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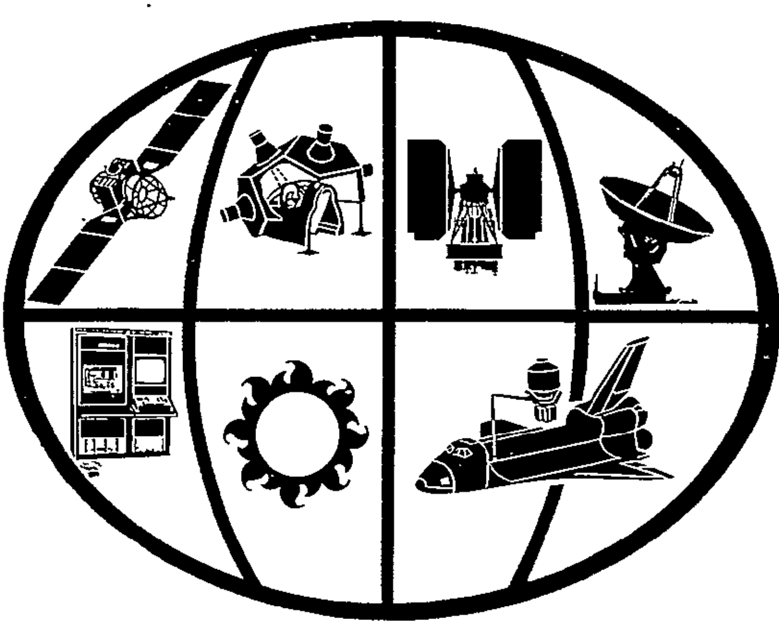
QUARTERLY REPORT NO. 2

CONCEPTUAL APPROACH STUDY OF A 200 WATT PER KILOGRAM SOLAR ARRAY

Prepared for
The Jet Propulsion Laboratory
California Institute of Technology

Under
Contract 954393



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PREPARED FOR

THE JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

PREPARED UNDER: CONTRACT 954393

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ABSTRACT

Four solar array candidate configurations (flexible rollup, flexible flat-pack, semi-rigid panel, semi-rigid flat-pack) have been analyzed in terms of their ability to meet the baseline requirements of this program, with the specific power (W/kg) requirement being the item of paramount concern. Two of these configurations (flexible rollup and flexible flat-pack) are seen to be capable of delivering specific powers equal to or exceeding the baseline requirement of 200 W/kg. While both of these acceptable design configurations are of the flexible substrate variety, only the flexible rollup is capable of in-flight retraction and subsequent redeployment.

The wrap-around contact photovoltaic cell configuration has been chosen over the conventional cell. The demand for ultra-high specific power forces the selection of ultra-thin cells (75μm) and cover material (13μm). That solar cells are manufacturable in this thickness is a tacit assumption of this phase of the program. Based on density and mass range considerations, it has been concluded that 13μm of FEP Teflon is sufficient to protect the cell from a total proton fluency of $2(10^{12})$ particles/cm^2 over a three-year interplanetary mission.

The V-stiffened, lattice boom deployed, flexible substrate rollup array holds the greatest promise of meeting the baseline requirements set for this conceptual approach study and remains the number 1 conceptual candidate design at this juncture.

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INTRODUCTION AND SUMMARY

This second Quarterly Report reports on the work performed during April, May and June 1976. The most significant event during this period of time was the Mid-term Report given to JPL personnel and invited guests on 17 June. Program action items were solicited during that meeting and five were received by the GE project manager. While this report does not specifically address these action items, the intent of some of them has been incorporated into this report.

The schedule of tasks for this program is shown in Figure 1-1. Task 1 is complete with no new work to be reported in this quarter. Task 2 work in Design Synthesis and Analysis is continuing with reports on stress analysis and thermal analysis in Section 2. 3 and in Appendices A and B. Some layout work has been completed in Task 3 and is reported throughout this report. There are two specific State-of-the-Art Projections, Task 4, to be reported at this time. Work on Task 5, Conceptual Design Specifications will not begin until the last quarter of the program.

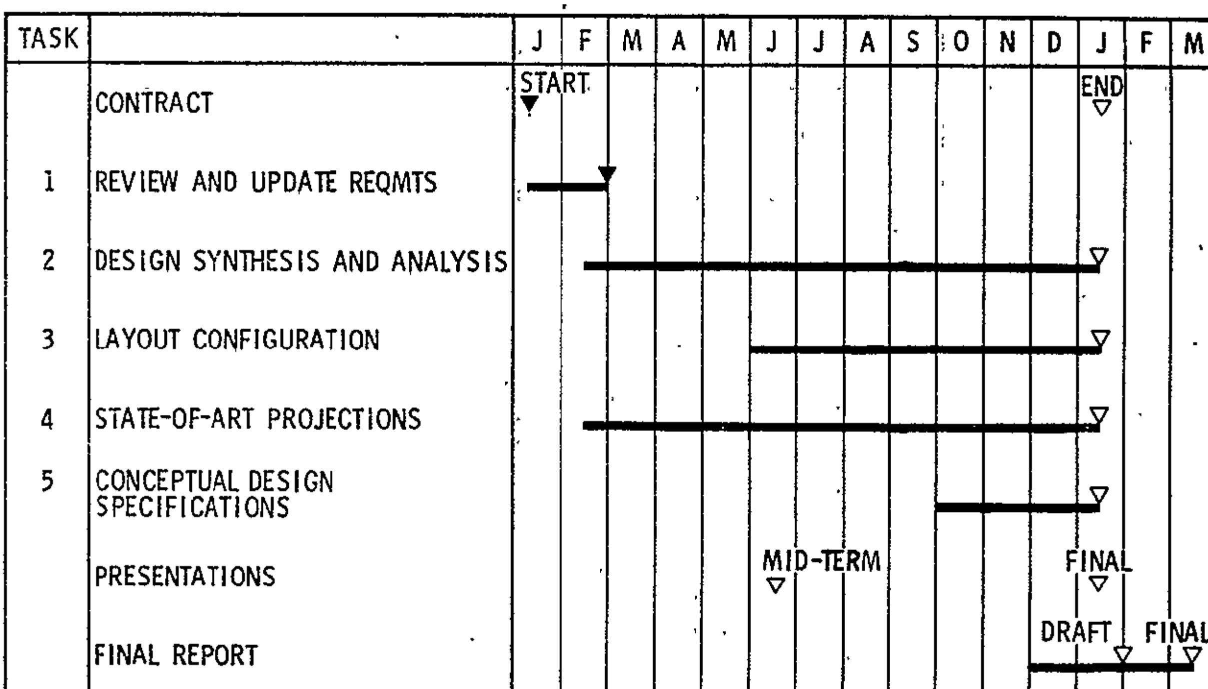

Figure 1-1. Schedule

At this half-way point in this study program, it may be said that the prospect of obtaining one or more designs that will meet or exceed the primary design objective of 200 watt/kilogram for the interplanetary mission are very good. Out of several current concepts that are being evaluated, one in particular, known as Concept 1, holds promise to meet all of the Baseline Requirements, including retractability. The mass breakdown of this concept and the mass allocation of an earlier study are shown in Table 1-1 for comparison with the tentative budget established for this program in the first quarter. The specifics of this conceptual design are subject to this report.

Table 1-1. Mass Allocation to Achieve 200 Watt/Kg

MASS IN KG

FUNCTION	110 W/KG STUDY	PROJECTED ALLOCATION	CONCEPT NO. 1
ELECTRICAL	48.5	25	24.0
MECHANICAL	39.0	25	25.53
TOTAL	87.5	50	49.53
WATTS/KG	114	200	202

TECHNICAL DISCUSSION

SECTION 2

TECHNICAL DISCUSSION

2.1 ELECTRICAL DESIGN

2.1.1 ELEMENTS OF DESIGN

The design philosophy adopted in this conceptual study, to meet the design goal of 200 W/kg, is to take the extreme position regarding weight in all elements of the design. This may lead to design margins that are subject to question and readjustment in a subsequent design iteration. The principal value of this approach is that each element of design may be minutely examined for characteristics that may lead to the desired ultra-light weight design. The principal elements of design are shown in Figure 2-1 together with the options that exist with each element. It will be noticed that several elements normally associated with solar arrays are missing from this figure. Coverglass adhesives have been eliminated on the basis that either integral coverglass or heat-sealed sheet materials will be used. Substrate adhesive is missing on the basis that a heat-sealed substrate may be used. Isolation diodes are not shown as an element in the array design since they are accounted for in the power conditioning circuitry which by direction is not a part of the array mass summary. Also shown in this figure are the major design requirements and characteristics of a singular design that results when unique design elements are chosen. This selection process will be discussed in the succeeding paragraphs of this section.

2.1.2 SOLAR CELL OPTIONS

The trade-off areas for solar cells are limited to cell thickness and configuration, coverglass thickness and density and the optional use of coverglass cements. The lower bound for cell thickness was set at 3 mils in the Baseline Requirements document of this contract (see Appendix A, 1st Quarterly Report dated 15 April 1976). While no lower bound per se was set for the coverglass material, the radiation environment defined in this same document for the interplanetary mission does imply a minimum thickness sufficient to protect the cell from radiation damage. The impact of the solar cell/coverglass mass contribution to the total mass budget of 50 kg may be judged by two examples: The 8 mil silicon solar cell and the 6 mil cemented coverglass chosen for SEPS [1] requires 1/2 the total mass budget in this 65 W/kg design.

