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SOLAR ARRAY CONCEPTUAL DESIGN
FOR THE
HALLEY'S COMET ION DRIVE MISSION

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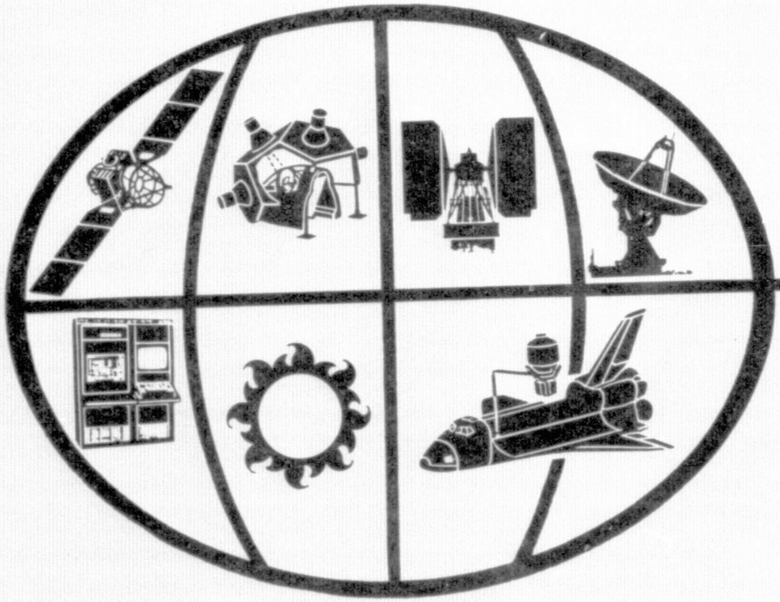

space division

GENERAL ELECTRIC

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FINAL REPORT
SOLAR ARRAY CONCEPTUAL DESIGN FOR THE HALLEY'S COMET ION DRIVE MISSION

PREPARED FOR
THE JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

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ABSTRACT

Since January 20, 1977, General Electric's Space Division has been performing conceptual design studies directed toward a high-power, ultra-lightweight solar array, compatible with the requirements for the Halley's Comet Ion Drive Mission. Two design concepts evolved. One is a planar, rollup array capable of producing 120 kW at 1 AU and 6 kW at 4.5 AU; the other is a concentrator, rollup array capable of producing 60 kW at 1 AU and 15.4 kW at 4.5 AU. Both arrays make maximum use of the thin-film, lightweight technology developed during the 200 Watt/Kilogram Conceptual Approach Study.

In parallel with the development of these arrays, the Halley's Comet spacecraft and mission requirements were evolving from preliminary definition to a more finalized and mature design. As the solar array requirements were updated, conceptual design iterations were necessary to keep pace with the rapidly changing program objectives and goals. On April 20, 1977, a multicenter NASA meeting was held at the Lewis Research Center to review the Halley's Comet Ion Drive Mission program status and design approaches. At that time, more realistic power requirements at 4.5 AU for the Ion Engines were established at the 12-16 kW range. This higher power necessitated a change from the planar array design to a concentrator array design in order to remain within suitable cost and weight objectives. The concentrator array produces more power with fewer solar cells.

Other significant changes to the solar array requirements evolved during the course of the program. Among these are:

- Change minimum deployed natural frequency from 0.04 to 0.015 Hertz
- Change solar cell efficiency from the projected value of 12.5% to a more realistic value of 11.1%
- Change solar array stowage configuration from along the side of the spacecraft to beneath the spacecraft (between spacecraft and Interim Upper Stage)
- Change array output voltage from the "direct drive dedicated" (both high and low voltage sections) to "conventional" (low voltage only).

The impact of these major changes, coupled with a rapidly moving program, necessitated considerable brainstorming and design iteration. The result is the Concentrator Solar Array concept that meets all the existing requirements of the Halley's Comet Ion Drive Mission.

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SECTION 1

INTRODUCTION

This report describes the work performed by the General Electric Space Division on the, "Conceptual Approach Study of a 200 Watt per Kilogram Solar Array." It covers the period January 20, 1977 to August 31, 1977. Two lightweight solar array designs are discussed. Part I of this report describes the conceptual design and performance aspects of a 60 kW per wing planar array, and Part II describes a 30 kW per wing solar array utilizing thin film concentrators to increase the power output at great distances from the sun. Both of these array designs were developed to the requirements imposed by the Halley's Comet Ion Drive Mission. However, the planar design proved to be impractical from a cost and power standpoint for missions requiring relatively high power at great distances from the sun.

The mission performance for the Halley's Comet Ion Drive Mission requires approximately 12-16 kW at 4.5 AU. Since the power output of a solar array varies roughly as the inverse of the square of the distance from the sun, concentrators appear to be a more desirable approach. The concentrators selected for the solar array design are known as the Compound Parabolic Concentrators, developed at the University of Chicago. As described in this report, a maximum effective concentration ratio of 3.2 to 1 is used. With this ratio at 4.5 AU, the solar array performs as it would at 2.5 AU, resulting in a significant power increase.

The solar cells used in both array designs are of the silicon type, 2 x 2 cm, 2 mils thick. Cells of this type are currently being produced in limited quantities. The technology development associated with the assembly of these thin cells onto a flexible substrate, along with the expertise gained in the welding, interconnecting, encapsulating, and testing of thin solar cell modules is described in a separate report entitled, "200 Watt/Kilogram Solar Array Conceptual Approach Study, "Phase II, Assessment Report, Number 200W/Kg-7.77-048, dated July 8, 1977.

This final report covering the Phase II activities performed under Contract Number 954393 with the Jet Propulsion Laboratory describes the system design and performance aspects of both the planar and concentrator solar array concepts.

SECTION 2

PART I – UNCONCENTRATED PLANAR ARRAY CONCEPT

SECTION 2

PART I – UNCONCENTRATED PLANAR ARRAY CONCEPT

2.1 PRINCIPAL REQUIREMENTS

The requirements imposed on the unconcentrated planar solar array by the Halley's Comet Ion Drive Mission are shown in Table 2-1. An overall power of 120 KW at 1 AU, AMO, will develop approximately 6 KW at 4.5 AU, AMO, when cable/diode losses and particulate radiation degradation are included. Two 60 KW wings are used to develop the 120 KW power required at 1 AU.

Two voltage levels are required to directly power the ion engines and supporting electronics in the "direct drive dedicated" configuration. Each 60 KW wing provides approximately 10 KW at the 200 to 400 VDC range and 50 KW at the 1600 to 4000 VDC range. The minimum high voltage current per thruster is 1.25 amperes. Maximum open circuit voltages of 420 VDC and 5000 VDC are required.

The dynamic loads shown represent the levels developed by a Shuttle launch. A 6-meter extension between the spacecraft and the solar array is required to keep the array outside of the ion engine plume. A mimumum deployed natural frequency of 0.04 Hertz was used for this design.

As the Halley's Comet Ion Drive design definition became more mature, several changes to these requirements were made, and these changes are reflected in the Concentrated Solar Array design described in Part II of this report.

Table 2-1. Principal Requirements, Planar Array

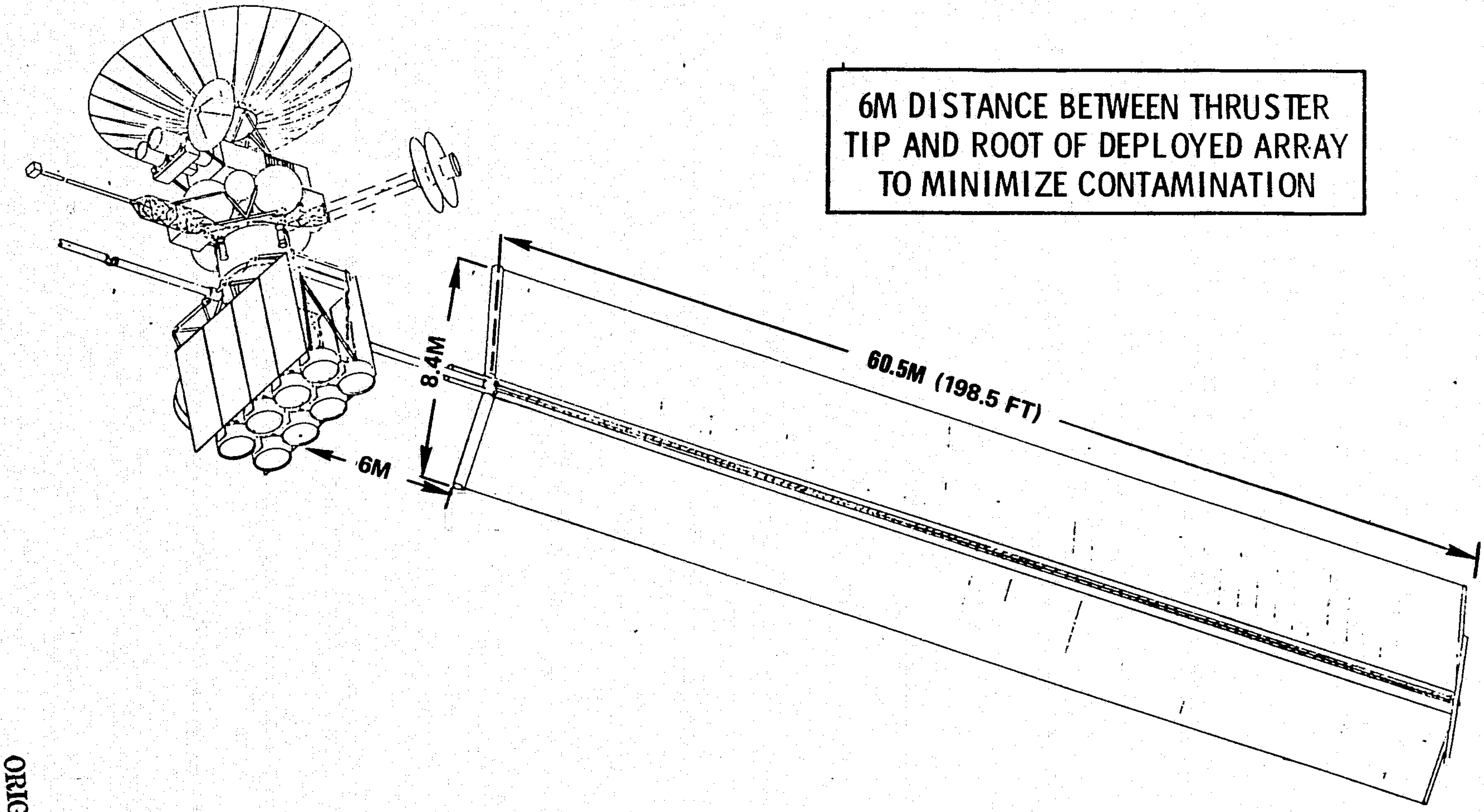
CATEGORY	REQUIREMENT
POWER BOL	120 KW
POWER TO WEIGHT RATIO	OBJECTIVE 200 W/kg GOAL 240 W/kg
ALLOWABLE ARRAY POWER DEGRADATION	LESS THAN 25% OVER FIVE YEARS
DEPLOYMENT/RETRACTION CAPABILITIES	DEPLOYMENT: FULL RETRACTION: 90% NUMBER OF CYCLES: 50
OPERATING TEMPERATURE RANGE (°C)	-130 TO +140°C
THERMAL SHOCKS	100 CYCLES OVER THE TEMPERATURE RANGE OF +120°C TO -190°C
FLATNESS PARAMETER	MAXIMUM 10° ACROSS THE OVERALL ARRAY WIDTH AND/OR LENGTH
OPERATING PRESSURE (TORR)	10^{-5}
NOMINAL VOLTAGE RANGE (VOLTS)	CONVENTIONAL: 200-400 DIRECT DRIVE: 1600-4000 (DEDICATED) PROVIDED AT 1.25 AMPERES CAN BE SUPPLIED BY EACH ARRAY OUTPUT THROUGHOUT THE MISSION
MAXIMUM VOLTAGE RANGE (VOLTS)	CONVENTIONAL: 420 DIRECT DRIVE: 5000
ARRAY NATURAL FREQUENCY (Hz)	0.04
DYNAMIC PACKAGING ENVELOPE (METERS)	4.5 DIA X 11.8 LENGTH
MAXIMUM LOADS (G's)	LONGITUDINAL ±4.0 (X) YAW ±4.0 (Y) PITCH + 10.0, -8.0 (Z)
VIBRATION LEVELS	25 - 100 Hz +6 dB/OCT 100 - 250 Hz $0.035\ G^2$ Hz 250 - 500 Hz -6 dB/OCT 500 - 2000 Hz $0.009\ G^2$ Hz
ACOUSTIC LEVELS (dB)	145
DEPLOYMENT CONSTRAINTS	THE DEPLOYED ARRAY CONFIGURATION SHALL BE CONSTRAINED TO ASSURE THAT ITS PERFORMANCE AND THE SPACECRAFT PERFORMANCE ARE NOT DEGRADED BY THE THRUSTER'S ION PLUME. THE CLOSEST DISTANCE BETWEEN THE DEPLOYED ARRAY CANISTER AND THE NEAREST THRUSTER ARRAY TIP SHALL BE A MINIMUM OF SIX METERS.

2.2 MECHANICAL DESIGN CONCEPT

2.2.1 DEPLOYED SOLAR ARRAY

The baseline design concept for the unconcentrated planar array consists of two cylindrical drums, 12-inches in diameter, onto which the flexible solar array substrate (or blanket) is stowed. A 0.5-meter diameter continuous longeron Astromast unravels the two blanket halves to the full 60.5 meter length as shown in Figure 2-1. The small cant angle shown between the two blanket halves (3.0 to 8.25 degrees) provides V-stiffening which allows the blanket to provide additional out-of-plane and torsional stiffness, thereby reducing the stiffness requirement for the Astromast. The result is a significant reduction in the Astromast weight to maintain the 0.04 Hertz minimum natural frequency.

The overall array size is 8.4 x 60.5 meters. The 6 meter extension from the spacecraft is required to prevent the cylindrical drums from entering the ion engine plume as the array is gimbled about its rotational axis.



6M DISTANCE BETWEEN THRUSTER
TIP AND ROOT OF DEPLOYED ARRAY
TO MINIMIZE CONTAMINATION

Figure 2-1. Deployed Solar Array

2.2.2 PARTIALLY DEPLOYED SOLAR ARRAY

The sketch of Figure 2-2 shows the solar array in the partially deployed configuration. The extension force developed by the Astromast is coupled through the Boom Tip Assembly and Header to the two blanket Leading Edge members. As the boom extends, a counter-rotating force developed from negator springs within drums, applies a constant blanket tension of 27.6 pounds. If the blanket tension is assumed to be reacted by the 0.001 inch Kapton substrate only (and not by solar cells or interconnects), the resulting load in the substrate would be 184 psi. However, in reality a portion of the reaction force would be shared by the solar cells and interconnects because they are an integral part of the solar array blanket.

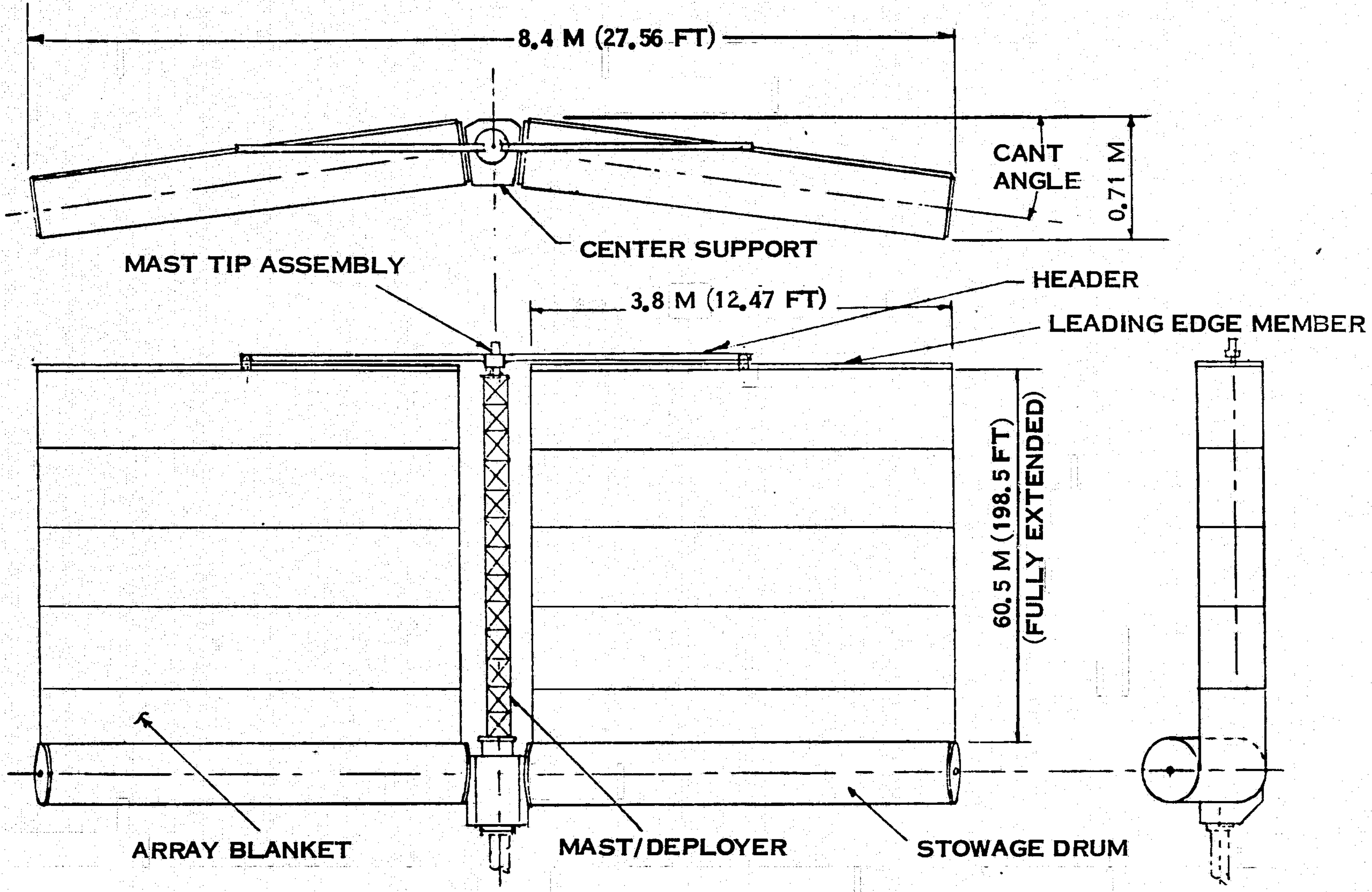


Figure 2-2. Partially Deployed Solar Array

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2.2.3 BOOM AND STOWAGE DRUM

The array is extended and supported by an astromast coupled with a stowage drum as shown in Figure 2-3. The basic size of the boom is 50 cm (20 inches) in diameter.

