REPORT NO. 67SD4403
OCTOBER 15, 1967

FEASIBILITY STUDY—30 WATT PER POUND ROLL—UP SOLAR ARRAY

QUARTERLY TECHNICAL REPORT NO. 1

JULY 1, 1967 TO SEPT 30 1967

PREPARED FOR

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CALIFORNIA INSTITUTE OF TECHNOLOGY
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PASADENA, CALIFORNIA

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, as sponsored by the National Aeronautics and Space Administration under Contract NAS 7-100.

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ABSTRACT

Results of the activities performed during the first quarter of the program to establish feasibility of a 30 watt per pound rollup Solar array are reported. These include the results of the configuration arrangements study, the results to date of the deployment rod tradeoff study, the summary of the parameters for each of the two candidate deployment configurations with each of the candidate rods, and the results to date of the initial detail design of the solar panel components.

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SECTION 1

INTRODUCTION

This report covers the first quarter of the Feasibility Study - 30 Watt Per Pound Roll Up Solar Array program being performed by the Spacecraft Department of the General Electric Company under Contract No. 951970 for Jet Propulsion Laboratory of the California Institute of Technology. The objective of the program is to perform a preliminary design and design analysis of a 250 square foot deployable (rollup) solar panel having a specific power capability of 30 watts per pound or greater, and which shall be capable of meeting the environmental requirements of JPL Specification No. SS 501407.

The power capability of the array is to be based on cells having an efficiency such that an electrical output of 10 watts/square foot will be achieved at air mass zero, $55^{\circ}C$, and 1.00 AU. Cells to be considered in the design are 0.008 thick, N/P, 10 ohm-cm type protected by a 0.003 thick filtered microsheet shield.

The initial section of the program consists of studies of candidate arrangements and deployment concepts to sufficient depth that a basis for optimization is established. These system tasks are supported by two additional detailed studies, one involving deployment boom and deployment mechanism preliminary design, and a second involved in conversion of empirical solar cell data into forms required by a general array design computer program.

The second major segment of the program involves the detail design of the components making up the 30 watt per pound rollup solar array. During this first quarter the studies at the system level have been largely completed and preliminary design of some components has been started.

SECTION 2

TECHNICAL DISCUSSION

2.1 TASK I - STUDY CANDIDATE ARRANGEMENTS AND SELECT PRIME ARRANGEMENT

2.1.1 INTRODUCTION

Task I was concerned with the selection of a basic rollup array concept or arrangement, for installation on the spacecraft. The purpose of this task was not the design of a system but, rather, the selection of a design concept which will be used for the design study. Within this definition, Task I has been concerned with the selection of a basic system configuration that can be stowed on the spacecraft within the required envelope, and then deployed to present the minimum solar panel area to meet the 30 watts per pound requirement.

2.1.2 SUMMARY

In the original proposal, seven arrangements were identified and evaluated, and one was selected as the preferred system. Task I continued the evaluation of the original arrangements plus variations and additional arrangements which appeared promising.

Layouts of each arrangement were made in sufficient detail to establish:

a. Stowed configuration.

b. Deployed configuration.

c. Number and size of solar penels (and drums) required.

d. Whether the drums are mounted in the spacecraft in a fixed position or require an initial drum deployment prior to unrolling the array.

Nine arrangements were evaluated (excluding minor variations), and the prime arrangement selected is identified as Configuration I of Figure 2-1. This configuration is similar to the preferred system in the proposal but uses a shorter drum and longer booms. The preferred arrangement consists of four identical systems, mounted in fixed positions, normal to the spacecraft vertical axis. A single drum will be mounted in each quadrant of the spacecraft mounting envelope, and all drums will be on the same elevation. Each drum will contain one 250 square foot solar panel with an approximate panel size of 8.33 feet by 31.4 feet. (This area is slightly in excess of 250 square feet to allow for some loss of panel area due to edge and end conditions, etc.)

2.1.3 DISCUSSION

2.1.3.1 Requirements

The following requirements, taken from JPL Specification SS501407A, were used as ground rules in determining the prime arrangement:

a. Thirty watts per pound power capability with 1000 square feet of deployable solar cell area.

b. The solar array, including release and deployment mechanisms, must fit within the envelope shown in Figure 2-2.

c. When deployed, the array will be oriented and maintained in a plane normal to the direction of the Sun by controlling the attitude of the spacecraft. Deflections from static spacecraft load inputs and thermal gradients shall not exceed ± 10 degrees.

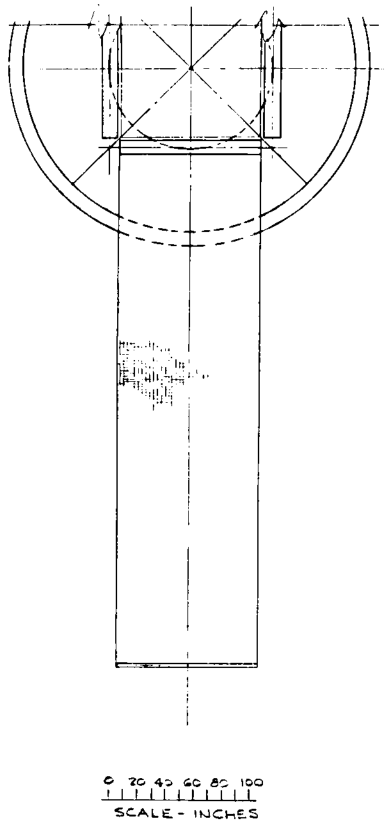
d. The solar array shall be capable of full deployment without interference between the array elements, and between the array and the spacecraft.

2.1.3.2 Candidate Systems

The nine candidate arrangements are shown in Figure 2-1. The following is a description of each configuration and a listing of their most important advantages and disadvantages.

2.1.4 CONFIGURATION I (PREFERRED)

This is the preferred arrangement; it is a simple, basic system consisting of a single, fixed drum per quadrant. The drum can be mounted close to the vehicle support structure and will provide a single solar panel per quadrant with no shadowing (panel overlap). The drum does not require deployment prior to extending the panel; however, the length of the drum is limited to 100 inches (8.33 ft) maximum, and the boom length will be the longest of any configuration.



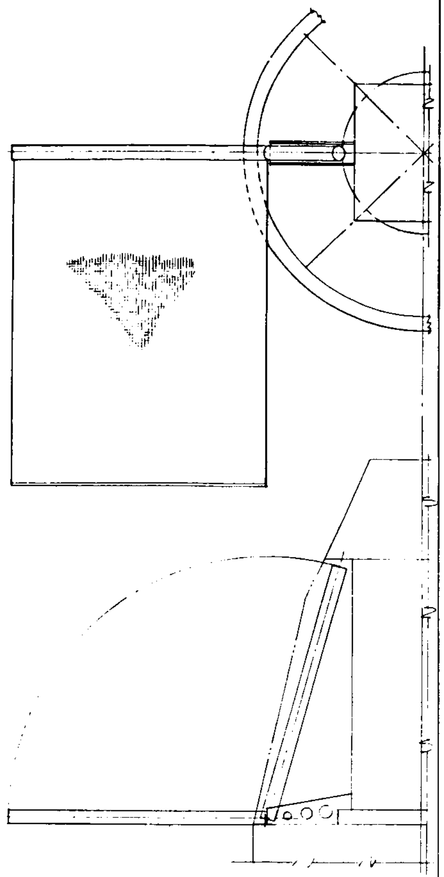
I

PROS

SYMMETRY
NO PRE DEPLOYMENT MOTION
NO SHADOWING
DRUMS CLOSE TO VEHICLE

CONS

WIDTH LIMITED
LONG BOOMS



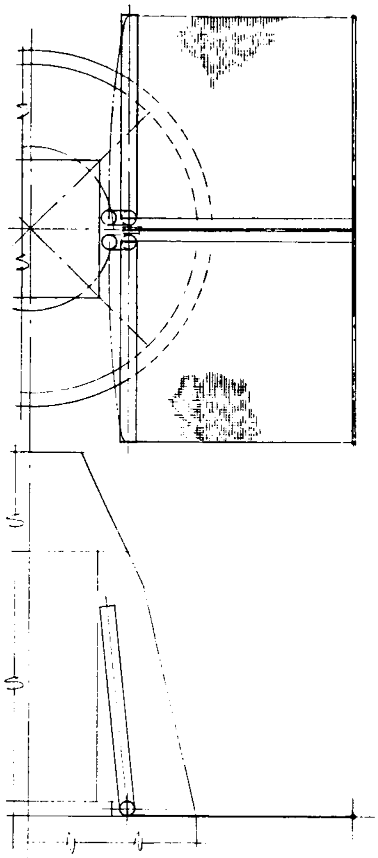
II

PROS

DRUM VERTICAL IN STOWED CONFIGURATION.
SHORT BOOMS

CONS

REQUIRES TWO STAGE DEPLOYMENT.
DOESN'T USE SPACE NEAR VEHICLE EFFICIENTLY.
CANTILEVERED DRUM
LONG DRUM.
ADDITIONAL BRACKETS REQUIRED FOR DRUM SUPPORT



III

PROS

VERTICAL STOWAGE OF DRUM
CAN BE MOUNTED CLOSE TO VEHICLE.
SHORT BOOMS

CONS

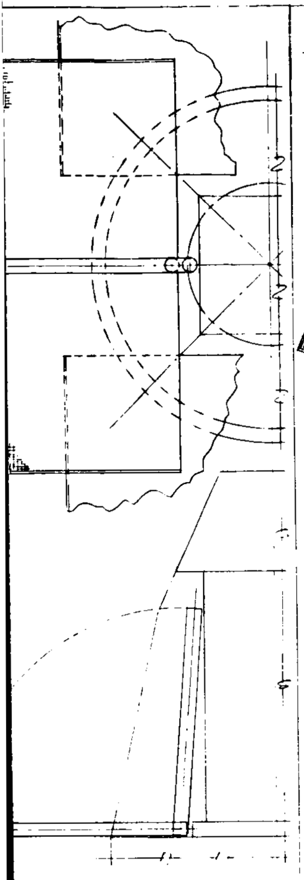
8 DRUMS AND 16 BOOMS TOTAL
SHADOWING - 10%
REQUIRES TWO STAGE DEPLOYMENT
DRUMS CANNOT BE IN SAME HORIZONTAL PLANE
DRUMS MUST BE DEPLOYED IN SEQUENCE TO
PREVENT INTERFERENCE WITH EACH OTHER

PROS

SMALLER NO. (
VERTICAL STO
(ALTERNATE VE

CONS

TWO STAGE DEPLOY
SHADOWING - 20%
4 DRUMS + 16 BOO
(SOLAR CELLS FAC
OF CURVATURE OF

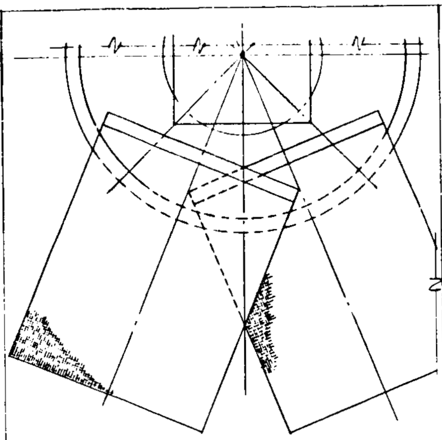


IV

DF DRUMS. (FOUR)
WAGE OF DRUM
RSION 2 DRUMS AND 8 BOOMS TOTAL)

MENT.

MS TOTAL
E TO FACE. ONE ARRAY HAS CELLS ON INSIDE
FILM.)



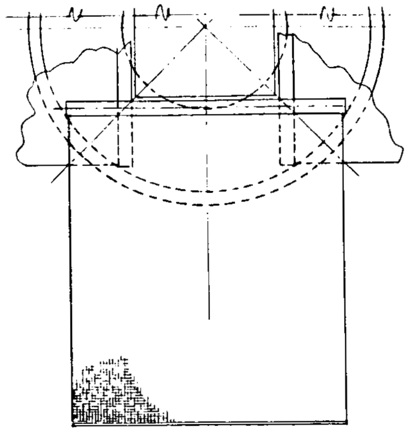
V

PROS

DRUMS CLOSE TO VEHICLE

CONS

SHADOWING - 10%
8 DRUMS + 16 BOOMS TOTAL
DRUMS NOT IN SAME HORIZONTAL PLANE
ATTACHMENT TO VEHICLE BECOMES COMPLEX



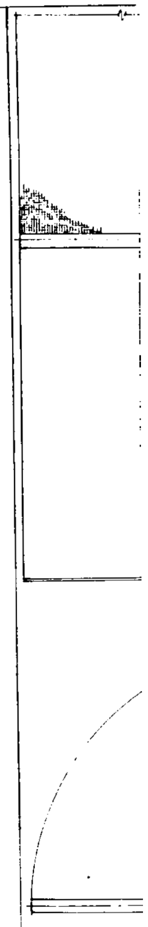
VI

PROS

MOUNTED CLOSE TO VEHICLE
BOOMS MOUNT DIRECTLY TO VEHICLE
BOOMS SHIELDED FROM SUN

CONS

SHADOWING - 4%
DRUM PERPENDICULAR TO VEHICLE AXIS.



NOTE:- TW

PROS:
TWO DRUM:
DRUM STOV
NO SHADOV

CONS:
TWO STAGI
CELLS FAC
CURVATUR
ADDITIONAL

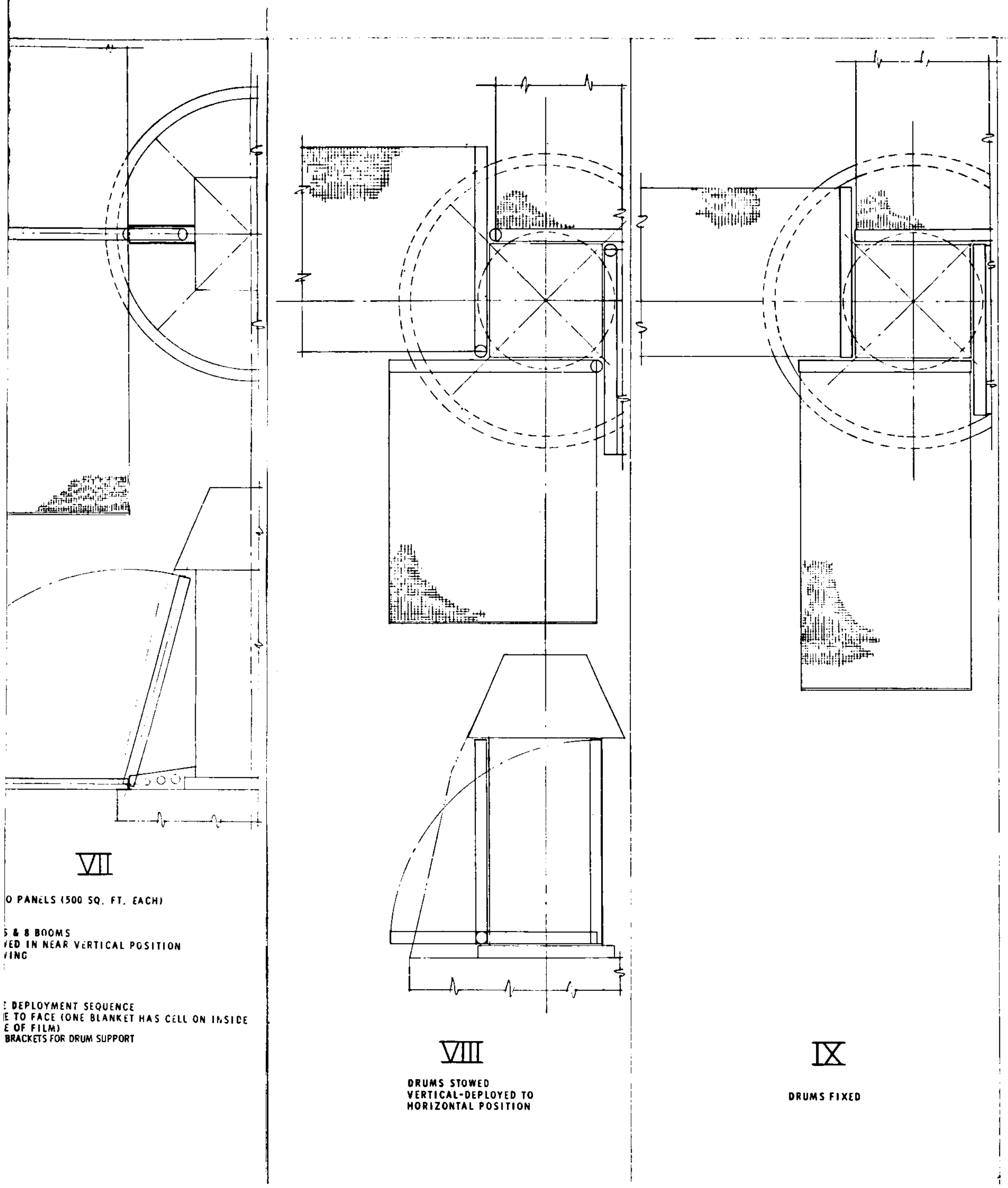
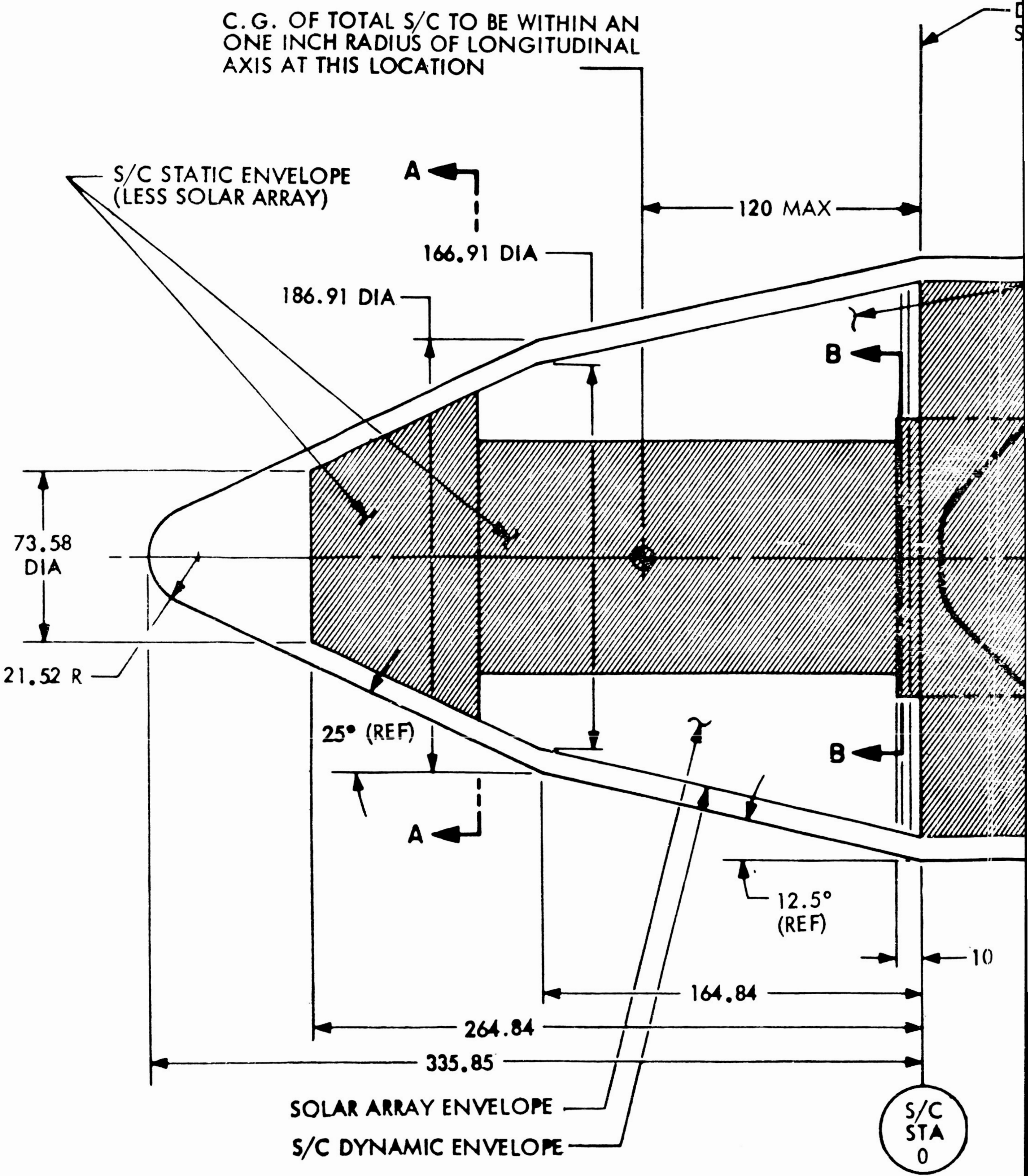


Figure 2-1. Candidate Arrangements



C.G. OF TOTAL S/C TO BE WITHIN AN ONE INCH RADIUS OF LONGITUDINAL AXIS AT THIS LOCATION
S/C STATIC ENVELOPE (LESS SOLAR ARRAY)
A
120 MAX
166.91 DIA
186.91 DIA
B
73.58 DIA
21.52 R
25° (REF)
B
A
12.5° (REF)
10
164.84
264.84
335.85
SOLAR ARRAY ENVELOPE
S/C DYNAMIC ENVELOPE
S/C STA 0

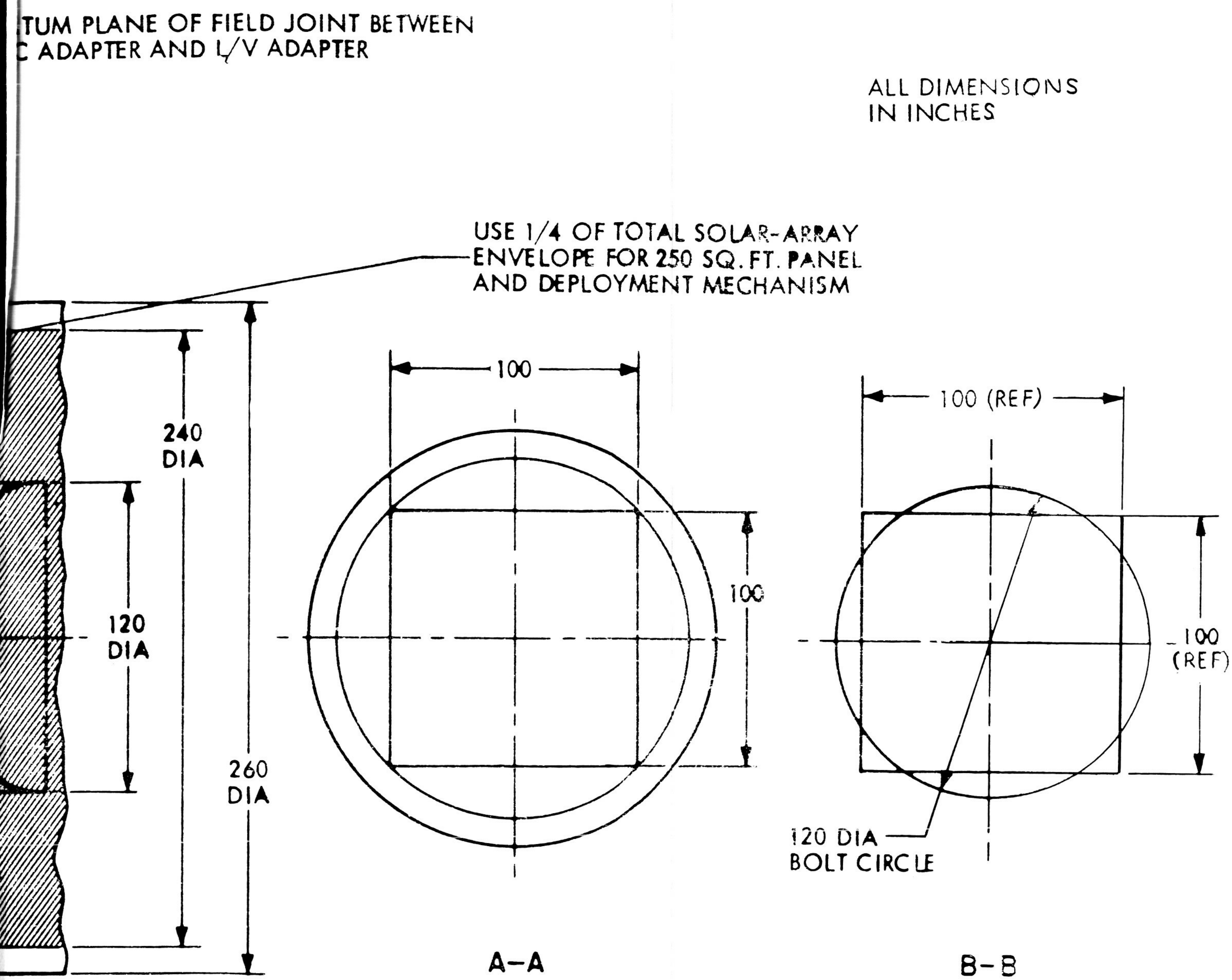


Figure 2-2. Typical Nose Fairing
and Spacecraft Envelope

This configuration was choosen as the preferred arrangement, because it meets all the system requirements, with the least complexity. Keeping the basic mechanical design simple will result in a more reliable, less complex, lower-weight system.