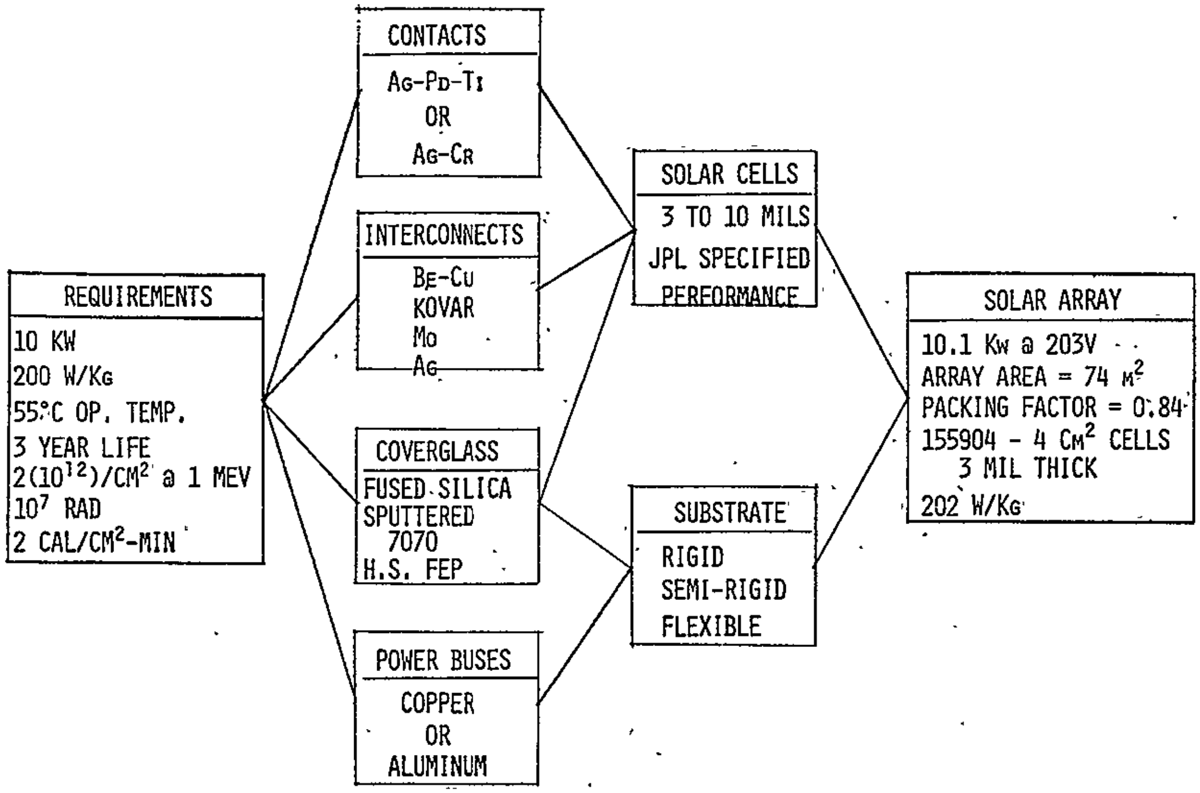

Figure 2-1. Solar Array - Elements of Design

The baseline design of an earlier ultra-lighweight solar array design[2] specified a 5 mil (125 μm) silicon solar cell with a 1.5 mil (37.5 μm) integral, RF-sputtered 7070 coverglass in a wraparound configuration. In this case, the cell/coverglass mass was 33 percent of the total array mass. Since the cell/coverglass combination account for such a major fraction of the total mass budget, it is apparent that a major weight reduction must be affected here.

The electrical performance expectation cited for solar array designs resulting from this study will be based on solar cell performance data enumerated in the Baseline Requirements document, cited above. The baseline cell thickness in this study will be 3 mil (75 μm) unless changed at a later date. The baseline operating temperature is assumed to be 55°C. Using the given current/voltage characteristic for a 10 mil (250 μm) 2 x 2 cm^2 cell (Figure 2-2), the change of output power with thickness (Figure 2-3), and the temperature coefficients for this cell (Table 2-1), the expected maximum power output for the baseline cell is calculated to be 66.3 mW at 1 AU and 55°C. A plot of power, current and voltage as a function of temperature is shown in Figure 2-4.

The prime candidate array design at this writing is a boom-deployed, flexible substrate array that is maintained in a plane surface by boom tension on the blanket. It is proposed that the blanket be composed of two layers of heat-sealed FEP Teflon backed up by a layer of Kapton for strength. In this concept, one FEP layer will double as the cell coverglass. Based on an interplanetary proton fluency of $2 (10^{12})$ particles/cm^2 over a three-year mission, as stated in the Baseline Requirements document, it is calculated that 13 μm of FEP will be sufficient to block these protons from any degrading influence on the cell. From the data at hand, it appears that the end of life (EOL) transparency in a UV environment of one solar constant will be no less than 90 percent of its initial value.

The alternative to heat-sealed FEP as a cement-less cell/coverglass combination is an integral 7070 coverglass. This is not as attractive as the sheet FEP in that the latter functions not only as a coverglass but in an integral member of the flexible blanket. With FEP on both sides of the cell, the thermally induced stress will be symetrically displaced from the mid-plane of the cell. This is in contrast to data on integral glass covers[3] where the non-symmetrical nature of the induced stress causes the thin cell to deflect out of a plane surface. A summary of cell/coverglass options is noted in Table 2-2. The present choice that will be reflected in the number one current solar array design is indicated as a 3 mil (75 μm) wraparound cell with 13 μm heat-sealed FEP as a coverglass. The specific power advantage of 13 μm FEP over 37 μm fused silica integral coverglass as a function of cell thickness is shown in Figure 2-5.

2.1.3 CELL INTERCONNECTION

The Baseline Requirements Document stipulates that the cell interconnect material option be limited to Beryllium-copper (Be-Cu), Kovar, molybdenum (Mo) and silver (Ag). A selection of characteristic properties for these materials, and several others, appear in Tables 2-3

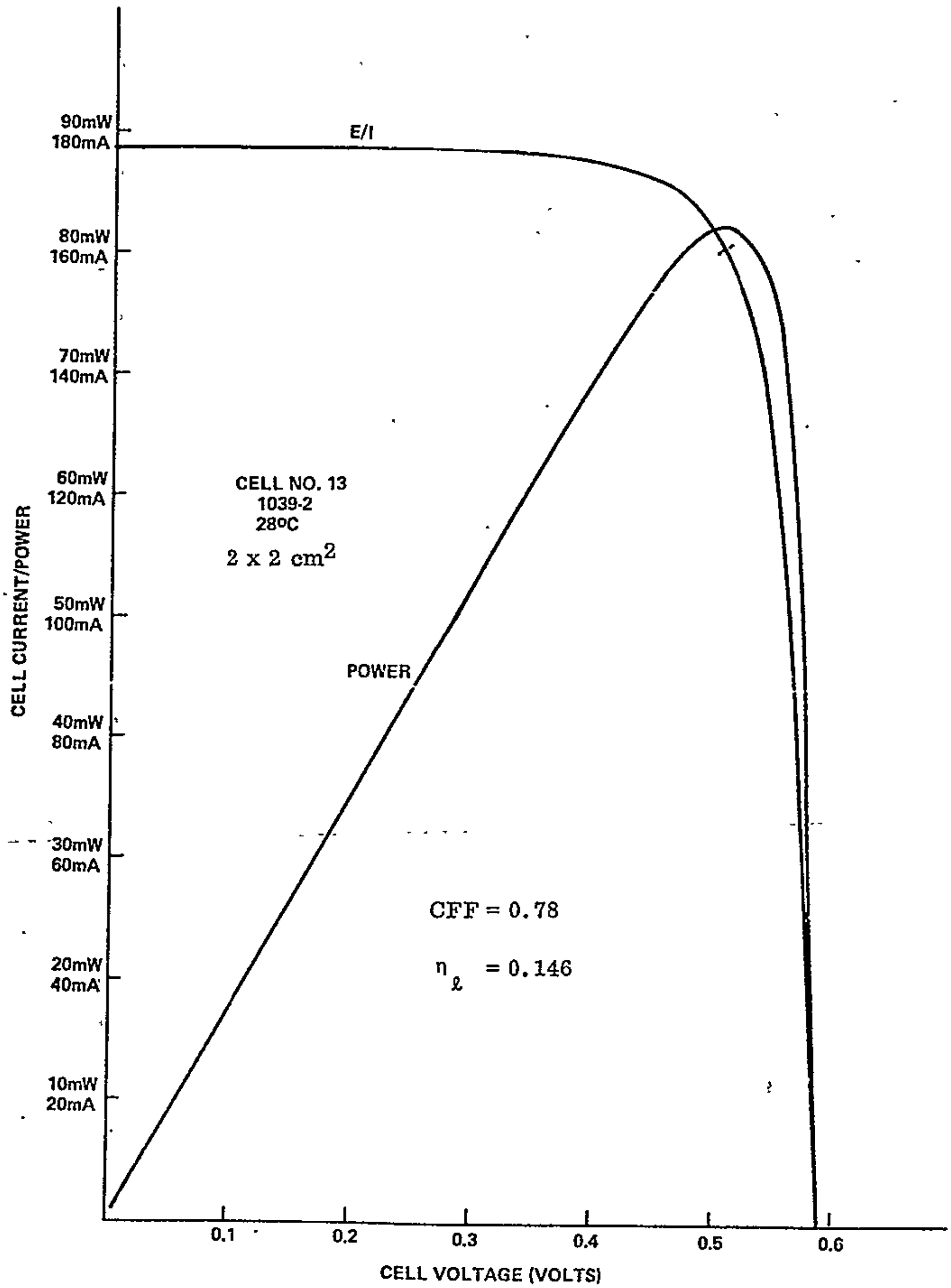

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Figure 2-2. Baseline Cell E/I and Power

