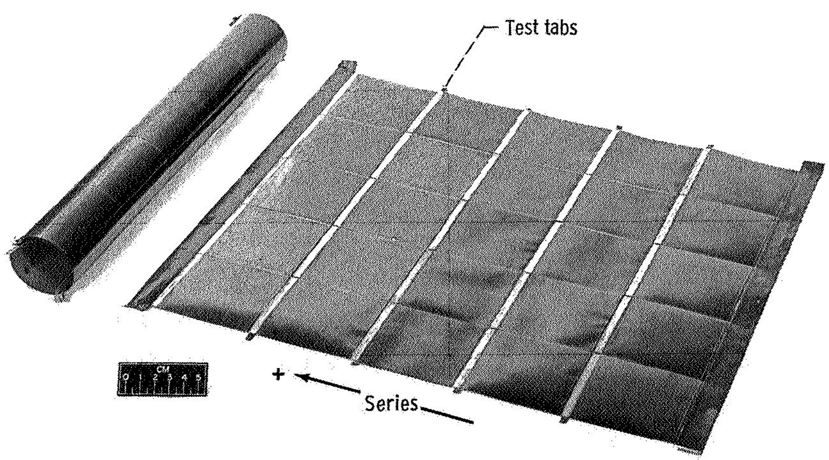

Figure 2. - Cadmium sulfide thin-film solar-cell module (25 cells) pictured flat and rolled on a 2-inch (0.0508-m-) diameter.

TABLE I. - SOLAR-CELL MODULE CHARACTERISTICS

[Plastic substrate cadmium sulfide solar cell. Nominal dimensions, 3 by 3 in. (7.6 by 7.6 cm).]

Number of cells per module	25
Cells in series	5
Cells in parallel	5
Module dimensions:	
Width, in.; m	14.5; 0.368
Length (in array), in.; m	16.7; 0.424
Module area (in array), ft^2; m^2	1.68; 0.156
Module weight (in array), lb; kg	0.120; 0.0545
Assumed module output (AMO; 60° C):	
Watts	5.0
Amperes	2.7
Volts	1.85
Module power density, W/ft^2; W/m^2	2.98; 32.1
Module specific power, W/lb; W/kg	41.6; 91.7

MODEL STRUCTURE

Deployment Boom

Figure 3 shows the solar array actuator boom. The actuator belongs to a class of mechanisms that provide a long, slender structural member capable of exceptionally compact storage (ref. 3). The familiar steel pocket tape measure is a specialized form of the mechanism. The actuator uses two thin-wall partial tubes, one nesting inside of the other, as shown in figure 3. In the stored condition, both partial tubes are flattened into tapes and rolled on a single storage drum in a stressed condition. The storage process is designed so that the yield strength of the tube material is never exceeded. When deployed, each tape relaxes to form a partly closed tube. The two partial tubes are nested with their slots 180° apart to form a closed tubular structural member. Since the actuator mechanisms have been described in detail in many technical publications (see ref. 3), this discussion will be limited to a few structural tests of special interest for the array model of this report.

Structural System

An exploded view of the model structure is shown in figure 4. In essence, the structure is a 5-inch (0.127-m) outside-diameter cylinder with a 5/8-inch- (0.0159-m-) thick