2.1.4.1 PRO

- Fixed mounting
- Drum is not deployed
- No shadowing
- Short drum length
- Drums mounted close to vehicle support structure
- Symmetrical (all drums, etc., are identical)

2.1.4.1 CON

- Long booms
- Drum length limited to width of vehicle support structure

2.1.5 CONFIGURATION II

In this configuration, the drum is stowed vertically and is the maximum length possible within the spacecraft packaging envelope. The drum is hinged at its lower end and must be deployed to a horizontal position prior to extending the array. This design will require a latch and release mechanism for the upper end of the drum, and a hinge and support or locking device at the lower end. In addition, a deployment device must be provided to rotate the drum at a controlled rate from its vertical, stowed position to the horizontal operating position. In this configuration, the hinged end of the drum is located away from the vehicle support structure and will require a long cantilever support. The drum, once it has been deployed, will not be retracted; consequently, the hinge and support (and drum) must be strong enough to withstand any vehicle maneuvers. (The solar panel, of course, will be retracted on the drum during maneuvers).

2.1.5.1 PRO

- Drum vertical when stowed
- Maximum drum length
- No shadowing
- Short boom length
- Symmetrical

2.1.5.2 CON

- Drum must be deployed
- Additional support required since drum lower end is located away from the vehicle mounting surface
- Drum is cantilevered

2.1.6 CONFIGURATION III

This arrangement uses an essentially square solar panel to optimize drum width to boom length. Although this system uses one of the shortest length booms, it is necessary to use eight drums (two per quadrant) to produce the required solar panel area. The drums are stowed vertically and must be deployed in sequence to prevent interference between drums in adjacent quadrants. Since the solar panels overlap at the corners, there will be some shadowing. The lower or hinged end of the drum is located close to the vehicle mounting surface; however, the mounts are not on the same horizontal level.

2.1.6.1 PRO

- Drum vertical when stowed
- Drum mounted close to vehicle
- Short boom length
- Symmetrical

2.1.6.2 CON

- Eight drums required
- Drums must be deployed
- Deployment must be sequenced
- Drums are cantilevered
- Shadowing (10%)
- Drums are not mounted in the same horizontal plane

2.1.7 CONFIGURATION IV

This arrangement is similar to Configuration III, with the exception that two solar panels are mounted on one drum. This reduces the number of drums to four and uses the shortest boom length of any configuration. Rolling two solar panels on one drum reduces the weight of the system, but introduces an added complication in that one of the panels will have its cells on the inside of the curvature of the stowed panel. This presents the additional requirement of providing protection between the two panels, since the solar cells will be stored face to face. There will be some overlap of adjacent panels at the corners, resulting in shadowing.

2.1.7.1 PRO

- Drums vertical when stowed
- Short boom length
- Symmetrical
- Drums mounted close to vehicle

2.1.7.2 CON

- Drums must be deployed
- Drums are cantilevered
- Two solar panels on one drum, cells face to face when stored

- Shadowing (14%)
- Drums not mounted in same horizontal plane

2.1.8 CONFIGURATION V

Configuration V is a fixed drum system using two drums per quadrant mounted on different levels, and positioned at a fixed angle to each other. Using this system no drum deployment is necessary, but eight drums are required to produce the required solar panel area. There is a considerable amount of overlap and shadowing, and the attachment to the vehicle structure becomes complex because of the different levels and attachment angles.

2.1.8.1 PRO

- Fixed mounting
- Drums are not deployed

2.1.8.2 CON

- Eight drums required
- Shadowing (10%)
- Drums not on same level
- Drums mounted away from vehicle support structure
- Attachment to vehicle is complex due to angular configuration

2.1.9 CONFIGURATION VI

This arrangement is similar to Configuration I in that there are four drums, one in each quadrant, mounted in fixed positions. Because the long drum length causes overlapping of the solar panels, the drums are mounted on different levels, and there is some shadowing at the corners.

2.1.9.1 PRO

- Fixed mounting
- Drums are not deployed
- Drums mounted close to vehicle
- Symmetrical
- Short booms

2.1.9.2 CON

- Drums not on same level
- Shadowing (4%)
- Long drums (extend beyond vehicle mounting surface)

2.1.10 CONFIGURATION VII

This is a variation of Configuration IV. Two solar panels are stored on a single drum with a total deployed area of 500 square feet per drum. This will require only two drums per vehicle and would eliminate overlap and shadowing.

2.1.10.1 PRO

- Two drums required
- Drums vertical when stowed
- Symmetrical
- No shadowing

2.1.10.2 CON

- Drums are cantilevered
- Drums are deployed
- Two solar panels on one drum, cells face to face when stored
- Drum lower end mounted away from vehicle

2.1.11 CONFIGURATION VIII

This is a variation of Configuration II in which the four drums are located at the corners of the vehicle mounting structure and are deployed adjacent to the mounting structure wall. This means that the lower drum support is close to the mounting structure, and the deployed drum can be supported by the spacecraft rather than cantilevered off the side. The drums are all on the same level, and there is no shadowing.

2.1.11.1 PRO

- Drums are stowed vertically
- Drums are mounted close to the vehicle
- No shadowing
- Drums can be supported by vehicle to prevent full cantilever
- Symmetrical
- Short booms

2.1.11.2 CON

- Drums are deployed
- Long drums

2.1.12 CONFIGURATION IX

This is a variation of the preferred Configuration I in which one end of each drum is permitted to extend beyond the limit of the 100-inch vehicle mounting surface. All four drums are in the same plane, and there is no overlapping of solar panels. This configuration will permit a longer drum and shorter boom than Configuration I, but requires one end of each boom to be cantilevered since it is beyond the vehicle mounting surface.

2.1.12.1 PRO

- Fixed mounting
- Drums are not deployed
- No shadowing
- Drums mounted close to vehicle

2.1.12.2 CON

- One end of each drum is cantilevered
- Supports not symmetrical

2.1.13 EVALUATION

In the following table, a figure of merit, 0 to 10, has been assigned to each configuration for each of eight criteria. To start the evaluation, each criterion was assumed to have a value of 10. As each configuration was evaluated, points were subtracted for unfavorable characteristics, so that the best system would accumulate the highest figure of merit.

Criteria	Configurations								
	1	2	3	4	5	6	7	8	9
Weight	10	2	2	5	4	7	2	4	8
Cost	10	6	4	5	6	8	5	7	8
Complexity	9	6	4	5	6	8	5	7	8
Reliability	9	7	5	6	8	9	7	7	9
Shadowing	10	10	8	7	8	9	10	10	10
Drum Deployment	10	2	0	2	10	10	2	2	10
Availability	10	9	9	7	10	10	7	9	10
Maintainability	9	7	4	5	7	8	7	8	8
TOTAL	77	49	36	42	59	69	45	54	71

a. Weight - This is one of the most improtant criteria and would have a strong influence upon the final choice. Since the solar panel area is fixed, its weight will be the same for all configurations, so that the major weight item is the drum. (Note: Task 1 is not concerned with the choice of actuators or booms; consequently, the weight of these items is not a major factor in the choice of arrangements.)

b. Cost - No cost figures were made for this evaluation, but a relative determination of cost was made, based upon the complexity, size, fabrication, etc., of the different configurations.

c. Complexity - This refers to the number of drums and booms required, whether or not the drums are deployed, requirement for a deployment sequence, number of solar panels per drum, etc.

d. Reliability - Here again no acutal figures of reliability were calculated, but an evaluation of relative reliability was made, based upon experience and the complexity of the configurations.

e. Shadowing - The configurations with no shadowing were rated highest, since additional solar cell panel area would have to be added to shadowed designs, to compensate for loss of effective panel area.

f. Drum Deployment - Systems with fixed drums were rated higher than systems requiring a drum deployment prior to extension of the solar panels. Deployment of a drum would require: a latch and release device, hinge support, deployment mechanism to swing the drum to its operating position, some method of controlling the speed of deployment, a latching device to lock the drum in its final position, etc.

g. Availability - This refers to the possible use of materials and/or techniques which are not proven and available for use immediately.

h. Maintainability - For this evaluation, a system requiring drum deployment was regarded as less maintainable than a fixed drum design because this type of system is more complex, has more moving parts, and cannot be removed and tested as one, integral unit.

The detail considerations which went into the composite rating of the arrangements are shown in Appendix A.

2.2 TASK 2 - STUDY CANDIDATE DEPLOYMENT CONCEPTS

The initial analysis of the configurations consisted of a recycling of the computer study, based on the engineering models developed on an IR&D program, to include the configuration of the proposed reference design and the single-rod design using the same properties and characteristics. The reference design is a conventional double-rod deployment system similar in overall characteristics to the engineering model shown in Figure 2-3. Geometric optimization of this concept for the 250 ft^2 rollup array of this program resulted in the design shown in Figure 2-4. The principal effect of the envelope and mounting constraints was to shift the rods three feet inward from the edges, a move favorable to efficient bracketry and to drum stiffness.

The second deployment concept candidate, the single-rod deployment, is shown in model form in Figure 2-5 and as adapted to the 30 watt per pound requirements in Figure 2-6.

To provide for concurrent efforts on the program during the initial stage, the following tasks were established:

a. First-cut optimization of both candidate concepts based on extrapolation of the design parameter characteristics derived from the previous General Electric model designs.

b. Detail sizing of the components to establish analytically the accuracy of the preliminary design, using assumed dynamic loading and blanket tension forces based on the experience of the IR&D program models.

c. Concurrent dynamic analysis of the preliminary design configuration to refine the load data, establish dynamic feasibility within the specified performance, and enable correction of the assumptions.

d. Iteration of the component design with the refined load values. The iterations included variation of the types of deployment rods to include all those for which design information had been established by the supporting study (Task A-Study of Deployable Boom Concepts).

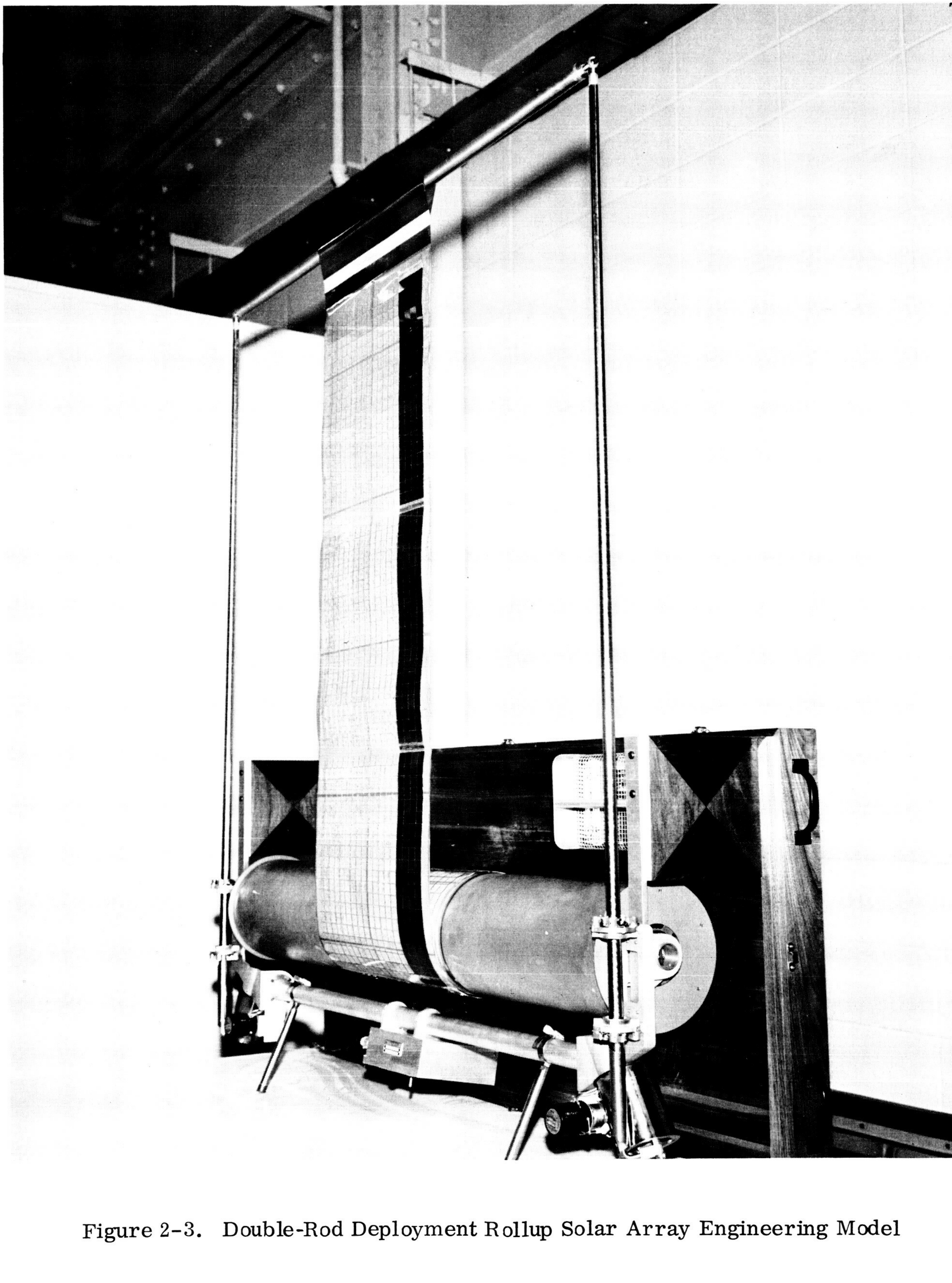
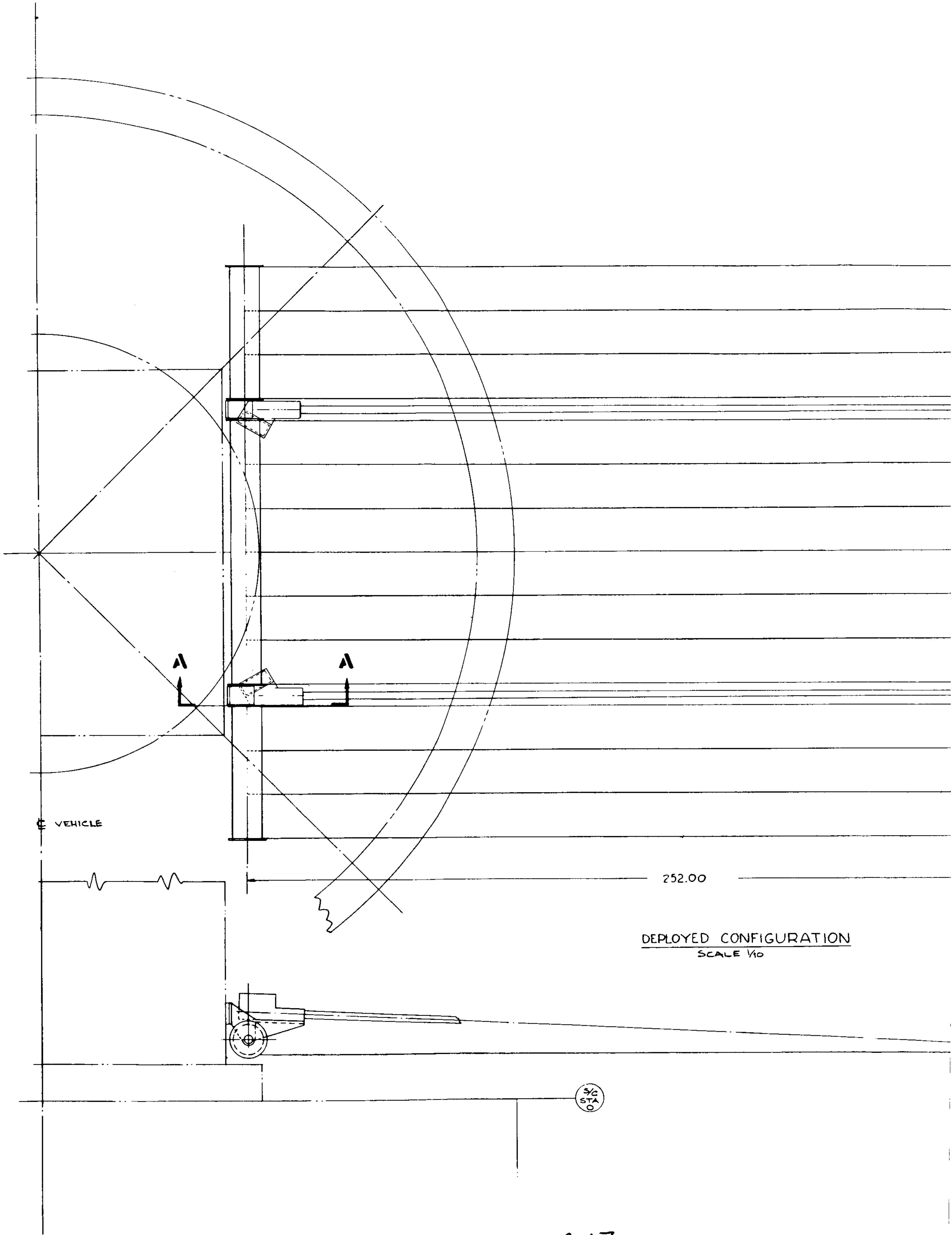