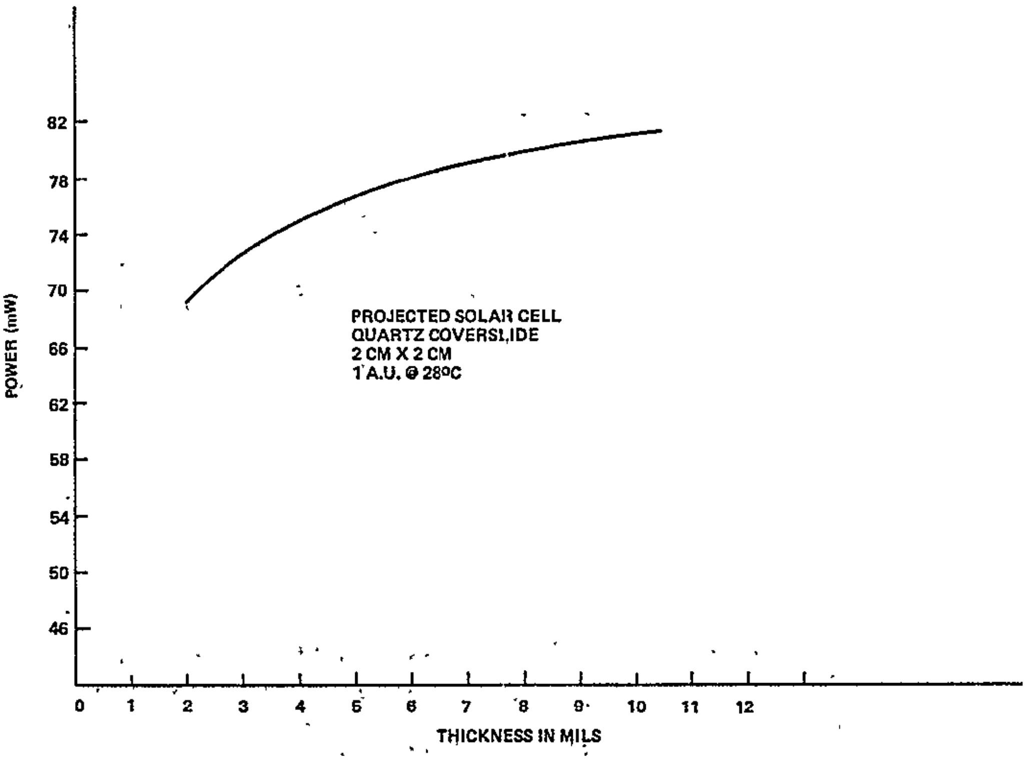

Figure 2-3. Baseline Cell Power vs Thickness

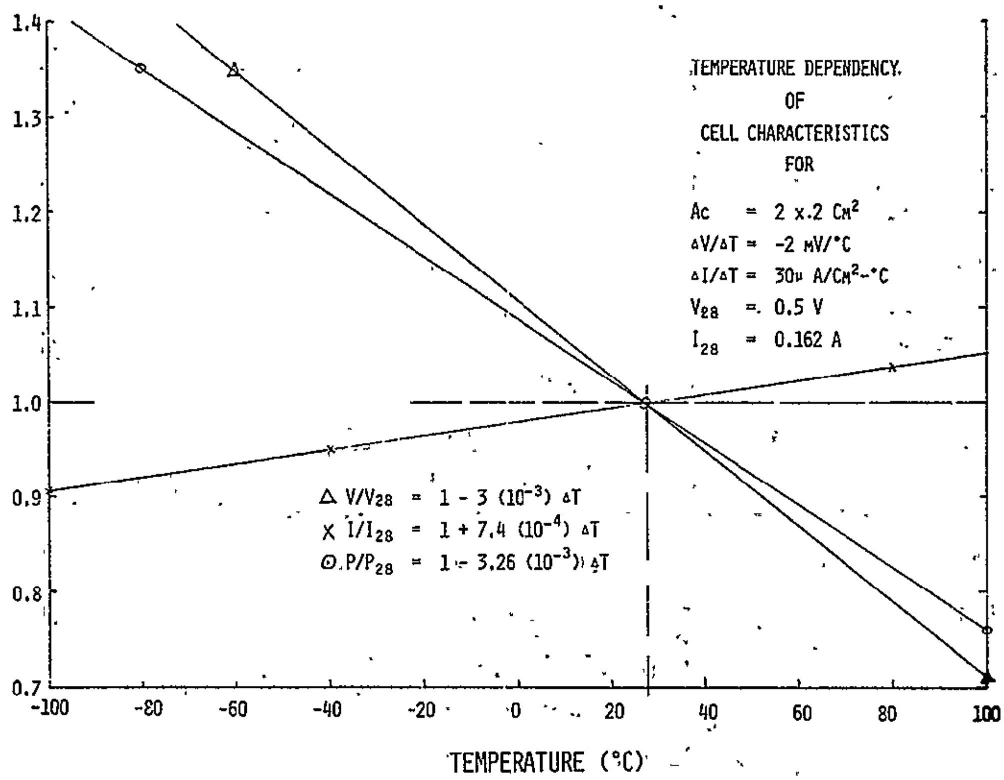

Figure 2-4. Temperature Dependency of Cell Characteristics

Table 2-1. Temperature Dependency

TEMPERATURE DEPENDENCY OF CELL PARAMETERS		
VOLTAGE:	$\Delta V/\Delta T$	= -2M V/°C
CURRENT:	$\Delta I/\Delta T$	= 30μ A/CM^2-°C
POWER:	$\Delta P/\Delta T$	= -264μ W/°C*
TEMPERATURE DEPENDENCY OF ARRAY PARAMETERS		
VOLTAGE:	$\Delta V/V_o$	= -0.4% ΔT
POWER:	$\Delta P/P$	= -0.33% ΔT

* 2 x 2 CM^2 AREA CELL

Table 2-2. Solar Cell Options

TYPE	PRO	CON
• CONVENTIONAL, 10Ω-CM (250 μM + 150 μM FUSED SILICA)	• FLIGHT QUALIFIED	• TO HEAVY (61 KG)
• WRAP-AROUND, REAR CONTACTS (125 μM + 30 μM 7070)	• AVOIDS HEAT DAMAGE TO JUNCTION • FLAT CONNECTORS TOP SURFACE CLEAN	• 50% OF WEIGHT BUDGET • NO. FLIGHT EXPERIENCE
• WRAP-AROUND, REAR CONTACTS (75 μM + 13 μM FEP)	• FEP COVER DOUBLES AS 1/2 BLANKET • CELLS ONLY 29% OF WEIGHT BUDGET	• NO EXPERIENCE WITH CELLS OF THIS THICKNESS

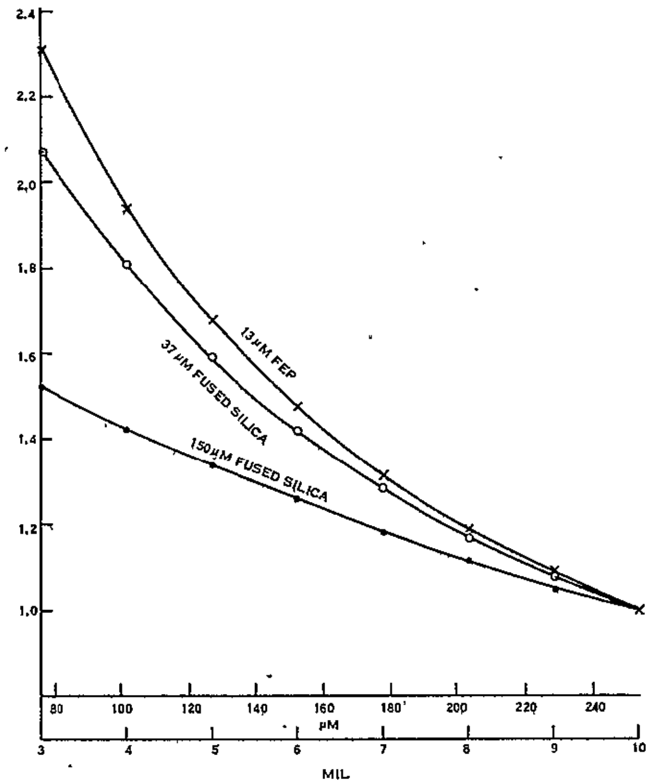

Figure 2-5. Relative Power to Weight vs Solar Cell Thickness (28°C)

and 2-4. Three principal concerns impact the selection of an interconnect material and design layout; viz, thermally induced stress, strength to weight ratio, electrical and thermal conductivity. A comparison of these properties relative to silver will point up some significant differences, see Table 2-5. Molybdenum is judged to be the best among these materials, especially when the thermal coefficient of expansion of moly is compared to silicon (see Table 2-3). The large specific stiffness of this material suggests that a moly interconnect could be thought of as a structural element of the array design, as well as an electrical conductor. A thin (2.5 µm) plating of silver on the moly may be desired to lower the voltage drop across the connector. The present thinking, then, is to utilize the interconnect as mechanical linkage between the cells in a group, so that the blanket tension of 1.3 pounds force (5.78N) will be borne by the cell/interconnect combination, for the main part.

While design optimization is not the intent at this phase of the program, it is necessary to identify a specific design in terms of weight, power loss and thermally-induced stress. A

Table 2-3. Material Properties - Interconnects and Buses

MATERIAL	DENSITY D GM/CM^3	ELECTRICAL RESISTIVITY ρ μ OHM-CM	$\frac{\Delta P}{\Delta T}$	THERMAL EXPAN. COEF. α 10^{-6}/°C	THERMAL CONDUCTIVITY WATT/CM-°K	USE
ALUMINUM	2.7	2.62	0.0039	22.9	2.18	BUS BARS
BE-CU (1)	8.26	5.7 TO 7.8		16.7	1.09	INTERCONNECTS
COPPER	8.96	1.72	0.0039	16.5	3.94	INTERCONNECTS BUS BARS
KOVAR	8.36	49.1		5.94 (2)	0.141 (2)	INTERCONNECTS
MOLYBEDENUM	10.2	4.77	0.0033	4.9	1.46	INTERCONNECTS
SILVER	10.5	1.62	0.0041	18.9	4.08	METALLIZATION INTERCONNECTS
SILICON BRONZE 96% CU, 3% SI	8.53	24.9		18.0	0.377	
SILICON BRONZE 97.7% CU, 1.5% SI	7.85	14.3		17.9	0.586	
SILICON	2.4	(2.0-10.0) 10^6		2.8 TO 7.3	0.84	PV CELL

(1) 2% BE, 1/4% CU, 0.35% NI; (2) AVE. OVER 0°C - 100°C

Table 2-4. Material Properties (Continued)

	MOD. OF ELASTICITY 10^6 PSI	TENSILE STRENGTH 10^3 PSI	YIELD STRENGTH 10^3 PSI	SPECIFIC STIFFNESS E/d 10^6 IN	ELONG %	d x ρ $\frac{\text{GM-OHM}}{\text{CM}^2}$ 10^{-6}
ALUMINUM	10	6.8	1.7	102.	60.	7.07
BE-CU	17	60 - 200 (3)	130.	57.	355.	55.7
COPPER	16	37.	6.5	49.	40.	15.4
KOVAR	19	77.5	59.5	63.	16.8	410.
MOLYBEDENUM	47	115.	100.	128.	4.	48.6
SILVER	11	18.2	7.9	29.	50.	17.0
SILICON BRONZE 96% CU, 3% SI	15	63.	30.	49.	55.	212.
SILICON BRONZE 97.7% CU,	17	50 (3)	35	60.	20.	112.
SILICON	10	30	24	115.	---	---

(3) FUNCTION OF HEAT TREAT

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limited amount of parametric analysis has been done regarding the design of the interconnect. The principal design criterian followed thus far is that the relative power loss in the interconnect shall be in the same ratio as the mass of the connector to the total mass of the blanket assembly; i. e.,

$$\frac{\Delta P}{P} = \frac{W_{cn}}{W_{tot}}$$

One parameter that these quotients have in common is the conductor width (ω). If the above relationships are expanded in terms of ω, the following results:

$$\frac{\Delta P}{P} = \frac{I^2 \rho L}{2tP}\left(\frac{1}{\omega}\right) \quad \text{and}$$

$$\frac{W_{cn}}{W_{tot}} = \frac{W_{cn}}{W_{cn} + \Delta W} = \frac{1}{1 + \frac{\Delta W}{W_{cn}}} = \frac{1}{1 + \frac{\Delta W}{dA_{cn}t}}$$

where:

I = cell current (at max. power)