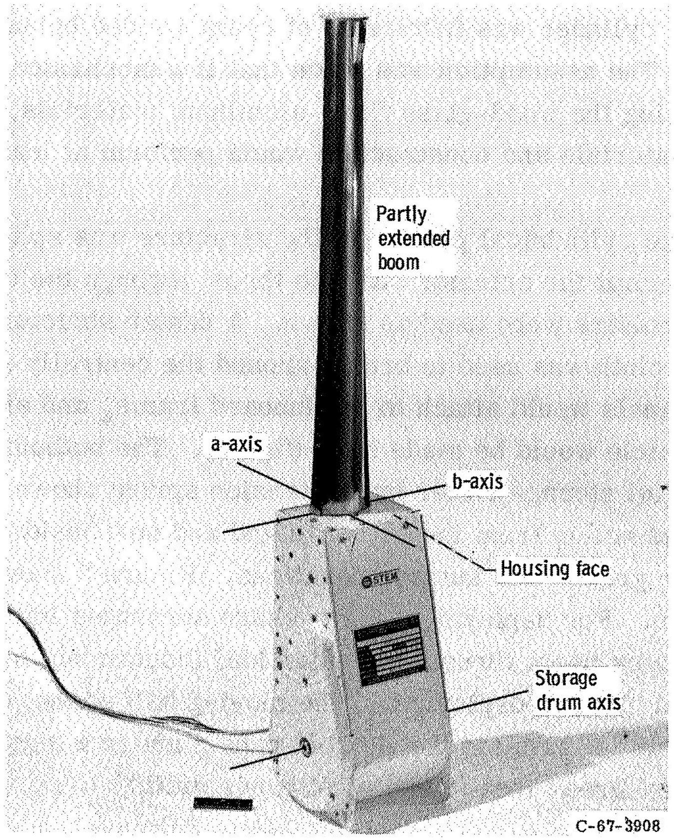

Figure 3. - Nominal 1.34-inch- (0.034-m-) diameter by 40-foot- (12.2-m-) long solar array actuator boom. Maximum dimension when retracted, 11.0 in. (0.279 m).

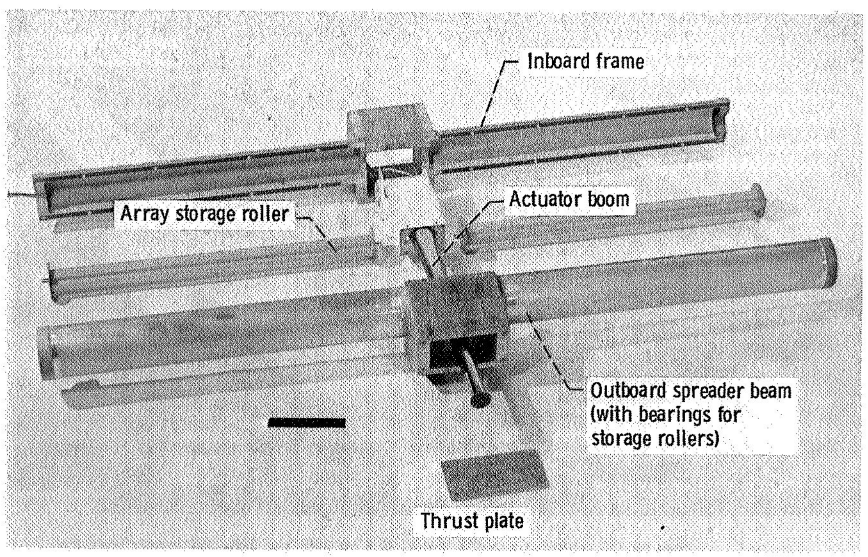

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Figure 4. - Exploded view of solar array model structure showing main components.

composite wall. This cylinder was fabricated of epoxy bonded balsa wood, fiberglass, and aluminum sheet. The assumption was made that if a mechanically acceptable structure could be made using the wood-glass fiber-aluminum materials, a flight structure of more sophisticated materials and construction would perform at least as well as the model structure.

In more detail, the cylindrical portion of the structure was split longitudinally into halves (fig. 4). To permit the actuator boom to thrust through the centerline of the panel storage rollers, two rollers were used as shown. A center structure of end-grain balsa blocks and fiberglass cloth was used to bridge around the centrally located actuator unit. The thin-film solar panels would attach to the inboard frame, and electrical connections between array and vehicle would be made here (fig. 5). The outboard end of the array would attach to the panel storage roller by the tension spring shown in detail in figure 6. Thus, the panels would rollup from the outboard end and nest inside the protective cylindrical structure for ground and launch operations. Figure 7 shows the model in the packaged configuration. For deployment the package separates into halves, as shown in figure 5, and the actuator boom thrusts the outer half (containing the rolled up panels) away from the vehicle. At full deployment, the moving half of the package forms the outboard spreader beam to maintain the flexible panels under a tension of about 5 pounds (22.2 N) or 1 pound per linear foot (15 N/m) of panel width.