Figure 2-3. Double-Rod Deployment Rollup Solar Array Engineering Model



A
A
℄ VEHICLE
252.00
DEPLOYED CONFIGURATION
SCALE 1/10
S/C STA 0

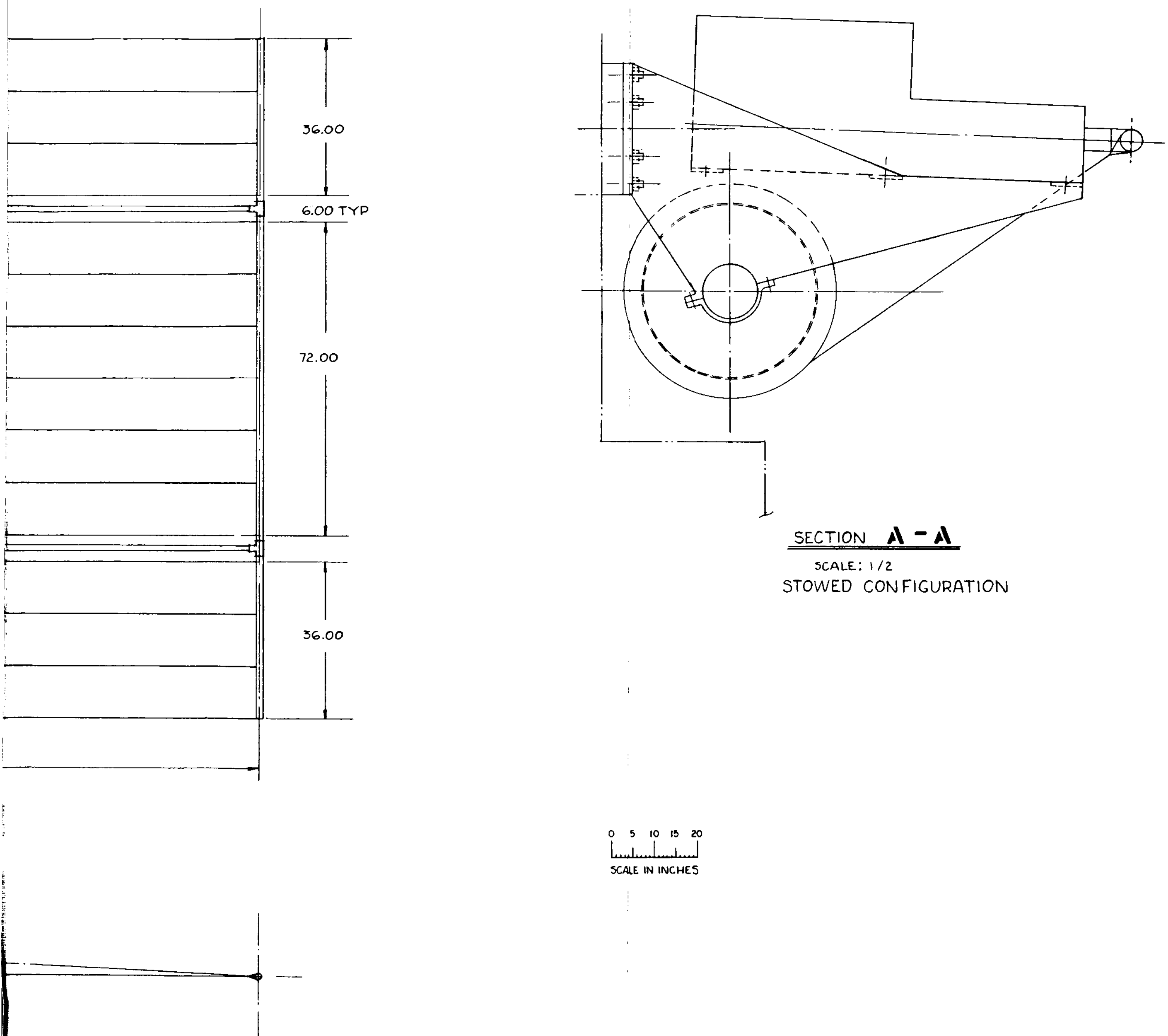


Figure 2-4. Rollup Solar Array Double Deployment Rod

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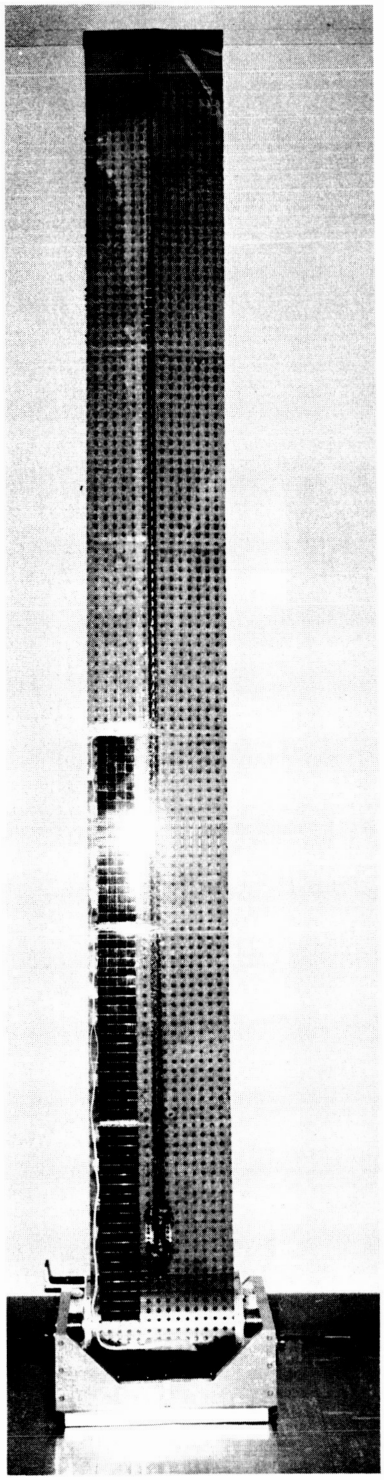
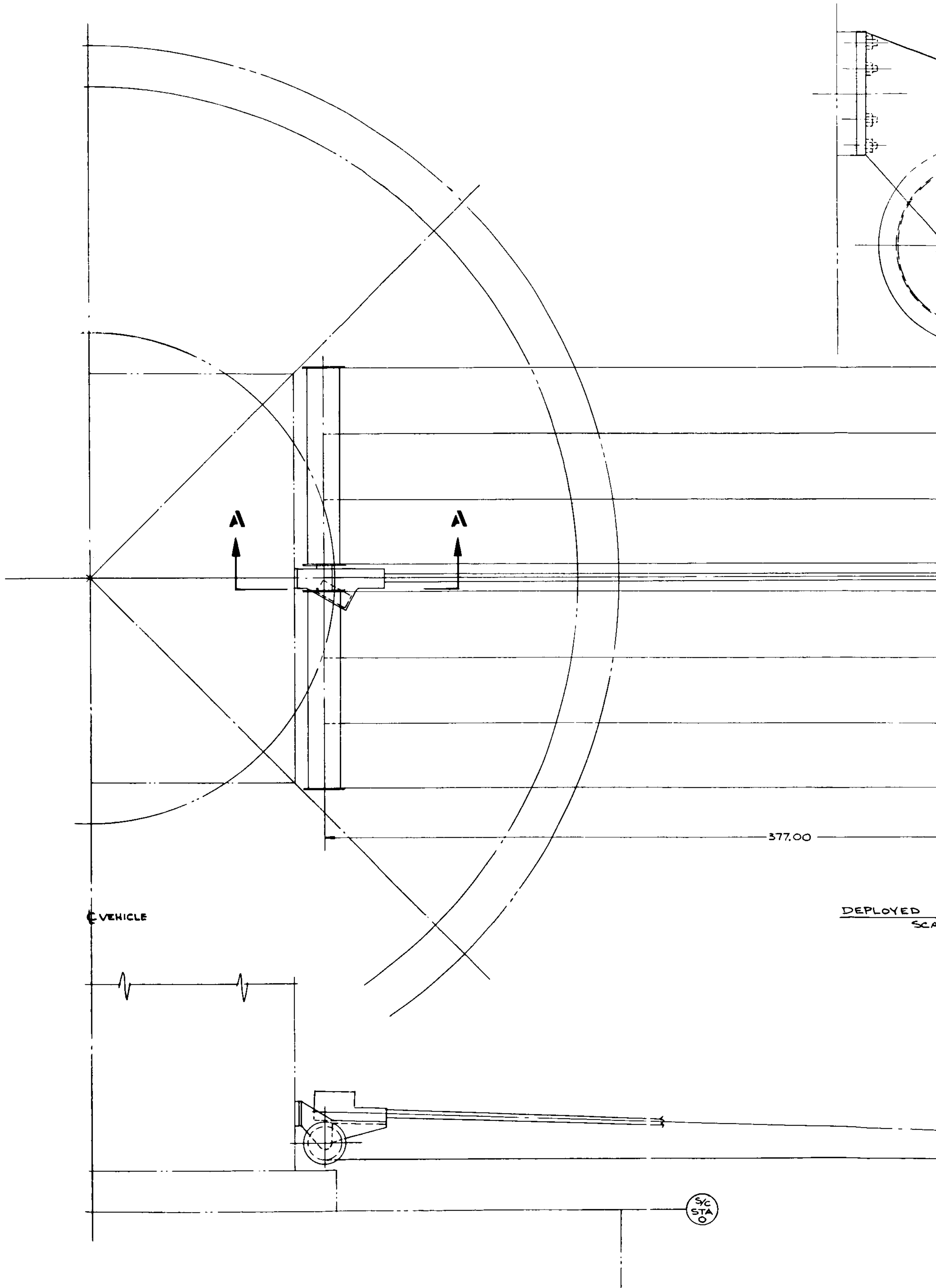


Figure 2-5. Single-Rod Configuration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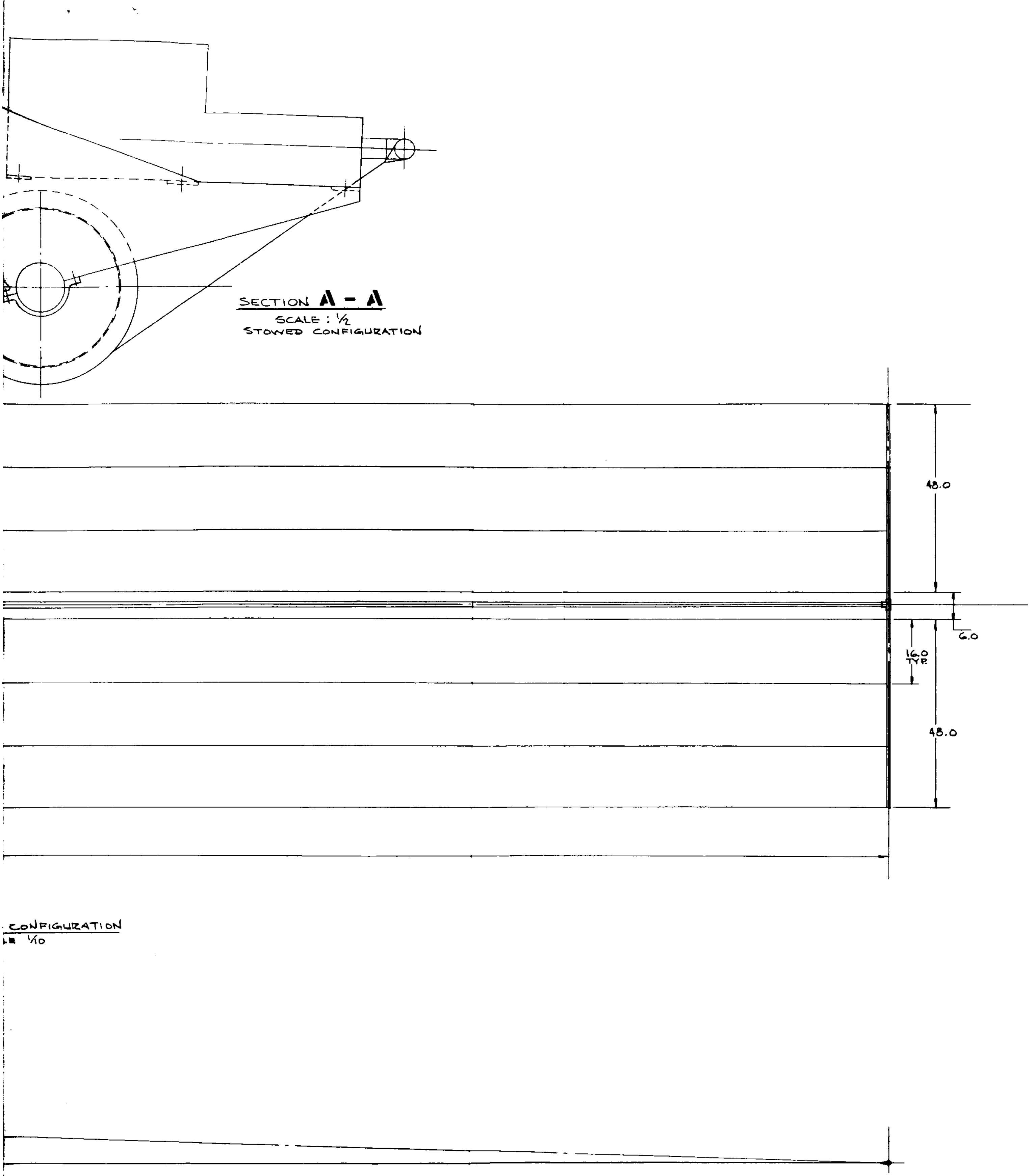


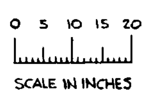


Figure 2-6. Rollup Solar Array Single Deployment Rod

Table 2-1. Double-Rod Rollup Array Candidates (12.0 ft Wide x 20.83 ft Long; 56.9 volts)

	180° Overlapped STEM		Interlocked Rod		BI-STEM		Hunter Stacer
Rod Material	BeCu	Moly	BeCu	Moly	BeCu	Moly	301 Stainless
Rod Diameter (In.)	1.00	1.00	1.00	1.00	0.86	0.86	0.56-1.67
Material Gauge (In.)	0.004	0.002	0.004	0.002	0.005	0.0025	0.006
Rod Tape Wgt (Lb)	2.836	1.734	2.191	1.339	3.610	2.34	8.744
Deployment Mech. Wgt (Lb)	10.0	10.0	12.0	12.0	5.00	5.00	8.8
Total Wgt, Rod Component (Lb)	12.836	11.734	14.191	13.339	8.610	7.34	17.544
Array Sheet Wgt (Lb)	45.917	45.917	45.917	45.917	45.917	45.917	45.917
Blanket Bus Bars Wgt (Lb)	0.889	0.889	0.889	0.889	0.889	0.889	0.889
Drum Wgt (0.040 Mg) (Lb)	12.941	12.941	12.941	12.941	12.941	12.941	12.941
End Pieces (Lb)	2.964	2.964	2.964	2.964	2.964	2.964	2.964
Weight Subtotal (Lb)	75.548	74.446	76.903	76.051	71.322	70.059	80.256
Balance Remaining for Hardware (Wiring, Connectors, Brackets, Latches, Caging, Detail Design Structural Beefing) within 83.33 Lb Contractual Goal (Lb)	7.785	8.887	6.431	7.282	12.012	13.274	3.077

Table 2-2. Single-Rod Rollup Array Candidates (8 ft Wide x 31.25 ft Long; 56.7 volts)

	180° Overlapped STEM		Interlocked Rod		BI-STEM	
Rod Material	BeCu	Moly	BeCu	Moly	BeCu	Moly
Rod Diameter (In.)	1.50	1.25	1.5	1.5	1.34	1.17
Material Gauge (In.)	0.006	0.0025	0.006	0.003	0.007	0.003
Rod Tape Wgt (Lb)	4.786	2.032	3.528	2.157	5.543	2.874
Deployment Mech. Wgt (Lb)	8.1	6.6	9.4	9.4	4.2	3.6
Total Wgt Rod Component (Lb)	12.886	8.632	12.928	11.557	9.743	6.474
Array Sheet Wgt (Lb)	45.917	45.917	45.917	45.917	45.917	45.917
Blanket Bus Bars Wgt (Lb)	2.081	2.081	2.081	2.081	2.081	2.081
Drum Wgt (0.045 Mg) (Lb)	10.818	10.818	10.818	10.818	10.818	10.818
End Pieces (Lb)	1.976	1.976	1.976	1.976	1.976	1.976
Weight Subtotal (Lb)	73.679	69.425	73.721	72.350	70.536	67.267
Balance Remaining for Hardware (Wiring, Connectors, Brackets Latches, Caging, Detail Design Structural Beefing) Within 83.33 Lb. Contractural Goal (Lb)	9.654	13.908	9.612	10.983	12.797	16.066

To date,the Deployable Boom Study (Task A) has yielded component design information on the following rods,enabling their inclusion into overall panel designs.

a. 180° Overlapped STEM Rod, Berylium Copper and Molybdenum Materials, Double Rod and Single Rod

b. Interlocked Rod, Berylium Copper and Molybdenum Materials,Double Rod and Single Rod

c. BI-STEM Rod, Berylium Copper and Molybdenum Materials,Double Rod and Single Rod

d. STACER (Spiral) Rod, Stainles Steel Material, Double-Rod System Only

As can be seen from the detail weight breakdowns shown in Tables 2-1 (double rod) and 2-2 (single rod), all of the candidate rods can be utilized with substantial margins remaining for the detail accessory hardware. A comparison of the single versus double rod deployment configurations can be made for each rod candidate individually, on the basis of the greatest weight margin remaining for accessory hardware and structural design variation.

Rod Type	Favored Configuration	Weight Margin (lb)
180° Overlapped STEM, BeCu	Single Rod	1.869
180° Overlapped STEM, Molybdenum	Single Rod	5.021
Interlocked Rod, BeCu	Single Rod	3.181
Interlocked Rod, Molybdenum	Single Rod	3.701
BI-STEM, BeCu	Single Rod	0.785
BI-STEM, Molybdenum	Single Rod	2.792

The material considerations for BeCu and molybdenum must be considered in the light of present and future states of development. BeCu rods of each type are readily available, while molybdenum rods for each type would have to be developed. The justification for such future development is in the superior performance of the molybdenum in each instance.

In order to avoid unreal effects of making comparisons between present known parameters and future estimated parameters, the types of rods can be best evaluated by comparing the types with the same material. Such a comparison based on the date of Tables 2-1 and 2-2 yields the following relative picture of the standing of the three rod types:

Rod Material & Configuration	Favored Rod Type	Weight Margin
Berylium Copper, Double Rod	BI-STEM	4.227 lb better than 180° STEM 5.581 lb better than Interlocked Rod
Molybdenum, Double Rod	BI-STEM	4.387 lb better than 180° STEM 5.992 lb better than Interlocked Rod
Berylium Copper, Single Rod	BI-STEM	3.143 lb better than 180° STEM 3.185 lb better than Interlocked Rod
Molybdenum, Single Rod	BI-STEM	2.158 lb better than 180° STEM 5.083 lb better than Interlocked Rod

The deployment rod study is still in progress and iterations of the system design will be made for the other candidate rods and rod materials as data becomes available. It is apparent from the results already at hand that there is a wide latitude in choice of the rods and the type system which will still meet the requirements of the 30 watts per pound system, and that the final configuration choice may be influenced by other factors, such as reliability and/or drum dynamics, without jeopardizing the contractual goals.

2.3 TASK A - STUDY OF DEPLOYABLE BOOM CONCEPTS

The object of the boom study is to select an optimum boom, consistent with the deployment requirements of the rollup solar array, with respect to minimum weight. With this objective in mind, it was initially determined that a broad spectrum of possible boom types would be considered, in order not to overlook a potential minimum weight system which has not yet been brought to a fully developed state. The boom types to be considered were:

a. STEM Type (Overlapping Split Tube)

b. Interlocking Rod

c. Spiral Wrapped Tube

d. Flattened Tube of Closed Section

e. Collapsible Truss

f. BI-STEM

Early analysis indicated that two basic types of loading existed which would size the boom and resultant deployment unit:

a. Beam-column loading of the erected boom as affected by blanket tension and eccentricities created by thermal bending.

b. Resistance to boom deployment by blanket tension which could stall the deployment motor or cause instabilities of the deploying boom element within the deployment mechanism.

Specific subtasks to accomplish Task A are:

a. Determine the performance characteristics of the various candidate booms with respect to thermal bending, beam column loading, and resistance to deployment.

b. Set up analytical models which will treat the above loading conditions and determine the size boom required.

c. Design a deployment mechanism for the size boom established in Subtask b.

d. Calculate the total weight of the boom and deployment mechanism required for each candidate boom.

e. Select the minimum weight system with due regard for reliability of operation, particularly with respect to previously untried systems.

The task is amplified by the tradeoffs to be considered for the different array configurations. This requires that two different sets of boom lengths and blanket tensions be considered.

Effort during this period consisted of the following:

a. A definition of specific boom requirements (documented in PIR 41M2-232; see Appendix C).

b. Conferences with a potential boom vendor to gain design data.

c. Sizing of booms and erection units of the STEM, Digitated Rod, and BI-STEM types for the various array configurations under study.

d. Design layouts of STEM and Digitated Rod deployer mechanisms for the boom sizes shown to be required to carry the design loads imposed.

Design information on boom types other than the STEM has been lacking to the extent that detail stress and thermal bending analyses have not been possible thus far. Effort has been directed toward gathering performance data on these booms in order to facilitate analysis. When this is completed, the booms can be sized for the loading conditions imposed, and realistic weight estimates can be generated. A computer program was generated which considered the combined thermal and structural loading and applied it to the STEM boom, yielding the data shown in Tables 2-3 and 2-4.

The boom element weights for the configurations were easily obtainable because they are a simple function of material density, diameter, thickness, and overlap factor. However, deployment unit weights were not readily available without detail design. The first cut weights were obtained as an extrapolation of experience supported by Figure 2-7. This curve presents a composite summary of the units of this type which have been built and flown by plotting the deployer weight/boom weight ratio as a function of boom length.