ρ = connector resistivity

L = connector length (series direction)

t = connector thickness

P = cell max. power

ω = conductor width

ΔW = weight of all other blanket components

d = connector density

A_{cn} = f (ω) = connector surface area

Table 2-5. A Comparison of Material for Cell Interconnectors

MATERIAL COMPARISON	MATERIAL PROPERTIES							COMMENTS
	DENSITY D	RESISTIVITY ρ	$D \cdot \rho$	THERMAL COEFFICIENT OF EXPANSION a	THERMAL CONDUCTIVITY K	YOUNGS MOD E	E/D	
Be-Cu / Ag	0.79	4.17	3.3	0.89	0.27	1.54	1.96	DENSITY FAVORABLE 3RD CHOICE
KOVAR / Ag	0.80	30.3	24.0	0.31	0.03	1.73	2.17	DENSITY FAVORABLE a IS FAVORABLE - 2ND CHOICE
MO / Ag	0.97	2.94	2.8	0.26	0.36	4.27	4.4	BEST CHOICE ON 6/7 COUNTS - 1ST CHOICE

A sketch of a cell interconnect is shown in Figure 2-6. The cross-hatched area represents the wrap-around N-type contact on one cell and the adjoining cell's P-type contact. Several weld points are shown for illustrative purposes. The overall connector width will be determined by the number of parallel-connected cells. A number of layouts were made for various values of conductor width (ω). The resulting connector surface area is shown in Figure 2-7. The above relationships for relative power loss and weight are plotted in Figure 2-8. From this plot it may be concluded that the optimum design point occurs at a conductor width (ω) of 96 μm (~4 mil). If a 2 percent power loss criterian is adopted, a 3 mil width is indicated with a corresponding weight saving.

At this juncture a conductor width of 100 μm will be adopted for calculation of specific power. The surface area of 0.084 cm^2 (from Figure 2-7) and thickness of 1 mil of Mo and 0.1 mil Ag together with associated densities gives a connector unit mass of

$$W_{cn} = 2.4 \text{ mg/cell}$$

For an array of 155,904 cells, a total interconnector mass of 374 gram results. This number is significantly under the first trial number of 2.08 kg assigned to the interconnects for mass summary purposes elsewhere in this report. Further work is needed to determine if a 100 μm conductor width has sufficient strength to operate as a structural member as well as electrical conductor.

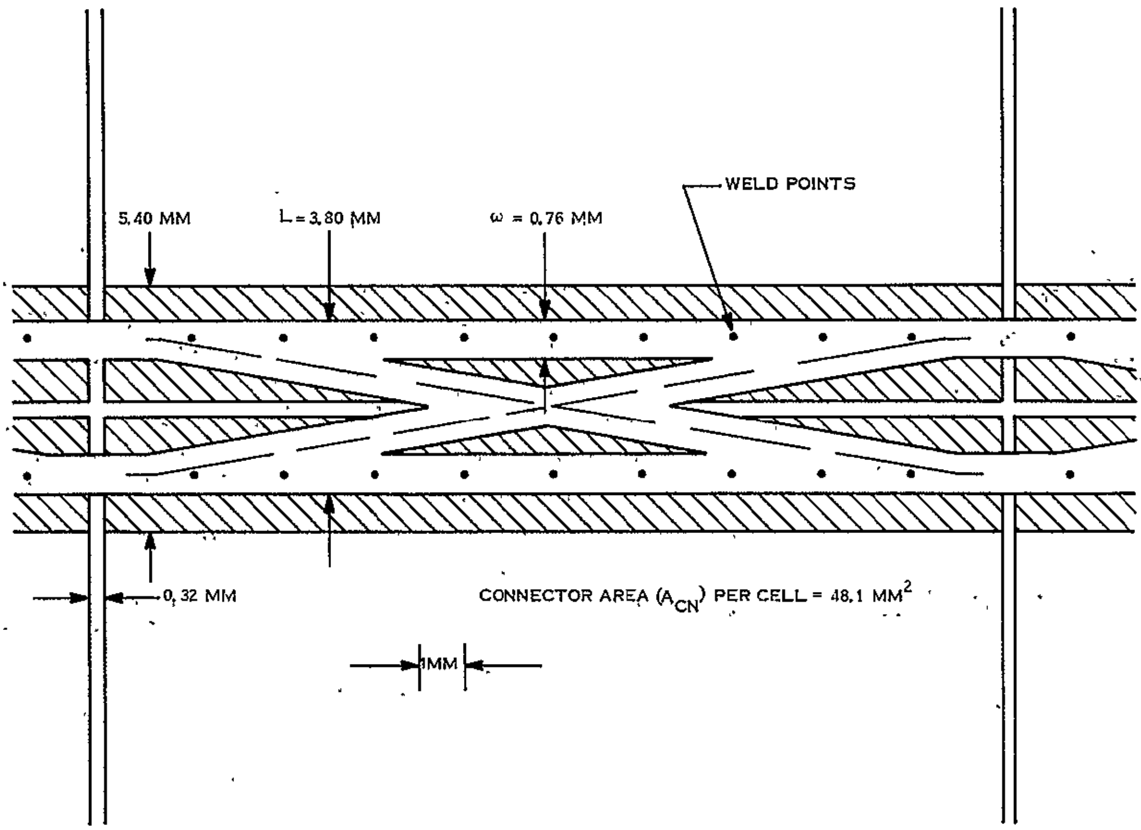

Figure 2-6. Trial Design Cell Interconnect

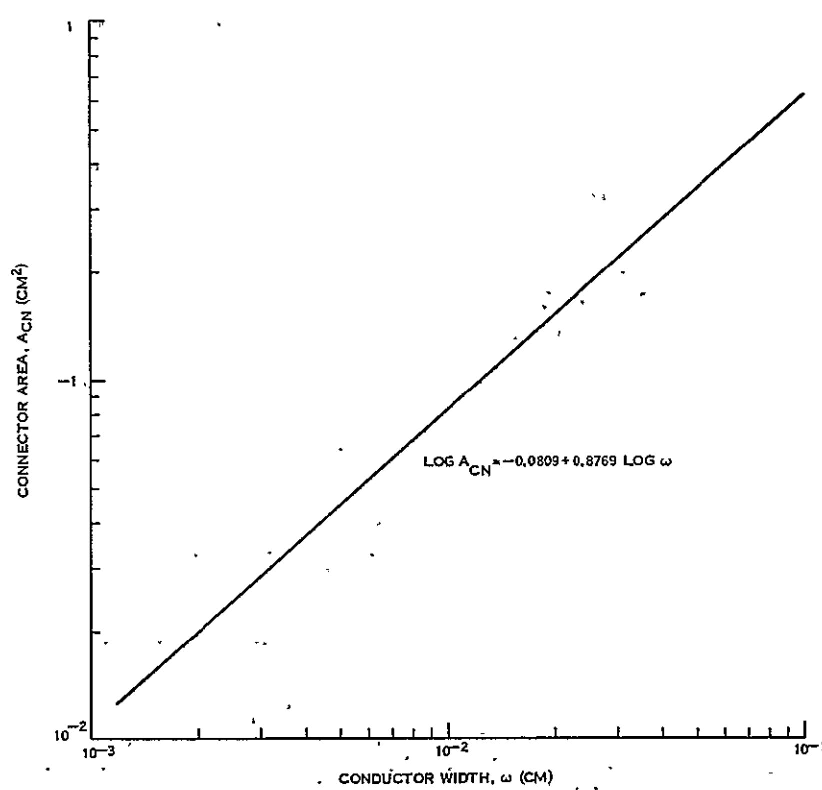

Figure 2-7. Connector Surface Area vs Conductor Width (ω)

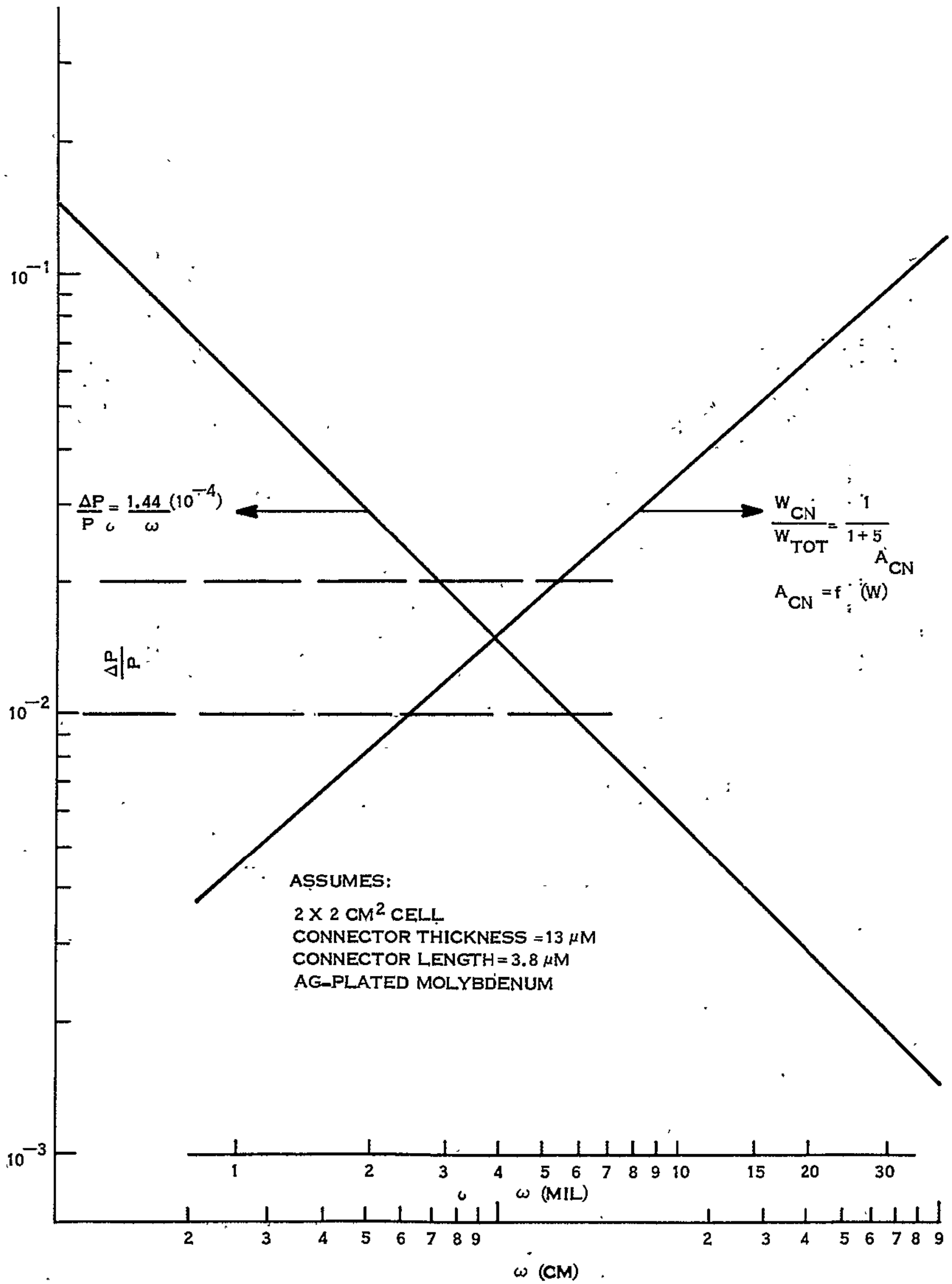

Figure 2-8. Optimization of Power Loss $(\frac{\Delta P}{P})$ and Relative Weight of Connectors $(\frac{W_{cn}}{W_{tot}})$ as a Function of Conductor Width, ω