The drum is supported in cantilever fashion by means of a preloaded bearing assembly. A dual negator spring motor provides a continuous tension on the blanket during extension through the torque imparted to the drum. This torque has a low gradient during the final stage of extension.

A slip ring assembly attached to the bearing housing serves as a power device and is capable of handling the high voltage involved.

The drum also contains the power switching module which connects the array sections into the required series and parallel combinations prior to power transfer.

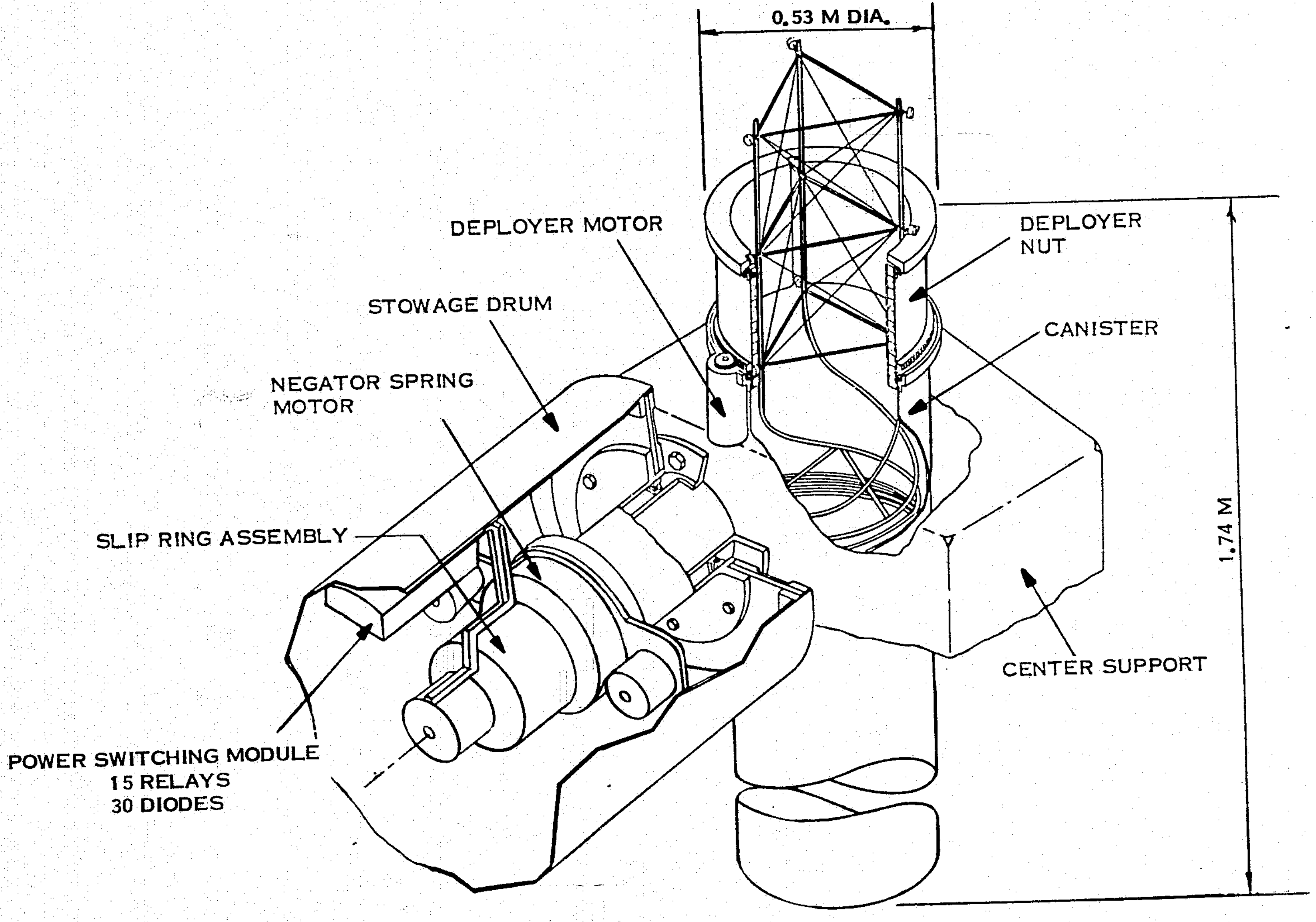


Figure 2-3. Cutaway View of Boom and Stowage Drum

2.2.4 MECHANICAL ELEMENTS DESCRIPTION

The astromast is of the coilable lattice boom type using continuous longerons of glass polymide composite for high temperature performance. The boom is driven by a motorized deployer and has retraction capability. This boom is selected for its high stiffness and minimum weight characteristics. The total mass of both boom and deployer is 68 kg (150 lbs.).

Continuous tension is maintained on the blanket during extension and retraction by a dual negator spring motor in which two springs are wound on a common drive spool. The total mass of this motor assembly is 12.5 kg (27.8 lbs.) for each dual motor. Power is transferred to the spacecraft propulsion module by means of a high voltage (4 kV) slip ring assembly. Eight power rings are adequate since the power switching of array sections is done inside the drum at the switching module. The power rings are rated 16 Amperes at 4000 Vdc. The estimated overall size of the slip ring including 8 signal rings, is 12 cm in diameter x 20 cm.

The mechanical elements are summarized in Table 2-2.

Table 2-2. Mechanical Elements Description

DEPLOYER

- ASTROMAST - CONTINUOUS LONGERON
- 50 CM (20-INCH) DIA., GLASS POLYIMIDE COMPOSITE
- 60-METER (196 FEET) EXTENSION
- SELECTED FOR HIGH STIFFNESS, MIN. WEIGHT
- TOTAL WEIGHT = 68 KG (150 LBS)

NEGATOR TENSION MOTOR

- PROVIDES 102 N (23 LBS) BLANKET TENSION STOWED, 133 N (30 LBS) DEPLOYED
- TWO DUAL MOTORS PER DRUM
- MOTOR SIZE 14.7 CM (5.8 INCH) DIA. MAX. X 7.6 CM (3 INCHES) WIDE
- SELECTED FOR MINIMUM COMPLEXITY
- TOTAL WEIGHT = 12.5 KG (27.8 LBS) PER ASSEMBLY
- MANUFACTURED BY AMETEK

SLIP RING ASSEMBLY

- ONE ASSEMBLY PER DRUM
- 8 POWER RINGS, 8 SIGNAL RINGS, 2 BRUSHES PER RING
- CURRENT/VOLTAGE RATING 16.0 AMPERES, 4000 VDC
- SIZE = 12 CM DIA X 20 CM LONG
- SELECTED FOR HIGH VOLTAGE, MINIMUM WEIGHT
- TOTAL WEIGHT, 2.26 KG PER ASSEMBLY
- MANUFACTURED BY POLY-SCIENTIFIC

2.2.5 DYNAMIC ANALYSIS RESULTS

The three principal parameters involved in establishing the dynamic adequacy of the deployed array are blanket tension, mast stiffness, and cant angle (see Table 2-3). In order to meet the 0.04 Hertz minimum natural frequency for the deployed array, a blanket tension of 27.6 pounds is required for each blanket half. The two blanket halves are supported by a single boom, and therefore, the axial compression load on the boom is 55.2 pounds. A boom with an EI of 245,000 lb-ft^2 will be sufficient throughout the temperature range expected. The 10^{-4} quasi static load imposed on the deployed array can be satisfied with a cant angle of as little as 0.75 degree. However, the more practical value of 3 degrees was selected as the baseline.

Table 2-3. Dynamic Analysis Results

- **TENSION**
  - 27.6 LBS REQUIRED FOR 0.04 Hz TORSIONAL FREQUENCY
- **MAST STIFFNESS**
  - 245,000 LB FT^2 NEEDED TO SATISFY CONSERVATIVE BUCLKING CRITERIA WITH 1.25 FACTOR OF SAFETY
- **CANT ANGLE**
  - ANALYSIS SHOWS 0.75^o SATISFIES 10^{-4} G QUASI STATIC LOAD REQUIREMENT
  - SELECTED CANT ANGLE OF 3^o PROVIDES AMPLE FACTOR OF SAFETY FOR QUASI-STATIC LOADING

2.2.6 MASS SUMMARY

Each solar array wing consists of electrical, mechanical, and structural elements as shown in the mass summary (see Table 2-4). The weight values shown for the boom, boom deployer, slip rings, and tension motors are estimates received from the associated manufacturers for those items. The weights shown for the solar cells, interconnects, substrate, adhesives, and cover material are based on actual measurements. All other weights are engineering estimates made by knowledgable structural and mechanical engineers.

Each solar array wing has a total projected weight of 271.6 kilograms. Based on the delivered power of 60.7 kW at 1 AU, the specific power is, therefore, 223.5 Watts per kilogram. If a 15 percent contingency is added to the total weight, the overall mass per wing is 312.3 kilograms or 194.5 Watts per kilogram.

Table 2-4. Mass Summary

ITEM	UNIT MASS (KG)	QUANTITY PER WING	TOTAL PER WING (KG)
ELECTRICAL			
SOLAR CELLS	78×10^{-6}	985,3444	76.86
SUBSTRATE	8.71	2	17.42
ADHESIVE	6.61	2	13.21
COVER MATERIAL (1 MIL)	11.09	2	22.17
INTERCONNECTS	4.82	2	9.65
BUS STRIPS	2.19	2	4.39
SLIP RING ASSY	2.26	2	4.52
CABLES	0.2	2	0.40
CONNECTORS	0.04	6	0.24
RELAYS	0.03	24	0.72
CONTROL MODULES	0.20	2	0.40
SUBTOTAL			149.98
MECHANICAL			
DRUMS	5.25	2	10.50
SHAFT ASSY	3.22	2	6.44
BEARINGS	0.15	6	0.90
CENTER SUPPORT	8.92	1	8.92
TENSION MOTORS	11.76	2	23.52
MAST DEPLOYER	31.00	1	31.00
SUBTOTAL			81.28
ARRAY STRUCTURE			
MAST	36.40	1	36.40
LEADING EDGE MEMBER	0.98	2	1.96
HEADER	1.98	1	1.98
SUBTOTAL			40.34

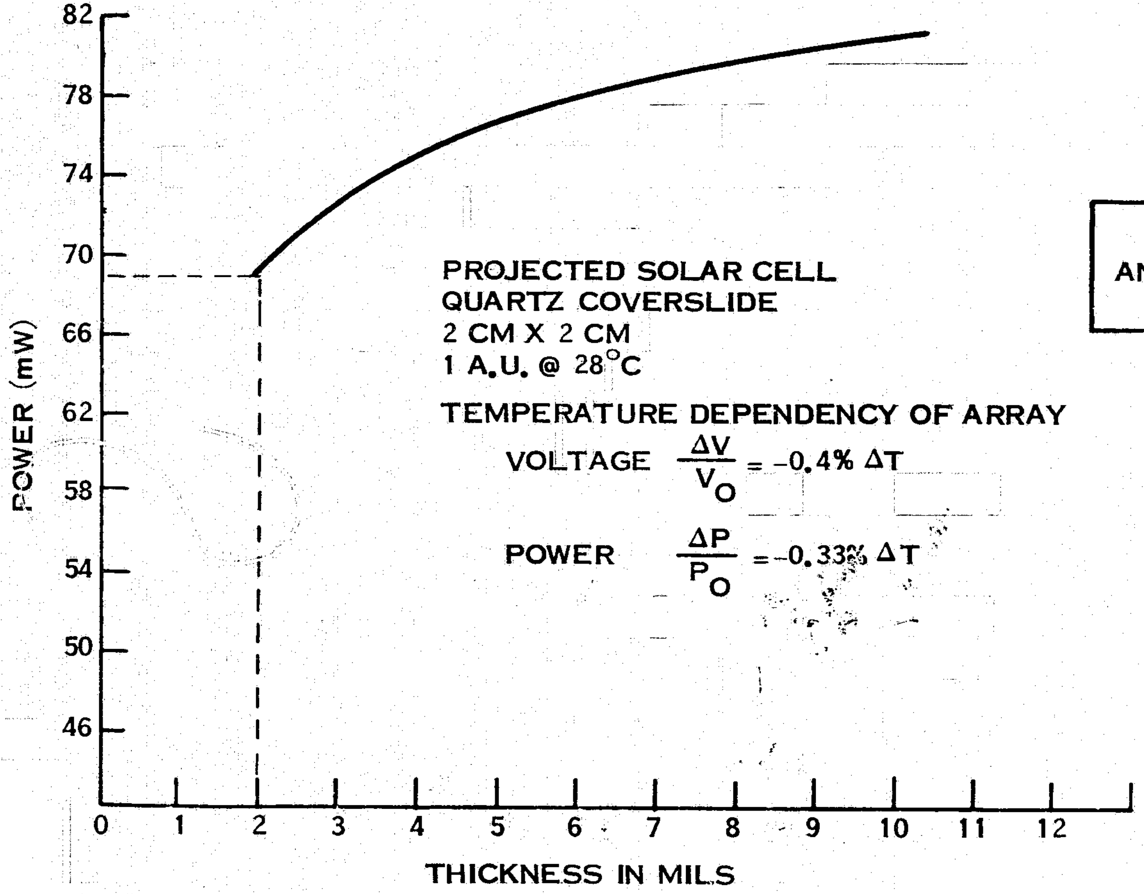
TOTAL WEIGHT PER WING = 271.6 kg
SPECIFIC POWER = 223.5 WATTS/kg
MASS CONTINGENTLY (15%) = 40.7 kg
SPECIFIC POWER (WITH CONTIN.) = 194.5 WATTS/kg

2.3 ELECTRICAL DESIGN CONCEPT

2.3.1 BASELINE SOLAR CELL

The electrical design of the unconcentrated planar array is based on a silicon solar cell, 2 cm x 2 cm, 2-mils thick (see Figure 2-4. This cell develops 67.6 milliwatts of power at 28°C (12.5 percent efficient). The use of this thin, lightweight cell enables a higher specific power to be achieved. For the unconcentrated array, the reduction in weight realized by using the thin cell greatly offsets the additional weight necessary to compensate for the lower efficiency (greater number of cells required). As will be seen in Part II of this report, the sensitivity to using heavier and higher efficient cells on the Concentrator Solar Array is much less. This is because the higher efficient cells not only permit reducing the size of the blanket, but also the concentrators.

The 12.5 percent efficiency represents a near-term projection for the 2-mil cells. Cells of this thickness currently being produced by a pilot plant at Solarex are running about 11.1 percent efficient. The conceptual design for the Concentrator Solar Array described in Part II of this report is based on a 2-mil cell having the 11.1% efficiency.