Table 2-3. Deployment Rod Properties — Double - Rod System Deploying 20.83 Feet

Blanket Length = 20.83 ft						Drum = 12 ft				Preload = 2.2 lb (total)			
Rod Type	Description Dia., Thick., Material	Weight per 2 Rods (lb)	Temp. Gradient (°F)	Max. Tip Defl. (in.)	Permissible Defl. (in.)	Preload Defl. (in.)	Approx. 1g Defl. (in.)	Critical Column Load (lb)	Critical Column Load 1g (lb)	** Margin of Safety-Column	Maximum Bending Moment (in.-lb)	Critical Bending Moment (in.-lb)	** Margin of Safety-Bending
* Over-lapped STEM	1.00, 0.004 BeCu	2.80	55	13.44	43.41	5.44	6.53	5.94	5.09	2.70	8.80	136	11.4
Over-lapped STEM	1.00, 0.002 Moly	1.76	80	3.61	43.41	4.03	4.34	7.75	7.31	4.32	9.41	88.5	6.5
Inter-locked Rod	1.00, 0.004 BeCu	2.18	55	12.50	43.41	7.62	8.91	3.39-4.58	2.85-4.04	1.07-1.94	8.82	105	8.5
*** Inter-locked Rod	1.00, 0.002 Moly	1.32	80	2.45	43.41	5.56	5.93	4.36-5.98	4.03-5.65	1.93-3.11	8.80	68.5	5.2
BI-STEM	0.86, 0.005 BeCu	3.54	45	12.46	43.41	5.56	6.10	5.96	5.06	2.66	8.80	188	16.1
*** BI-STEM	0.86, 0.0025 Moly	2.30	70	3.68	43.41	4.11	4.30	7.75	7.21	4.22	8.80	—	—

*180° Overlap **Ultimate Factor of Safety = 1.25 *** Future Possibilities

Table 2-4. Deployment Rod Properties — Single-Rod System Deploying 31.25 Feet

Blanket Length = 31.25 ft					Drum = 8 ft					Preload = 3.1 lb			
Rod Type	Description Dia., Thick., Material	Weight per 2 Rods (lb)	Temp. Gradient (°F)	Max. Tip Defl. (in.)	Permissible Defl. (in.)	Preload Defl. (in.)	Approx. 1g Defl. (in.)	Critical Column Load (lb)	Critical Column Load 1g (lb)	** Margin of Safety-Column	Max. Bending Moment (in.-lb)	Critical Bending Moment (in.-lb)	** Margin of Safety-Bending
* Over-lapped STEM	1.5, 0.006 BeCu	4.79	79	35.61	65.12	7.08	9.04	13.36	10.96	1.83	24.9	458	13.7
Over-lapped STEM	1.5, 0.003 Moly	2.94	112	11.43	65.12	5.18	5.73	17.44	15.97	3.12	25.3	299	8.5
	1.25, 0.0025 Moly	2.04	91	7.31	65.12	12.85	14.58	8.41	7.39	0.90	26.9	173	4.1
Inter-locked Rod	1.5, 0.006 BeCu	3.53	79	36.54	65.12	10.36	13.47	6.30-10.12	4.53-8.35	0.17-1.16	26.3	338	9.0
*** Inter-locked Rod	1.5, 0.003 Moly	2.16	112	10.34	65.12	7.39	8.21	8.02-13.22	6.94-12.14	0.79-3.14	24.8	220	6.4
*** BI-STEM	1.17, 0.006 BeCu	4.46	60	36.12	65.12	13.05	20.91	8.53	6.30	0.62	30.7	—	—
BISTEM	1.34, 0.0035 BeCu	3.88	70	35.10	65.12	6.37	8.33	14.96	11.99	2.10	24.8	576	17.6
BISTEM ***	1.34, 0.003 Moly	3.88	95	10.85	65.12	4.69	5.29	19.50	17.56	3.53	24.8	—	—
BISTEM ***	1.17, 0.003 Moly	2.77	85	9.01	65.12	9.14	10.62	12.78	11.39	1.93	25.2	—	—

*180 of Overlap **Ultimate Factor of Safety = 1.25 ***Future Possibilities

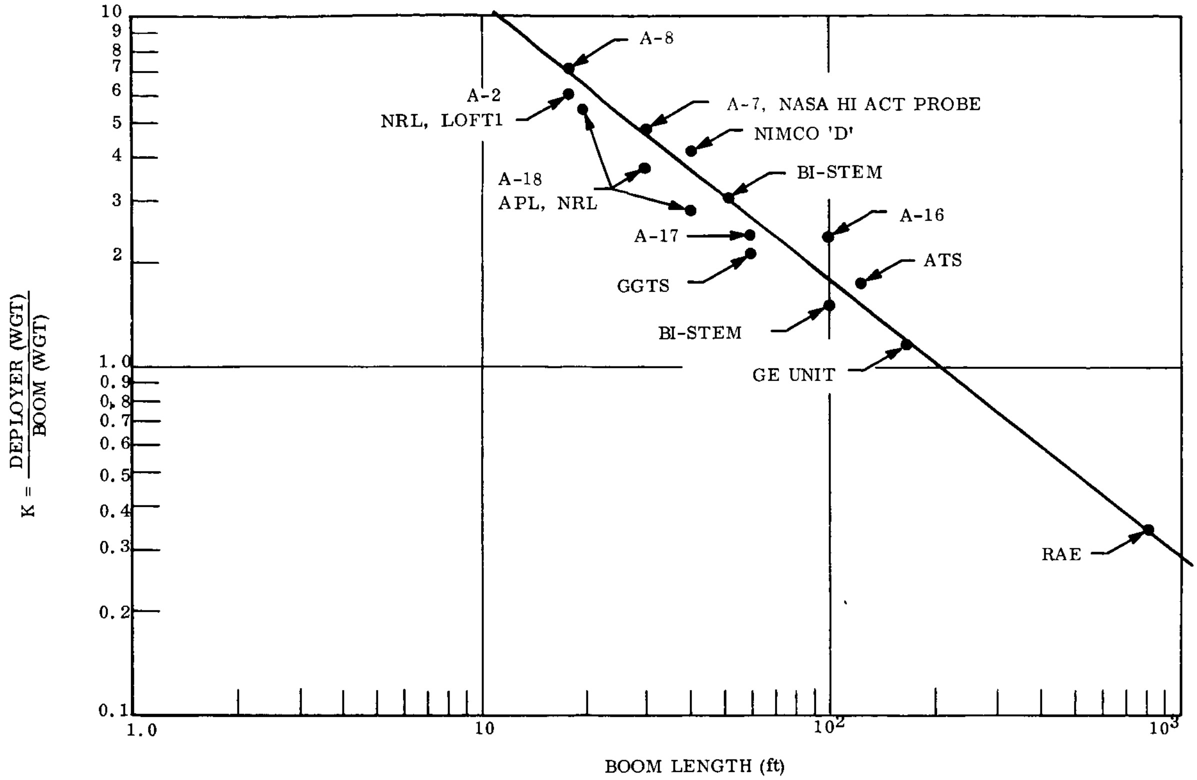


Figure 2-7. Typical Deployer Weight as a Function of Boom Length and Weight for Overlap-Type Extensible Booms

Using this curve and the calculated boom element weights, the following depolyment mechanism and total deployment system weight estimates were derived.

Boom Length (ft)	Boom Configuration Dia & Gauge	Boom Weight (lb)	Deployer Weight (lb)	No. of Booms	Total Boom System Weight (lb)
21	1.0 x 0.004	1.4	8.7	2	20.2
27	1.5 x 0.006	4.3	20.4	1	24.7
31	1.75 x 0.007	6.5	23.5	1	30.0

These boom system weights exceed the weight objective. It was recognized that they might be unrealistically conservative because of the manner in which the deployment mechanism weights were extrapolated. Most of the units in Figure 2-7 were designed for boom lengths considerably in excess of the 20- to 30-foot range of this application. Although deployment unit weight is not a strong function of boom length (but rather of diameter), it was felt that a better weight estimate (and improved performance) could be accomplished if a design specifically addressed to this goal were undertaken. Therefore, the following action was initiated:

a. A reduced set of blanket tensions, consistent with a minimum frequency of 0.06 cps, was calculated and is shown following:

Boom Length (ft)	Blanket Tension Required for 0.06 cps Minimum Freq. (lb)
31	3.1
28	2.6
21	2.2

b. Stress analysis was conducted on both the STEM, Interlocked Rod, and BI-STEM, using the reduced loads. (See Tables 2-1 and 2-2 for current values.)

c. Design layouts were initiated on deployment devices for the sizes of booms established in Step b. Both STEM and Interlocked Rod deployment mechanisms were considered. These layouts were in sufficient detail to permit an iteration of the weight analysis to be started (see Figures 2-8 and 2-9). Overall configuration differences are apparent in the outline dimensions (18.37 x 8.75 x 5.25 inches for the STEM mechanism as opposed to 29.0 x 6.0 x 5.25 inches for the Interlocked Rod mechanism). The detail weight analysis was then performed. The weight of each of the parts thus conceived was calculated; the results are shown below.

Boom Length (ft)	Boom Configurations Dia. & Gauge	Boom Type	Calculated Deployer Weight (lb)	Deployer Size (ft)
31	1.5 x 0.006	STEM	8.1	18-3/4x8-3/4x5-1/4
31	1.5 x 0.006	Digitated	9.4	29 x 6 x 5-1/4

In addition, it was recognized that deployer weights for booms of smaller diameter might be of interest for other blanket configurations and boom materials. Accordingly, the following results were calculated based on known relationships between weight and diameter:

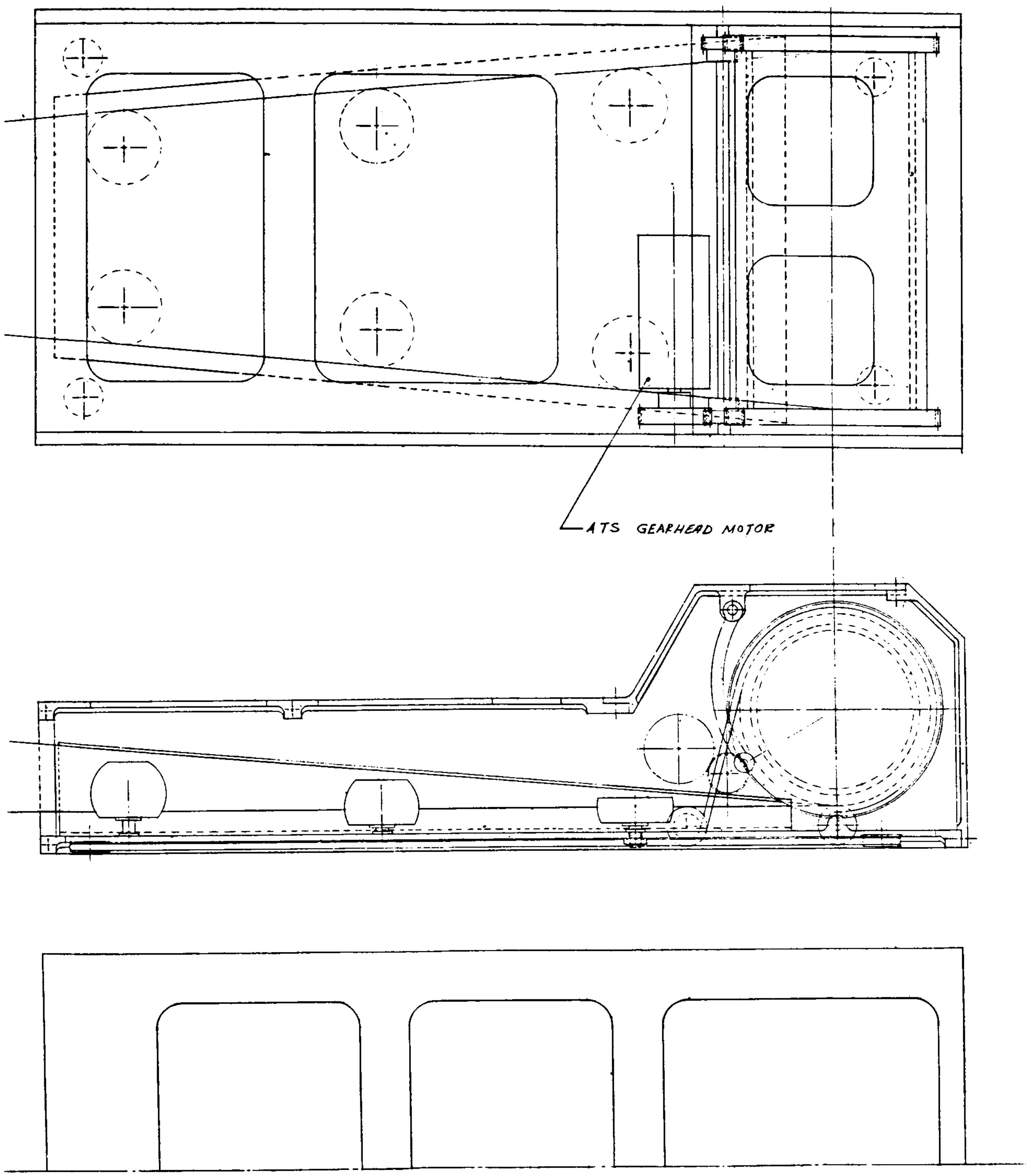
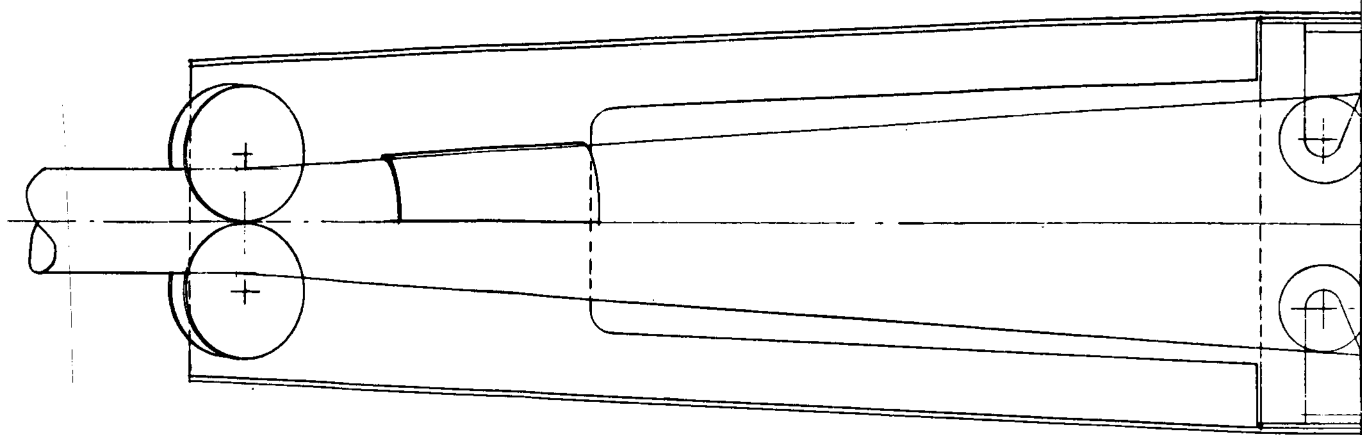
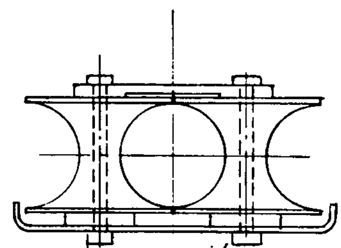
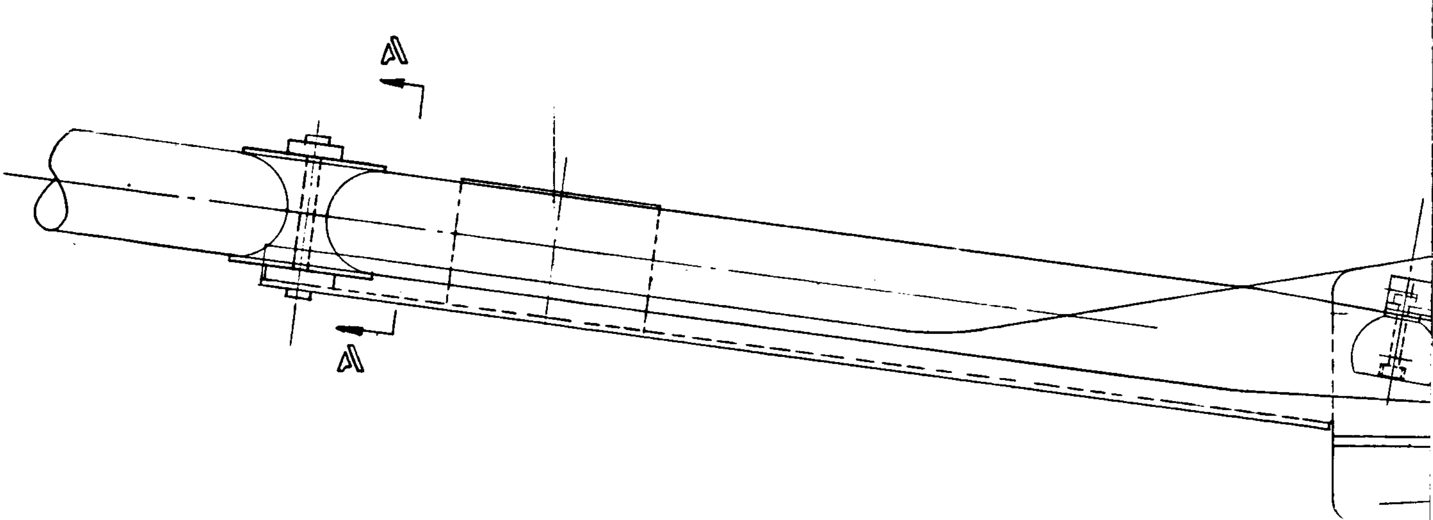


Figure 2-8. Deployment Mechanism for 1.5-Inch Diameter Stem Boom





SECTION A-A



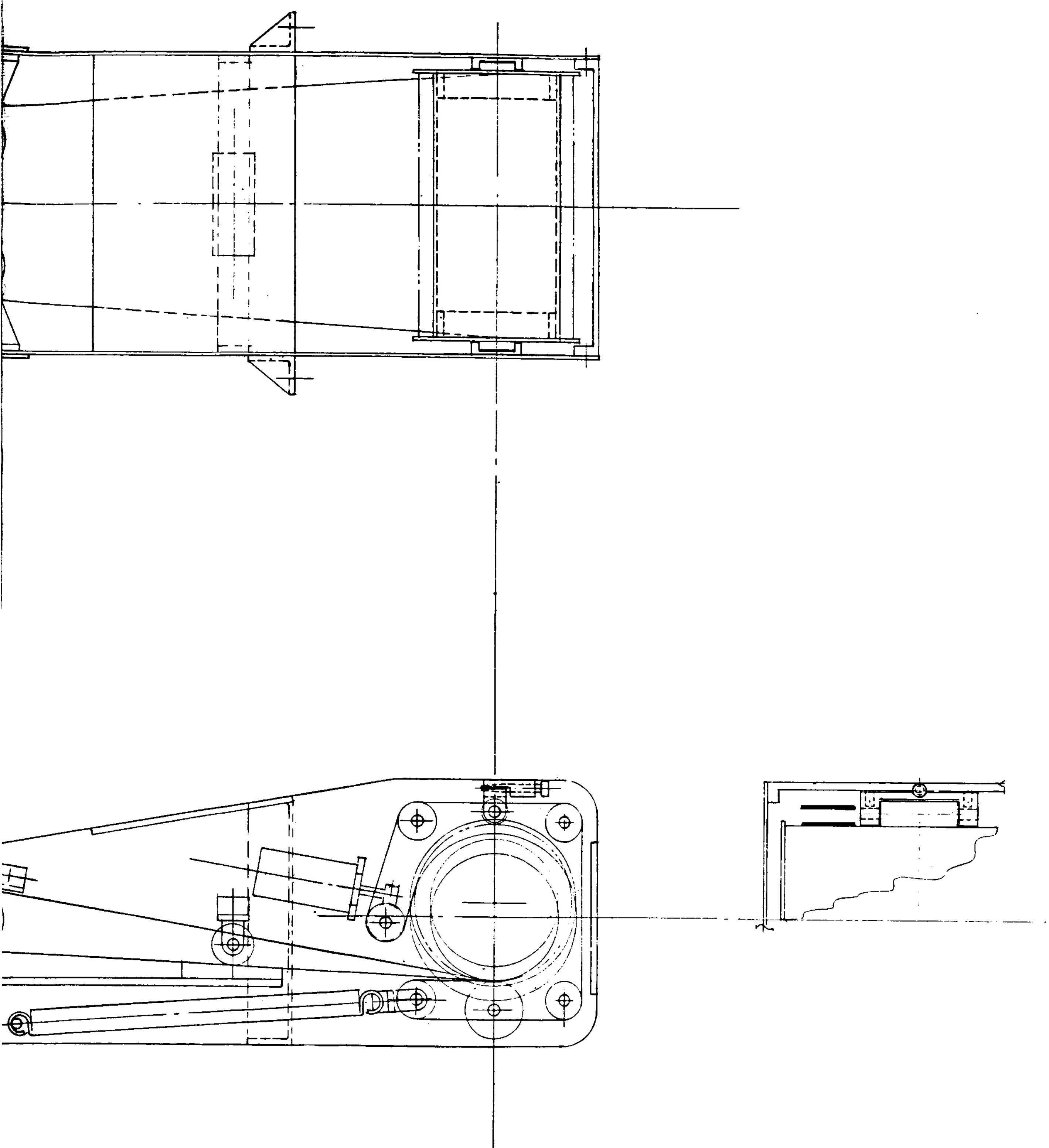


Figure 2-9. Deployment Mechanism for
1.5-Inch Diameter Interlocked Rod

[redacted]

Boom Diameter	Boom Type	Deployer Weight* (lb)
1.00	STEM	5.0
1.25	STEM	6.6
1.00	Digitated	6.0
1.25	Digitated	7.7

*Assuming boom length less than 40 feet

In addition to the work on the originaly designated boom configurations, attention was directed toward the deHavilland BI-STEM because of the attractive weight-to-strength/stiffness ratios when deployer weight is considered. (Note: The BI-STEM enjoys the unique advantage of ploy lengths approximately one-half those of the ordinary STEM. BI-STEM results are as follows:

Boom Length (ft)	BI-STEM Configuration Req'd	BI-STEM Weight (lb)	BI-STEM Deployer Weight	No. of BI-STEMS Req'd	Total Boom Weight
31	1.34 x 0.007	5.94	4.2	1	10.14
21	0.86 x 0.005	1.77	2.5	2	8.54

2.3.1 VENDOR CONTACT ON BOOMS

One of the attractive boom types for this application is the Hunter Stacer Spiral Wrapped Boom. This boom appears advantageous from the standpoint of ejecting force (internal to deployer) and from an overall weight standpoint referenced to the first cut deployment mechanism weights. However, only minimal information is available with respect to its performance as a thermally loaded beam column. Working sessions were held with the vendor in an attempt to gather more design data. From the results of these sessions, it appears that a moderate development test program is required to acquire the needed data. Such a program is currently under way. A sample rod of the 0.006 x 6 tape, having a length of 27 feet, tapering from 0.62 inch at the tip to 1.81 inches at the root, and weighing 5.6 pounds, has been initially subjected to load deflection tests in the GE water tank test installation. Data reduction to empirically establish structural performance of the rod is under way.

Based on internal ejecting forces only, the following sizes and weights were calculated by the vendor:

No. of Booms	Boom Length (ft)	Deployment RE Resistance Load per Boom (lb)	Boom Configuration	Boom Weight Each (lb)	Deployer Weight Each (lb)	Total Boom System Weight (lb)
2	21	1.65	0.006 x 6 tape	4.1	4.4	17
1	31	5.8	0.008 x 8 tape	10	10	20

Note: The axial loads are those previously defined for the 0.08 cps minimum system frequency. New sizes are currently being calculated for the lighter loads. Note that the above boom sizes have not been analyzed for thermal beam column loading conditions, and weight may therefore increase when the analysis is complete. Note also that the deployer weights are merely engineering estimates.

2.3.2 EJECTING FORCE

The ejecting force capabilities of the candidate STEM type booms are far above the 3.1 pound resistance to deployment. A 0.5-inch diameter, 0.002-inch thick STEM unit has previously been demonstrated to repeatedly deploy against a 2-pound resistance. A similar size interlocking unit deployed against a 5-pound resistance. The mode of failure involved in buckling as a flat plate in compression. Force is theoretically a function of t^2. Accordingly, the 0.006-inch thick STEM boom should carry;

$$F = 2 \times \frac{(0.006)^2}{(0.002)^2} = 18 \text{ pounds}$$

The self-ejecting force for this boom was calculated to be 3.5 pounds. The motor selected can deliver 11.5 pounds tangent to the drum at normal running load. Therefore, the 1.5-inch diameter STEM unit can deploy against a 15-pound load without overloading the motor and can statically react an 18-pound load internally to the deployment unit without tape-buckling.

2.4 TASK B - SOLAR CELL TECHNOLOGY EXTRAPOLATION

This task, which consisted mainly of converting the JPL-supplied data on the Heliotek 8-mil, N/P, 10 ohm-cm solar cell into the form usable by the GE I-V curve generating computer program, has been completed. I-V calculations were made for the various temperature ranges from +120°C to -120°C and checked against the empirical data supplied. The set of voltage-current characteristic curves, which were the supplied data, are shown in Figure 2-10. Also plotted are individual points from check curves calculated by the computer program after its modification with the coefficients derived from the basic curves.