2.1.4 POWER BUSES

The Baseline Requirement stipulates that diode isolation for the array shall be provided off the blanket in the power conditioning circuitry. For this reason, both electrical terminals from each module will be brought out to the spacecraft interface. The Baseline Requirements also require that module layout and interconnection result in a minimum magnetic field. This condition is obtained when successive modules alternate in polarity position, as indicated in Figure 2-9. This conceptual layout results in both polarities at both sides of the blanket. While one of the polarities could be served by a common line and thus eliminating 41 individual lines on each side of the blanket, the total mass of conductive runs would not change. The most flexibility is obtained by bringing all module terminals out to the inboard end of the blanket. At this point the 82 individual lines may be combined or selected in the most appropriate manner desired.

Using the same criterian that was applied to the interconnects; viz,the relative power loss in the buses should be comparable to the relative mass of the buses, the point of equality for aluminum buses results in a larger cross-sectional area than is desirable from a minimum weight point of view. A more appropriate design guide, it would appear, is to design for an equal and maximum power loss in each of the module buses. Accordingly, a design goal of 1 percent was established for all the power loss in the buses. If the bus thickness is kept constant, the width of the buses serving modules successively more remote from the terminus at the spacecraft must increase so that the bus length to width is unity.

In the case of the present primary design, where the module length, L = 32.5 cm, the bus length is given by

$$L_n = 32.5 (N + 1) \text{ cm}$$

where:

$n = 0, 1, 2, 3 \ldots\ldots\ldots\ldots\ldots 42$ (0 represents the inboard leader length) also the bus width is

$$\omega_n = (n + 1)\,\omega_1$$

where the width of the first bus is determined from

$$\frac{\Delta P}{Pm} = \frac{2I^2 \rho L_1}{\omega_1 t P_m}$$

solving for ω_1

$$\omega_1 = \frac{200 I^2 \rho L_1}{tPm}$$

Using the data from the primary design:

I = 0.6 Ampere/module at max. power

ρ = 2.62 (10^{-6}) ohm-cm (Al)

Pm = 120.5 Watt/module

L_1 = 32.5 cm

t = 2.54 (10^{-3}) cm (1 mil)

then

ω_1 = 0.2 cm (8 mil)

In case of the 42nd module

L_{42} = 1398 cm (46 feet)

and

$$\omega_{42} = 0.86 \text{ cm } (0.34 \text{ inch})$$

The total surface area for all the buses is

$$A_B = \sum_{0}^{42} L_n \omega_n = 1.84 \text{ m}^2$$

The total mass is

$$W_B = dA_B t = 126 \text{ gm}$$

The total bus width (both sides of blanket)

$$\omega_{tot} = \sum_{0}^{42} \omega_n = 19.2 \text{ cm}$$

The layout width will be greater than ω_{tot} by the sum of the margins between buses. If 1 mm margins are chosen

$$\omega_L = 82\,(0.1) + 19.2 = 27.4 \text{ cm}$$

or 13.7 cm (5.4 inches) on each side of the blanket. A further reduction of this number is offered if thicker buses are used, or if $\Delta P/Pm > 10^{-2}$ is chosen.

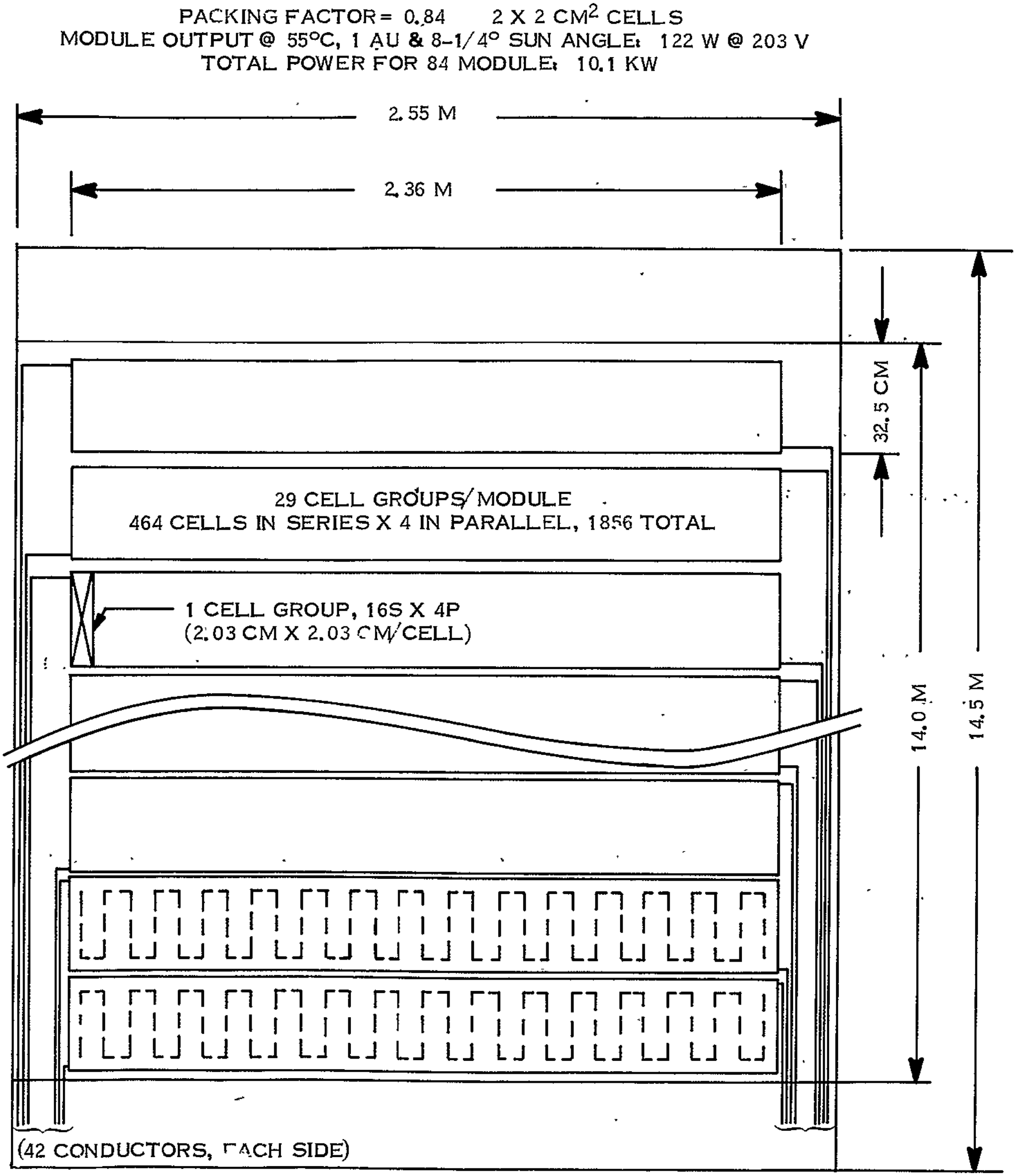

Figure 2-9. Conceptual Design - 42 Module Half Blanket

2.1.5 SUBSTRATE SELECTION

Next in order of necessity and importance to the integrity of an ultra-lightweight design is the array substrate. It is the largest single item in area, 74 m^2 in the primary concept, of all the components in the array. The current concept of a flexible blanket, consisting of a sheet of FEP heat sealed to the top of the cells as a coverglass and a combination of FEP and Kapton heat sealed to the bottom of the cells and cell interconnects, is shown in Figure 2-10. No adhesives are contemplated. The principal properties of candidate sheet materials suitable for the substrate/coverglass component are shown in Table 2-6. The optical properties of FEP and its usable temperature range make it an obvious choice for the coverglass. The fact that it is a thermoplastic that readily lends itself to heat sealing is key to the elimination of adhesives. Kapton has excellent strength to weight (specific stiffness), low density, good creep resistance and a wide usable temperature range.

The principal characteristic of some concern at this juncture is the thermal emissivity of both FEP and Kapton in the space environment. It would appear that ultra-thin sections of these materials suffer from low emissivity and thus a higher than desired blanket temperature. This will be the subject of some investigation in the next quarter of this program.

In a similar vein, the sufficiency of ultra thin sections of material as barriers for high energy radiation particles is of concern. The present conclusion is that 13 μm of FEP is adequate to insure no degradation in cell performance for a fluency of 2 $(10^{12})/cm^2$ 1 MeV particles over a three-year mission.

2.1.6 MODULAR DESIGN

The present concept may be seen in Figure 2-9 where one-half of the total array is shown. Forty-two modules are indicated, joined to each other by a reinforced strip of blanket. The length of this strip will be progressively longer to insure that the reinforcing strips will fall at the edges of the four-sided drum, as successive layers are wound on the drum.