PROJECTED SOLAR CELL
QUARTZ COVERSLIDE
2 CM X 2 CM
1 A.U. @ 28°C

TEMPERATURE DEPENDENCY OF ARRAY

VOLTAGE $\frac{\Delta V}{V_O} = -0.4\% \Delta T$

POWER $\frac{\Delta P}{P_O} = -0.33\% \Delta T$

67.6 MW @ 28°C
AND 2 MIL THICKNESS

Figure 2-4. Baseline Cell Vs Thickness

2.3.2 ARRAY BLANKET LAYOUT

Each solar array wing consists of two separate blankets as shown in Figure 2-5. Each blanket is subdivided into three sections configured to develop the high voltage power, and one section to develop the low voltage power. The sections are further subdivided into units, half units, modules and circuits. Power is routed from the units and half units via flat aluminum conductors along the sides of the blanket, as shown. The half unit is the lowest level of solar cell grouping from where power is drawn off the array. Switching of the units and half units into various series/parallel configurations is necessary to maintain the voltage levels within the required range over sun distances of 0.6 to 4.5 AU. The switching is performed by the Mode Switching Logic located within the cylindrical drum. The conductor cross sections are sized to equalize the losses for the various length runs so that equal unit voltages appear at the Mode Switching Logic.

The smallest replaceable solar cell grouping is the circuit. Each high voltage circuit is made up of 22 cells in series by 4 cells in parallel. A high voltage module is 43 circuits in series across the width of the blanket. Each high voltage unit is composed of 12 modules, connected in 4 parallel groupings of 3 modules in series. The voltage output at 1 AU per unit is, therefore (excluding losses):

$$\frac{\text{22 SERIES CELLS}}{\text{CIRCUIT}} \times \frac{\text{0.42 VDC}}{\text{CELL}} \times \frac{\text{43 CIRCUITS}}{\text{MODULE}} \times \frac{\text{3 SERIES MODULES}}{\text{UNIT}} = \text{1192 VDC}$$

The power per unit is 2.8 kW. Two full units and two half units make up a section. The three high voltage sections per blanket produce about 25.2 kW.

The low voltage section is configured in a similar manner with the cell groupings and interconnections adjusted to develop 0.86 kW at 105 Vdc for each full unit. The low voltage section consists of 4 full units and 4 half units. It develops 5.16 kW for use in the low voltage applications. The voltage switching is performed in the Mode Switching Logic located in the cylindrical drum.

The overall array blanket is 3.8 x 60.5 meters in dimension and develops a total power output of 30.36 kW at 1 AU. Two blankets per wing, therefore, produce 60.7 kW at 1 AU. Twelve high voltage conductors and eight low voltage conductors are routed along each blanket side to the Mode Switching Logic located within the cylindrical drum. Each wing contains 985,344 silicon solar cells, 2 x 2 cm x 2 mils thick having an efficiency of 12.5% at 28°C, 1 AU.

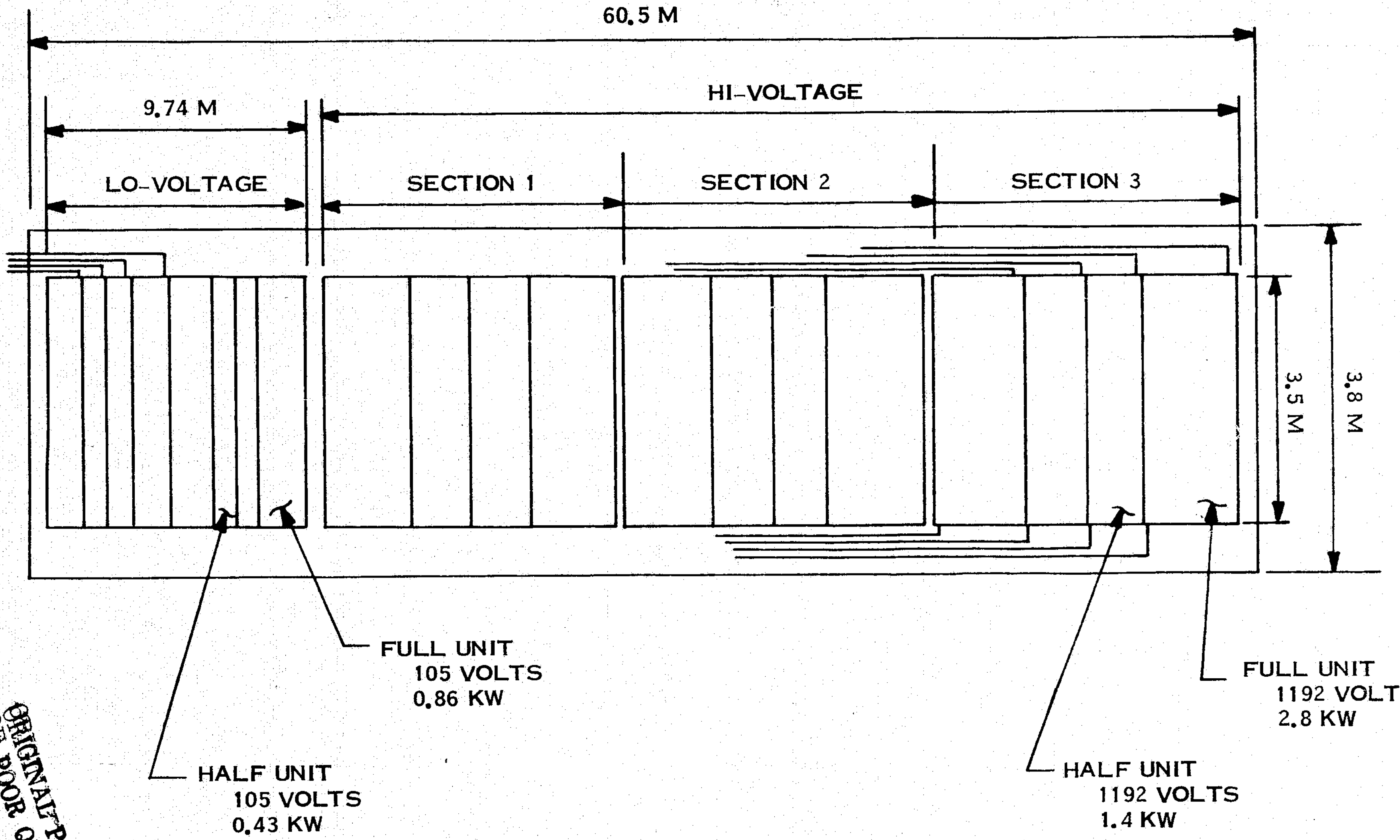


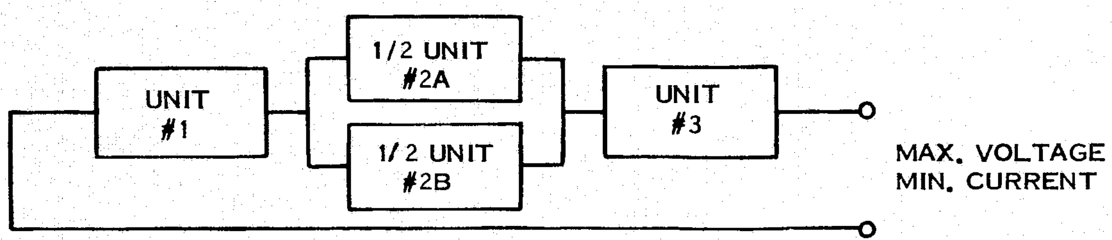
Figure 2-5. Array Blanket Layout (2 Per Wing)

2.3.3 SELECTED MODE SWITCHING CONFIGURATIONS

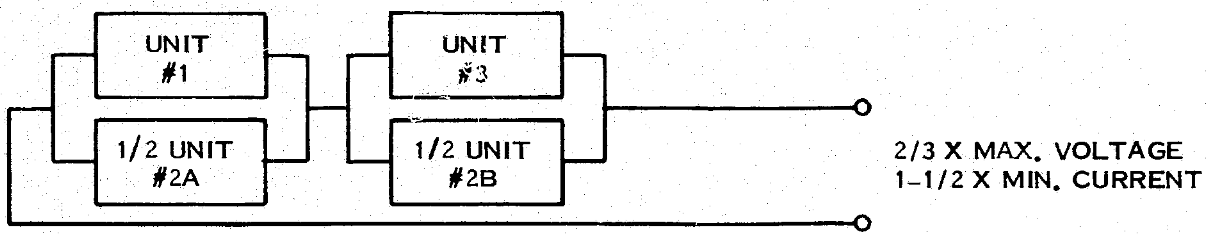
As the spacecraft travels away from the sun, the incident solar energy decreases as the inverse of the square of the distance. This decrease in solar energy causes the array power to decrease and the array voltage to increase. Mode switching is required to maintain the array voltage within the required limits of 1.6 to 4.0 kV for the high voltage and 200 to 400 Vdc for the low voltage.

As can be seen in Figure 2-6, the units and half units for each section are connected into one of three separate configurations depending upon the spacecraft distance from the sun. Configuration #1 produces the highest voltage since the units are connected in series. This configuration is used for distances of 0.6 to 1.2 AU. At 1 AU, the output voltage would be three times the unit voltage or 3.5 kv (3 x 1.192 kv). The low voltage output at 1 AU would be 315 Vdc (3 x 105 Vdc). As the distance increases beyond 1.2 AU, Configuration #2 is used to reduce the voltage to two-thirds of the value just prior to switching. At distances greater than 2.2 AU, Configuration #3 reduces the voltage output to that of a single unit. The low voltage section only requires the first two switching mode configurations.

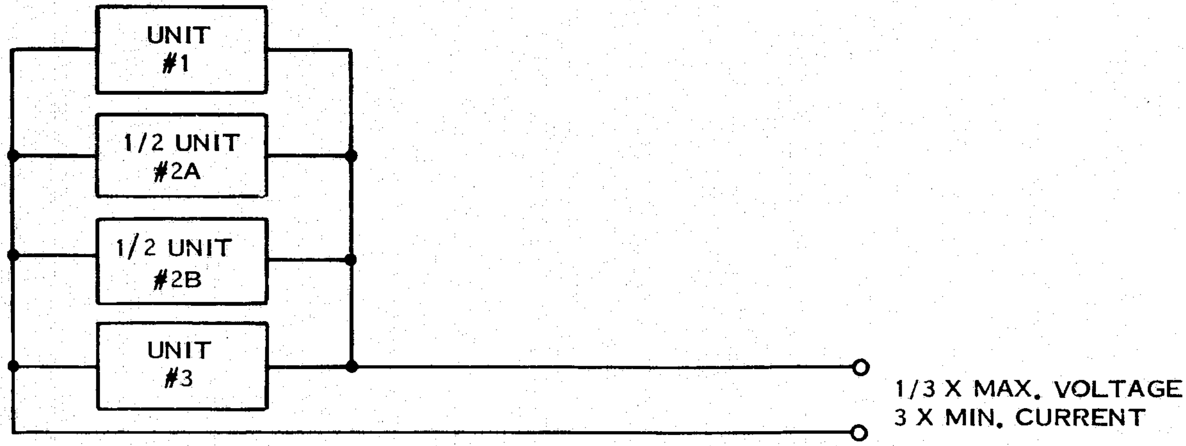
Each cylindrical drum houses the relays and diodes necessary to switch the units from its associated solar array blanket. The series/parallel unit switching is accomplished by utilizing single pole, single throw relays and steering diodes. This is considerably lighter and more reliable than using double pole, double throw relays to accomplish the same function. Each drum contains 15 SPST relays and 30 steering diodes.



CONFIGURATION #1 (0.6 TO 1.2 AU)



CONFIGURATION #2 (1.2 TO 2.2 AU)



CONFIGURATION #3 (2.2 TO 4.5 AU)

Figure 2-6. Selected Mode Switching Configurations Dedicated System — High Voltage

2.3.4 TOTAL ARRAY VOLTAGE VS AU

The total solar array output voltages as a function of distance from the sun are shown in Figure 2-7. Particulate radiation degradation and I^2R losses are included in the voltage values. The curves are based on solar cell test measurements made at JPL and documented per JPL Engineering Memo No. 341-018A, dated April 13, 1977, "Parametric Testing of Solarex 50 Micron Solar Cells."

The spacecraft initially travels inbound from 1 AU to 0.6 AU. During that time the high and low voltage outputs decrease from 3.4 kV to 2.2 kV, and from 300 Vdc to 200 Vdc, respectively. Configuration #1 (as previously described) is the mode switching state. As the spacecraft moves outbound from 0.6 AU to 4.5 AU, the mode switching states are changed to Configuration #2 at 1.2 AU and to Configuration #3 at 2.2 AU. Configuration #3 is not used in the low voltage case.

As can be seen in Figure 2-7, the voltage ranges over distances of 0.6 to 4.5 AU are maintained within the specified limits.

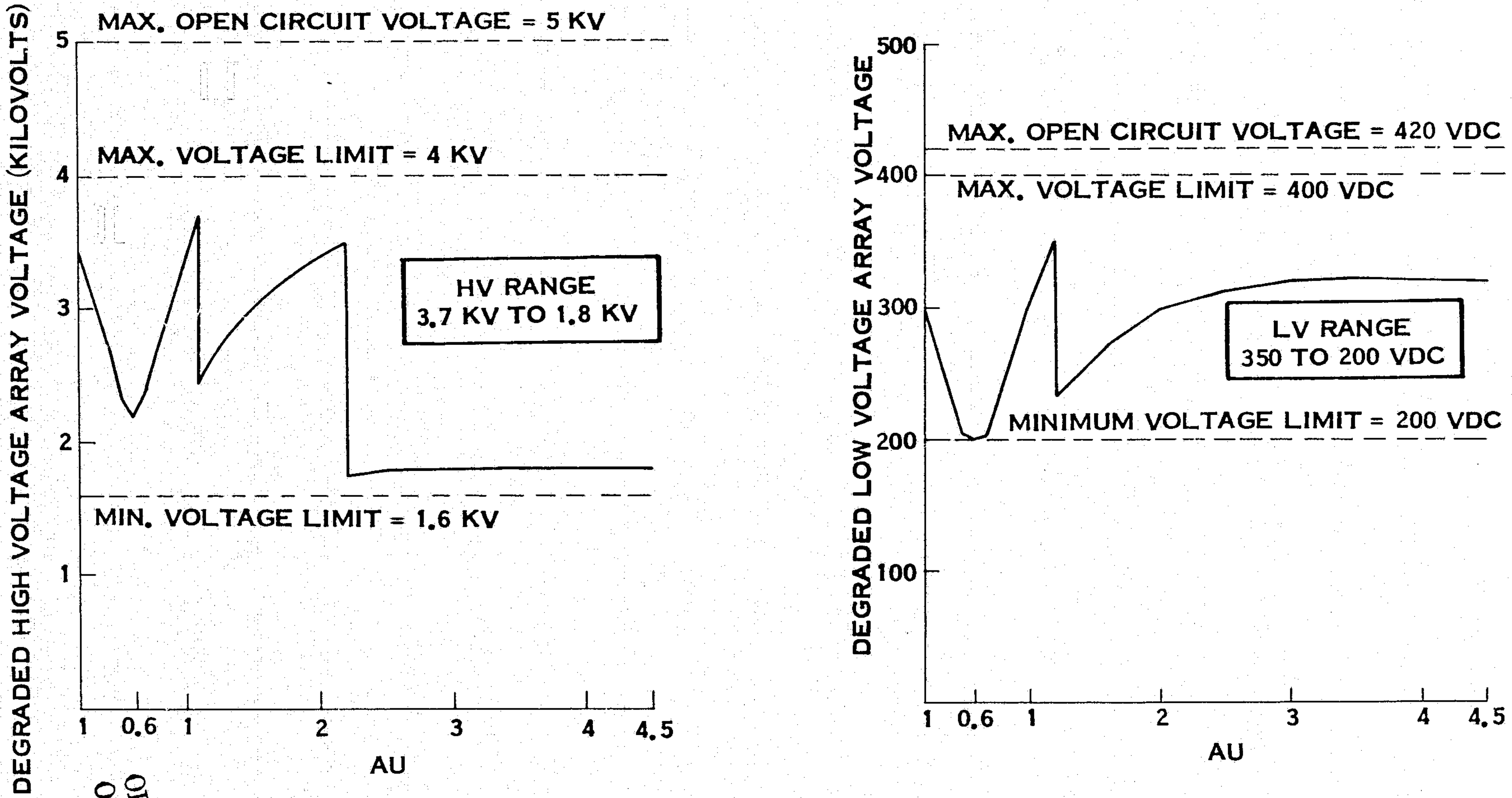


Figure 2-7. Total Array Voltage Vs AU

2.3.5 THRUSTER CURRENT VS AU

In the direct drive dedicated system, the high voltage sections of the solar array are used to directly power the ion beam generation portions of the Ion Thrusters. During this phase of the conceptual design, the Halley's Comet Mission spacecraft is configured for 12 Ion Thrusters. Each thruster requires a minimum current of 1.25 Amperes for proper operation. As the spacecraft moves outbound from the sun, mode switching is required (as previously discussed) to maintain the proper voltage. As the solar array power decreases, a fewer number of thrusters are powered simultaneously. Between 3.5 and 4.5 AU, only two thrusters can be powered and still maintain the 1.25 Amperes minimum current for each. Figure 2-8 shows the mode configuration, total number of thrusters powered, and the available current per thruster as a function of AU.