Variations from the empirical data in the region between the knee of the curve and short circuit current are less than 1 milliamp for all curves, and less than 5 millivolts in the region between the knee and open circuit voltage. I-V curves for each of the potential cell arrangements, for both the single rod and double rod configurations, were generated with the modified computer program. The 56.9 volt curve applicable to both the double and single rod configuration is shown in Figure 2-11 with the nearest lower voltage configuration curve for each of the deployment methods.

In order to attain the performance shown, the cell performance must be 10.58 percent at AMO, 140 mw/cm^2 intensity, and at 28°C temperature. The basic cell on which the empirical data was generated has an efficiency of 10.09 percent at these conditions. Shifting the design point to the higher efficiency in order to attain the specified 10 watts/square foot when operating at 55°C was one of the JPL directives at the initiation of the program. A cover glass loss of 0.94 percent is included in the performance curves shown.

Current-voltage data from the program was also used for the basic input to the busbar study.

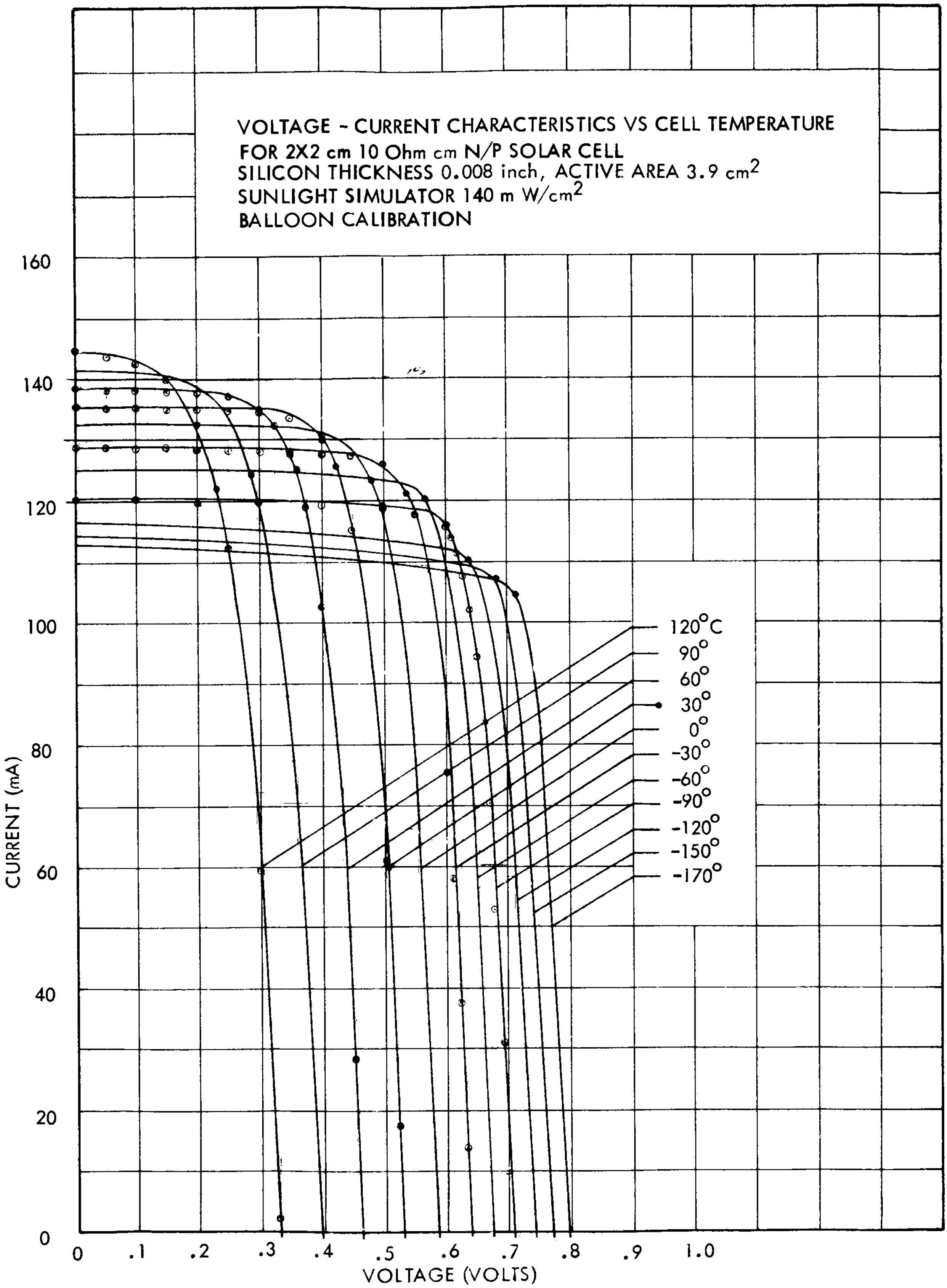
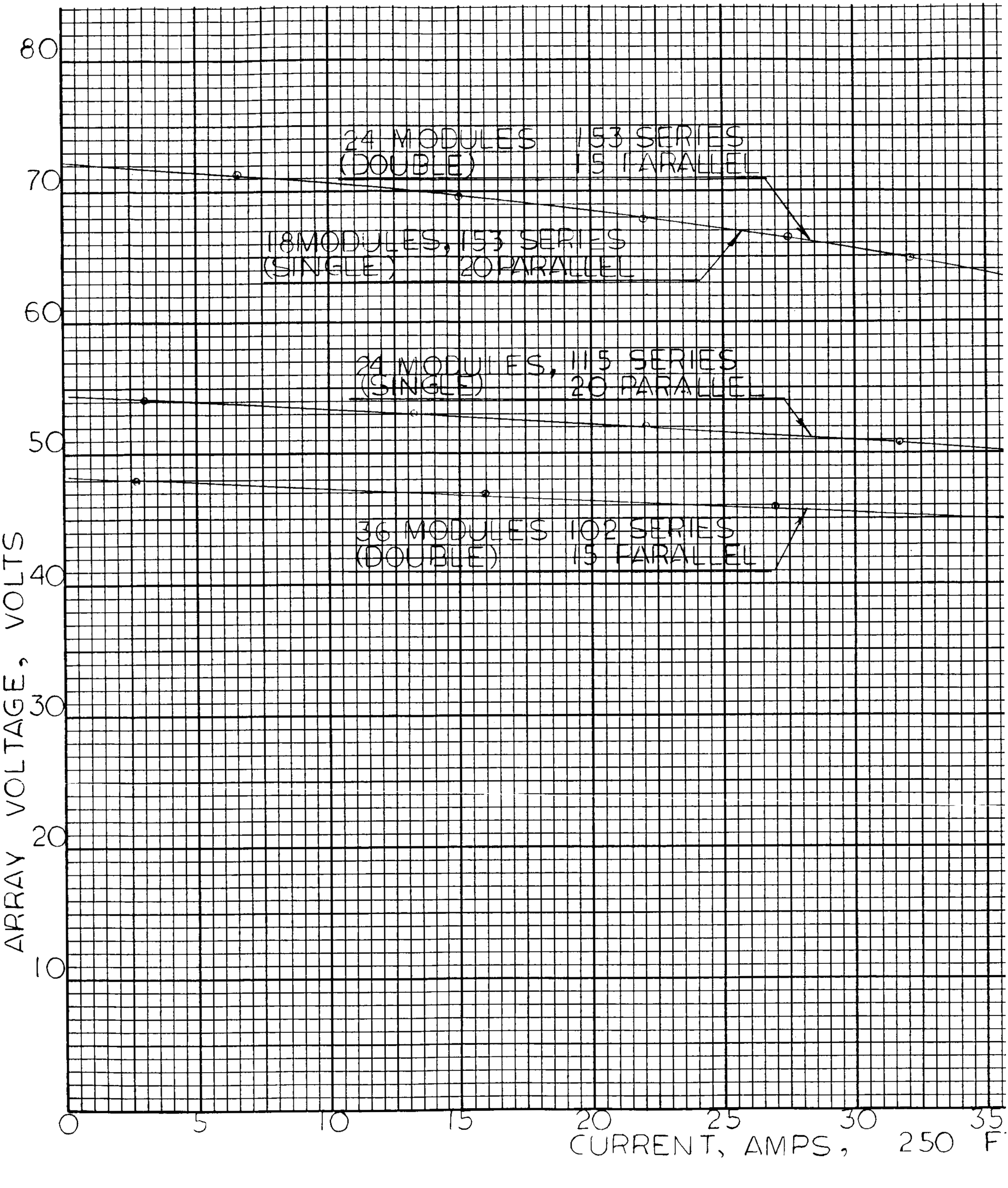


Figure 2-10. Voltage-Current Characteristics vs Cell Temperature



24 MODULES 153 SERIES
(DOUBLE) 15 PARALLEL
18MODULES, 153 SERIES
(SINGLE) 20 PARALLEL
24 MODULES, 115 SERIES
(SINGLE) 20 PARALLEL
36 MODULES 102 SERIES
(DOUBLE) 15 PARALLEL
ARRAY VOLTAGE, VOLTS
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CURRENT, AMPS, 250 F

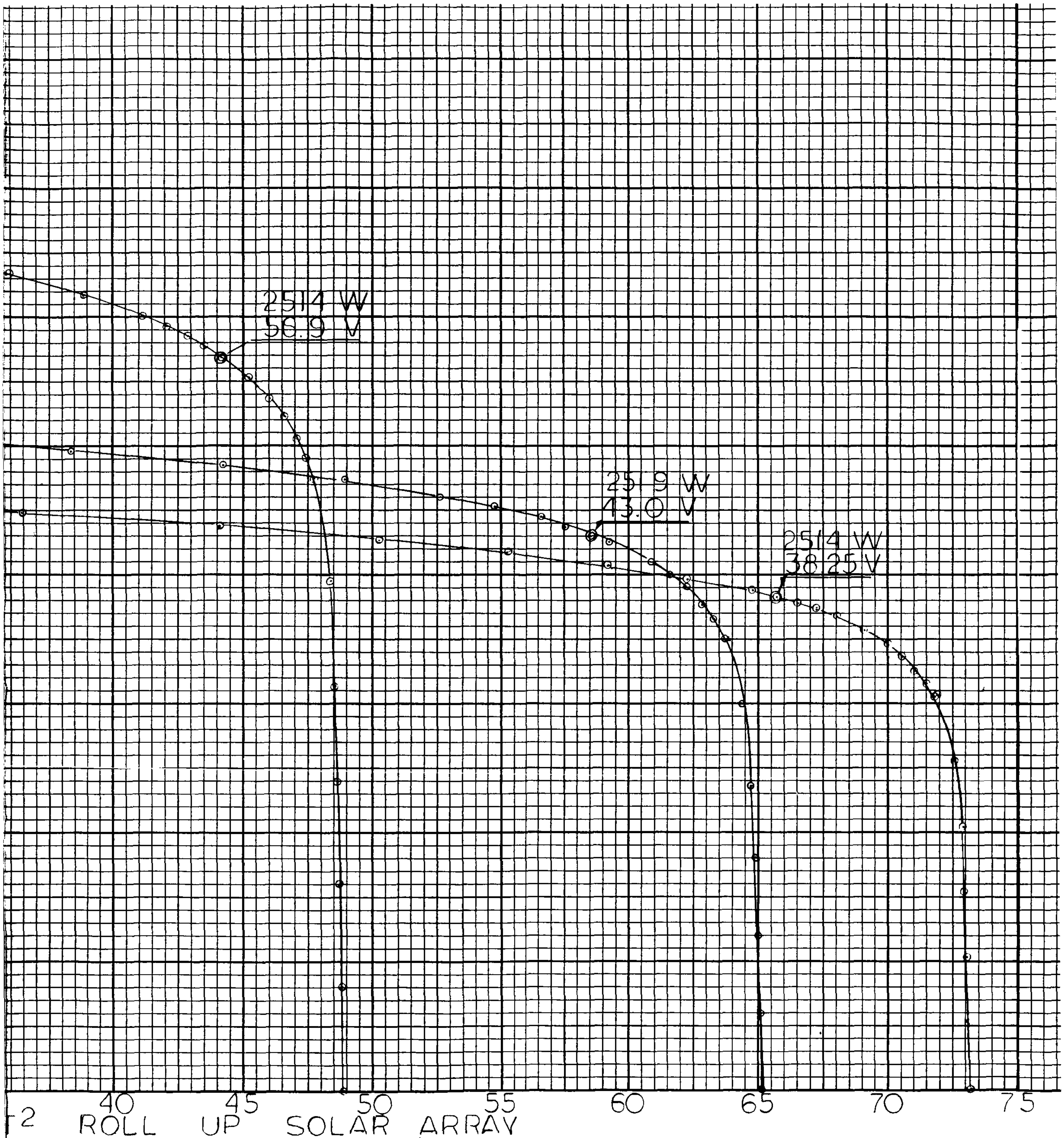


Figure 2-11. I-V Curves for Single and Double Rod Configurations

2.5 TASK 3 - SOLAR CELL COMPONENT REQUIREMENTS

To keep the most effort concentrated on the program during the initial stage, the following pattern has been followed with regard to establishment of candidate configurations:

a. Perform detail sizing of the components to establish, analytically, the accuracy of the preliminary design using assumed dynamic loading and blanket tension forces based on the experience with the CIRP model.

b. Concurrently perform dynamic analysis on the preliminary design configuration to refine the load data and enable correction of the assumptions.

c. Iterate the component design with the refined load values.

This approach was selected because, in the initial setting up of the design analysis for each of the components, there is considerable effort which is performed on a one-time basis, and which is independent of the actual accuracy of the loading assumptions. Iterative cycling to update the design in view of the corrected loading assumptions is achieved efficiently through the utilization of a desk-side computer system.

The principal assumptions affecting this design approach are as follows:

a. Amplification factor for vibration in the drum = 25. (This results in 25 x 4 g = 100 g design load for the drum stress study.)

b. An initial 5-pound blanket tension for the 12-ft wide x 20.83-ft long array. This has been revised to 3.3 pounds for attainment of a critical frequency of 0.08 cps. A second revision based on the decision to design closer to the specification goal of 0.04 cps has placed this load at 2.2 pounds, producing a design frequency of 0.06 cps.

c. An 8-pound blanket tension for the 8-ft wide x 31.25-ft long array. This was subsequently revised to 5.8 pounds (0.08 cps) and finally to 3.1 pounds (0.06 cps).

The deployment mechanisms have been covered in detail in Section 2.3. The remaining components on which sizing design has been performed to date will be covered in this section, and include the drum, array, and the array busbars.

2.5.1 DRUM

The goal of this effort has been to achieve the drum function with the most efficient structure.

Both the double-rod and single-rod designs considered have sections of the drum cantilevered from the mounting structure. As initially conceived, the central stationary shaft which anchors the spiral busbar and power connection provided the support for the drum. Under the assumed loading (amplification factor of 25 x the 4 g sinusoidal input), the weight of a member to support the drum became prohibitive -- approximately 12.7 pounds (in contrast with the 1.01 and 0.76 pound values allotted to this member in the extrapolation of the IR&D technology).

An alternative load support which utilized the drum skin was devised and is illustrated in Figure 2-12. Sizing of both drums was performed, and the critical crippling stress was the limiting consideration for a single-ply drum skin. The resulting skin thicknesses (aluminum) were 0.032 inch for the 12-foot double-rod system drum (11.58 pounds skin + 3.85 pounds for each fittings = 15.43 pound drum weight) and 0.049 inch for the single-rod drum (resulting in a skin weight of 13.30 pounds and an end fitting weight of 4.0 pounds for a total drum weight of 18.1 pounds.

Use of magnesium for the drum material results in a weight saving without loss of dynamic performance. For the 12-foot drum described above the skin thickness required with magnesium is 0.040 inch, which yields a corresponding drum skin weight of 9.19 pounds, for a 2.39 pound saving. The weight advantages for the end fittings have not been determined.

2.5.1.1 Iteration of Stresses When Ends Are Supported

A revision of the supports for the drum was considered and is shown in Figures 2-13 and 2-14. The maximum moment occurs at the fixed end and is 24,750 inch-pounds. The drum section thickness required is 0.036 inch for aluminum, with a corresponding weight of 8.68 pounds. For the purposes of this design, a magnesium drum will be more efficient. Gauge of material required for the 8-foot drum is 0.045 inch in magnesium. The drum skin weight will be 6.95 pounds. These weights are based on the assumed amplification of 25 for the vibration loads and need to be verified by dynamic analysis.

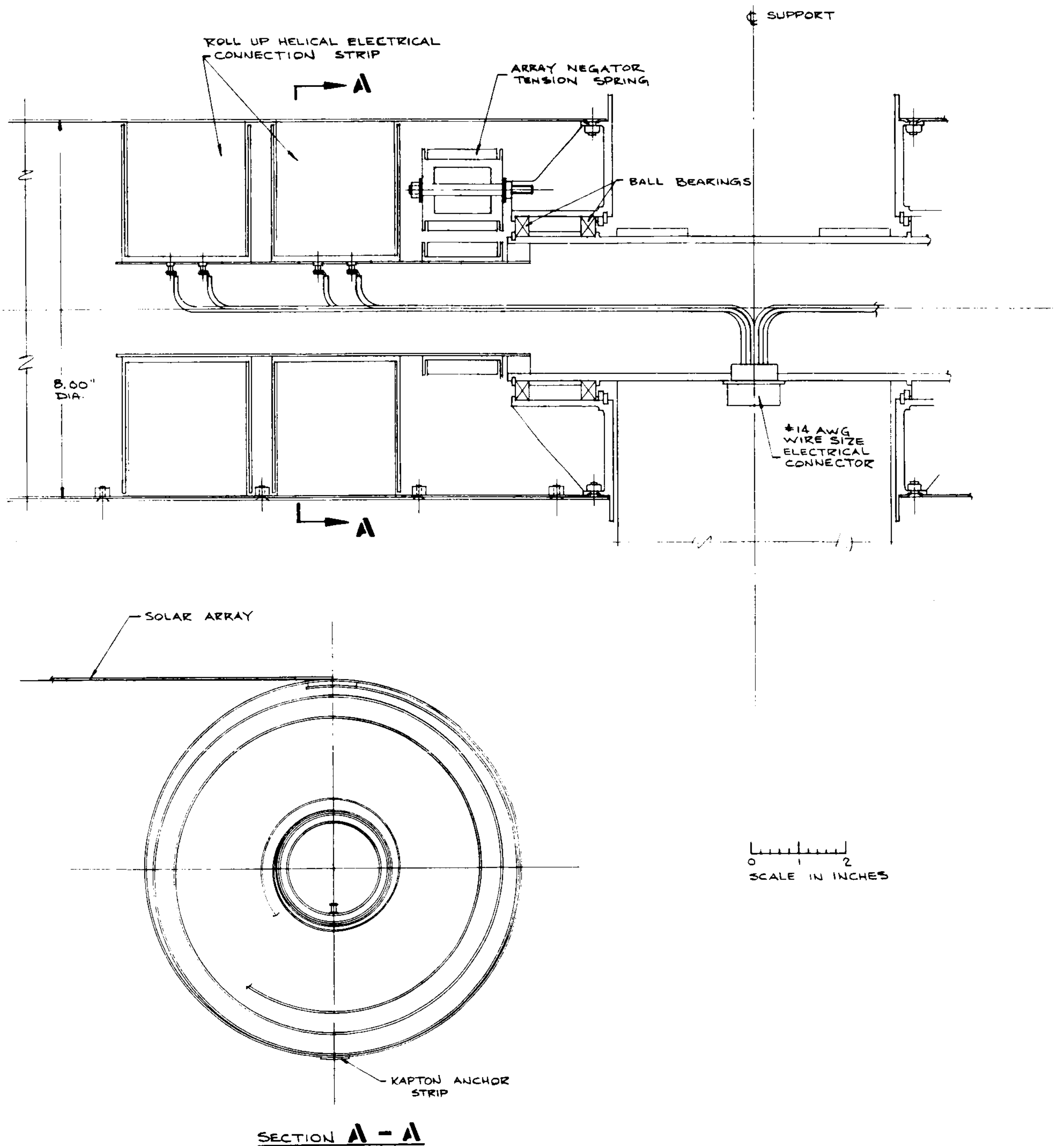
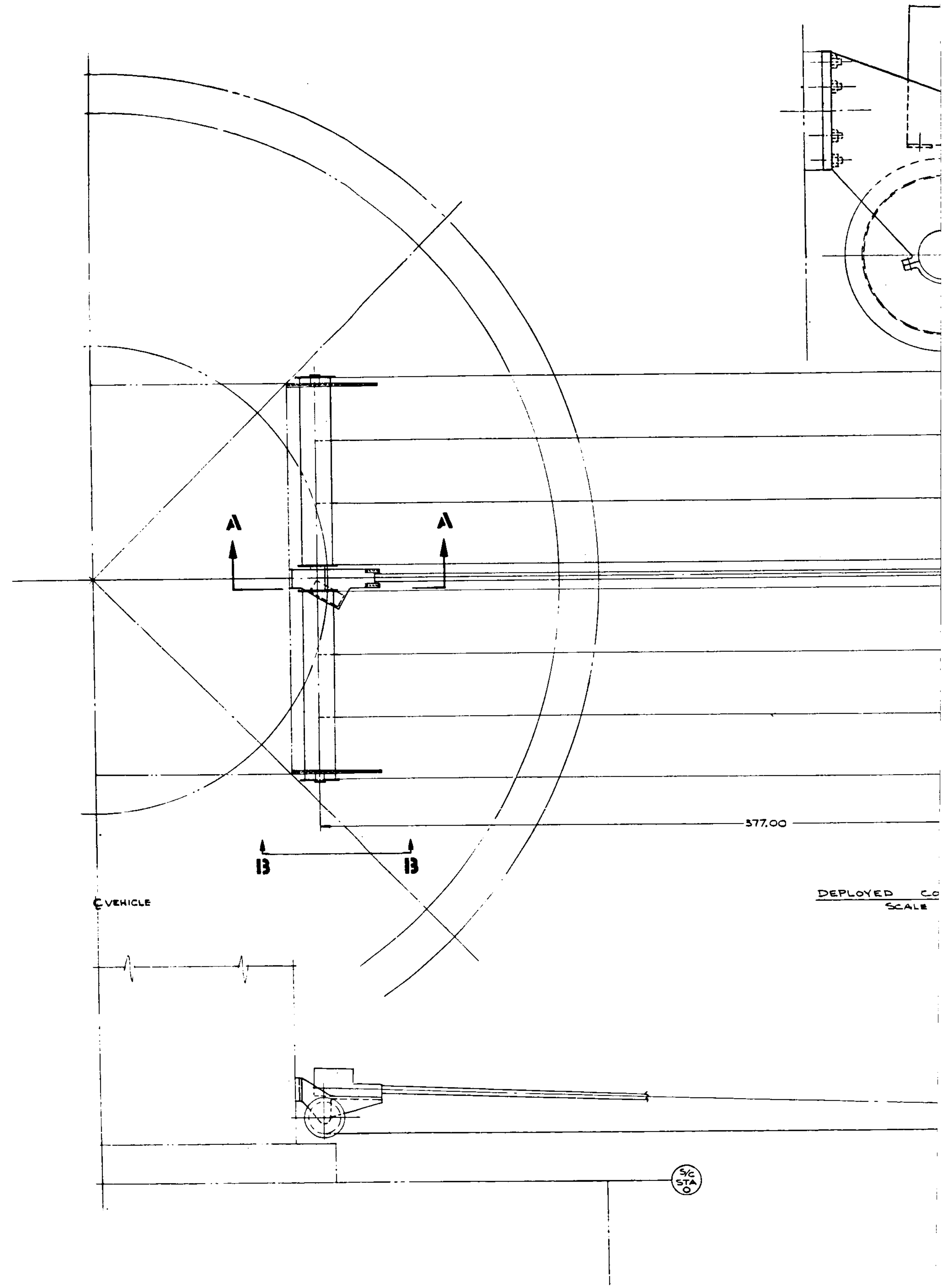