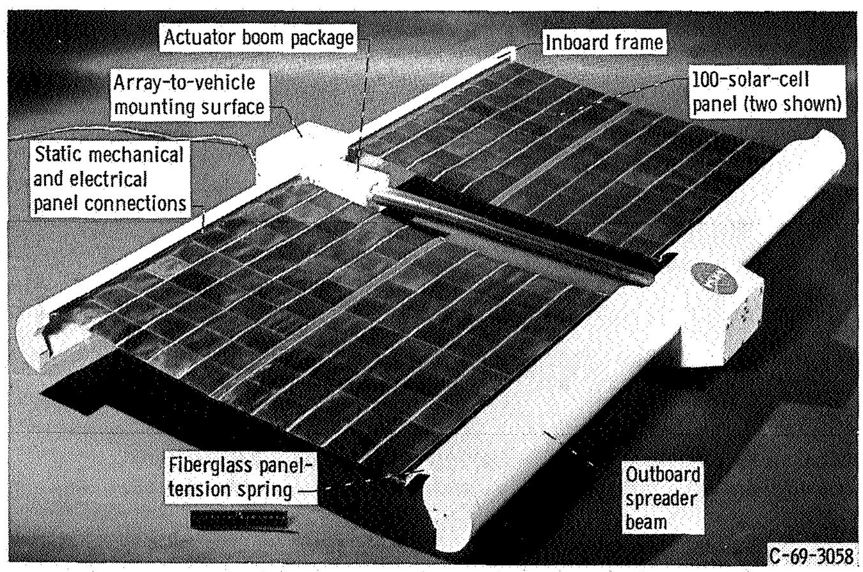

Figure 5. - Array model extended about 3 feet (0.915 m) with two 100-cell panels installed.

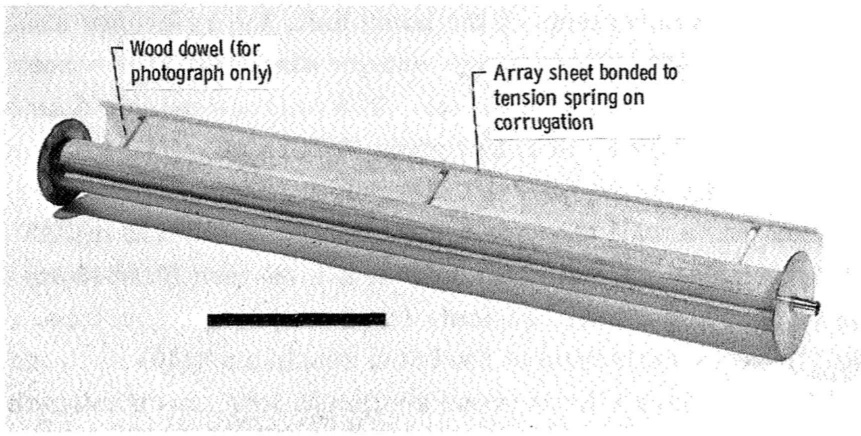

Figure 6. - Array storage roller, 2.0-inch (0.0508-m) outside-diameter by 30 inches (0.762 m) long, showing fiberglass panel tension spring.

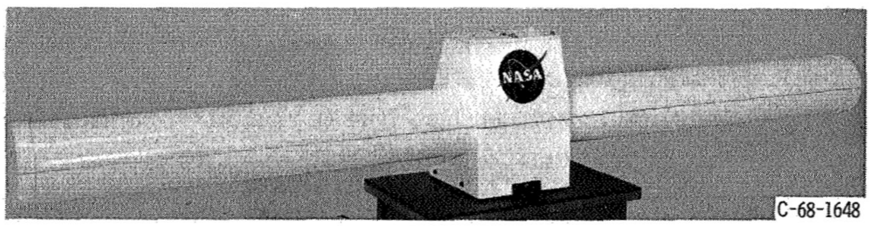

Figure 7. - Array model in packaged state. Length, 70.0 inches (1.78 m); volume, 1.07 cubic feet (0.0303 m^3); specific volume, 2.14 cubic feet per kilowatt (0.0606 m^3/kW).