As the spacecraft travels from 1 to 0.6 AU, the mode switching is in Configuration #1 and all 12 thrusters are on the line. The available current per thruster varies between 2.3 amperes at 1 AU to 4.2 amperes at 0.6 AU. As the spacecraft travels outbound from 0.6 AU the total available current per thruster, number of thrusters powered, and mode configurations are varied as shown in the figure.

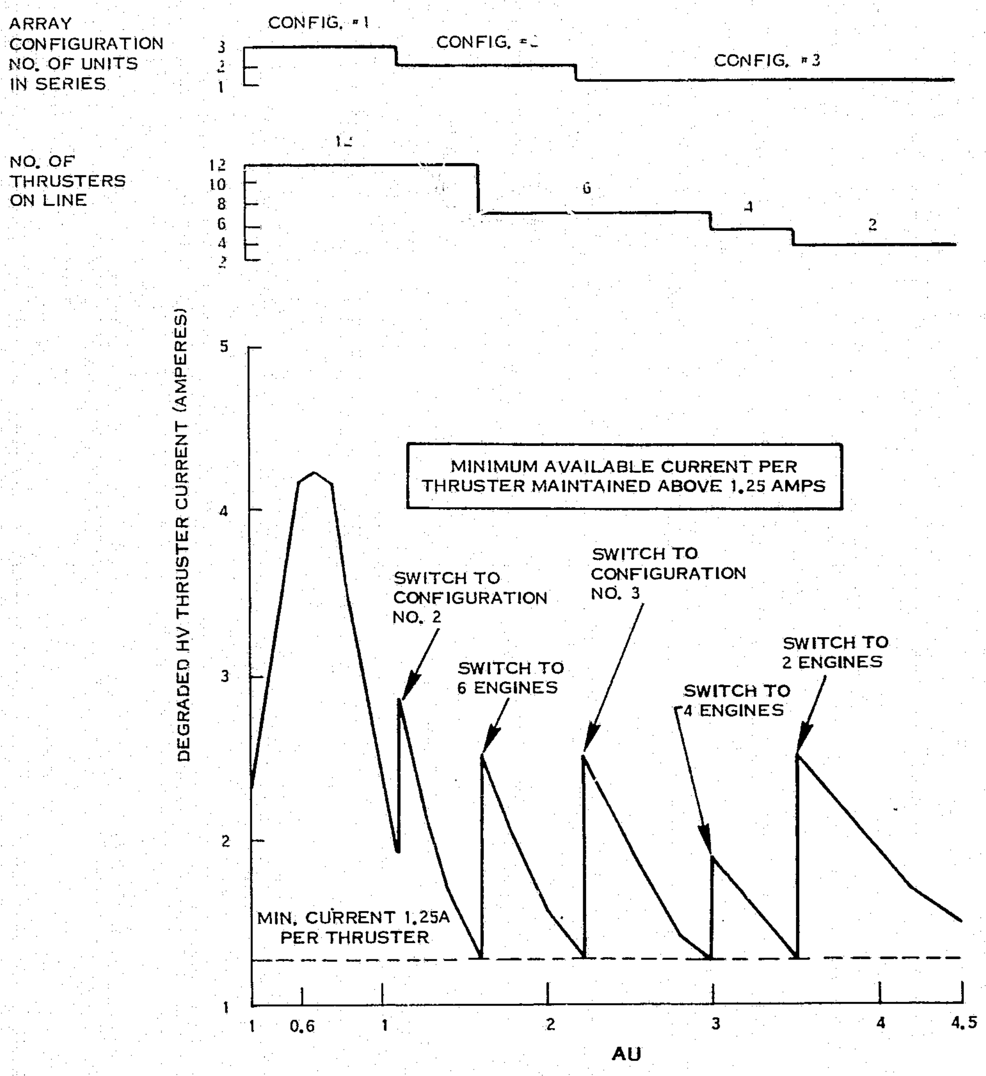


Figure 2-8. Thruster Current Vs AU

2.3.6 RADIATION FLUENCE

The interplanetary electron and proton fluence integrated over the entire Halley's Comet Mission is shown in Table 2-5. These levels were established for a mission profile that brought the spacecraft initially inbound to 0.6 AU and then outbound to 4.5 AU. They are more severe than those used for the Concentrated Solar Array design, where the trajectory was initially outbound to 4.5 AU and did not reach 0.6 AU until after Comet rendezvous.

As will be described later in this report, the fluence level shown results in an overall power degradation of 8 percent for the mission. This does not include ultraviolet radiation degradation.

Table 2-5. Radiation Fluence

INTERPLANETARY PROTON

95% PROBABILITY THAT THE FLUENCE LEVELS ARE NOT EXCEEDED DURING THE HALLEY'S MISSION

ENERGY E (MeV)	PROTON FLUENCE (F CM^{-2})
1	4 X 10^{10}
2	2.9 X 10^{10}
5	1.8 X 10^{10}
10	1.1 X 10^{10}
20	6.0 X 10^{9}
50	1.4 X 10^{9}
100	5.5 X 10^{8}

INTERPLANETARY ELECTRON

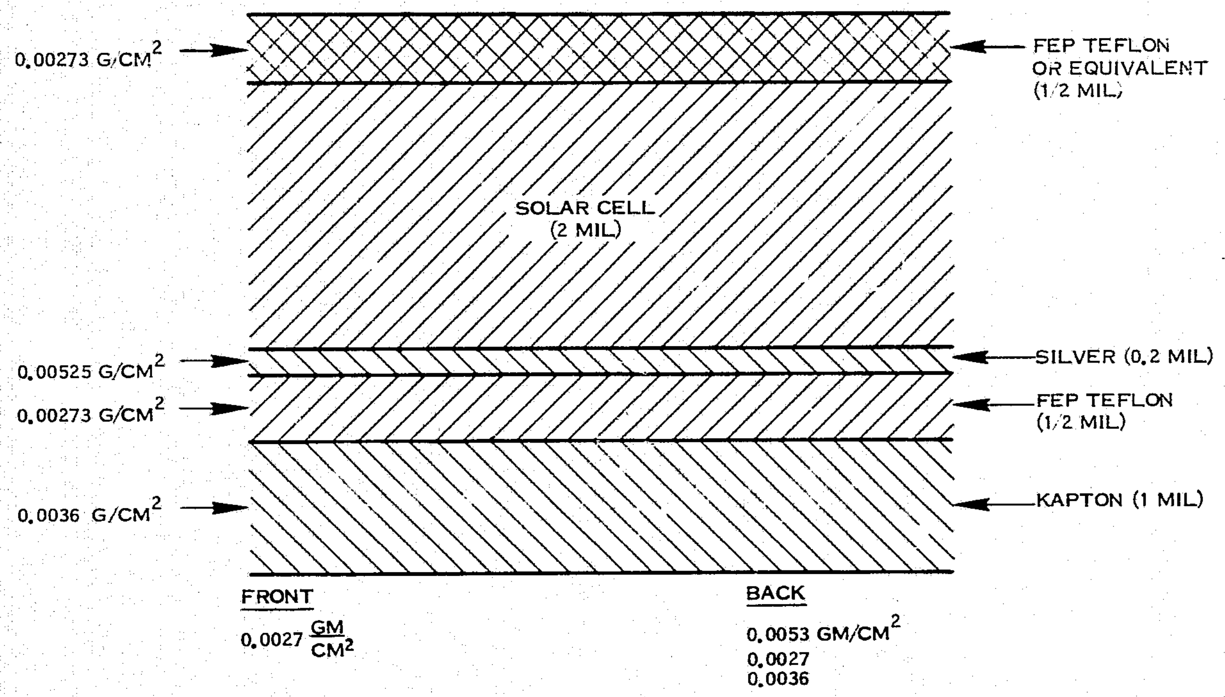
(USE FACTOR OF 2 DESIGN MARGINS)

ENERGY eV	ELECTRON FLUENCE (F CM^{-2})
0	3.0 (16)
10 eV	3.0 (16)
20 eV	2.2 (16)
30 eV	1.5 (16)
100 eV	1.6 (15)
1 keV	1.6 (13)
10 keV	1.6 (11)
100 keV	1.6 (9)
1 MeV	8.5 (7)
10 MeV	2.0 (7)
100 MeV	1.9 (7)

2.3.7 RADIATION ANALYSIS

A radiation analysis was performed to determine the amount of solar array power degradation experienced over the Halley's Comet Mission (Figure 2-9). The electron and proton fluence over the mission was obtained from JPL (Mr. Neil Divine). The resulting analysis shows a total power degradation of 8 percent due to the particulate radiation. This does not include the effects of ultraviolet radiation.

A slightly different radiation environment was used for the analysis performed on the Concentrator Solar Array, as described in Part II of this report. The differences are due to the different mission trajectories.


SOLAR CELL RADIATION MODEL

- ELECTRON AND PROTON FLUENCE AT DISCRETE ENERGY LEVELS OVER MISSION SUPPLIED BY JPL
- USED VALUES AS IS FOR 95% OF PROBABILITY OF PROTON FLUENCE NOT TO EXCEED
- USED SAFETY MARGIN OF 2 FOR ELECTRON FLUENCE
- DETERMINE DENI AT 1 MEV FOR SHIELD DENSITY-THICKNESS OF CONCEPT CONFIGURATION PER SOLAR CELL RADIATION HANDBOOK (JPL/TRW-6/73)
- JPL SUPPLIED CURVES (TEST DATA) USED TO DETERMINE CELL LOSS FOR DENI ELECTRON FLUENCE AT 1 MEV (9/76)

POWER DEGRADATION OVER ENTIRE HALLEY'S COMET MISSION	
0.92 x BOL	(8% LOSS)
EXCLUDING UV DEGRADATION	

Figure 2-9. Radiation Analysis

2.4 PLANAR SOLAR ARRAY, CONCEPT OVERVIEW

The size and functional characteristics are summarized in Table 2-6. The power level at 1 AU is 60.7 kW reducing to about 3 kW per wing at 4.5 AU.

The specific power level of this array has a relatively high value of 194.5W/kg at 1 AU using a total cell area of 422 m^2. A boom stiffness of .149 x 10^6 $N\text{-}m^2$ (52 x 10^6 lb.-in^2) coupled with a minimum cant angle (V-stiffening) of 3.25° provides a minimum natural frequency of .04 Hertz.

The cylinder stowage drum is sized at 30.5 cm (12 inches) diameter) to be compatible with an acceptable number of turns for the negator spring motor.

Table 2-6. Planar Solar Array Concept Overview

POWER (PER WING) 55°C	60.7 kW @ 1 AU (985,344 CELLS)
WEIGHT (PER WING)	312 kg
SPECIFIC POWER	194.5W/kg @ 1 AU BOL
TOTAL WING SIZE	8.4M x 60.5M
TOTAL WING AREA (CELLED)	422M^2
ASPECT RATIO (L/W)	8:1 (BLANKET)
MAST EXTENSION	60.5M (198.5 FT)
MAST DIAMETER	0.5M920 IN)
MAST STIFFNESS	.149 x 10^6 N-M^2 (52 x 10^6 LB-IN^2)
DEPLOYED NATURAL FREQUENCY	0.04 Hz
STOWAGE METHOD	CYLINDRICAL DRUM 30.5 CM (12 IN DIA)
BLANKET ORIENTATION	V-STIFFENED 3.0 TO 8.25 DEG
POWER TRANSFER	SLIP RINGS

SECTION 3

PART II

CONCENTRATOR SOLAR ARRAY CONCEPTUAL DESIGN FOR HALLEY'S COMET ION DRIVE MISSION

SECTION 3

PART II - CONCENTRATOR SOLAR ARRAY

3.1 PRINCIPAL REQUIREMENTS

The principal requirements on the Concentrator Solar Array for the Halley's Comet Ion Drive Mission are shown in Table 3-1. The total unconcentrated power is 60 KW at 1 AU or 30 KW per wing. The total maximum array weight, including support structures, deployment devices, blankets, slip rings, etc., is 800 kg. The concentrator and array blanket are stowed between the spacecraft and the Interim Upper Stage (IUS) within the Shuttle Cargo Bay.

The minimum deployed natural frequency for the Concentrator Solar Array is 0.015 Hertz - a reduction from the 0.04 Hertz specified for the Planar Array. Two discrete concentration ratios are required; 1.8 for spacecraft-to-sun distances out to 1.5 AU, and 3.2 for spacecraft-to-sun distances beyond 1.5 AU. The concentrators are sized for sun view angles of ±5 degrees from normal. The dynamic environments are those specified for Shuttle launched payloads. The array is designed to provide power at voltages between 200 and 400 Vdc.

Table 3-1. Principal Requirements

POWER, BOL, UNCONCENTRATED	60 KW AT 1 AU
POWER DEGRADATION	< 25%, OVER 5 YEARS
VOLTAGE RANGE	200-400 VDC
NATURAL FREQUENCY, DEPLOYED	> 0.015 Hz
ENVIRONMENTS, STOWED	SHUTTLE LAUNCH
ENVELOPE, STOWED	1.4 X 4.3 X 1 METERS BETWEEN SPACECRAFT & IUS
CONCENTRATION RATIOS	1.8 AND 3.2 EFFECTIVE
FLATNESS	10 DEGREES, MAXIMUM
SUN ORIENTATION (CONCENTRATOR SIZING)	± 5 DEGREES
WEIGHT GOAL	< 800 Kg

3.2 MECHANICAL DESIGN CONCEPT

3.2.1 CONCENTRATOR SOLAR ARRAY CONCEPT (Figure 3-1)

In this design concept, thin film parabolic reflectors on the sides of a rollout solar array blanket provide the adjustable concentration of solar flux required for a mission profile of this type.

The artist's rendering shown in Figure 3-1 illustrates the large deep trough type concentrator which is approximately 18 meters wide by 15 meters deep by 74 meters long per wing.

Both arrays are positioned 14 meters away from the spacecraft to avoid impingement of the ion engine plume on the surface of the reflectors.

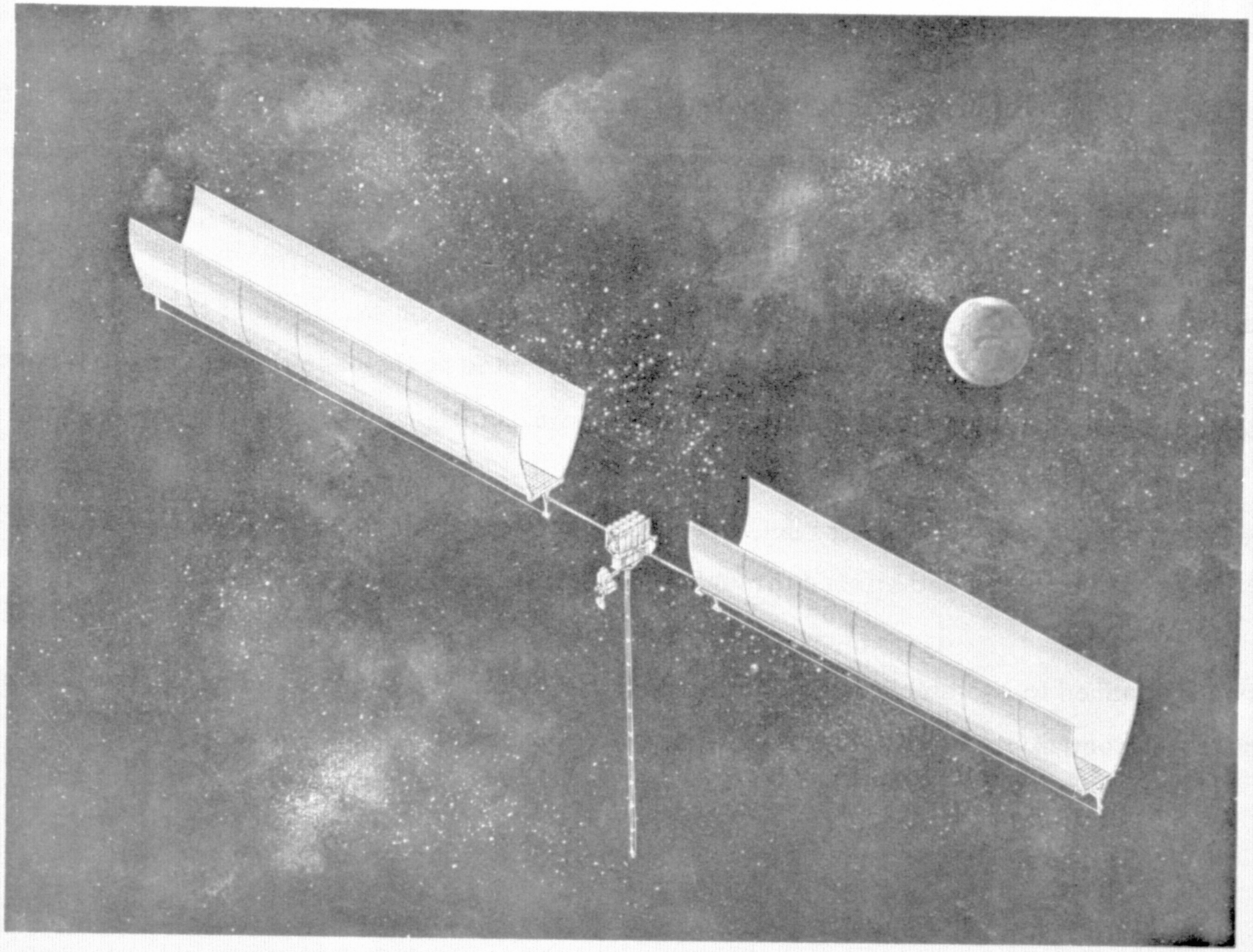


Figure 3-1. Concentrator Solar Array Concept (Artist Rendering)

3.2.2 BASELINE DESIGN

The baseline design of the solar array for the Halley Comet Mission (Figure 3-2) involves a rollout-type blanket (4.3 m wide by 73.9 m long). The array is deployed by means of a 40 cm (20 inch) diameter astromast which is attached to the stowage drum support.