Figure 2-12. Rollup Solar Array Drum Support and Details, Single-Rod Arrangement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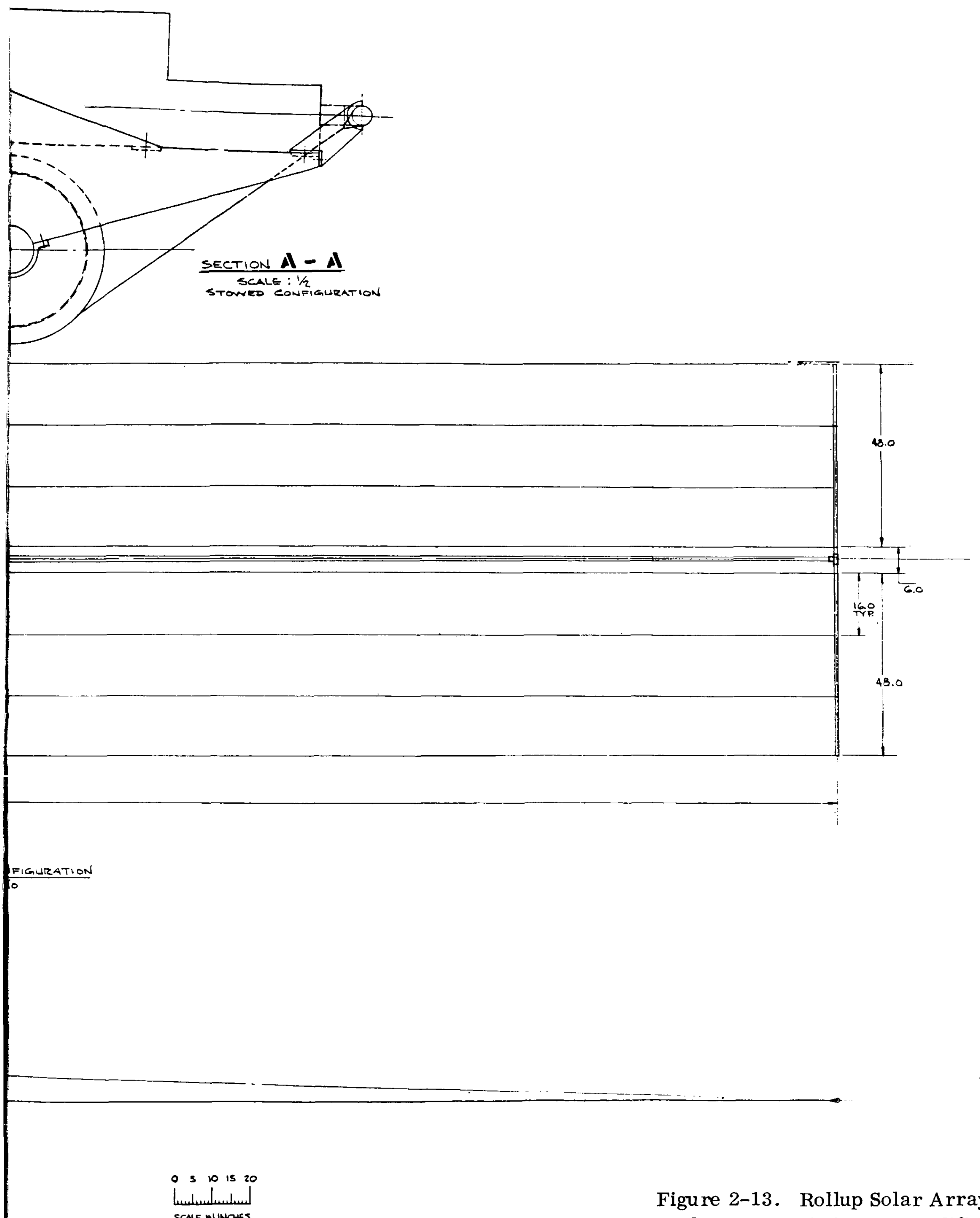
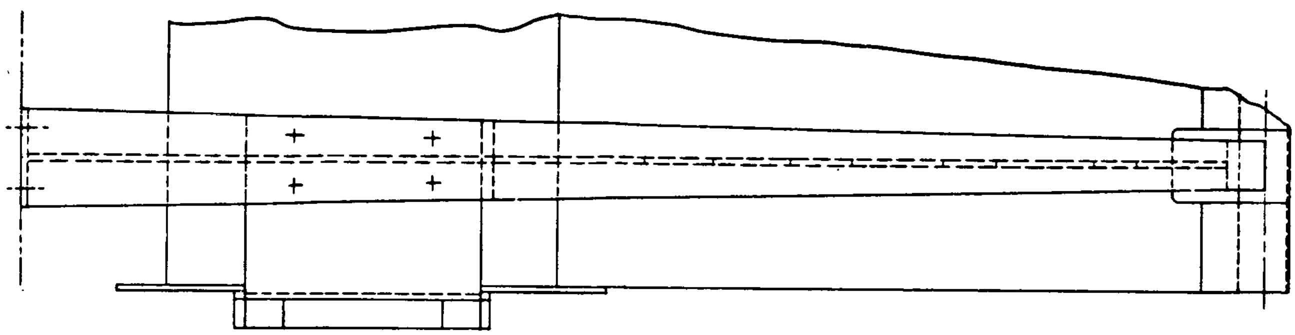
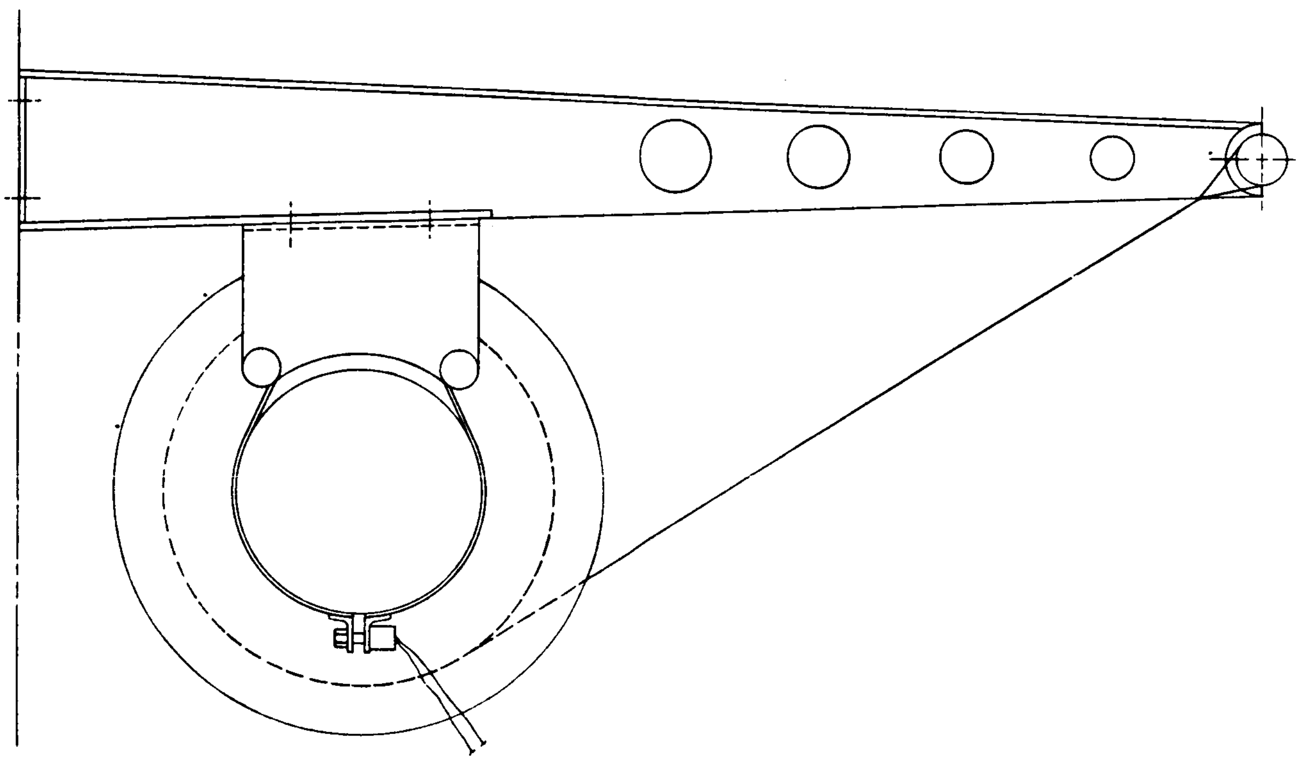


Figure 2-13. Rollup Solar Array Single Deployment Rod Showing Modified Drum Supports (Deployed Configuration)



TOP VIEW



VIEW B-B

STOWED CONFIGURATION

Figure 2-14. Rollup Solar Array Single Deployment Rod Showing Modified Drum Support (Stowed Configuration)

2.5.2 BUSBAR ARRAY PANEL DISTRIBUTION

A promising material (SchjelClad 5550 or L7510) to fulfill the busbar function on the rollup array has been evaluated electrically and under flexure for another application. A desk-side computer program to size the busbar as a function of power loss was written and the parametric results for both 12.0 x 20.83 foot and 8.0 x 31.25 foot solar arrays are given in Tables 2-5 and 2-6 and Figures 2-15 and 2-16. As can be seen from the curves, the bus-bar weight requirements become important weight factors below voltages of 60 volts for the 2 and 3 percent loss cases, and below 88 for the 1 percent loss case. It is also evident that weight continually decreases with increasing voltage so that other considerations will provide the restraints that will limit the voltage level.

Given a voltage, there is an optimum busbar loss as shown in Figures 2-17 and 2-18. These curves trade off busbar weight at constant voltage with the weight of the additional array system required to make up the loss in the busbars. The voltages considered are the ones that result from integral numbers of series strings of solar cells fitted within the lengths of panel derived in the configuration studies. Restricting the performance loss due to the complete failure of a module to less than 6 percent of the total panel capability resulted in selection of 153 series cells in a module for both systems which provides a peak power voltage at 55°C of 56.9 volts.

Table 2-5. Busbar Weight as a Function of Voltage and Power Loss (8 ft x 31.25 ft Array)

No. Modules In Array	No. Cells per Module			Peak Power Voltage	Bus Bar Weight (lb)			Bus Bar Weight & System Weight (@ 30 w/lb) to Make Up Losses (lb)		
	Series	Parallel	Total		1% Voltage Drop	2% Voltage Drop	3% Voltage Drop	1% Voltage Drop	2% Voltage Drop	3% Voltage Drop
6 x 6 (36)	77	20	1540	28.8	16.862	8.431	5.621	17.695	10.097	8.120
5 x 6 (30)	92	20	1840	34.2	11.766	5.883	3.922	12.599	7.549	6.421
4 x 6 (24)	115	20	2300	43.0	7.401	3.700	2.467	8.234	5.366	4.966
3 x 6 (18)	153	20	3060	56.9	4.162	2.081*	1.387	4.995	3.747	3.886
2 x 6 (12)	230	20	4600	86.5	1.741	0.871	0.580	2.574	2.537	3.079
1 x 6 (6)	459	20	9181	170.6	0.356	0.178	0.119	1.189	1.844	2.618

*Tentative Design Point

Table 2-6. Busbar Weight vs System Voltage and Power Loss (12.0 ft x 20.83 ft Array)

No. Modules in Array	No. Cells per Module			Peak Power Voltage	Bus Bar Weight (lb)			Bus Bar Weight & System Weight (@ 30 w/lb) to Make Up Losses (lb)		
	Series	Parallel	Total		1% Voltage Drop	2% Voltage Drop	3% Voltage Drop	1% Voltage Drop	2% Voltage Drop	3% Voltage Drop
5 x 12 (60)	65	15	975	24.37	12.258	6.129	4.086	13.091	7.795	6.585
4 x 12 (48)	77	15	1155	28.30	7.428	3.714	2.476	8.261	5.380	4.975
3 x 12 (36)	102	15	1530	38.25	4.078	2.039	1.359	4.911	3.705	3.858
2 x 12 (24)	153	15	2295	56.90	1.777	0.889*	0.592	2.610	2.555	3.091
1 x 12 (12)	306	15	4590	114.75	0.350	0.175	0.117	1.183	1.841	2.616

*Tentative Design Point

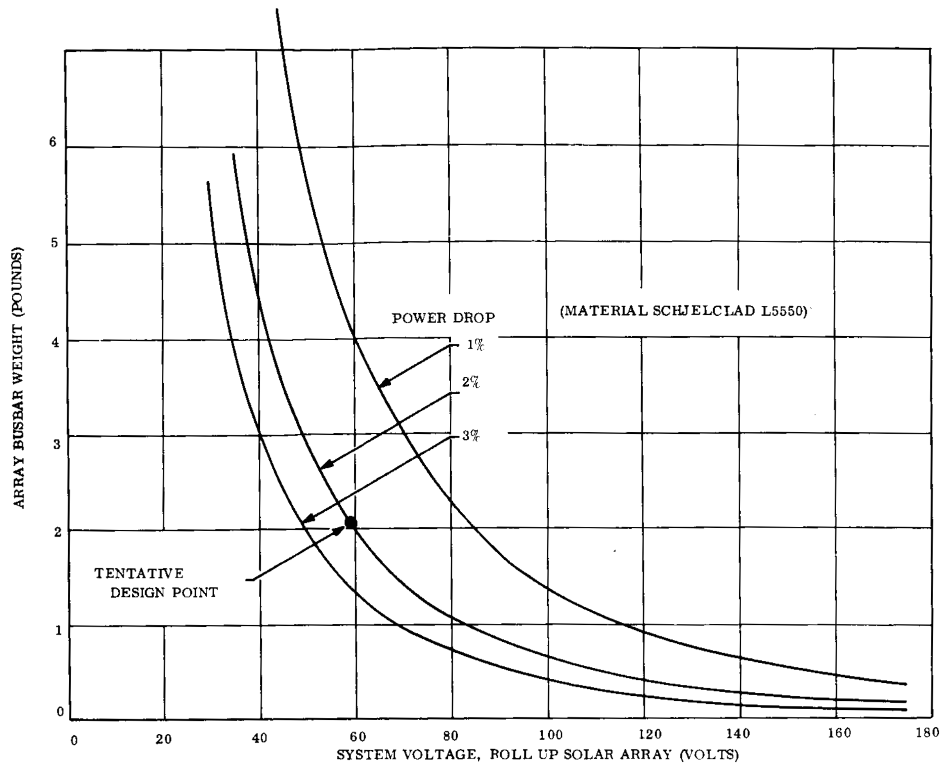


Figure 2-15. Busbar Weight vs System Voltage for 8 ft x 31.25 ft Solar Array Panel

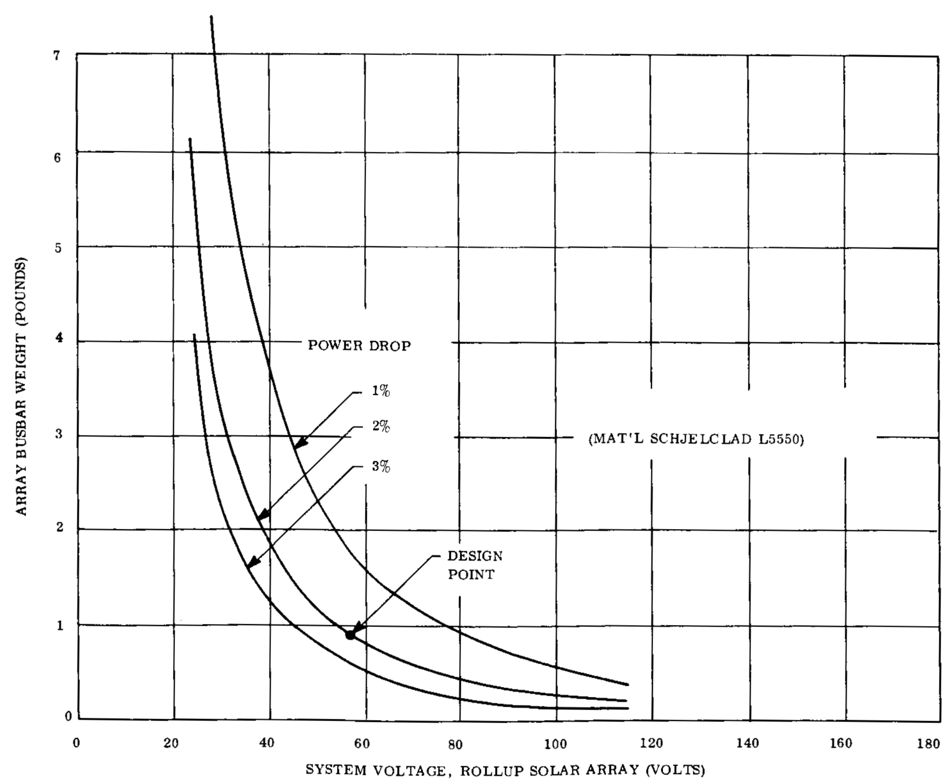


Figure 2-16. Busbar Weight vs System Voltage for 12.0 ft x 20.83 ft Solar Array Panel

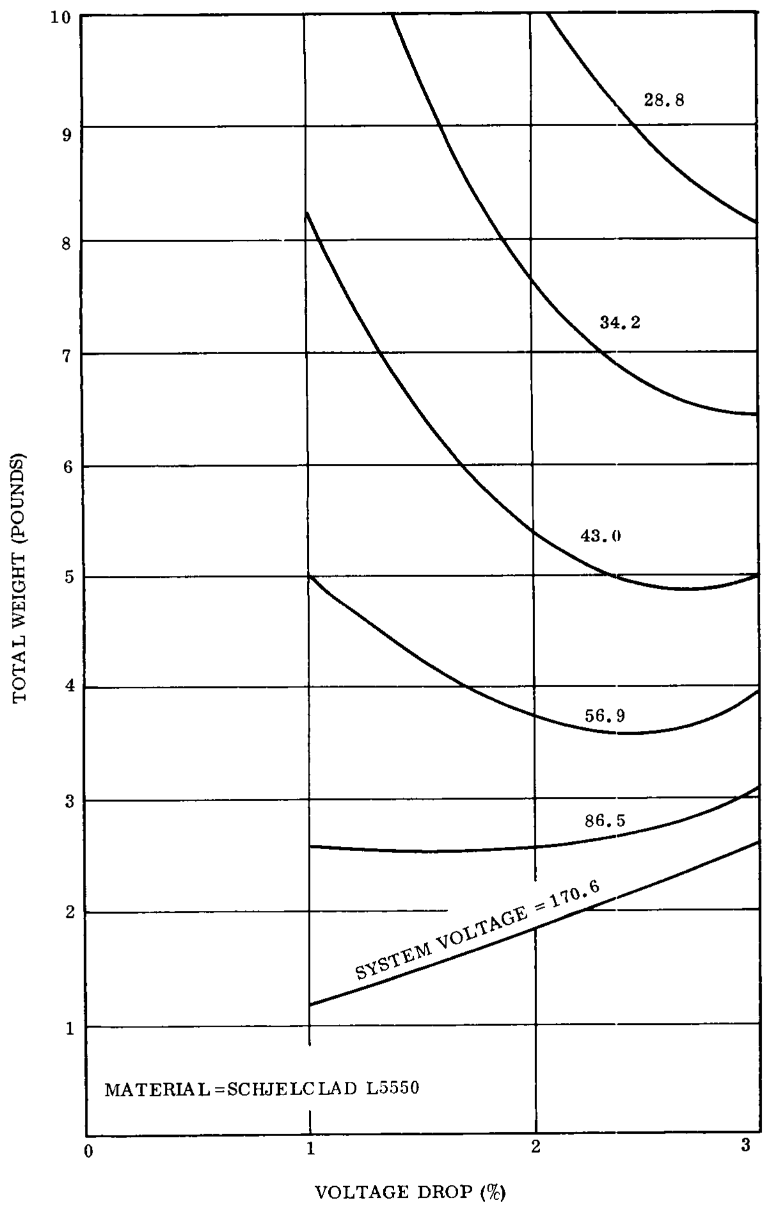


Figure 2-17. Total Weight (Busbars and System Weight Penalty) for Solar Array Panel (8 x 31.25 ft)

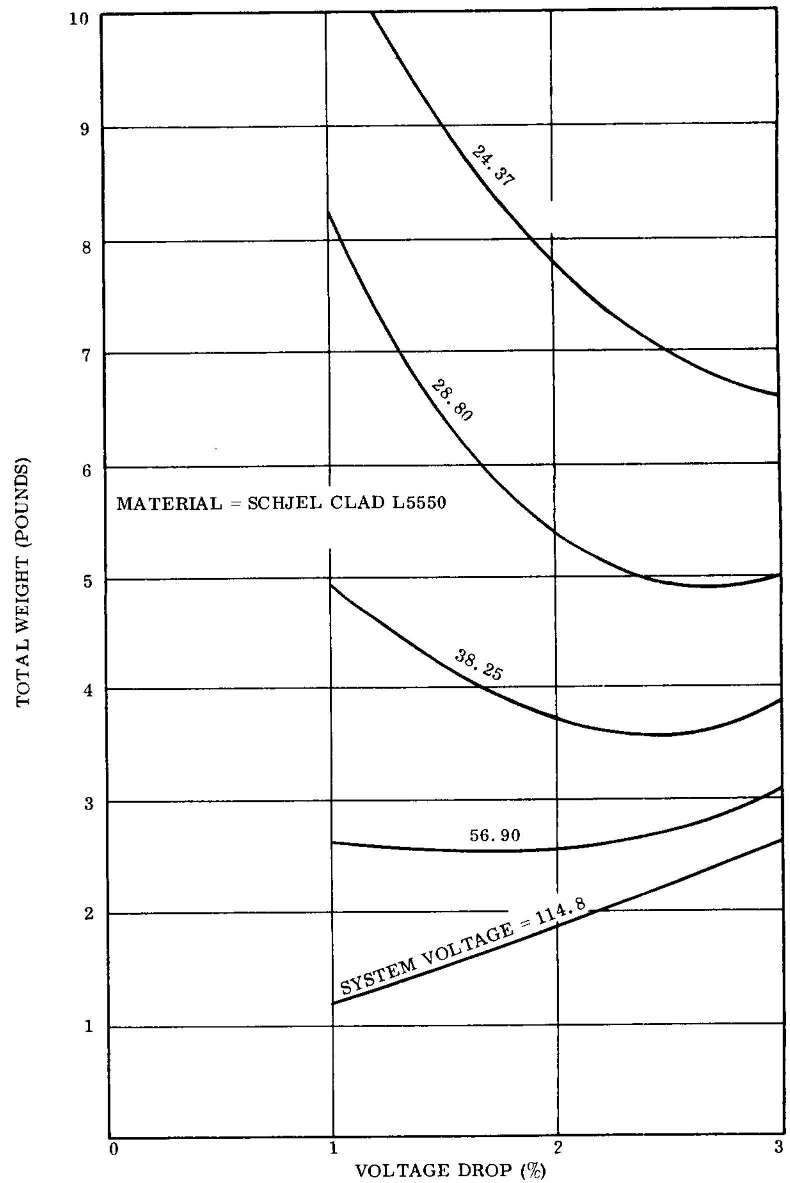


Figure 2-18. Total Weight (Busbars and System Weight Penalty) for Solar Array Panel (12 x 20.83 ft)

2.5.3 SOLAR CELL ARRAY

Materials and practices to be used in the solar cell array component will utilize to the greatest extent possible those which resulted in the successful vibration test of the CIRP model. The basic film on which the cells are to be laid is Kapton. The gauge previously used was 0.003, but it is possible that the SchjelClad busbars will provide sufficient stiffness to allow reduction of this to 0.002.