Deployment Boom Tests

The model array was designed to be flattened in the deployed condition by the tension force mentioned in the previous section. Using the actuator boom as a long column an outward force is maintained on the outboard spreader beam. This restrains the array wing to a flat plane in the same way a bifilar instrument suspension (ref. 4) or a trapeze tends to return to a null position wherein all the tension members lie in a common plane. Thus, the column characteristics of the actuator boom are critical to the model. Also of interest, because of array-vehicle dynamic interaction, is the natural cantilever frequency of the array wings. This is a function of the boom stiffness and the distribution of the mass attached to the boom (ref. 5). Therefore, tests were performed to determine the column and beam characteristics of the actuator boom.

For the geometric measurements of the boom unit, the reference axis system illustrated in figure 3 was used. The average outside diameter D_a, perpendicular to the storage drum axis, is 1.37 inches (0.0348 m). The average outside diameter D_b, parallel to the storage drum axis, is 1.33 inches (0.0338 m). The average width of the longitudinal slot in the outer boom tube is 0.24 inch (0.0061 m). The type 301 stainless-steel boom tubes each has a wall thickness of 0.007 inch (0.000178 m). Thus, the deployed boom characteristics approximate those of a 1.35-inch (0.0343-m) outside diameter, 0.014-inch (0.000356-m) wall, 40-foot- (12.2-m-) long round tube. This approximation holds well until the deflection of the boom reaches a value such that local buckling of the partial tubes causes a local cross section to lose its circular shape. In the work reported here, the boom was never loaded to the point of local buckling.

One interesting characteristic of this specific boom type is that most of the length required for the transition from flat tape to fully nested partial tubes occurs outside of the storage package. This is an important factor in minimizing the storage package dimension parallel to the boom axis. For about the first 2 feet (0.61 m) from the housing face (fig. 3), the boom diameter is larger than the final free boom diameter. The maximum outside dimension of the boom parallel to the a-axis is 1.81 inches (0.046 m) located 4.5 inches (0.114 m) from the housing face. The maximum b-axis dimension, 2.4 inches (0.061 m), occurs at the housing face.

The cross section area moment of inertia I of the boom was calculated from its measured geometry and from its actual deflection characteristics under load. Using the cross section measurements, the average area moments of inertia about the a-axis I_a and about the b-axis I_b were calculated to be, respectively, 0.0128 inch^4 (0.532 cm^4) and 0.0120 inch^4 (0.499 cm^4). The lower value of I_b reflects the reduced area moment about the b-axis because of the longitudinal slots in the boom partial tubes.

Since the actuator boom is used as a column member in the subject array model, the boom's critical column load was of interest. Using the value of I_b computed in Euler's long column formula (for hinged-ended columns) yields a critical column load of 14.9 pounds (66.3 N). A test was set up to check the critical load experimentally, as shown in figure 8. The boom was supported at 4-foot (1.22-m) intervals with a wire-pulley-counterweight system. This system gave a crude simulation of zero gravity by allowing the boom tip to deflect horizontally by pendulum motion of the wires or in a vertical direction by the rise or fall of the suspension counterweights. This system had the weakness of suspension pulley friction in the vertical direction and pendulum restoring forces in the horizontal plane. However, by loading the boom in this system with two tension wires (figs. 8 and 10) the critical column load was estimated to be between