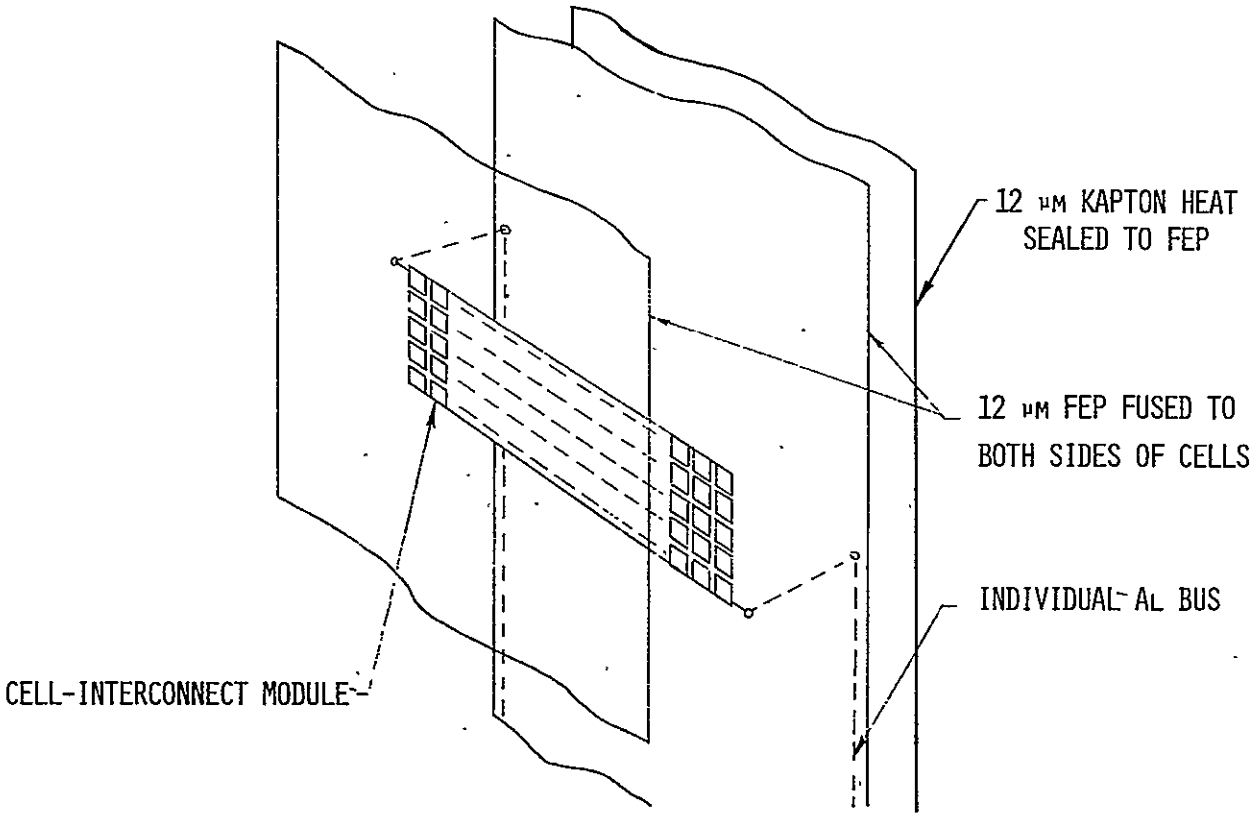

Figure 2-10. Array Module Conceptual Design 200 W/Kg

Table 2-6. Material Properties Coverglass/Blanket Candidates

CHARACTERISTICS	KAPTON-H (1 MIL)	FEP (1 MIL)	MYLAR-T (1 MIL)	TEDLAR (1 MIL)
OPTICAL TRANSMITTANCE, BOL	0.66	0.96	0.86 @ 8 μM	0.91
HEAT SEALABLE	NO	YES	IF TREATED	YES
THERMAL EMISSIVITY	0.80	0.85	-----	0.55
COEFFICIENT OF THERMAL EXPANSION (°C)	2 (10^{-5})	[2.6 TO 5] 10^{-5}	1.7 (10^{-5})	5 (10^{-5})
COEFFICIENT OF THERMAL CONDUCT. (W/CM-°K)	1.56 (10^{-3})	1.95 (10^{-3})	1.55 (10^{-3})	
SPECIFIC GRAVITY	1.42	2.15	1.28	1.38 TO 1.57
TENSILE STRENGTH (10^3 PSI)	25	3	45	7 TO 18
SPECIFIC STIFFNESS (E/ρ)(10^6 IN)	8.4	0.9	16.1	5.0
ULTIMATE ELONGATION (%)	70	300	40	115 TO 250
INITIAL TEAR STRENGTH (GM/μM)	20.1	10.6	17.7	17.7 TO 14.4
PROPAGATING TEAR STRENGTH (GM/μM)	0.31	4.9	0.79	0.47 TO 3.94
CREEP RESISTANCE	GOOD	POOR	GOOD	AVERAGE
USABLE TEMPERATURE LIMIT (°C)	-269 TO 400	-240 TO 200	-70 TO 150	-70 TO 110

KAPTON FOR STRENGTH, FEP FOR OPTICAL PROPERTIES

The basic building block for the module will be a cell group, consisting of a number of parallel-connected series strings of cells. One end-cell connector will be twice as long as the others so that it may be welded to the next cell group. This assembly technique is continued until 29 cell groups have been interconnected to make up a module.

The aluminum buses will be pre-fabricated on strips of substrate of the overall length indicated. Electrical connection will be made to the module via the end cell connectors. These substrate strips will be heat sealed to the module substrates to form the completed blanket.

2.1.7 ARRAY REPAIRABILITY

A conceptualization of how the array might be repaired, as necessitated by a broken or inoperative cell, is schematically shown in Figure 2-11. This concept trades heavily on the thermoplastic properties of FEP and the relative ease with which it may be softened and repaired. In the case of open electrical connections or high resistance joints, the repair procedure may only involve use of the parallel bar welding tool.

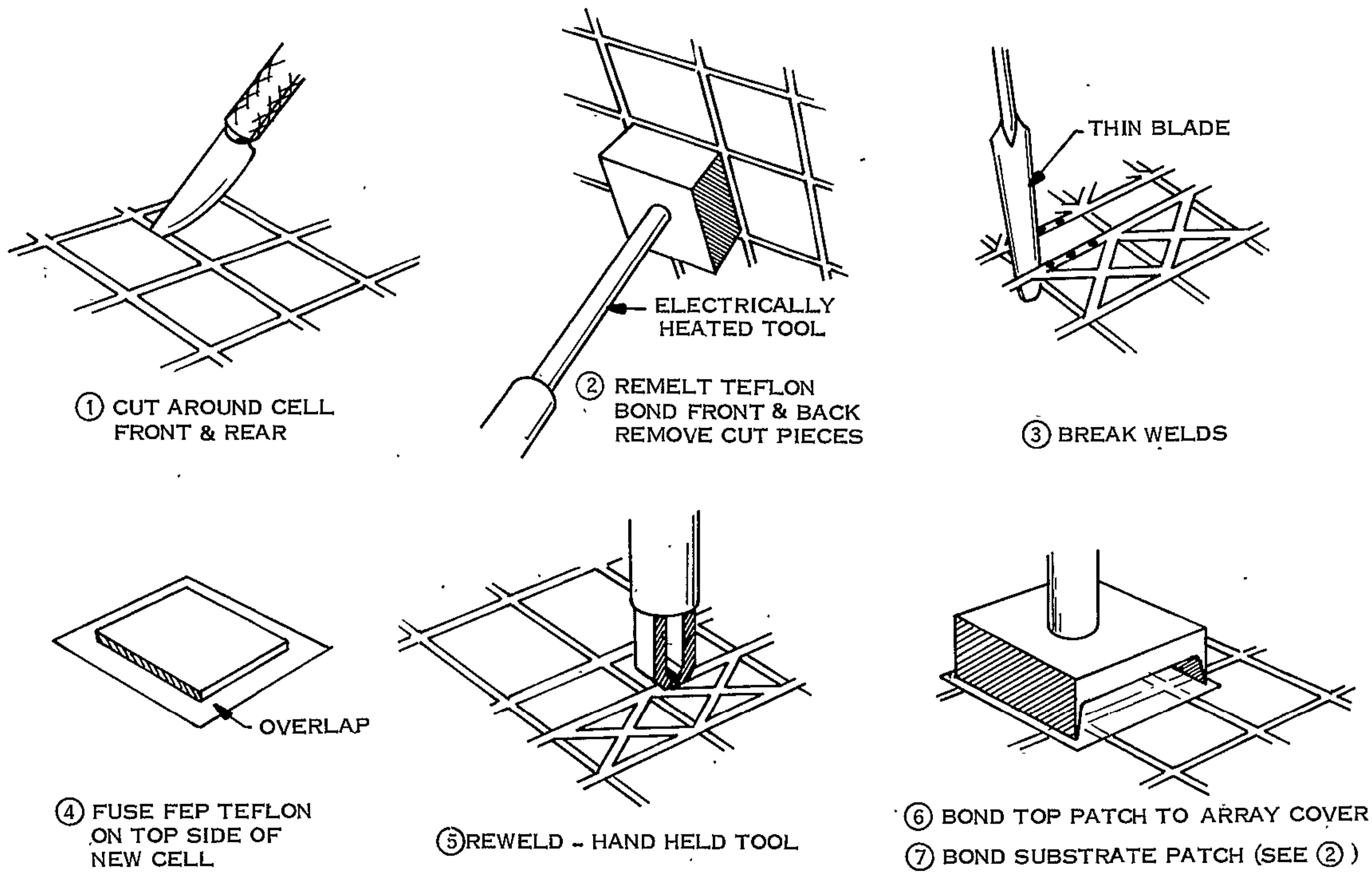

Figure 2-11. Conceptualization of Cell Repair

2.2 MECHANICAL DESIGN

For purposes of study, the mechanical system is divided into six subsystems, namely:

1. Basic Array Structures
2. Extendible Booms
3. Stowage Configurations
4. Power Transfer
5. Tensioning Mechanisms
6. Launch Retention

2.2.1 BASIC ARRAY STRUCTURES

The prime function of the array structure is to support the huge quantity of solar cells and their electrical interconnection in a common plane normal to the sun line. This array structure can be cateforized by the three basic types illustrated in Figure 2-12. Rigid structures such as honeycomb hinged to form folding panels have been most commonly used in the orbiting spacecraft. A good example of a semi-rigid approach is the General Dynamics concept for a SEPS array using isogrid structure for panel support of the array blanket. The preformed panels are stowed flat but snap into a curved configuration when deployed forming a stiff structure by the "carpenter's rule" principle. Flexible arrays consist of cells and interconnects mounted on very thin flexible substrates. The flat condition of the array is obtained by supporting the blanket under tension through the use of auxiliary lightweight structural members.

The relative merits of these types of structures are listed in Table 2-7. Rigid structures of course offer best support for the cells, but are inherently heavy. The semi-rigid structure can offer relatively low mass for large arrays, but is handicapped by deployer complexity. The flexible array (tensioned blankets) has the most to offer in the ultra low mass field of endeavor.