Cushioning of the layers of the array sheet when wrapped around the drum is accomplished by 0.250-inch diameter foamed buttons of RTV 580. These buttons are evident in the photograph of Figure 2-19. The vibration testing limits to which this unit was subjected are listed in the following tabulation:

SINE	5-14 cps	0.25 in_{0-P}
	14-400 cps	5.0 g_{0-P}
	400-2000 cps	7.5 g_{0-P}
	Sweeprate 1 oct/min 2 axes	
RANDOM	25-400 cps	0.7 g^2/cps
	400-2000 cps	0.13 g^2/cps
	Time: 5 min; 6 db/octave roll off	
ACOUSTIC	147 db O.A. for 5 min	
	154 db O.A. for 2 min	
SPECTRUM	127 db at 200 cps	
	138 db at 300 cps	

Interconnection of the solar cells will be by means of flexible photoetched beryllium copper tabs shown in a sample assembly in Figure 2-20. Interconnection of the modules will be by use of the same SchjelClad material used in the flexible busbars. Tabs of the same material and similar in their flexibility have been subjected to thermal cycling between +200°F and -200°F for 500 cycles successfully.

The active face of the sample solar cell assembly is shown in Figure 2-21. The cells are mounted on kapton and have a spacing of 0.818 inch in the series direction and 0.800 inch in the parallel direction.

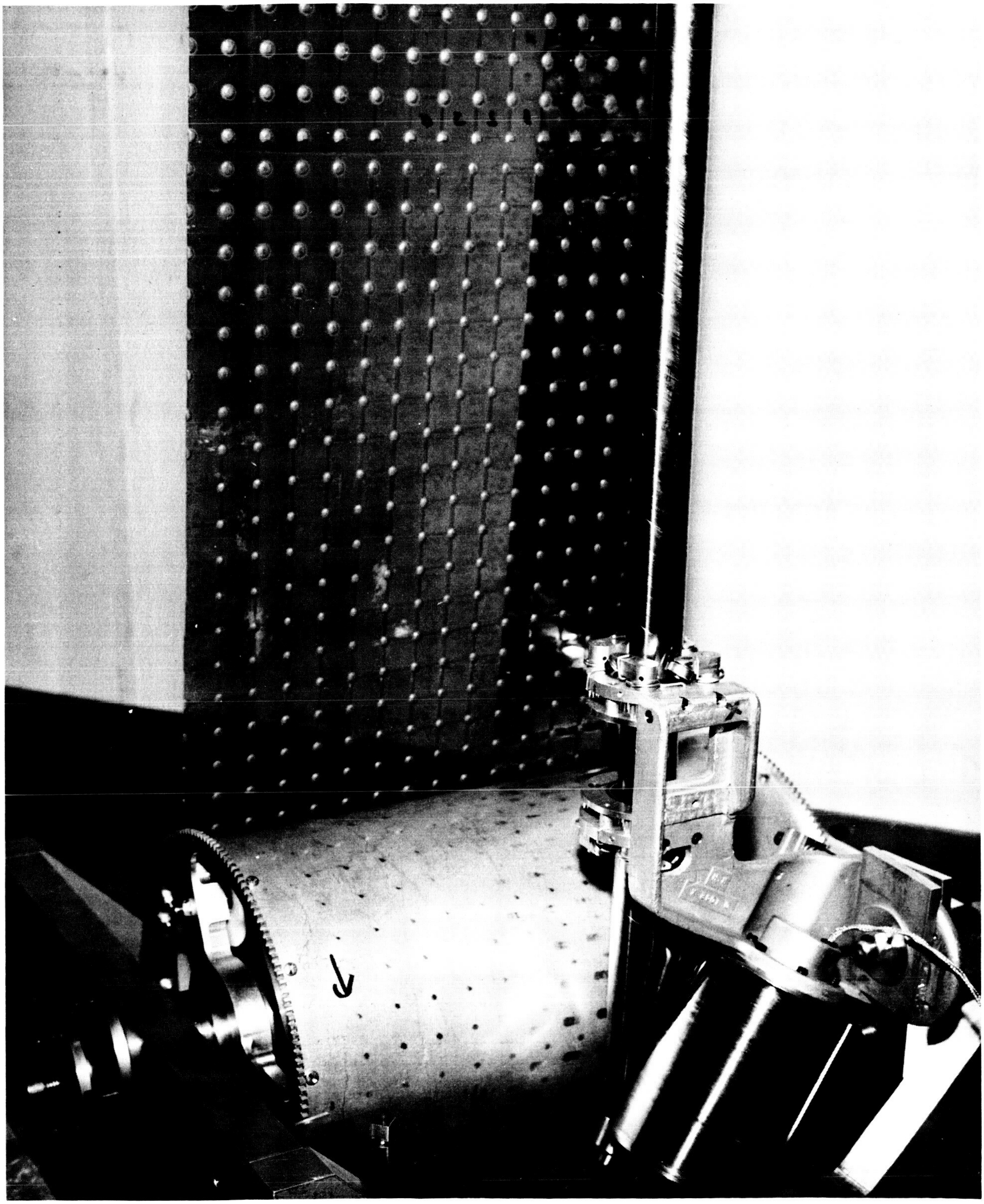


Figure 2-19. Underside of Solar Cell Array Sheet, CIRP Rollup Array Model

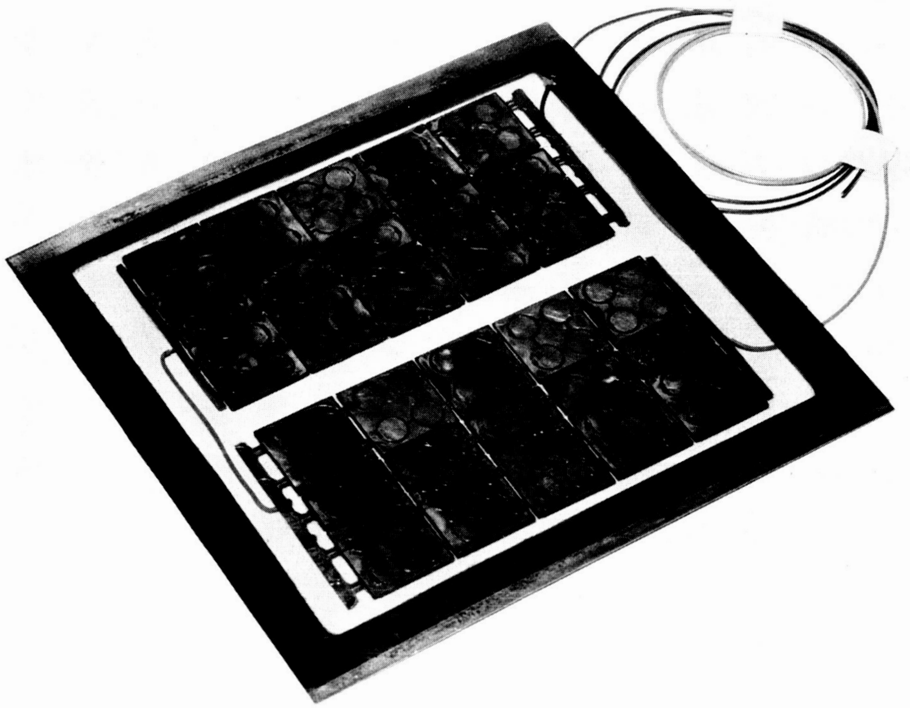


Figure 2-20. Sample Solar Cell Assembly Showing Flexible Interconnection Tabs

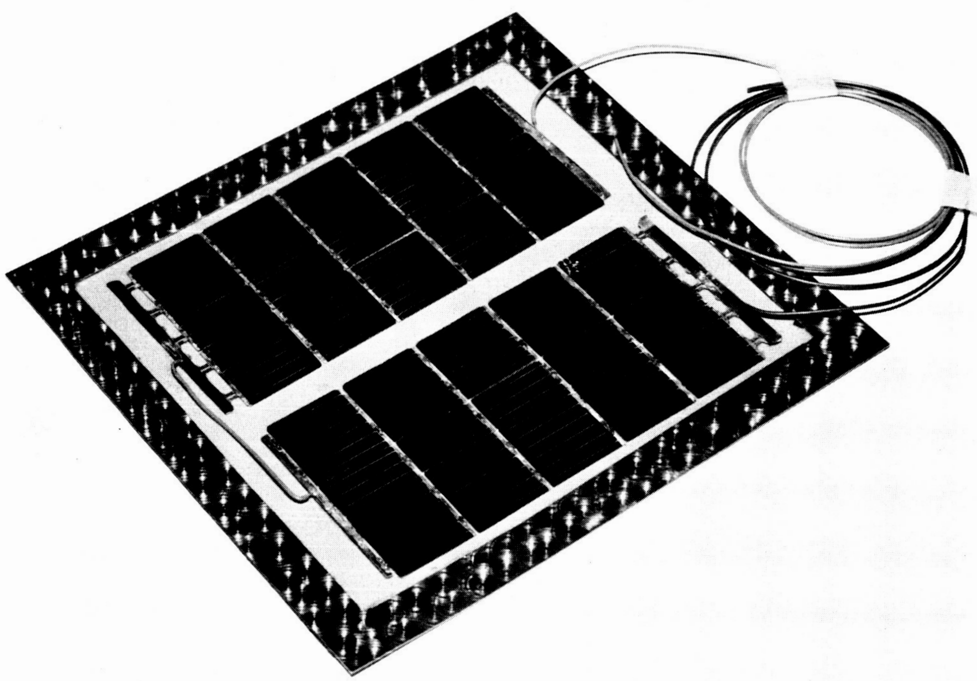


Figure 2-21. Sample Solar Cell Assembly, Active Side

SECTION 3

CONCLUSIONS

The following conclusions are presented:

a. A simple arrangement of the solar panels with respect to the vehicle provides a straightforward engineering approach to the requirements of this program. The selected arrangement consists of a single, fixed-drum per quadrant. A weight summary of a design typical of this arrangement is as follows:

Item	Weight (lb)	Percent of Total
Rod Tape	5.54	6.6
Deployment Mechanism	4.20	5.0
Array Sheet	45.92	55.1
Array	2.08	2.5
Drum	10.82	13.0
End Pieces	1.98	2.4
Miscellaneous and Margin	12.80	15.3
	83.34	99.9

b. It is practical to meet the weight and structural requirements with either a single or double boom deployment system. The single boom system is preferred from the standpoints of weight and simplicity. It has been shown by analysis that the required structural performance can be achieved by means of tension in the solar array blanket. A single boom model provides a physical demonstration of the dynamics of the system and the torsional restraint provided by the tension in the solar array blanket.

c. Studies to date show that the deployable boom selection is a choice between several options with nearly equal performance. Off the shelf engineering models have demonstrated the required characteristics in many important respects. At this point it is concluded there will be no need for a high risk development program aimed at a deployable boom performance that is, at best, marginal.

SECTION 4
RECOMMENDATIONS

Based upon the program results achieved to date it is recommended that efforts in the following period be focused on selecting a design solution that meets specifications and which can be developed in a logical fashion. This should be followed by detailed design of the elements of the system which will result in the identification of problems and requirements associated with the auxiliaries of the system. Solutions to these problems as well as a complete understanding of the detailed requirements of the system elements must be obtained to provide assurance that the system specifications can be met.

It is appropriate that design reviews on the key program decisions be initiated.

SECTION 5

NEW TECHNOLOGY

No reportable items of new technology have been identified.

APPENDIX A

DETAIL EVALUATION TABLES - STUDY OF CANDIDATE ARRANGEMENTS

WEIGHT

CONFIGURATION	FM	REMARKS
I	10	Short drum (0): mounted close to vehicle (short supports) (0): cantilevered from center, no fixed end supports (0): not deployed (0)
II	2	Long drum (-3): drum mounted out from vehicle (requires added supports) (-2): deployed from (-2): cantilevered from one end (heavy support) (-1)
III	2	Medium drum (-1): drum mounted close to vehicle (0): cantilevered from one end (-1): deployed drum (-2): deployment sequenced (-1): 8 drums req'd (-3)
IV	5	Longer than 3 (-2): mounted close to vehicle (0): cantilevered from one end (-1): deployed drum (-2)
V	4	Medium drum (-1): mounted out from vehicle (-2): not deployed (0): 8 drums (-3)
VI	7	Long drum (-3): mounted close to vehicle (0): not deployed (0)
VII	2	Long drum (-3): mounted close to vehicle (-2): deployed drum (-2): cantilevered from one end (-1)
VIII	4	Long drum (-3): mounted close to vehicle (0): d deployed drum (-2): cantilevered from one end (-1)
IX	8	Medium drum (-1): mounted close to vehicle (0): not deployed (0): supports not symmetrical (-1)

COMPLEXITY

CONFIGURATION	FM	REMARKS
I	9	Simple support (0): not deployed (0): 4 drums (0): cantilevered from center (-1): short drum (0)
II	6	Support out from vehicle (-1): deployed (-1): cantilever (hinged support) (-1): long drum (more complex drum design) (-1)
III	4	Deployed drum (-1): cantilevered support (-1): medium length (-1): sequenced deployment (-1): mounted on different levels (-1): 8 drums (-1)
IV	5	Deployed drum (-1): cantilevered support (-1): medium length (-1): two solar panels per drum (-1): mounted on different levels (-1)
V	6	Not deployed (0): 8 drums (-1): medium length (-1): support out from vehicle (-1): mounted on different levels (-1)
VI	8	Not deployed (0): long drum (-1): mounted on different levels (-1)
VII	5	Deployed drum (-1): support out from vehicle (-1): cantilevered support (-1): two solar panels per drum (-1): long drum (-1)
VIII	7	Deployed drum (-1): cantilevered support (-1): long drum (-1)
IX	8	Medium drum (-1): not deployed (0): supports (-1)

COST

CONFIGURATION	FM	REMARKS
I	10	4 drums: simple supports; no deployment: no hinged supports: same level: symmetrical: short drums
II	6	4 drums: deployed (-1); hinged (-1): long drums (-1): supports away from vehicle (-1): symmetrical: same level
III	4	8 drums (-1): deployed (-1): sequence deployment (-1): hinged (-1): different levels (-1): symmetrical: medium length drums (-1)
IV	5	4 drums: deployed (-1): hinged (-1): different levels (-1): medium length drums (-1): 2 panels per drum (-1)
V	6	8 drums (-1): no deployment: different levels (-1): supports away from vehicle (-1): nonsymmetrical supports (-1)
VI	8	4 drums: simple supports: no deployment: no hinges: different levels (-1): symmetrical: long drums (-1)
VII	5	2 drums: deployed (-1): hinged (-1): same level: symmetrical: long drums (-1) supports away from vehicle (-1): 2 panels per drum (-1)
VIII	7	4 drums: deployed (-1): hinged (-1): same level: symmetrical: long drums (-1)
IX	8	4 drums: no deployment: no hinge: simple support: support nonsymmetrical (-1): medium length drums (-1): same level

RELIABILITY

CONFIGURATIONS	FM	REMARKS
I	9	No deployment (0): 4 drums (-1) simple supports (0)
II	7	Deployed (-1): 4 drums (-1): hinged and cantilevered support (-1)
III	5	Sequence deployed (-2): 8 drums (-2): hinged and cantilevered support (-1)
IV	6	Deployed (-1): 4 drums (-1): 2 panels per drum (-1): hinged and cantilevered support (-1)
V	8	No deployment (0): 8 drums (-2): simple supports but away from vehicle (0)
VI	9	No deployment (0): 4 drums (-1): simple supports (0)
VII	7	Deployed (-1): 2 drums (0): 2 panels per drum (-1): hinged and cantilevered support (-1)
VIII	7	Deployed (-1): 4 drums (-1): hinged and cantilevered support (-1)
IX	9	No deployment (0): 4 drums (-1): simple supports (0)

SHADOWING

CONFIGURATIONS	FM	REMARKS
I	10	None
II	10	None
III	8	10%
IV	7	14%
V	8	10%
VI	9	4%
VII	10	None
VIII	10	None
IX	10	None

DRUM DEPLOYMENT

CONFIGURATIONS	FM	REMARKS
I	10	None
II	2	Drum deployed
III	0	Sequenced deployment
IV	2	Drum deployed
V	10	None
VI	10	None
VII	2	Drum deployed
VIII	2	Drum deployed
IX	10	None

AVAILABILITY

CONFIGURATION	FM	REMARKS
I	10	Readily available support, fab.
II	9	Deployment and support techniques available but require development and testing
III	9	Deployment and support techniques available but require development and testing
IV	7	Deployment and support techniques available but require development and testing plus winding two arrays per drum
V	10	Readily available support, fab.
VI	10	Readily available support, fab.
VII	7	Deployment and support techniques available but require development and testing plus winding two arrays per drum
VIII	9	Deployment and support techniques available but require development and testing
IX	10	Readily available support, fab.

MAINTAINABILITY

CONFIGURATION	FM	REMARKS
I	9	4 drums (-1): mounted on same level (0): not deployed (0): simple supports (0)
II	7	4 drums (-1): deployed (-1): cantilevered and hinged (-1)
III	4	8 drums (-2): deployed (-1): cantilevered and hinged (-1): mounting on different levels: (-1): deployed in sequence (-1)
IV	5	4 drums (-1): deployed (-1): cantilevered and hinged (-1): mounting on different levels (-1): twin panels per drum (-1)
V	7	8 drums (-2): not deployed (0): simple supports (0): mounting on different levels (-1)
VI	8	4 drums (-1): not deployed (0): simple supports (0): mounnting on different levels (-1)
VII	7	2 drums (0): deployed (-1): mounted on same level (0): two panels per drum (-1): cantilevered and hinged (-1)
VIII	8	4 drums (-1): mounted on same level (0): cantilevered and hinged (-1): deployed
IX	8	4 drums (-1): mounted on same level (0): not deployed (0): supports nonsymmetrical (-1)

APPENDIX B

PRELIMINARY DYNAMIC ANALYSIS FOR DEPLOYED ROLLUP SOLAR ARRAY

APPENDIX B

PRELIMINARY DYNAMIC ANALYSIS FOR DEPLOYED ROLLUP SOLAR ARRAY

B.1 INTRODUCTION

This appendix presents the results of the preliminary dynamic analyses conducted on the deployed 30 watt/lb rollup solar array. The analyses include the calculation of the frequencies and mode shapes of the single rod and double rod configurations. A primary objective of the analyses is to determine the feasibility of the single rod configuration from the standpoint of torsional rigidity.

An analysis of a membrane attached rigidly at one end and free at the other, as determined from string theory, is included for comparative purposes.

B.2 CONCLUSIONS

For the single rod system a study of the results presented herein indicate that the torsional capability provided by the preload in the membrane is sufficient to provide a first mode frequency in excess of the 0.04 Hz requirement. If the results presented in Table B-1 are compared to those presented in Figure B-1 it is evident that the preload in the membrane is the dominant element and that the rod contributions from a stiffness standpoint have little effect on the first mode-frequency but do affect the mode shape.

Based on an extrapolation of the results presented herein it is recommended that the following preloads be used in future design studies.

Length	Preload (lb)	System Configuration
31.25	3.1	Single rod
27.77	2.6	Single rod
20.83	2.2 (total)	Double rod

These preloads will provide a nominal 0.06 Hz first mode frequency which will provide sufficient margin until such time as a more detailed analysis is conducted.