Concentration of the solar flux is provided by two thin film reflectors on each side of the blanket. Each side reflector is supported by means of two ribs which are mounted at the base through power hinges which facilitate deployment and adjustment of the concentration ratio in flight.

The lightweight elements, called shaping ribs, are spaced about 10 meters apart along the reflector to insure that the proper curve is established throughout its length.

A tension cable attached to two stabilizer arms provides a moment at the end of the mast which compensates for the cantilever moment produced by tension in the reflector and array elements.

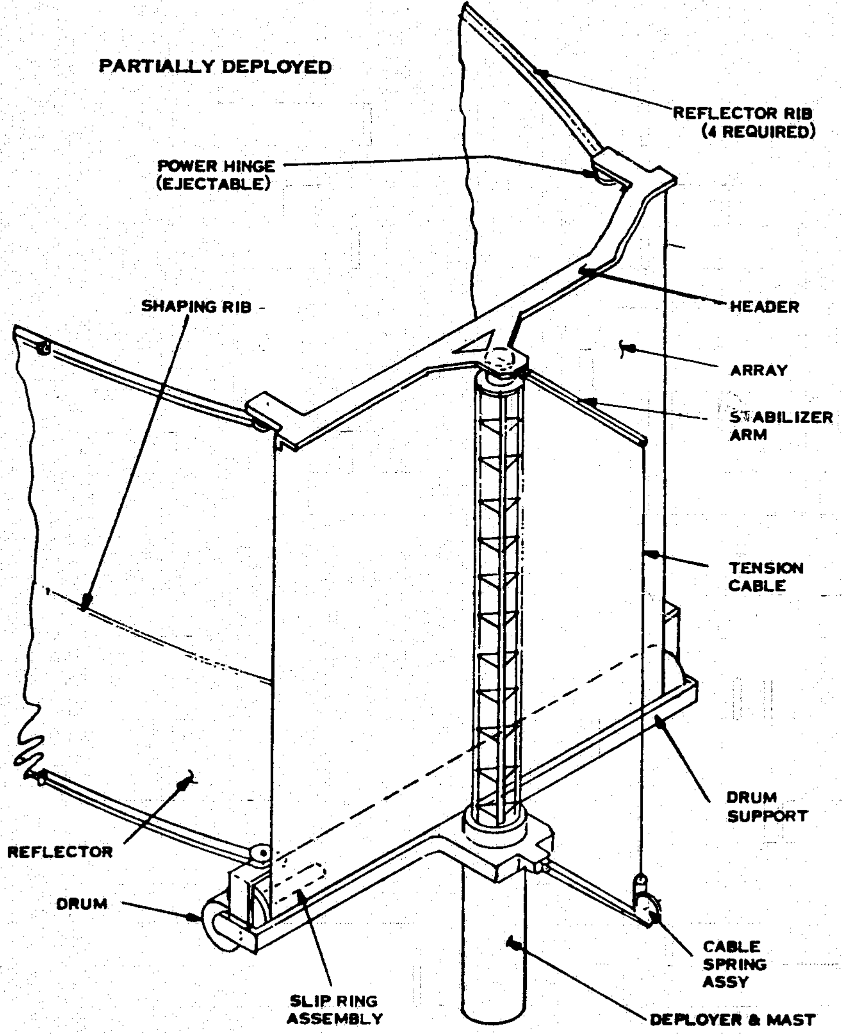


Figure 3-2. Baseline Design (Partially Deployed)

3.2.3 CONCENTRATOR – STOWED CONFIGURATION

The concentrators are stowed by folding the thin films in an accordian fashion between the fine folding segments of the support ribs (see Figure 3-3). First envision the reflector as being retracted from the full extended position. The width of the cross fold can be the full 1/2 container width of 0.35 m, or can be folded from both ends forming a stack width of 0.175 m. The later approach provides less entrapment of air and hence less susceptibility to launch pressure effects. In both cases the stack height is 212 reflector layers (27 cm) of Kapton film and 1.0 cm thickness of shaping rib per each of the five reflector segments. Therefore, the total stack height of reflector and rib for the stowed condition is 5 x 1.27 cm or 6.35 cm. Since the container height is 70 cm, the equivalent packing factor is 11:1. It is anticipated that the shaping ribs will be extremely lightweight and will be attached to each other at the rib fold lines by means of flex hinges, so that they will be mutually self supporting.

The left and right reflector of a single wing are stacked along side of each other in a common container. A separation panel between the stacks prevents to the two assemblies from becoming entangled with each other.

The support rib hinges are positioned in line so that they will form a firm stack which can be retained with a suitable pyro release mechanism. Due to the parabolic curvature of the support ribs, the stack will extend a little above the 0.7 m dimension in their free state. It will, therefore, be necessary to compress the stack slightly when attaching the retention device. The resultant forces will help retain the mechanisms during launch environment, and will help jettison the container cover prior to deployment.

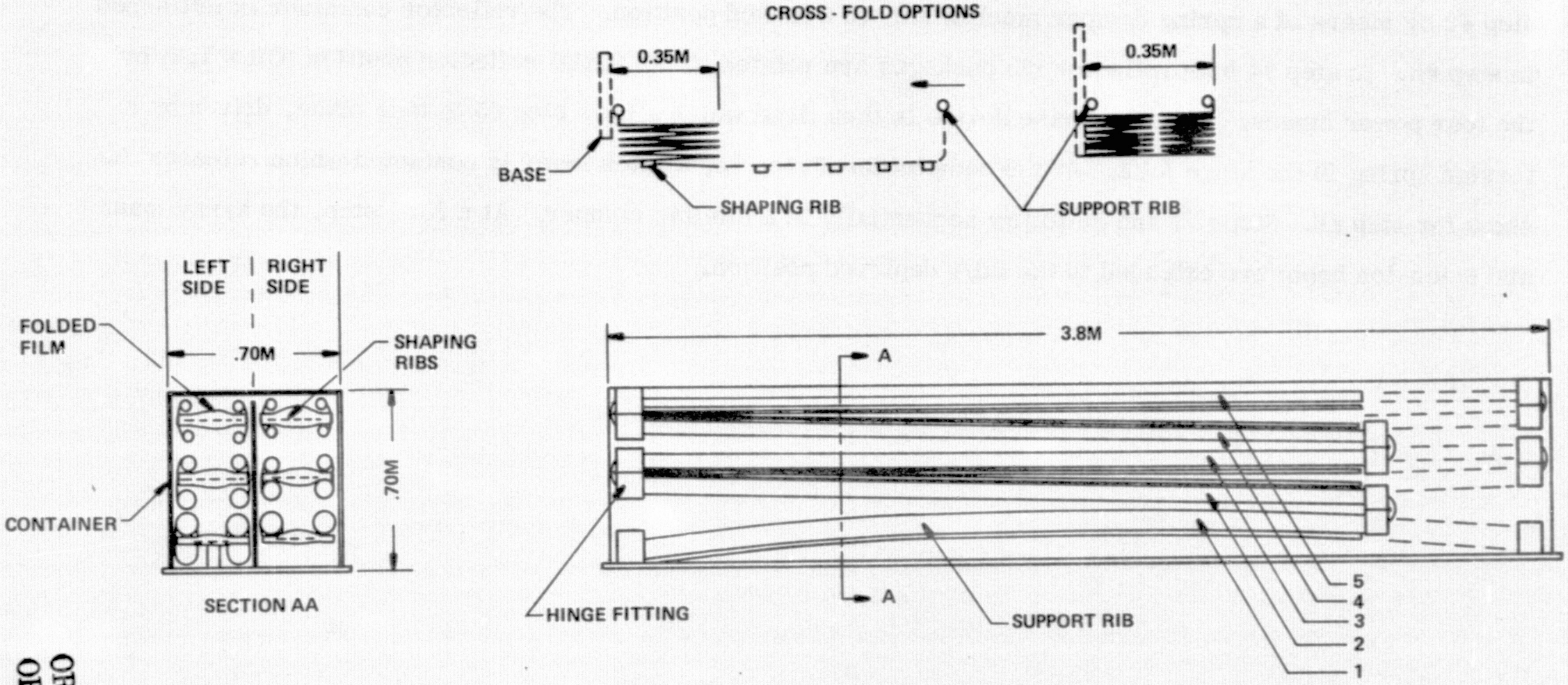


Figure 3-3. Concentrator – Stowed Configuration

3.2.4 DEPLOYMENT SEQUENCE

The array is free to be deployed after separation of the spacecraft from the IUS (see Figure 3-4). The action is initiated in step #1 by firing a pyrotechnic retention device. The array assembly is then rotated 90° as in step #2 by means of a spring damper mechanism to a locked position. The reflector container is jettisoned in step #3. In step #4 both reflector rib packages are rotated to the initial reflector position (CR = 1.8) by the four power hinges. A pyro release device is then fired which allows step #5 to take place, driven by a torsion spring in the hinge joint. At the completion of step #5, a latch lever is contacted which releases the stack for step #6. Steps #7 and #8 follow sequentially in a similar manner. At a final step, the array mast and extension boom are extended to the fully deployed position.

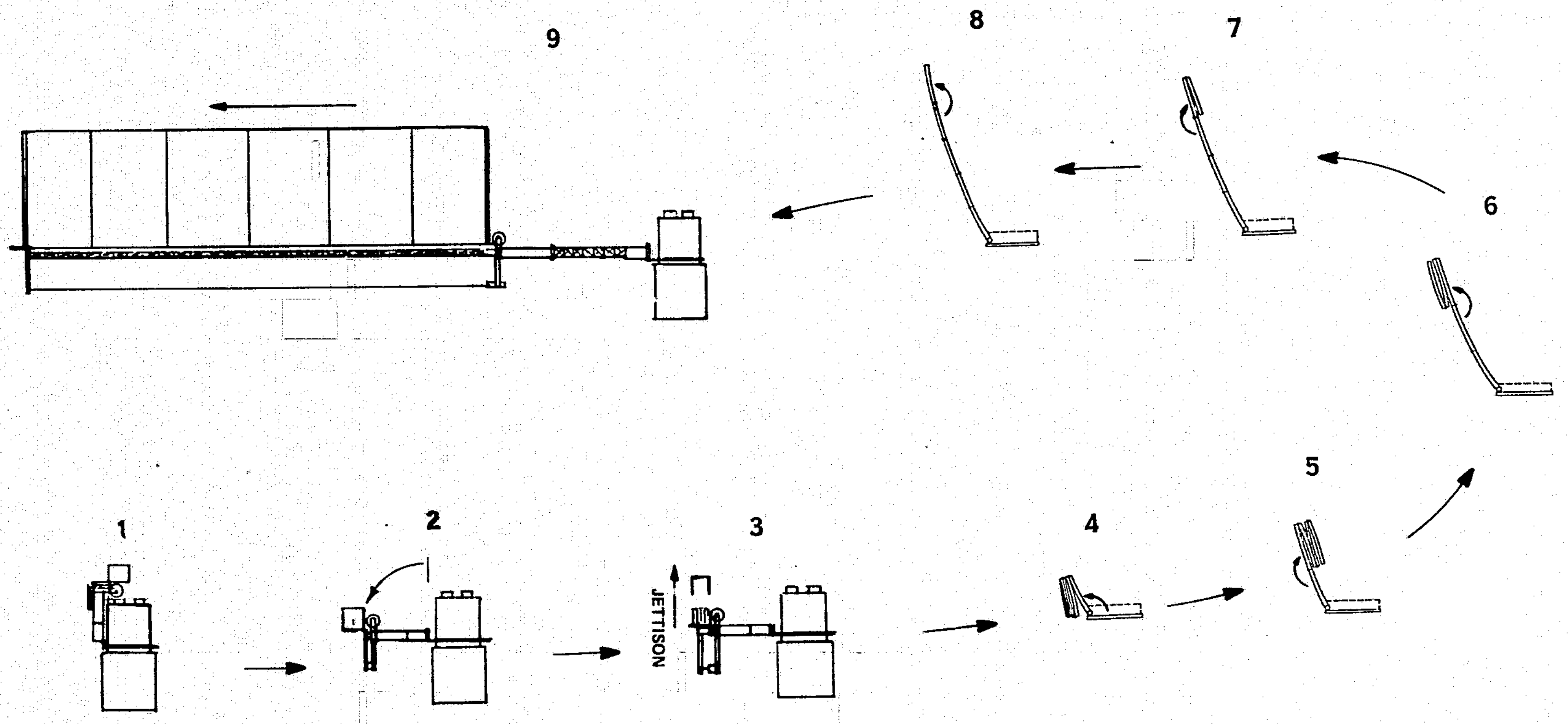


Figure 3-4. Deployment Sequence

3.2.5 FULLY DEPLOYED CONFIGURATION

When fully deployed the concentrator and array extend 74 meters (see Figure 3-5). The width and height will be governed by the concentration factor required. At the beginning of the mission, the aperture is set at 14.1 m (effective concentration factor = 1.8). At a solar distance of 1.5 AU, the reflectors are moved outward to form an aperture of 18.6 m (effective concentration factor = 3.2).

The tension in the array blanket and side reflector assemblies are in the order of 89N (20 lbs) and 44.5 N (10 lbs) respectively. The net moment resulting from these forces is balanced by the tension wire force of 233.5 N (52.5 lbs) for a three meter long stabilizer arm. The resultant axial (buckling force) on the mast is then 411.4 N (92.5 lbs).

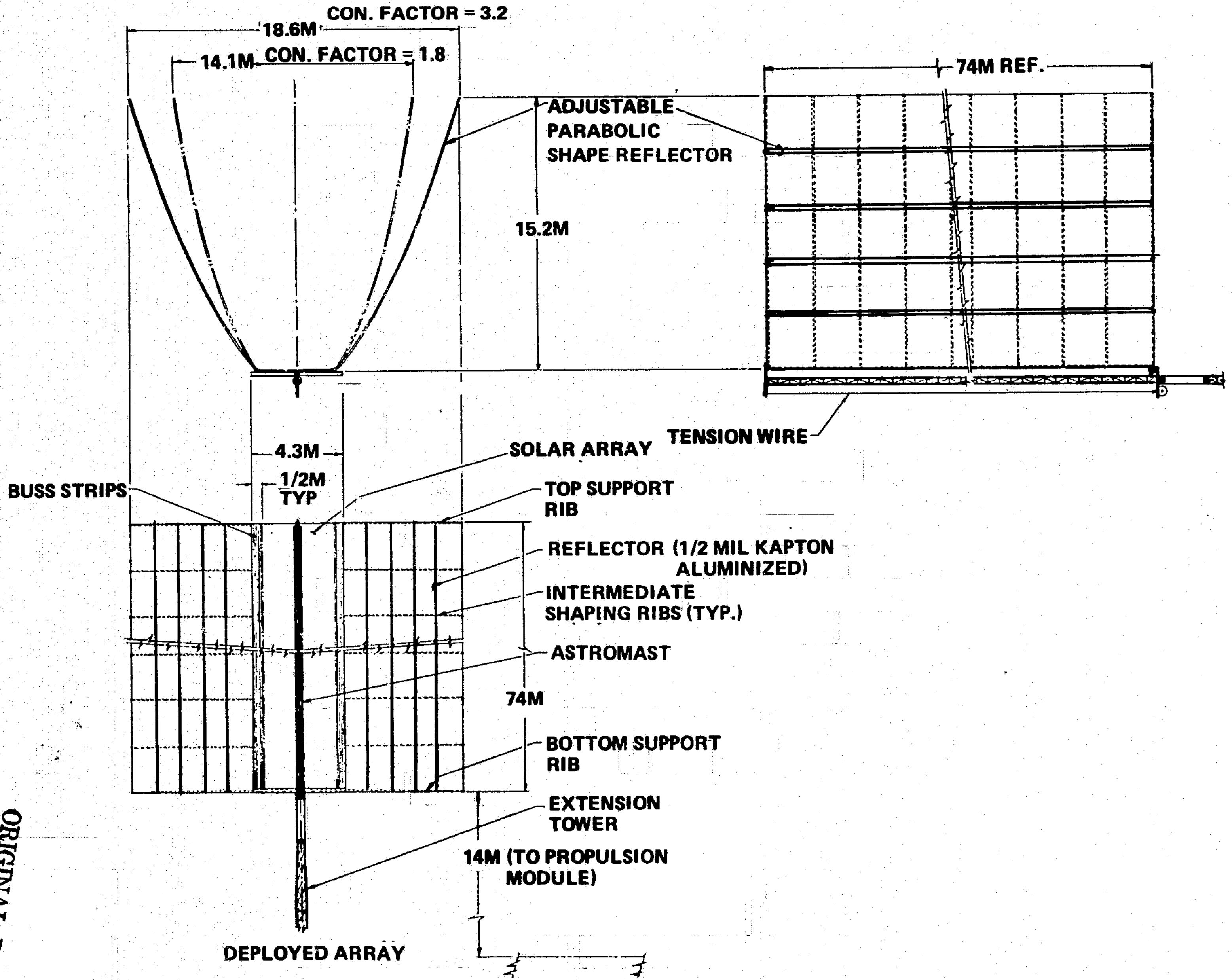


Figure 3-5. Fully Deployed Configuration

3.2.6 COMPOUND PARABOLIC CONCENTRATORS

The Compound Parabolic Concentrators selected for use on the Solar Array for the Halley's Comet Ion Drive Mission were developed at the University of Chicago for terrestrial applications (see Table 3-2). The non-imaging properties of these concentrators provide a high efficiency through the concentration of diffuse light. Geometric concentration ratios of 4.66 and 2.0, resulting in effective ratios of 3.2 and 1.8, respectively, are sufficient for the Halley's Comet Ion Drive Mission. Losses due to reflection, distortion, and transparency act to reduce the geometric ratios to those shown.