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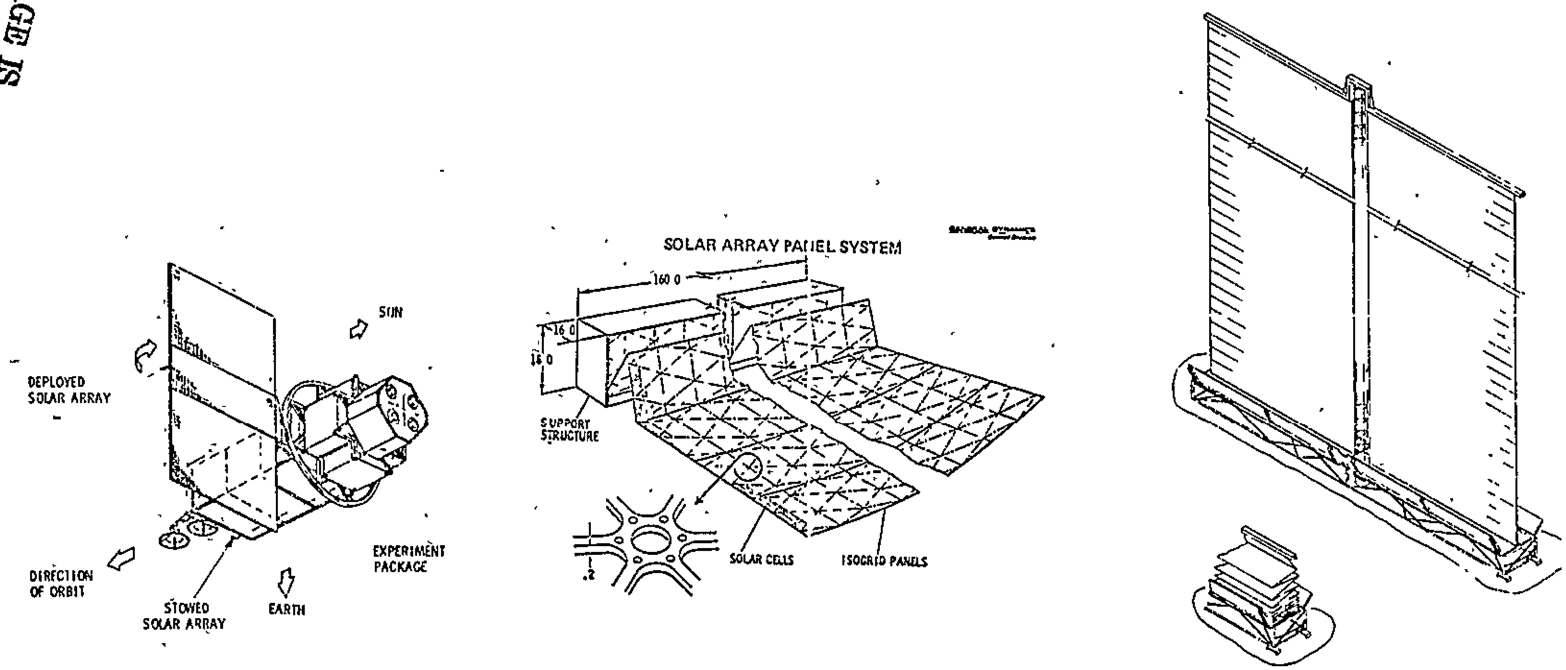


RIGID | SEMI RIGID | FLEXIBLE

Figure 2-12. Basic Array Structures

Table 2-7. Array Type Comparison

TYPE	RIGID	SEMI-RIGID	FLEXIBLE
ADVANTAGES	• STRUCTURALLY STIFF • GOOD CELL SUPPORT • FLIGHT PROVEN	• INHERENT STIFFNESS AT HINGE LINES • RELATIVELY LOW MASS	• LOW MASS • COMPACT STOWAGE • COMPATIBLE WITH LIGHTWEIGHT EXTENDIBLE BOOMS • EASILY RETRACTED BY ROLL-UP
DISADVANTAGES	• HIGH STOWAGE VOLUME FOR LARGE ARRAYS • BULKY FOR LAUNCH VEHICLES • LOW POWER WEIGHT RATIO	• NEW CONCEPT, UNPROVEN • REQUIRES COMPLEX DEPLOYER & RETRACT MECHANISMS	• REQUIRES SEPARATE SUPPORT STRUCTURE • DIFFICULT TO CONTROL FOLD-UP

Some typical examples of structure mass (Kg/M^2) are given in Table 2-8. This mass is made up of support structure only (deployer not included). In the case of the flexible array, the support structure is defined as the header, leading edge member for the blanket, and the extendible boom element. It appears evident that high flexibility (thin blanket assembly) creates low mass conditions. Structure for a 200 Watt/Kg array is expected to be in the order of 0.05 Kg/M^2 of array area.

2.2.2 EXTENDIBLE BOOMS

The function of the extendible boom is to extend one end of the array blanket, hold the blanket under tension during the mission, and in some cases, partially or fully retract the blanket for reduced exposure or restowage.

The three most promising candidates were chosen for comparison with a possible evaluation of a fourth type being currently developed by General Dynamics. These booms are illustrated in Figure 2-13. The semi-rigid structural boom evaluation is subject to release of detail design information by General Dynamics in time to be included in this study.

Table 2-8. Structure Mass (Typical)

TYPE	ARRAY EXAMPLES	MASS PER* UNIT ARRAY AREA Kg/M^2
RIGID	GE BROADCAST SATELLITE EXPERIMENT	1.67
SEMI-RIGID	CONVAIR PROPOSAL (ISOGRID STRUCTURE)	0.09
FLEXIBLE	GE 30 WATT/LB ROLL-UP LMSC SEPS ARRAY GE 110 WATT/Kg (STUDY)	.246 .272 0.059
* SUPPORT STRUCTURE ONLY (DEPLOYER NOT INCLUDED).		

The continuous longeron astromast can provide best low-mass benefits as shown by the curves in Figure 2-14. For our minimum requirement of a stiffness of 1×10^5 lb-in^2 (287 N-M^2), an element mass of approximately 0.04 lb/ft (0.06 Kg/M) is attainable.

The coilable lattice (continuous longeron) boom has been tentatively selected for the array for the following reasons:

1. Best mass-to-stiffness ratio
2. Lowest boom plus deployer mass
3. Relatively low sensitivity to thermal bending
4. Low backlash characteristics
5. Related application (LMSC SEPS array)

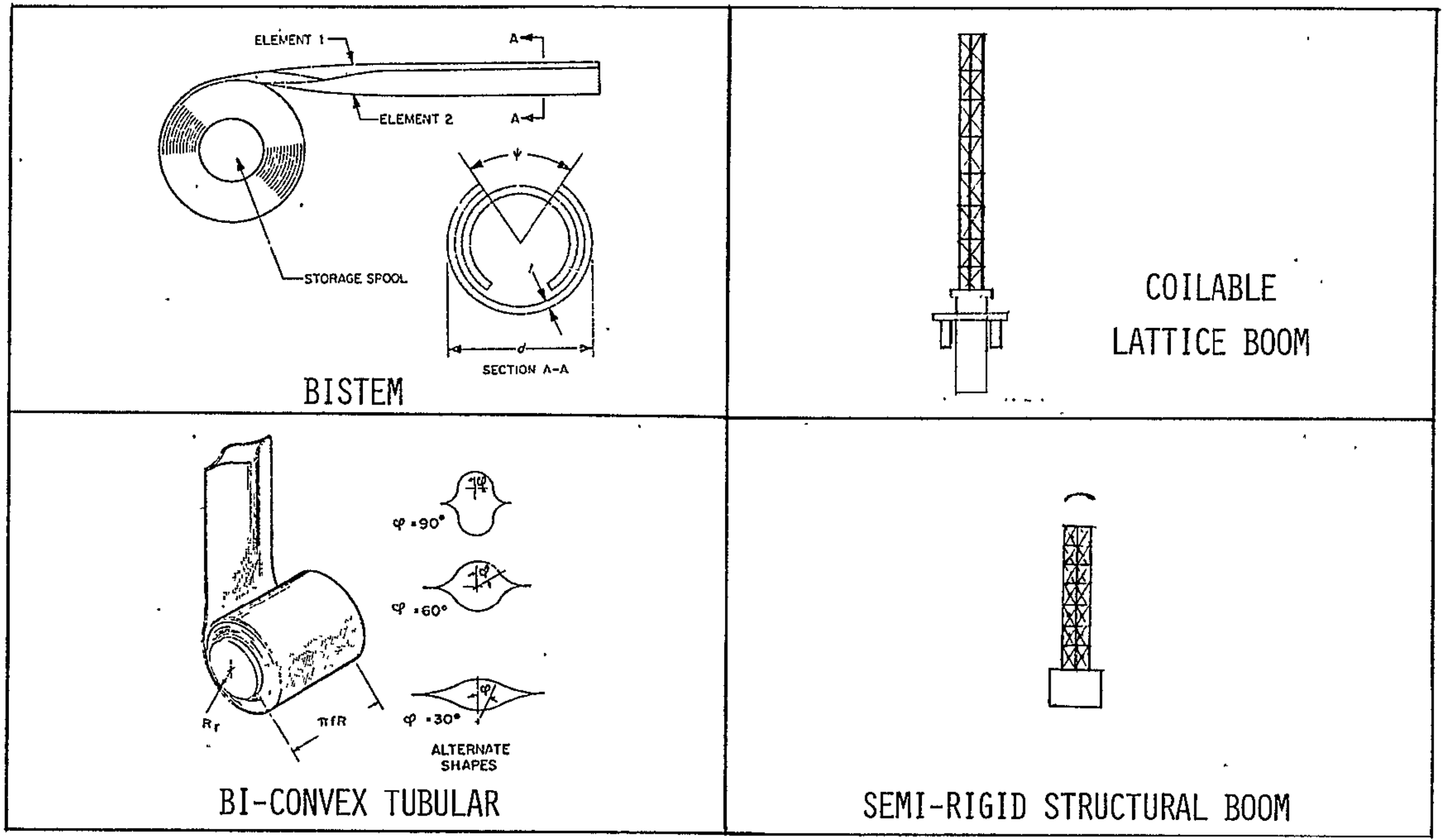


Figure 2-13. Extendible Boom Candidates

6. Room for further weight optimization in deployer

7. Development of booms operable up to 200°C in process

The relative merits of a bi-convex boom of graphite composite material (another boom candidate) will receive further study.