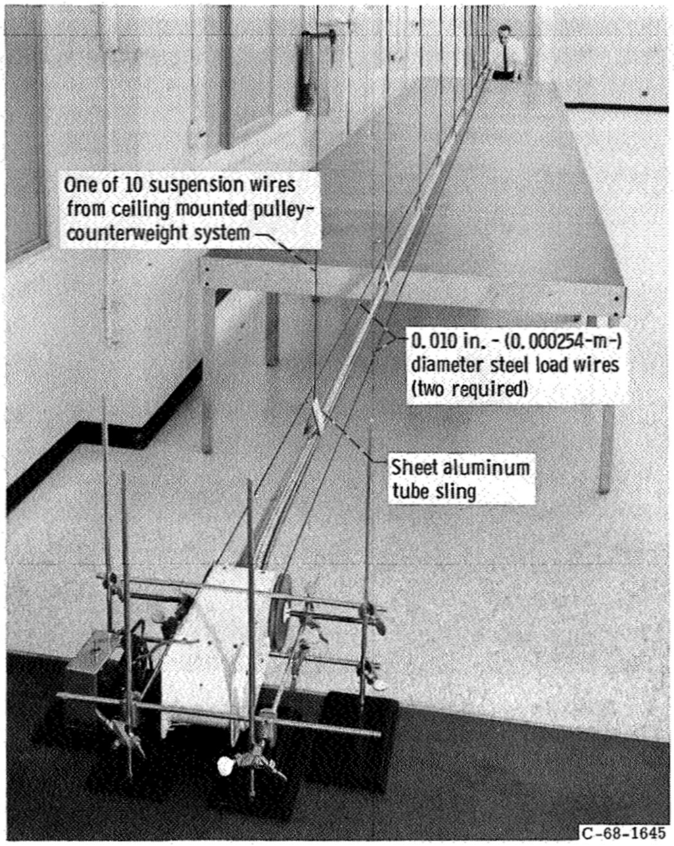

Figure 8. - Fully extended (40 ft or 12.2 m) actuator boom in counterweight (weights not shown) suspension system for critical-column-load test.

14 and 16 pounds (62 and 71 N).

The point at which the critical column load was reached was estimated by observing the sudden onset of boom tip deflection to a value of several feet as the critical load was approached.

A better simulation of zero gravity than that provided by the counterweight system was achieved by suspending the boom from 10 helium-filled radiosonde balloons, as shown in figure 9. With this suspension system the critical load was estimated to be between 14.2 and 14.7 pounds (63 and 65 N). This system is free of the friction and restoring forces characteristic of the pulley and counterweight suspension. Since the array design required a maximum column force of 5 pounds (22.2 N) from the boom, the capacity of the device seemed quite adequate.

The stiffness characteristics of the boom were checked further by subjecting it to a transverse oscillation as a cantilever beam while supported by the radiosonde balloons. In this simple test, the tip of the actuator boom was deflected about 4 inches (0.10 m) from equilibrium and allowed to oscillate in a vertical plane. The oscillating mass of