Figure 3-5 shows the physical dimensions of the concentrators. The concentration ratio is changed by rotating the concentrators about their longitudinal axes, thereby changing the aperture from 18.6 meters (effective CR = 3.2) to 14.1 meters (effective CR = 1.8).

Table 3-2. Compound Parabolic Concentrators

DESCRIPTION

- IDEAL CYLINDRICAL LIGHT-COLLECTOR TROUGHS
- DEVELOPED BY DR. R. WINSTON, UNIVERSITY OF CHICAGO, FOR TERRESTRIAL SOLAR THERMAL APPLICATION

PROPERTIES

- NON-IMAGING
- HIGHER EFFICIENCY FOR ACCEPTING DIFFUSE LIGHT
- FOR TRACKING, SMALL VIEW-ANGLE SYSTEMS, HIGHER CONCENTRATION PER UNIT AREA
- AVERAGING DEVICES
  - – CONCENTRATION UNIFORMITY ALONG LENGTH OF TROUGH
  - – CONCENTRATION DISTORTION ALONG WIDTH OF TROUGH

PERFORMANCE

- VIEW ANGLE ±5%
- SURFACE TEXTURING, AVERAGE DISTORTION 2.4 ARC MIN
- GEOMETRIC CONCENTRATION RATIO 4.66 2.0
- CPC LOSSES @ CR OF 4.66
  - – REFLECTION 15%
  - – DISTORTION 15%
  - – TRANSPARENCY 5%
- EFFECTIVE CONCENTRATION RATIO 3.2 1.8

3.2.7 KEY MECHANICAL ELEMENTS

The concentrator array requires the use of some basic mechanical elements (Figure 3-6), three of which are very similar to the elements chosen for the 200 Watt/kg array.

Mast – The mast is an Astromast with deployer similar to the 200 W/kg element except for length and mass. The extension capacity of this mast is 74 m with a total mass of 90.7 kg. Polymide resin is used in the structural members to withstand high mission temperatures.

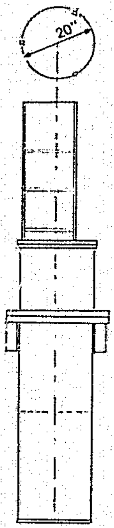
Blanket Tension Device – Blanket tension is provided by a typical negator spring motor on the drum axis. For the long concentrator array, the mechanism will be effective over only the last 10% of deployment. A small drag brake will provide a suitable tension for the first 90% of travel.

Reflector tension is generated by tension springs which come into play near the end of extension.

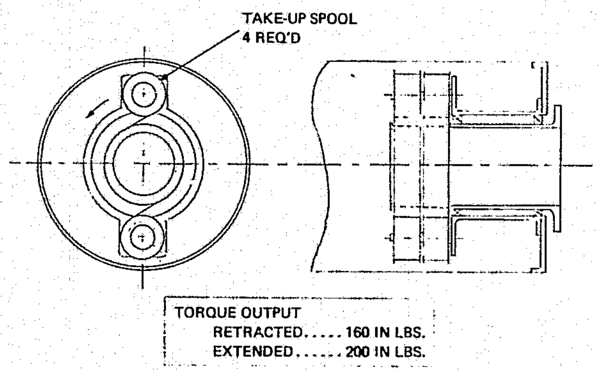
Slip Ring Assembly – The slip ring assembly consists of 26 power rings with returns capable of handling 30 A each, and a small number of signal rings rated at 0.5 Ampere each.

Support Rib Hinge – The reflector strips are supported by two support ribs segmented into five sections which fold at four points about 3 m apart. The support rib joint consists of two tube fittings mounted to a hinge pin with pre-loaded ball bearings to eliminate all radial and axial play. A spring loaded locking cam serves to hold the hinge joint closed after deployment and to create a self tightening characteristic in the joint.

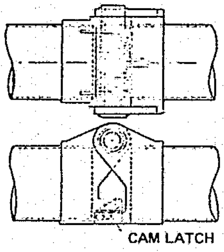
Reflector Sequence Release – The sequence release device consists of two spring loaded links which hold the rib segments together in the folded stowed condition. After the pyro release of the first pivot point, actuating fingers on the hinge fitting at the second pivot strike the link near the end of the hinge rotation and release the adjacent rib segment. This device also exists at the 3rd and 4th hinge points.



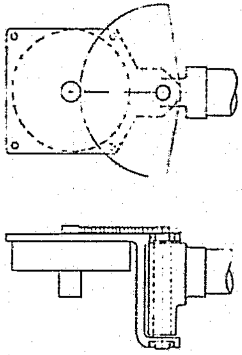
ARRAY MAST



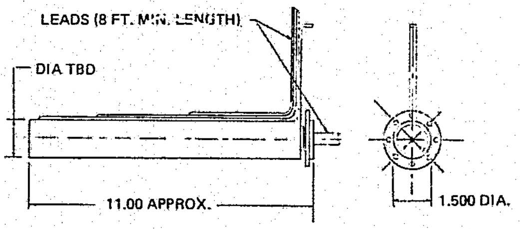
TYPICAL NEGATOR SPRING



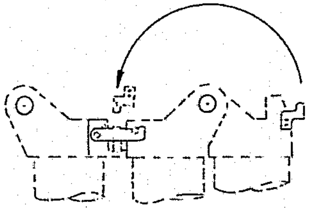
SUPPORT RIB HINGE



POWER HINGE



SLIP RING ASSEMBLY



REFLECTOR SEQUENCE RELEASE

Figure 3-6. Key Mechanical Elements

3.2.8 SOLAR ARRAY POINTING ERRORS

Boeing Aircraft Company performed an analysis to determine the overall pointing accuracy of the Concentrator Solar Array as configured on the Halley's Comet Ion Drive spacecraft. The worst case pointing error was determined to be 1.97 degrees, which is well within the concentrator sun view angle of 5 degrees. Study results are summarized in Table 3-3.

The dynamic inputs to the deployed array from the ion thrusters, scan platform slewing, and reaction wheels results in a pointing error of 0.55 degrees. This value, added to the errors due to the vehicle control loop, sun sensors, star tracker, and array tip deflection, results in the worst case value of 1.97 degrees.

Table 3-3. Solar Array Pointing Errors

BOEING STUDY

ARRAY DYNAMIC INPUTS

THRUSTERS	a ~ 0.0001 G
SCAN PLATFORM	$\ddot{\theta} \sim 0.005\ ^{\circ}/\mathrm{SEC}^2$
REACTION WHEELS	T ~ 0.3 N-M

ARRAY POINTING ERRORS

VEHICLE CONTROL LOOP – 0.3°

SUN SENSORS – 0.5°

STAR TRACKER – 0.08°

TIP DEFLECTION – 0.54°

– 0.55°

WORST CASE – 1.97°

($1\sigma = 0.97^{\circ}$)

CONCENTRATOR VIEW ANGLE ± 5°

3.2.9 SPACECRAFT/SHUTTLE INTERFACE

The solar array is attached to the spacecraft by virtue of its intermediate attachment to the extension boom which in turn is mounted on the solar array shaft. An actuator at base of the boom rotates the array 90° to the deployed position (see Figure 3-7).

The estimated axial space required to package the array and concentrator is 1.2 m. This dimension is governed primarily by the compactness of the stowage of the concentrator support rib assembly.

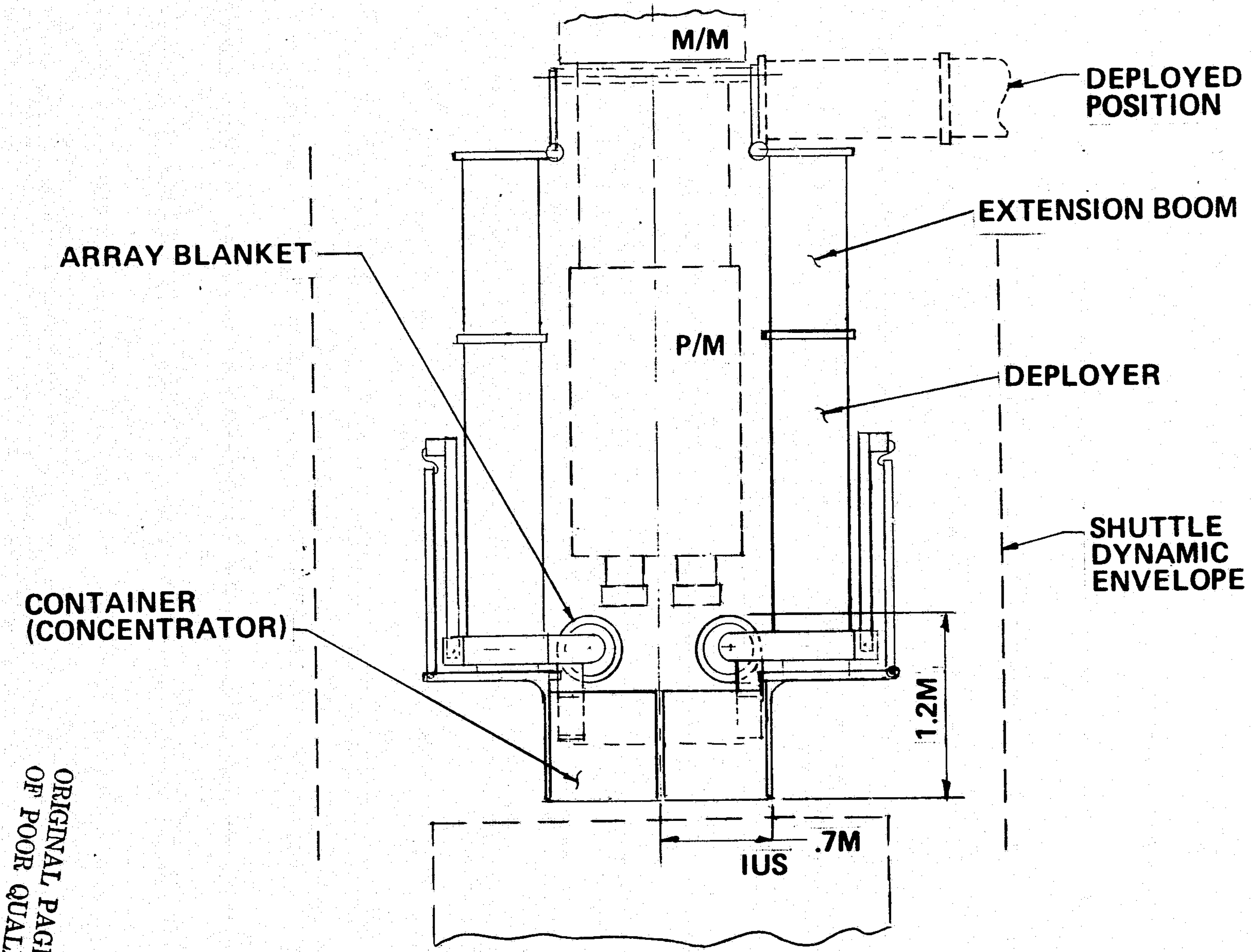


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Figure 3-7. Spacecraft/Shuttle Interface (Stowed)

3.2.10 MASS SUMMARY

The total mass prediction of 395 kg per wing is derived from the summation of the items listed in the Mass Summary chart, Table 3-4. The values in the blanket section are realistic in that they are based on measured weight of ultra lightweight blanket elements developed on phase II of the 200 Watt/kg study.

The remaining values are estimates calculated in the conceptual design. Mast and deployer weights are based on estimates provided by industry sources. In making these weight estimates, an attempt has been made to apply sound engineering judgement without being either overly optimistic or conservative.

It is evident that although the total mass of 790 kg meets the design goal, mass is critical and a high concentration on minimum weight will be necessary in the detailed design phase.

Table 3-4. Mass Summary

Item No.	Item	Unit Mass kg	Quantity Per Wing	Baseline Design kg
	<u>Blanket (Electrical)</u>			
1.	Solar Cells	78×10^{-6}	596,960	46.56
2.	Substrate	$.036/m^2$	$317.8\ m^2$	11.44
3.	Adhesive (1 mil RTV)	$.01/m^2$	$243.8\ m^2$	2.44
4.	Cover Material (3 mil RTV)	$.03/m^2$	$243.8\ m^2$	7.32
5.	Interconnects	25 mg	596,960	14.92
6.	Bus Strips	.144/m	73.9 m	10.6
7.	Slip Rings Assy	7.0	1	7.0
8.	Cable	.2	1	.2
9.	Connectors	.04	4	.24
10.	Switching Relays	.03	52	1.56
11.	Control Modules	.20	1	.20
	Sub Total			102.57
	<u>Blanket Support/Stowage</u>			
12.	Drum	5.93	1	5.93
13.	Drum Support	24.83	1	24.38
14.	Shaft & Bearings	3.67	2	7.34
15.	Mast	68.0	1	68.0
16.	Mast Deployer	23.0	1	23.0
17.	Stabilizer Arms	1	2	2.0
18.	Tension Wire Assy	.84	1	.84
19.	Header	6.0	1	6.0
20.	Blanket Tension Springs	.2	5	1.0
21.	Drum Drag Brake	.2	1	0.2
	Sub Total			138.69
	<u>Concentrator</u>			
22.	Reflector (Kapton Film)	20	2	40.0
23.	Support Rib	10.5	4	42.
24.	Shaping Rib (Inc. Flex Hinge)	.59	12	7.08
25.	Rib Folding Joint	1	16	16.0
26.	Rib Power Hinge	4	4	16.0
27.	Jettison Adapter	2.3	4	9.2
28.	Container Support	5.5	1	5.5
				135.78
29.	Misc. Hardware	-	-	5.0
30.	Extension Mast	12.9	1	12.9
	Total Mass	12.9		394.94

3.3 ELECTRICAL DESIGN CONCEPT

3.3.1 BLANKET LAYOUT

The conceptual design for the solar array blanket used in the Concentrator Solar Array is shown in Figure 3-8. The 2-mil thick silicon solar cells (2 x 2 cm) are bonded to a 1-mil thick flexible Kapton substrate, measuring 4.3 meters wide by 73.9 meters long. Each wing contains 596,960 solar cells grouped into 26 sections, 20 parallel modules per section, and 41 series circuits per module. The smallest replaceable grouping is the circuit, which consists of 28 cells arranged in a 7 series x 4 parallel matrix. Each wing develops 30 kW at 1 AU with no concentration. The output voltage varies between 200 and 400 Vdc, depending upon the distance from the sun, the switching mode configuration, and the concentration ratio used.

A solar cell efficiency of 11.1 percent at 28°C was assumed. As previously noted, the solar cells used for the Planar Array (Part I of this report) assumed a cell efficiency of 12.5 percent at 28°C. Solar cells of 11.1 percent efficiency, 2-mils thick, are presently being produced in a pilot plant operation at Solarex.

The power from each of the 26 sections is brought out on two flat aluminum conductors running along the sides of the blanket. The conductors are sized in cross section according to the length of their run to equalize section voltages at the array output. Approximately 0.5 meters of blanket width is provided on each side to accommodate the 26 flat aluminum conductors. The conductors are positioned underneath the concentrators so they will not be exposed to concentrated sunlight. The maximum expected current for each conductor is 20 amperes (1 AU, CR = 1.8, AMO, 110°C).