Table B-1. Results of Single Rod Analysis

Case	Length (ft.)	Preload (lb)	Rod Stiffness Included	First Mode		Second Mode	
				Frequency (Hz)	Type	Frequency (Hz)	Type
1	31.25	10.0	No	0.015	BND.	0.113	TOR.
1a	31.25	10.0	Yes	0.113	TOR.	0.199	BND.
1b	31.25	5.8	No	0.083	BND.	0.087	TOR.
1c	31.25	5.8	Yes	0.087	TOR.	0.116	BND.
2	27.77	10.0	No	0.113	BND.	0.119	TOR.
2a	27.77	5.0	Yes	0.084	TOR.	0.148	BND.
3	20.83	10.0	No	0.134	BND.	0.136	TOR.

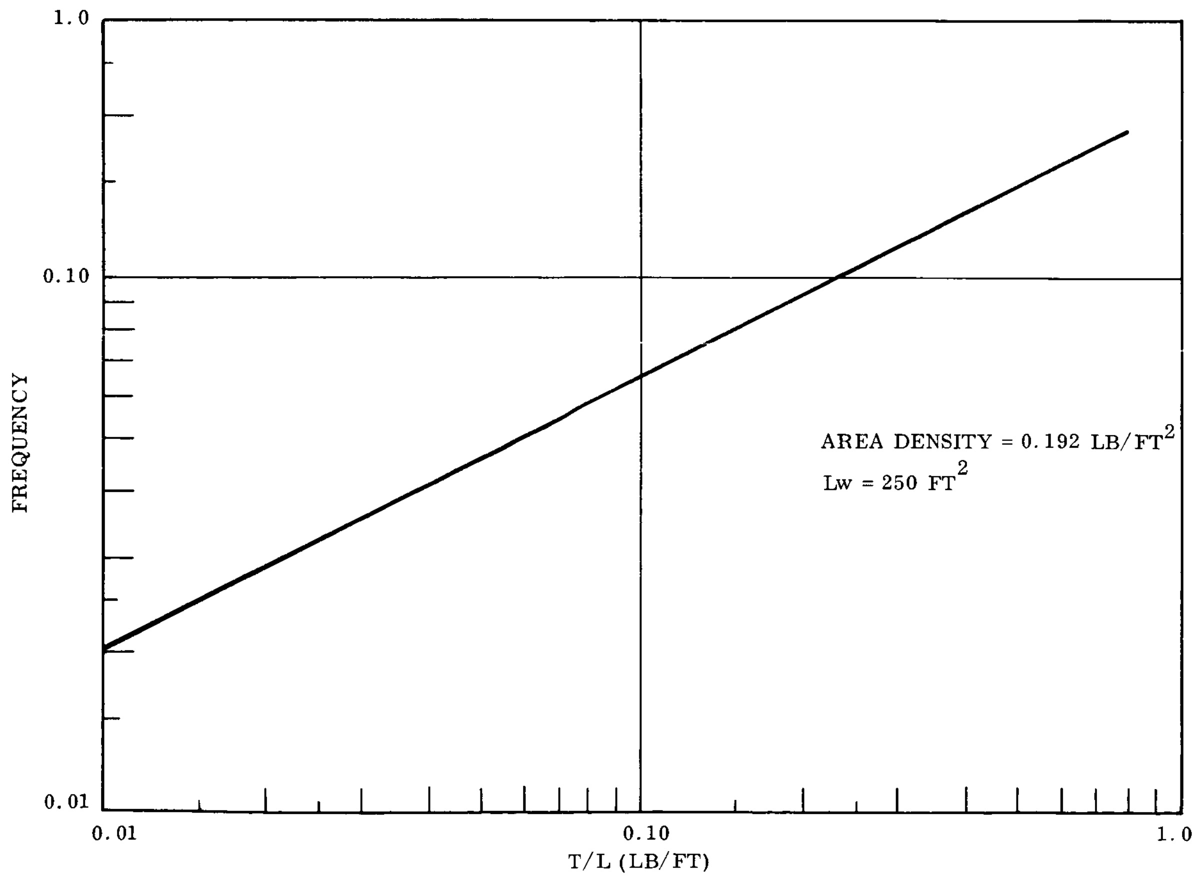


Figure B-1. Natural Frequency of a Fixed Free Membrane as a Function of T/L

B.3 SINGLE ROD ANALYSES

B.3.1 METHOD OF ANALYSES

The single rod configuration consists of a deployable rod, an end piece, and two sections of solar cell blanket. The two blankets are placed on either side of the deployable rod and are attached at one end to the spacecraft and at the other to the end piece which is in turn attached through a bearing to the end of the deployable rod. The mathematical model is presented in Figure B-2 and consists of 10 degrees of freedom located at nine mass points. There are nine translational degrees of freedom, eight associated with the blanket out of plane motions (X_1 through X_8), and one associated with the tip of the rod, the single rotation coordinate is located at the center of the end piece at the point where it is attached to the deployable rod. The end piece is assumed rigid and the solar cell blankets are considered to act as equivalent strings attached to the end piece at the mid point of the blanket.

The stiffness matrix is written directly and is presented in Figure B-3. The restoring force caused by the displacement of the string is T/L where T is the tension and L is the length of the string between coordinates. The deployable rod, because of the end bearing, contributes no torsional stiffness to the system.

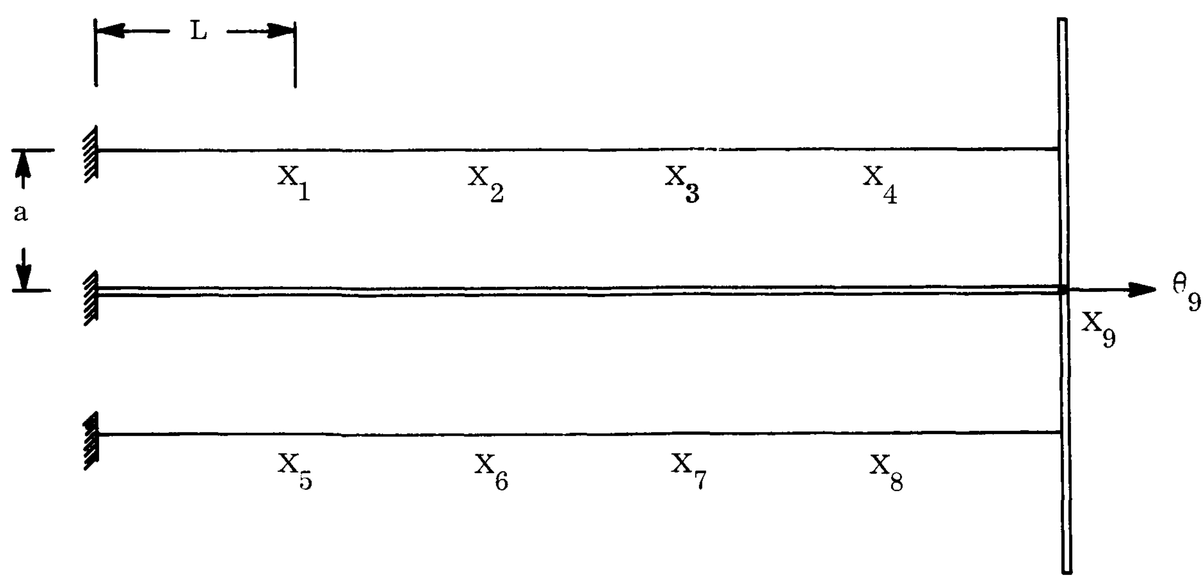


Figure B-2. Mathematical Model for Single Rod Configuration

$$
\left[\begin{array}{cccc|cccc|cc}
2T/L & -T/L & & & & & & & & \\
-T/L & 2T/L & -T/L & & & & & & & \\
 & -T/L & 2T/L & -T/L & & & & & & \\
 & & -T/L & 2T/L & & & & & -T/L & +Ta/L \\
\hline
 & & & & 2T/L & -T/L & & & & \\
 & & & & -T/L & 2T/L & -T/L & & & \\
 & & & & & -T/L & 2T/L & -T/L & & \\
 & & & & & & -T/L & 2T/L & -T/L & -Ta/L \\
\hline
 & & & -T/L & & & & -T/L & 2T/L+K & 0 \\
 & & & -Ta/L & & & & -Ta/L & 0 & 2T/La^2
\end{array}\right]
\left[\begin{array}{c} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \\ X_8 \\ X_9 \\ \theta_9 \end{array}\right]
\left[\begin{array}{c} FX_1 \\ FX_2 \\ FX_3 \\ FX_4 \\ FX_5 \\ FX_6 \\ FX_7 \\ FX_8 \\ FX_9 \\ M_{\theta 9} \end{array}\right]
$$

NOTE: K IS THE ROD STIFFNESS IN BENDING.
T IS THE TENSION IN EACH EQUIVALENT STRING.

Figure B-3. Single Rod Stiffness Matrix

The mass matrix is a diagonal matrix consisting of the mass associated with each coordinate. Because there are several cases analyzed, the mass matrices are not presented herein. However, it is noted that the mass associated with coordinate X_9 consists of the following:

a. End piece

b. The mass associated with 42 inches of array

c. 1/3 the rod weight

and the moment of inertia associated with coordinate 8 or 9 consists of:

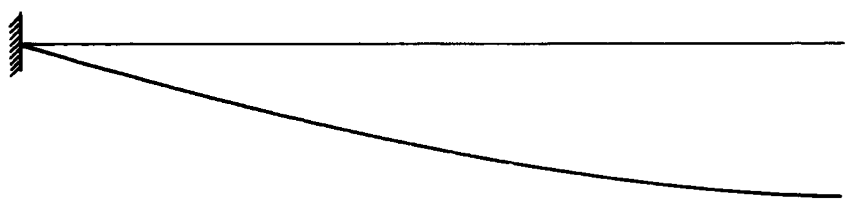
a. Inertia of end piece

b. Effects of point mass under item b above.

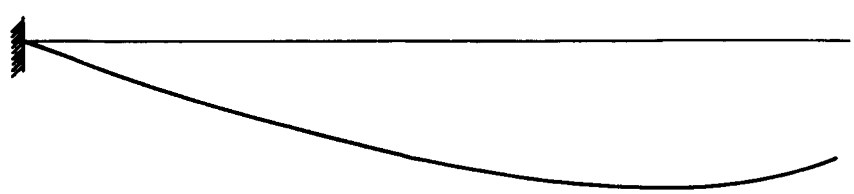
The dynamic matrix was iterated utilizing the Jacobian technique to determine eigenvalues and eigenvectors.

B.3.2 RESULTS

The results of the single rod analyses are presented in Table B-1. A total of seven cases were analyzed, four of which have a length of 31.25 ft; two have a length of 27.77 ft and one has a length of 20.83 ft. Three of the seven cases were analyzed without the bending stiffness characteristics of the deployable rods included. The effect of the inclusion of the bending stiffness was to increase the frequency of the bending mode to a value greater than the torsion mode without affecting the torsional mode frequency. The result is that the first mode for the cases analyzed without the rod stiffness effects is a bending mode while the first mode obtained for the cases analyzed with the rod stiffness included is a torsional mode. Typical mode shapes for the bending mode with and without the rod stiffness effects included are presented in Figure B-4.



CASE 1B NO ROD STIFFNESS   f = 0.083 Hz



CASE 1C WITH ROD STIFFNESS   f = 0.116 Hz

NOTE: MODE SHAPES ARE NORMALIZED TO A GENERALIZED MASS OF ONE.

Figure B-4. Mode Shape of First Bending Mode Single Rod Configuration

An extrapolation of the tension required for a first mode frequency of 0.06 Hz was made utilizing the fact that the frequency varies as the square root of the spring constant. Since the spring constant K is proportional to the preload, the tension required to provide a fundamental frequency of 0.06 Hz canbe calculated from the analytical results in Table B-1.

B.4 TWO ROD ANALYSES

B.4.1 METHOD OF ANALYSES

The two rod configuration consists of three strips of solar array blanket separated by two deployable rods and connected on the end by an end piece.

The mathematical model is presented in Figure B-5 and consists of eight degrees of freedom located at seven mass points. There are seven translational degrees of freedom (out of plane), two for each section of solar array blanket and one at the mid-point of the end piece, and a single rotation coordinate located at the midpoint of the end piece. The end piece is assumed rigid and the solar array blanket is considered to act as equivalent strings located at the center of each blanket strip. The stiffness matrix is written directly and is presented in Figure B-6.

The mass matrix for the two rod system is obtained in the same manner as that presented for the single rod system.

B.4.2 RESULTS

The configuration analyzed has a rod length of 20.83 ft with a total preload of 3.6 pounds. As in the single rod analyses the configuration was analyzed with and without the rod bending stiffness characteristics included. Without the stiffness effects the first two modes are: a bending mode at 0.077 Hz and a torsion mode at 0.078 Hz. With the rod stiffness effects included the first mode is a torsion mode at 0.097 Hz and a bending mode at 0.104 Hz. Because some torsional stiffness is provided by differential bending of the two rods,both the bending and torsion mode frequencies are increased by including the rod stiffness.

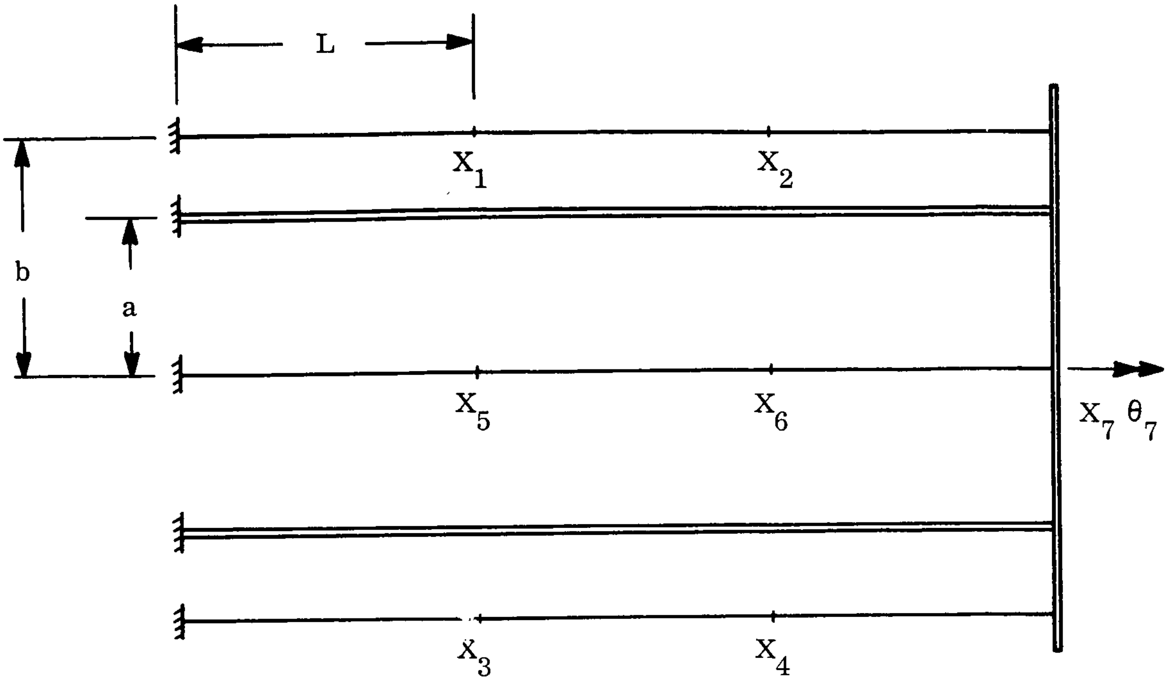


Figure B-5. Mathematical Model for Double Rod Configuration

2T/L	-T/L							X_1	F_{X_1}
-T/L	2T/L					-T/L	(-T/L)b	X_2	F_{X_2}
		2T/L	-T/L					X_3	F_{X_3}
		-T/L	2T/L			-T/L	(+T/L)b	X_4	F_{X_4}
				4T/L	-2T/L			X_5	F_{X_5}
				-2T/L	4T/L	-2T/L		X_6	F_{X_6}
	-T/L		-T/L		-2T/L	4T/L+2K		X_7	F_{X_7}
	(T/L)b		(-T/L) b				$(2Ka^2+(2T/L)b^2)$	θ_7	M_{θ_9}

NOTE: K IS THE ROD STIFFNESS IN BENDING.

a AND b ARE AS SHOWN IN FIGURE B-5.

T IS THE TENSION IN THE OUTER EQUIVALENT STRINGS.
THE CENTER EQUIVALENT STRING HAS 2T TENSION.

Figure B-6. Stiffness Matrix for Double Rod Configuration

An extrapolation of the tension required for a first mode frequency of 0.06 Hz can be made in the same manner as that shown for the single rod case. The result of 2.2 lb tensions for the 20.83 ft array and is based on the analyses which does not include the rod stiffness.

B.5 STRING ANALYSES

The frequencies of vibration for a string supported at one end and free at the other can be expressed as:

$$f_n = \frac{(2n - 1)c}{4L}$$

where

n = mode number

L = length of string

c = $(T/\delta)^{1/2}$

T = tension in string

δ = linear density - lb/ft

For the first mode of vibration this reduces to

$$f_1 = \frac{c}{4L} \qquad \text{(B-1)}$$

Since a rectangular membrane supported on opposite ends acts as a series of parallel strings in its first mode of vibration we can use the above equation to estimate the natural frequency of the membrane*

If the area density of the membrane is γ, then the linear density of a strip w inches wide is:

$$\delta = \gamma w \qquad \text{(B-2)}$$

*Reference: Kinsler, L.E. and Frey, A.R., Fundamentals of Acoustics, 2nd Edition

Making the substitution that $c = (T/\delta)^{1/2}$ and that $\delta = \gamma$ into Equation (B-1) results in:

$$f = 1/4 \left(\frac{T}{L^2 \gamma w} \right)^{1/2}$$

or

$$f = \left(\frac{1}{16 L w \gamma} \right)^{1/2} \frac{T}{L}^{1/2} \tag{B-3}$$

Now, since the area of the membrane is fixed, Lw is a constant and can be expressed as:

$$f = \text{constant} \ (T/L)^{1/2} \tag{B-4}$$

The constant for the case where $Lw = 250 \ ft^2$, and $\gamma = 0.192 \ lb/ft^2$ is 0.206; therefore the frequency of the membrane can be expressed as:

$$f = 0.206 \quad (T/L)^{1/2} \tag{B-4a}$$

and is plotted in Figure B-1. From Equation (B-4a) it can be seen that for a given frequency the tension required varies linearly with the length of the membrane.

Table B-2. Description of Rods Used in Analysis

Case	Type	Diameter (in.)	Thickness (in.)	I_{min}	Material
1a	180^o overlap STEM	4.0	0.005	0.170 $in.^4$	BeCu
1c	180^o overlap STEM	1.75	0.007	0.0201 $in.^4$	BeCu
2a	180^o overlap STEM	1.5	0.006	0.0109 $in.^4$	BeCu
Two Rod System	180^o overlap STEM	1.0	0.004	0.0021 $in.^4$	BeCu

APPENDIX C

DEFINITION OF BOOM REQUIREMENTS

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DEFINITION OF BOOM REQUIREMENTS

C.1 PURPOSE

The purpose of this PIR is to outline the required performance for the deployment booms for the 30 W/lb rollup solar array, as learned from various documentation presently available in-house. It will updated as additional definition becomes available.

C.2 CONFIGURATION

The deployment booms will be used to deploy rectangular solar array panels of three possible aspect ratios as outlined in Table C-1. The require blanket tensions (to meet frequency requirements) are also outlined in Table C-1. Note: These required blanket tensions are based on the assumption that the blanket is attached to the boom only at the outboard end. If the blanket can be attached to the boom along its entire length (as is the case with the Ryan boom) these tensions can be reduced.

Table C-1. Length and Tension Data

Drum Length (ft)	Boom Length (ft)	Blanket Tension	
		Unit Load (lb/ft of drum)	Total Load (lb)
8	31.25	0.39	3.1
9	27.77	0.29	2.6
12	20.83	0.18	2.2

Two basic boom arrangements will be considered. They are:

a. Two booms, one at each end of the blanket.

b. One boom, centrally located.

The required blanket tension will be the same regardless of the number of booms supporting the array.

The boom deployment mechanism will be displaced eight inches from the drum/blanket tangency point if the rods are located on the sunlit side of the blanket, and will be displaced a distance of eight inches plus drum diameter if the rods are on the shaded side of the blanket. Structural/thermal considerations will determine which side of the blanket the rods are located on.

C.3 LOADING AND DEFLECTION REQUIREMENTS

C.3.1 OPERATIONAL CONDITION

Under steady state conditions, when the spacecraft is oriented with the cell side of the blanket facing the sun, the booms shall maintain all portions of the blanket normal to the spacecraft/sun line within ± 10 degrees. This constraint applies with the booms loaded by blanket tension and sun induced thermal gradients but not loaded by dynamic inputs. For purposes of this analysis the spacecraft structure at the point of array and boom attachment will be assumed to be ideally oriented.

For purposes of this analysis the thermal loading conditions are:

a. Solar illumination 260 mw/cm^2 steady state.

b. Transient thermal shock from $-100^{o}C$ to $+75^{o}C$ at a rate of $30^{o}C$ per minute

Blanket tensions are per Paragraph C.2 and Table C-1.

C.3.2 DYNAMIC LOADING CONDITION-DEPLOYED CONFIGURATION

Same blanket tensions and thermal loadings as Paragraph C.3.1 plus repeated discreet applications of a square wave pulse with a duration of not less than 13 seconds nor more than five minutes and a maximum amplitude of 2×10^{-5} $radians/sec^2$. These accelerations will be assumed acting about the drum axis, or about an axis in the blanket plane and normal to the drum axis.

For purposes of this analysis, the sun incidence line will be assumed to be coming from any angle, including array back lighting.

The booms shall survive this condition without failure or subsequent degradation of performance, but deflection constraints will not apply.

C.3.3 GROUND HANDLING

The booms will be expected to support themselves and blanket tensions but not the array weight in a lg environment without the aid of test equipment (direction of deployment may be vertical.)

C.3.4 LAUNCH CONFIGURATION

In the stowed condition the booms shall survive the following:

a. Sinusoidal vibrational inputs of 0 to 200 Hz with an exponential sweep of two octaves/minutes at a level of four g, 0 to peak, in the three or most critical directions.

b. Random Caussian vibration for three minutes at 0.1 g^2/Hz band-limited between 200 and 600 Hz, with a rolloff at six db/octave below 200 and above 600 Hz.

c. Static loads generated by a steady state acceleration at +13 g or -4 g directed along the spacecraft longitudinal axis and a maximum of 6 g directed normal to the spacecraft longitudinal axis.

d, Flight acoustic environments during the launch phase as shown in Figure 2 of JPL Specification No. SS501407A.

C.4 ELECTRICAL INTERFACE

To be supplied at a later date.