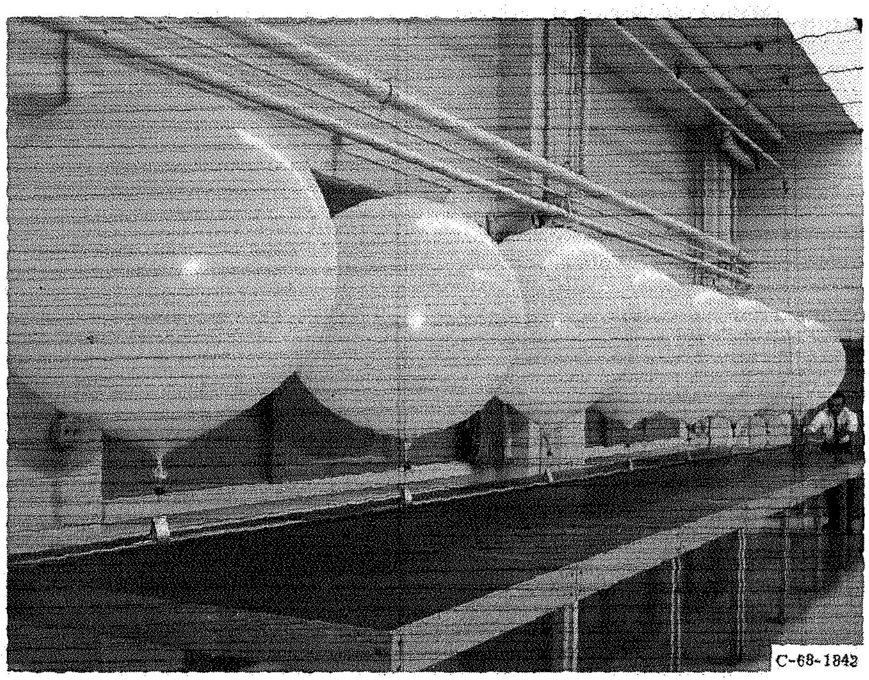

Figure 9. - Fully extended actuator boom suspended by helium-filled radiosonde balloons (10 balloons total) for critical column-load and cantilever-frequency test.

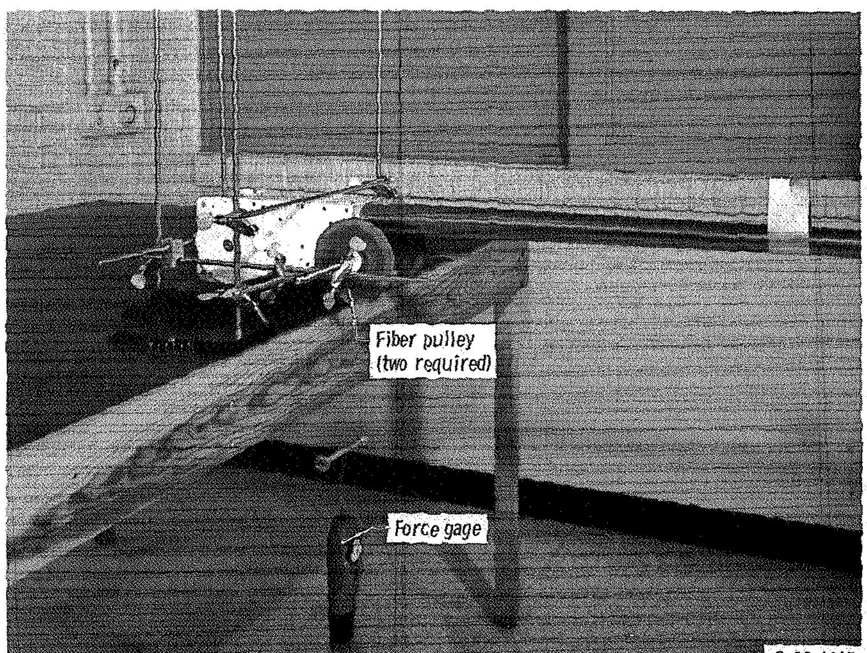

Figure 10. - Actuator unit mounted in loading fixture. Fiber pulleys transform dead weight load on force gage to axial compression (by steel tension wires) in boom.

the boom plus suspension system was about 0.051 pound per inch (0.91 kg/m) of boom length. The oscillation frequency was measured with a stopwatch to be about 1/8 hertz. This frequency and known boom constants (i.e., boom length, mass, and modulus of elasticity) were used to compute the moment of inertia I_b of the boom (ref. 5). A value of 0.012 inch^4 (0.50 cm^4) was obtained which agrees well with I_b as computed from tube geometry.