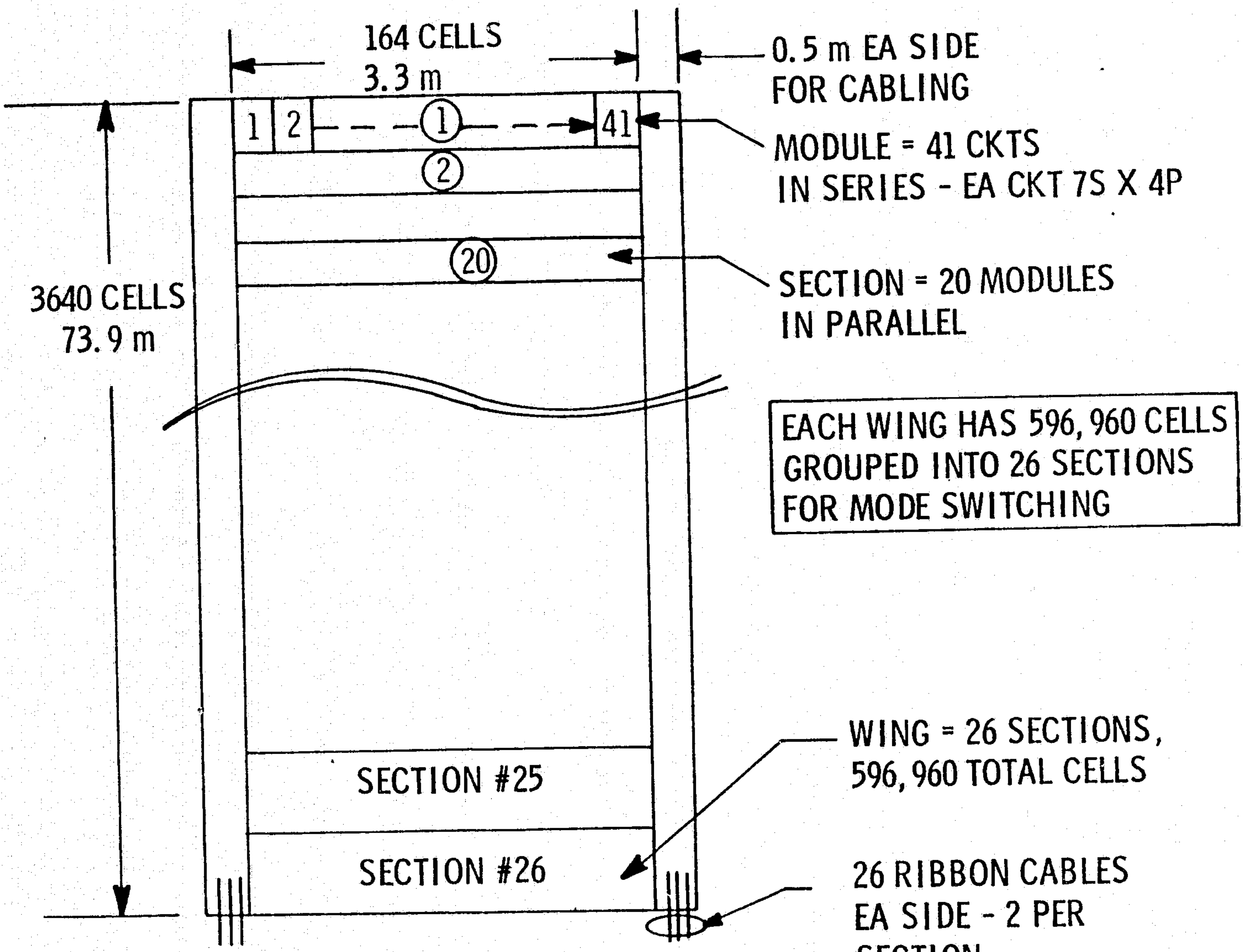

Figure 3-8. Blanket Layout

3.3.2 MODULE INTERCONNECTIONS

A solar cell module consists of 41 circuits connected in series across the width of the blanket as shown in Figure 3-9. Each circuit is orientated 180 degrees from its adjacent circuit to alternate the direction of current flow and thereby minimize the magnetic fields generated. The 41 series circuits represent a total of 1148 cells connected 287 in series by 4 in parallel. Each module produces 57.7 Watts at the maximum power point (1 AU, AMO, 55°C) and develops a maximum power voltage of 109 Volts.

A solar cell section is the smallest area of the total blanket from which external cabling is routed to the spacecraft. Each section is composed of 20 alternate modules connected in parallel. This permits current flow across the width of the blanket to be in opposite directions for adjacent modules and thereby minimize the magnetic fields generated. The 20 modules in each section represent 22,960 solar cells connected 287 in series by 80 in parallel. This produces 1155 Watts at the maximum power point (1 AU, AMO, 55°C) and a maximum power voltage of 109 Volts.

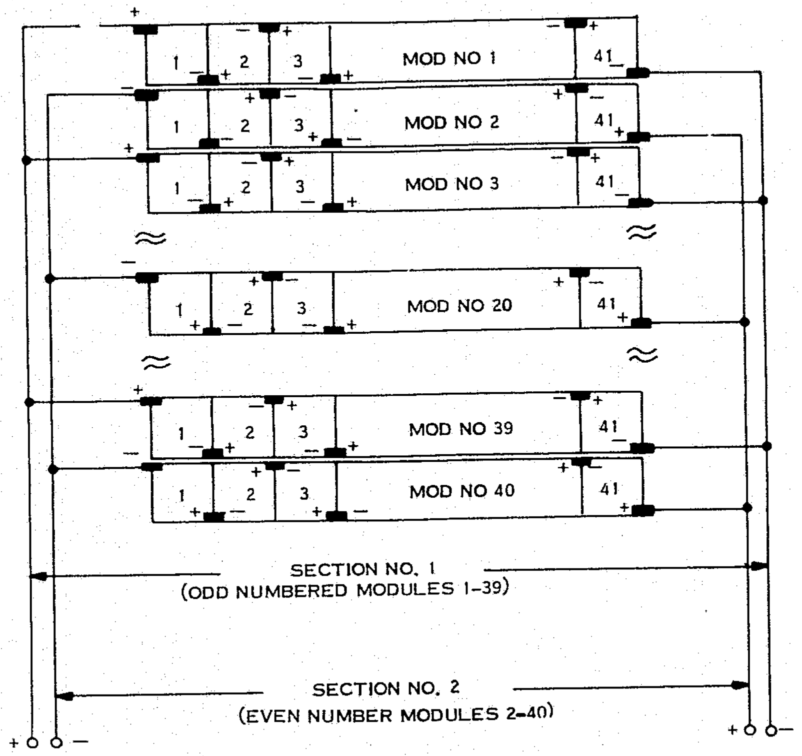

Figure 3-9. Module Interconnections

3.3.3 MODE SWITCHING

Each solar array wing is composed of 26 sections. The power from each section is routed along the blanket sides via flat aluminum cables to the mode switching relays located within the array drum. The relays connect the individual sections into two groups of nine sections in parallel and two groups of four sections in parallel. The four groups are then interconnected into one of two configurations as shown. The array output then passes through the slip rings located within the drum onto the power bus. The two mode switching configurations are necessary to maintain the array output voltage between 200 and 400 Vdc. A power controller can be added between the array output and the bus if additional regulation is required. The arrangement is shown in Figure 3-10.

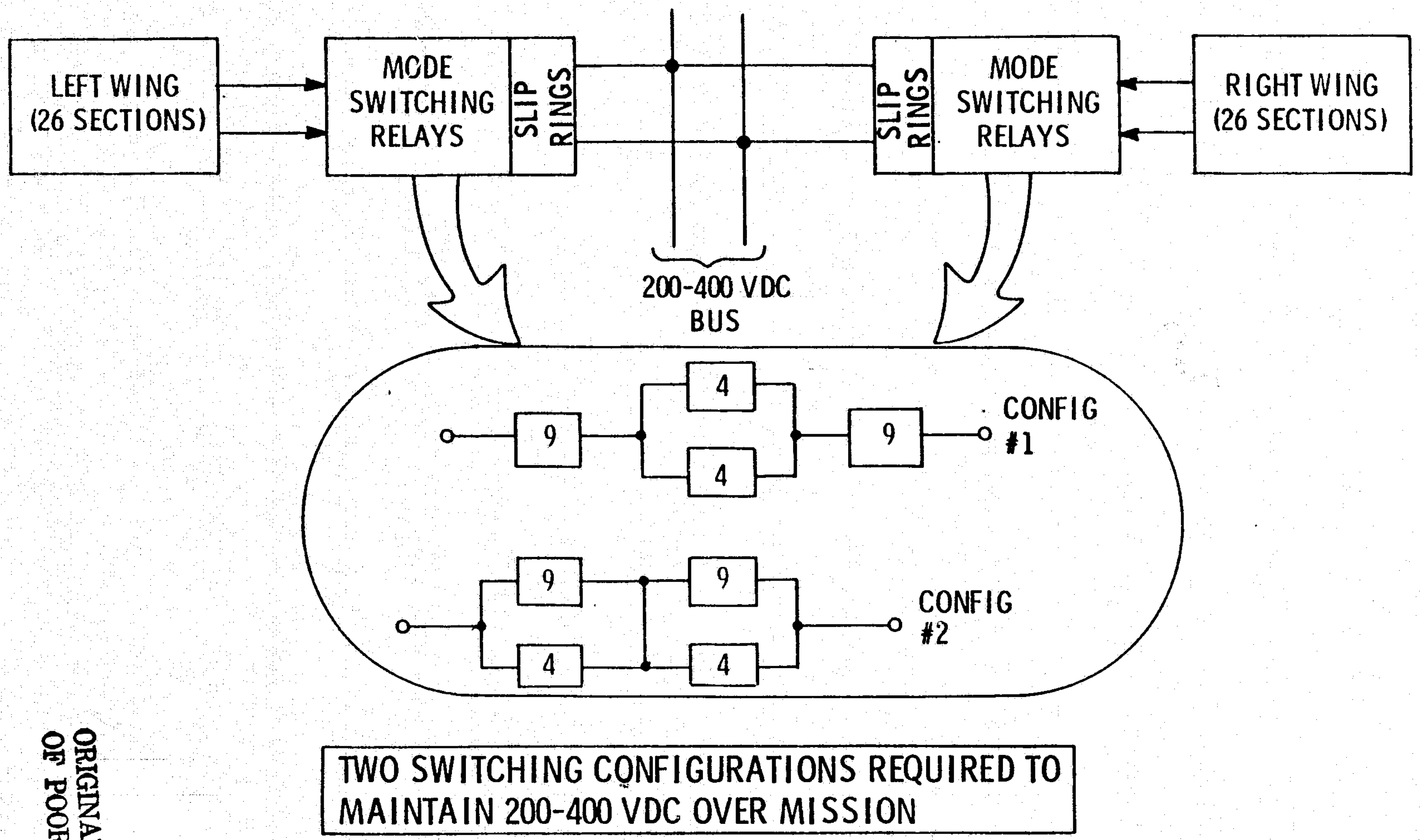

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Figure 3-10. Mode Switching

3.3.4 HCRM TRAJECTORY (Ecliptic Plane Projection)

The mission trajectory used to estimate the array performance is shown in Figure 3-11. After launch at 1.0 AU, the spacecraft travels outbound to a maximum distance of 4.5 AU over a time period of approximately 750 days. At 4.5 AU, the spacecraft moves inbound along the orbit of the comet for rendezvous at about 1.1 AU. The time period for the spacecraft to travel from 4.5 AU to 1.1 AU is about 530 days. Therefore, rendezvous with the comet is about 1280 days after launch (3-1/2 years). After rendezvous, the spacecraft follows the comet reaching a minimum sun distance of 0.6 AU.

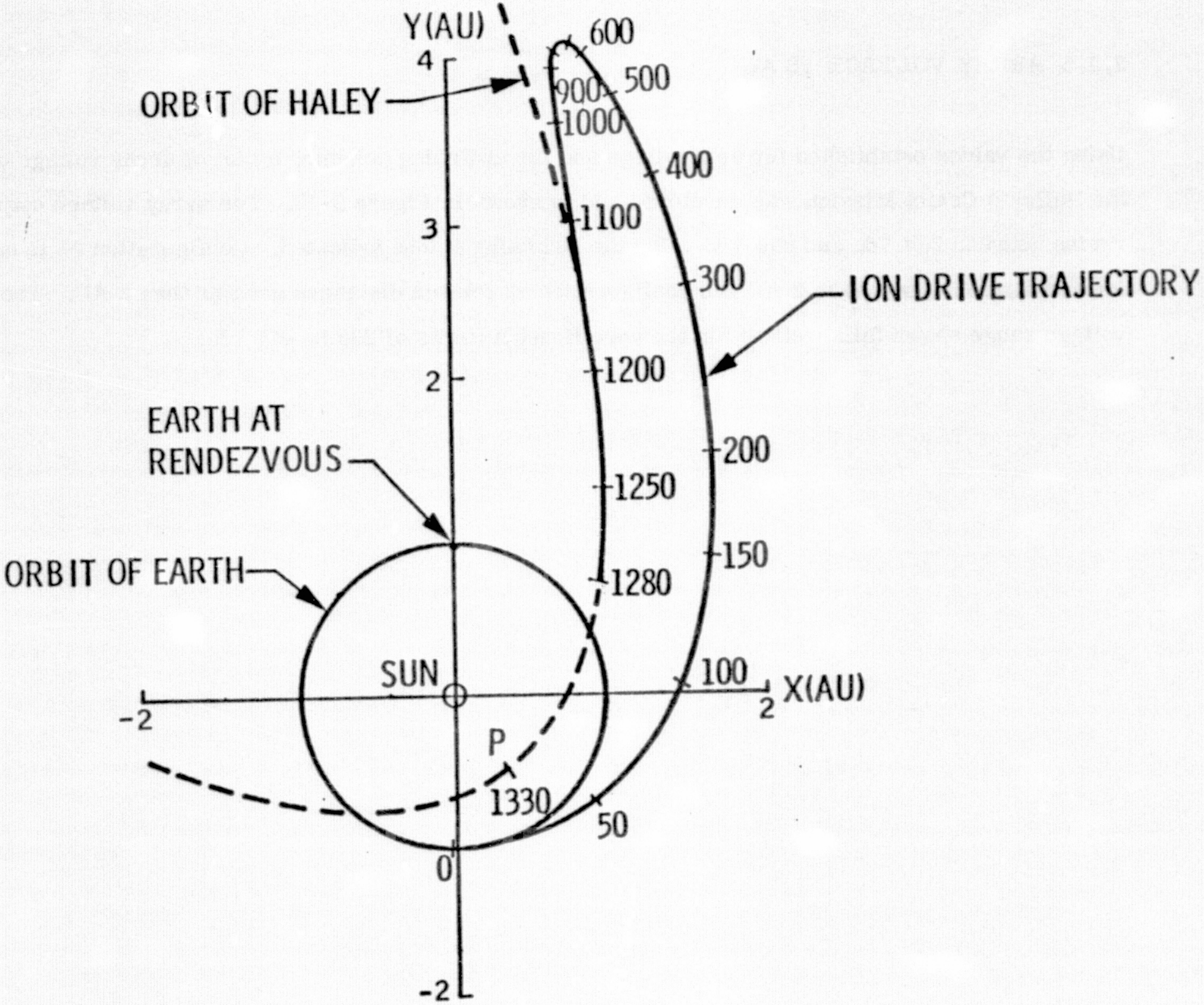


Figure 3-11. HCRM Trajectory - Ecliptic Plane Projection

3.3.5 ARRAY VOLTAGE VS AU

Using the values established for cell voltage and the switching scheme, a plot of array voltage over the Halley's Comet Mission was developed and is shown in Figure 3-12. The array voltage output varies between 232 Vdc and 390 Vdc using the switching points indicated. Configuration #1 is used for sun distances less than 2 AU and configuration #2 for sun distances greater than 2 AU. The voltage range shown falls well within the specification limits of 200 to 400 Vdc.