GENERAL ARRAY CHARACTERISTICS

Table II summarizes some of the more important characteristics of a hypothetical

TABLE II. - CHARACTERISTICS OF A SOLAR-CELL ARRAY BASED ON PRESENT STRUCTURAL MODEL AND SOLAR-CELL MODULE OF TABLE I

Overall dimensions of array wing:	
Length (deployed), ft; m	40; 12.2
Width, in.; m	70; 1.78
Panel area of array with 112 modules, ft^2; m^2	188; 17.5
Array volume (packaged), ft^3; m^3	1.07; 0.0303
Array weight breakdown (see fig. 4):	
(1) Outboard spreader beam and thrust plate, lb; kg	4.17; 1.89
(2) Two storage rollers with tension springs, lb; kg	1.14; 0.52
(3) Outboard weight subtotal ((1) + (2)), lb; kg	5.31; 2.41
(4) Inboard frame, lb; kg	4.40; 2.00
(5) Actuator boom unit, lb; kg	13.00; 5.90
(6) Structure subtotal ((3) + (4) + (5)), lb; kg	22.71; 10.30
(7) 112 Modules at 0.120 lb (0.0544 kg) each, lb; kg	13.43; 6.09
(8) Total array weight ((6) + (7)), lb; kg	36.14; 16.39
Total array power output, W	560
Specific array power, W/lb; W/kg	15.5; 34.2
Specific array weight, lb/kW; kg/kW	64.5; 29.2
(Structure weight)(Panel area), lb/ft^2; kg/m^2	0.12; 0.59
Estimated lowest natural frequency of array wing (transverse vibration) using method of ref. 5, Hz	0.09
Estimated lowest natural torsion frequency of array wing using method of ref. 4, Hz	0.1
Estimated solar heating deflection of boom tip using method of ref. 6 for -	
Bare 301 stainless steel, ft; m	4.82; 1.47
Silver-plated 301 stainless steel, ft; m	0.93; 0.28

flight-type solar array using the model design. In the array weight breakdown, item (7), the weight of the thin-film modules does not include allowance for electrical conductors. This may or may not be realistic. If all modules in a wing half panel were connected in series, the current path could begin and end at the vehicle end of the array. The array power would be delivered at about 100 volts, and no additional electrical conductors would be required on the array wing. However, other mission requirements may require a more complex electrical network in the array power wiring and, thus, greater conductor weights. One example of such a requirement would be the necessity of routing the array conductors to minimize the magnetic field of the array.

The solar heating deflection of the actuator boom was computed by using the method of reference 6 and assuming direct boom exposure to air mass zero (AMO) sunlight through the central open strip along the array wing. This open strip permits the boom centerline to lie in the plane of the array panels so that the column load on the boom due to array tension will not be applied eccentrically. However, after the column load tests were performed on the boom it became evident that the boom had sufficient column load capacity to carry an appreciably eccentric load. Thus, a possible design improvement might be to use a single full width array panel with the actuator boom just behind and in the shadow of the array. This change would

(1) Provide an additional 25 square feet (2.32 m^2) of active array area with negligible change in package volume or structure weight

(2) Shade the boom from direct sunlight resulting in reduced boom deflection due to solar heating

It is interesting to note the significant improvement in array output obtained by using the best available cells. The module output (5.0 W) listed in table I was based on a single cell of 2.7 percent efficiency yielding a power of 0.20 watt at AMO and 60° C. However, some production cells are 3.4 percent efficient and produce 0.25 watt at AMO and 60° C. If the production yield of these cells were high enough to use, the module output would be 6.25 watts and the array output would be 700 watts or 19.4 watts per pound (42.7 W/kg). Also, the present polyimide (ref. 1) cover plastic for the front face of the CdS cells absorbs as much as 20 percent of the useful incident solar light. If an improved cell cover plastic can be developed it seems reasonable to expect the subject array design performance to exceed 20 watts per pound (44.1 W/kg).

SUMMARY OF RESULTS

The solar array structural model fabricated for this effort exhibited a ratio of deployment structure weight to solar panel area of 0.12 pound per square foot (0.59 kg/m^2).

Using presently available thin-film cells, arrays of the type reported can yield 15.5 watts per pound (33 W/kg) and such arrays using the best available cells should yield about 20 watts per pound (44.1 W/kg) at air mass zero and 60° C.

The 40-foot- (12.2-m-) long actuator boom had adequate strength and deployment thrust to satisfy the design requirements of the tested array model.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 30, 1969,
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