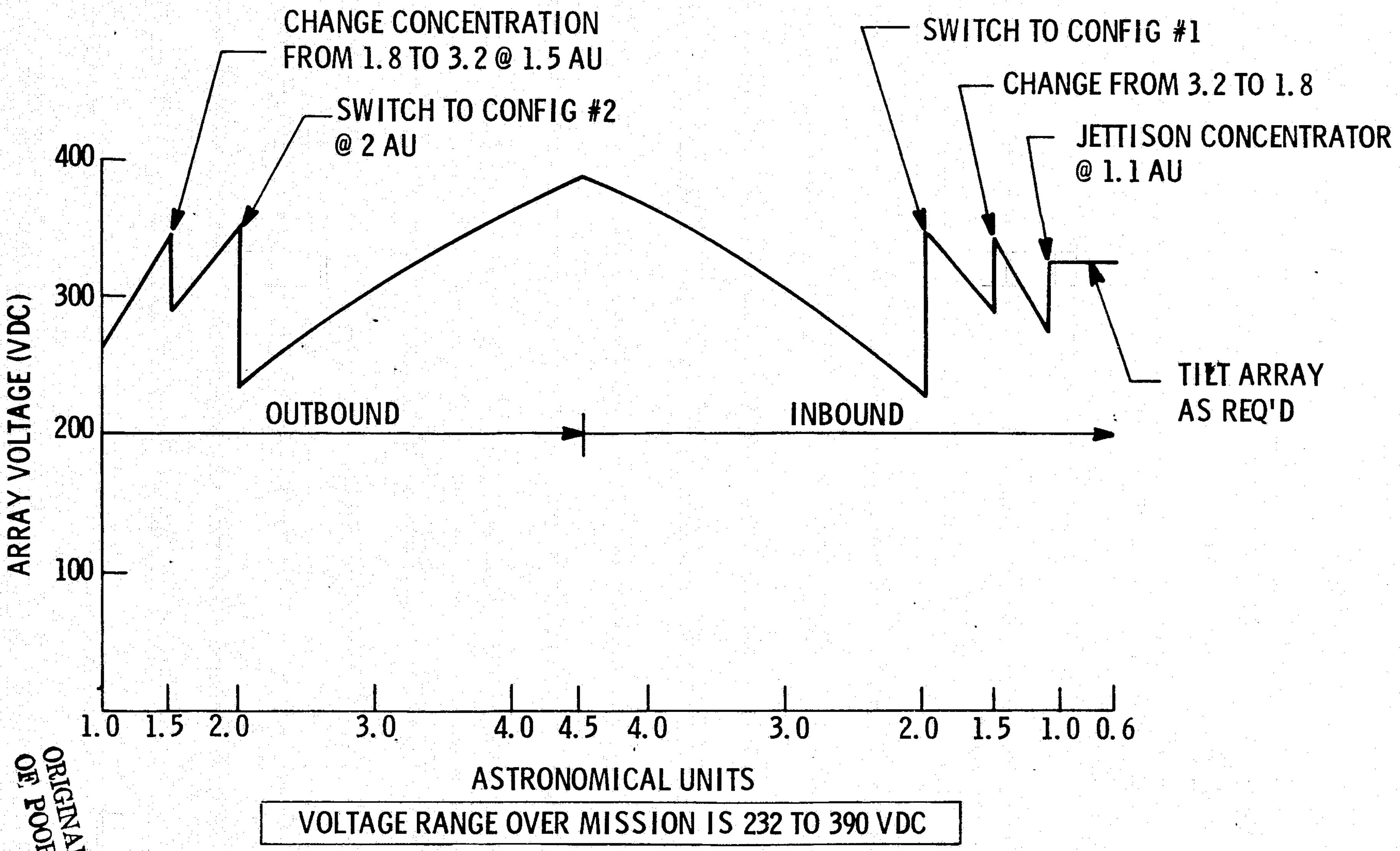
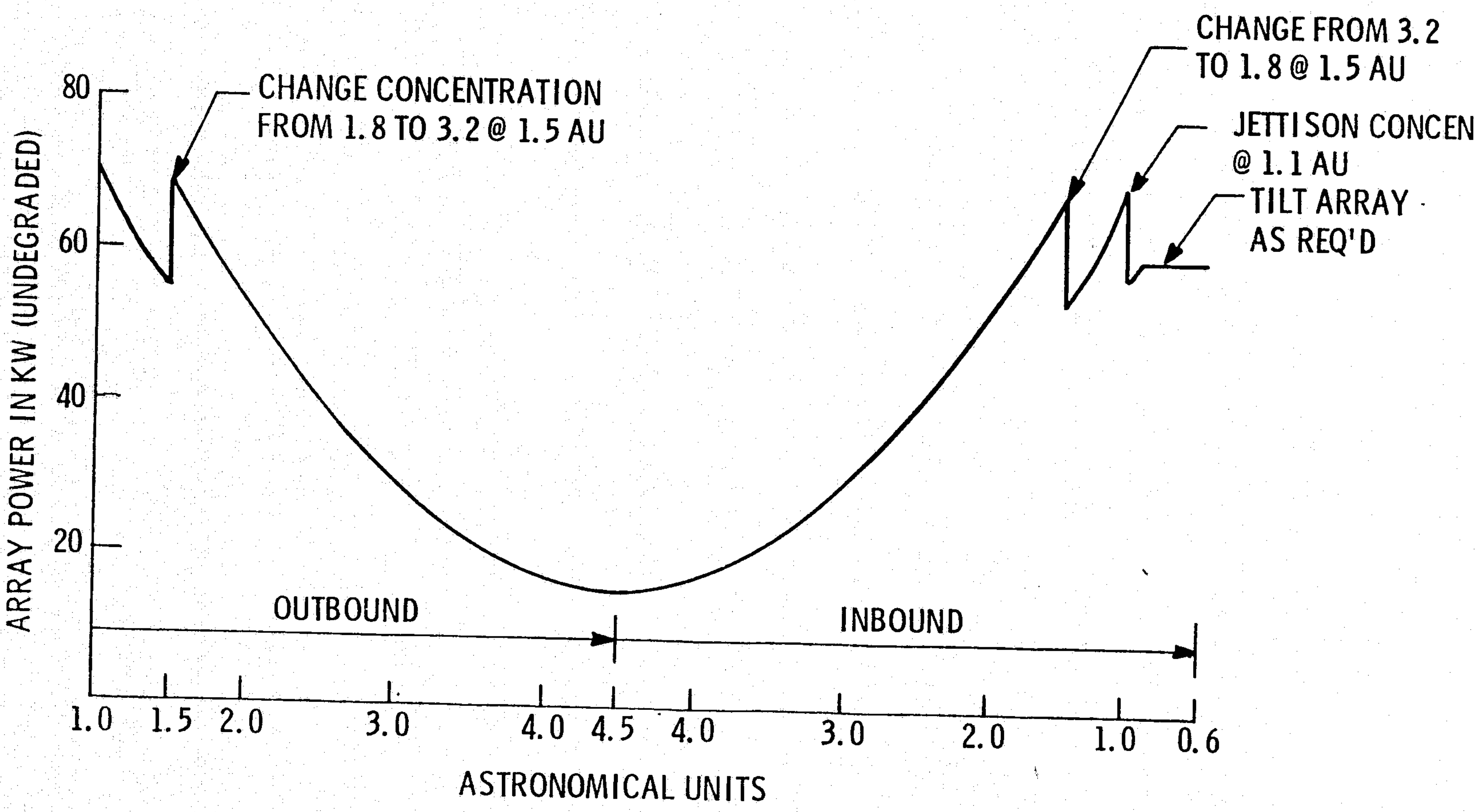


Figure 3-12. Array Voltage Vs AU

3.3.6 UNDEGRADED POWER VS AU

Figure 3-13 is a plot of the total undegraded array output power as a function of AU. From initial array deployment at 1.0 AU to about 1.5 AU, the parabolic concentrators are set for an effective concentration ratio of 1.8. At 1.5 AU, the ratio is changed from 1.8 to 3.2. The concentration ratio remains at 3.2 until the spacecraft completes its outbound journey and returns inbound to 1.5 AU (approximately 1135 days). At 1.5 AU, the concentrators are moved back to the 1.8 ratio position until just prior to comet rendezvous (approximately 1.1 AU). At this point, the concentrators are jettisoned as their usefulness has terminated. In order to maintain temperature control (120°C maximum), the array can be tilted as the spacecraft travels inbound from about 0.8 AU.

The total undegraded array output power varies from 70kW at 1 AU to 15.4kW at 4.5 AU, as seen on the figure. If an overall degradation of 12% is assumed, those values will drop to 61.6kW and 13.6kW, respectively. A requirement to drive six ion engines at 2kW per engine at 4.5 AU will result in a power margin of 1.6kW for the degraded array.



UNDEGRADED POWER AT 4.5 AU IS 15.4 KW

Figure 3-13. Undegraded Power Vs AU

3.3.7 RADIATION ANALYSIS

A radiation analysis was conducted using the electron and proton fluence supplied by JPL for the Halley's Comet Mission (Ion Drive). The fluence levels stated at 50% probability were doubled for the analysis. The results show a maximum power degradation of 5% over the mission. This value was obtained by using the JPL supplied test data of power loss versus the damage equivalent normally incident (DENI) electron fluence at 1 MeV. This value excludes the effect of UV radiation.

Projections based on ultraviolet testing at GE of solar cell modules indicate an overall power loss of about 7 percent is possible due to the ultraviolet radiation over the mission. Based on the particulate analysis (5%) and the ultraviolet projection (7%), an overall power loss of 12 percent is assumed.

Table 3-5. Radiation Analysis

- ELECTRON AND PROTON FLUENCE AT DISCRETE ENERGY LEVELS OVER MISSION SUPPLIED BY JPL
- USED VALUES AS IS FOR 95% OF PROBABILITY OF PROTON FLUENCE NOT TO EXCEED
- USED SAFETY MARGIN OF 2 FOR ELECTRON FLUENCE
- DETERMINE DENI AT 1 MEV FOR SHIELD DENSITY-THICKNESS OF CONCEPT CONFIGURATION PER SOLAR CELL RADIATION HANDBOOK (JPL/TRW-6/73)
- JPL SUPPLIED CURVES (TEST DATA) USED TO DETERMINE CELL LOSS FOR DENI ELECTRON FLUENCE AT 1 MEV (9/76)
- UV DEGRADATION, BASED ON 1 SUN TESTS AT GE IS PROJECTED TO BE ABOUT 7% OVER MISSION

POWER DEGRADATION OVER ENTIRE HALLEY'S COMET MISSION
IS ESTIMATED AT 12%; I.E., 0.88 BOL
OF WHICH 5% IS ASSIGNED TO PARTICULATE DAMAGE

3.3.8 MISSION PERFORMANCE

The basic building block for the Halley's Comet solar array is a 2 cm x 2 cm x 0.002 inch solar cell having an efficiency of 60 mW at 28°C (11.1%). Estimates of cell power were made using the JPL test data (JPL IOM #341-018A, "Parametric Testing of Solarex 50 Micron Solar Cells", April 13, 1977, Mr. Bruce Anspaugh), and upgraded the efficiency from those tested (9.96%) to the present 11.1%. Effective concentration ratios of 3.2 and 1.8 were used to establish the solar incident energy impinging on the solar cells (geometric ratios are 4.6 and 2.0 respectively). These data, along with the solar cell temperature estimates over the Halley's Comet Mission, were used to calculate array power..

Table 3-6 summarizes the results of the analysis relating to array power and voltage as a function of distance from the sun. Effective concentration ratios of 3.2 and 1.8 were used. The solar incident energy falling upon the cells was calculated as:

$$\text{Incident Energy} = \frac{\text{Solar Constant } (135.3 \text{ mW/cm}^2)}{(\text{AU Distance})^2}$$

By using the incident energy along with the corresponding cell temperature, the cell power and voltage (at maximum power point) was determined using the JPL test data previously mentioned. The cell power was ratioed upward by 11.1/9.96 to account for the present cell efficiency. The undegraded array power is the product of the total number of cells times the cell power (no losses assumed at this point).

As previously described, a solar cell section is composed of 20 modules connected in parallel. Each module consists of 41 circuits connected in series. Each circuit is a 7 series by 4 parallel celled building block. Therefore, the voltage developed per section (same as module) is 7 cells/circuits x 41 circuits, or 287 cells in series. The column labeled "section voltage" is 287 times the cell voltage. The cell voltage was taken directly from the JPL test data. The switching configurations either doubles (Configuration #2) or triples (Configuration #1) the voltage from each section. The column labeled "Array Voltage with Switching" shows the resulting values.

Table 3-6. Mission Performance

AU DISTANCE	RATIO CONCENTRATION	ARRAY TEMP. (°C)	UNDEGRADED ARRAY POWER (KW)	ARRAY VOLTAGE WITH SWITCHING (VDC)
1	1	55	60	327
1	1.8	110	70	258
1.1	1.8	85	69.4	276
1.1	1	50	57.8	327
1.5	1.8	45	54	344
1.5	3.2	90	68.4	288
2.0	3.2	40	53.6	348/232
2.8	3.2	0	33.8	287
3.0	3.2	-15	29.4	310
4.0	3.2	-50	17.6	356
4.5	3.2	-72	15.4	390

3.4 CONCENTRATOR SOLAR ARRAY, CONCEPT OVERVIEW

The Concentrator Solar Array conceptual design utilizes the lightweight technology developed for the 200W/kg rollup solar array. The blanket substrate, solar cells, interconnects, boom, tension motors, cylindrical drum, and slip rings take full advantage of this lightweight technology. Compound Parabolic Concentrators have been added to increase the power output at great distances from the sun. With an equivalent number of cells, the power at 4.5 AU with concentrators is over 2 times greater than that produced without concentrators.

The total array power at 1 AU without concentration (sometimes called "bought power") is 60 kW. This power is developed by two wings, each having 596,960 solar cells and an overall dimension of 4.3 x 74 meters. With the mode switching scheme developed (3.3.3), the array output voltage is maintained in the 200-400 Vdc range throughout the Halley's Comet Mission.

The total weight for the Concentrator Solar Array is 790 kg.

Table 3-7. Concentrator Solar Array, Concept Overview

TOTAL ARRAY POWER, 1 AU, CR = 1 (2 WINGS)	60 KW, BOL
NO. OF CELLS PER WING	596,960
CELL AREA PER WING	244 M^2
BLANKET SIZE	4.3 x 74 M
CONCENTRATOR SIZE (1)	15 x 74 M
CONCENTRATION RATIOS	1.8/3.2
TOTAL ARRAY POWER, 4.5 AU, CR = 3.2 (2 WINGS)	15.4 KW, UNDEGRADED
DEPLOYED NATURAL FREQUENCY	0.015 Hz
STOWAGE METHOD	CYLINDRICAL DRUM, 30.5 CM (12 IN. DIA.)
POWER TRANSFER	SLIP RINGS
TOTAL WEIGHT	790 Kg

SECTION 4

SOLAR ARRAY COMPARISONS

SECTION 4

SOLAR ARRAY COMPARISONS

The planar and concentrator solar arrays described for the Halley's Comet Ion Drive Mission have some significant differences as shown on Table 4-1. In order to obtain 6 kW at 4.5 AU with an unconcentrated planar array, nearly 2 million solar cells are required. This is nearly twice the number required for the concentrator array, which produces over twice the power at 4.5 AU (15.4 kW). In other words, the concentrator array produces over twice the power at 4.5 with nearly half the number of solar cells - a significant cost savings. However, the weight savings obtained by using fewer cells is more than offset by the weight of the concentrator and associated supporting structures. The concentrator array is 24% heavier than the unconcentrated planar array.

Table 4-1. Solar Array Comparisons

CHARACTERISTIC	PLANAR ARRAY	CONCENTRATOR ARRAY
TOTAL POWER, 1 AU, BOL, UNCONCENTRATED	121.4 KW	60 KW
TOTAL POWER, 4.5 AU, UNDEGRADED	6.0 KW	15.4 KW (CR = 3.2)
TOTAL NUMBER OF CELLS	2×10^6	1.2×10^6
SOLAR CELL SIZE	2 x 2 CM x .002 IN.	2 x 2 CM x .002 IN.
SOLAR CELL EFFICIENCY (ASSUMED) @ 28°C	12.5%	11.1%
ARRAY VOLTAGE OVER MISSION	1.8 TO 3.7 KV 200 TO 350 VDC	232 TO 390 VDC
BLANKET SIZE (PER WING)	8.4 x 60.5 M	4.3 x 74 M
BLANKET TEMPERATURE OVER MISSION	-120°C TO + 120°C	-72° TO 120°C
DEPLOYED NATURAL FREQUENCY	0.04 Hz	0.015 Hz
TOTAL WEIGHT	624 KG	790 KG

SECTION 5

RECOMMENDATIONS

SECTION 5

RECOMMENDATIONS

The Concentrator Solar Array described in Part II of this report evolved in an environment of rapidly changing requirements, and within the framework of extremely tight schedule restraint. Although the performance projections are considered realistic, much of it is based on top-level analyses and evaluations. In many areas, detailed analyses have not been performed. The lack of detailed analyses and validations always leaves the door open to question. Concentrator Solar Arrays, coupled with low thrust propulsion such as the Ion Engine, represent a considerable potential for many interplanetary and comet rendezvous missions. The technology associated with the Concentrator Solar Array should be developed in greater depth. A few areas requiring additional investigation are summarized below:

1. Parametric studies to optimize the concentration ratio as a function of cost, power, weight and maximum heliocentric distance
2. Detailed dynamic analyses of the deployed array
3. Detailed analyses relating to thermal deflections of the deployed array
4. Optimization studies for the stowage and deployment of thin-film parabolic concentrators
5. Evaluation of concentrator performance, including measurements of the uniformity of solar distribution, surface texturing of reflector surfaces, distortion losses, etc.
6. Design and test appropriate sequencing mechanisms for concentrator deployment
7. Design and test a suitable scale model of the array to optimize concentrator stowage and deployment sequences