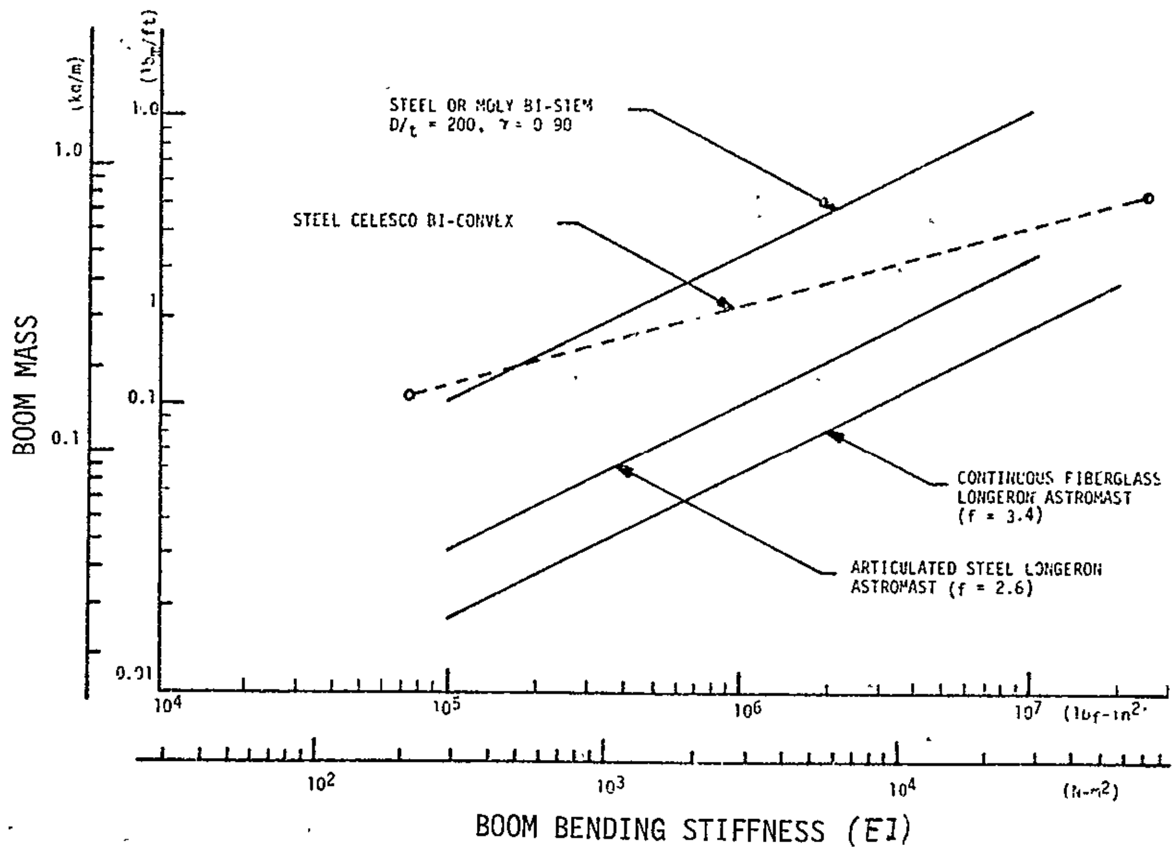


Figure 2-14. Boom Mass vs Stiffness

2.2.3 ARRAY STOWAGE

The array stowage equipment must contain the array in a safe condition during launch environments, release the array during deployment, and if required, restow the array on retraction. With high flexible array, their function becomes more difficult to perform. This area does constitute a major source of weight reduction possibilities through the use of high strength/ weight ratio materials and techniques.

Three options for stowage are being considered for the 200 Watt/kg array. As illustrated in Figure 2-15, the flat pack method provides a compact method for initial stowage and containment during launch. The cylindrical drum is a straightforward and logical approach to extension, tension, and retraction of a highly flexible array. However, its usage is limited by the effect of the radius of curvature on the degradation of cells. A drum with sides which are only sligthly curved has been conceived to combine the advantages of the other two approaches. The amount of bending, which very thin cell blanket assemblies can tolerate, is currently an unknown. A radius of curvature of 36 inches is tentatively selected as an acceptable condition.

Some key characteristics of the three stowage approaches are listed in Table 2-9. The flat pack is the most compact and holds cell assemblies in a flat configuration, but is difficult to retract. The curved sided drum is attractive because of its roll up and easy retraction capabilities. However, blank sections of substrate must exist at each corner increasing overall blanket length. Care will be required in design to insure that the blanket modules register properly with the sides of drum during roll up and launch.

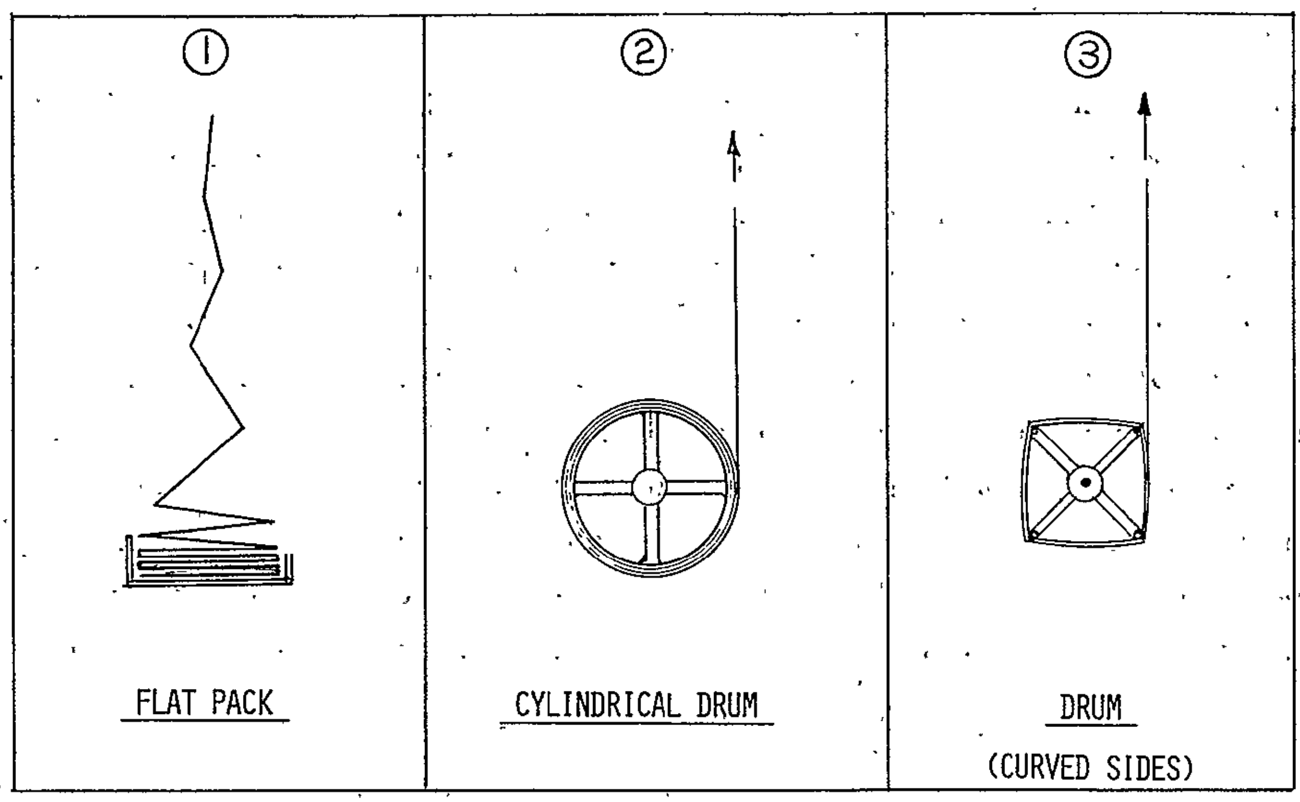


Figure 2-15. Stowage Configuration Options

Table 2-9. Stowage System, Key Trade-offs

TYPE	ADVANTAGES	DISADVANTAGES
1 FLAT PACK	• HOLDS CELLS IN FLAT CONDITION FOR STOWAGE & LAUNCH • DOES NOT REQUIRE SPECIAL POWER TRANSFER DEVICES	• DIFFICULT TO CONTROL FOLD UP ON RETRACTION • RETRACTION AIDS ADD WEIGHT
2 DRUM (CYLINDRICAL)	• SIMPLIFIES DEPLOY AND RETRACT MECHANISMS • MAINTAINS TENSION ON BLANKET AT ALL TIMES	• CAUSES CELL BENDING WHEN STOWED • BLANKET COMPRESSION FORCES RELATED TO BLANKET TENSION
3 DRUM (CURVED SIDES)	IN ADDITION TO 2 ABOVE • PERMITS REDUCTION OF CELL BENDING • ADAPTABLE TO MODULARITY	IN ADDITION TO 2 ABOVE • REQUIRES BLANK SUBSTRATE AREAS AT CORNERS INCREASING BLANKET LENGTH

The choice of the number of sides on the drum is explained in Figure 2-16. Four sides offer a reasonable compromise between the height of each module and an acceptable tension ratio, which is the ratio between the radius to the corner and the radius to the middle of the curved side. The sides are curved so that the tension of wrap will impact some radial force to hold the cell assemblies against the drum during vibration environments. The relationship between radial force and tension is shown in Figure 2-17. Note that the tension levels equivalent to dynamic loading are much higher than the tension (1.3 pounds) required during normal deployed flight conditions. Therefore, if tension alone is utilized for securing the blanket for launch, the value of this tension will be in excess of 20 pounds applied manually prior to launch. This condition brings up questions of creep and register which will require further evaluation based on actual blanket characteristics which are currently being analyzed.

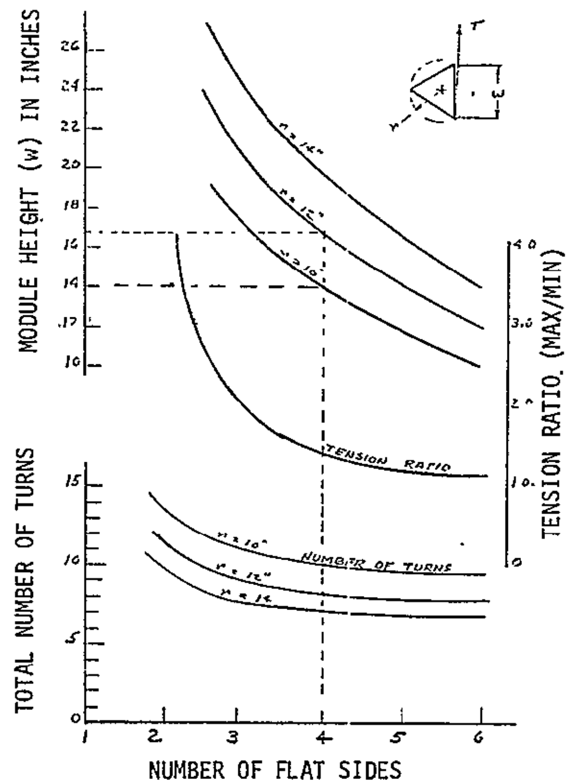


Figure 2-16. Roll-up (Flat Sides)

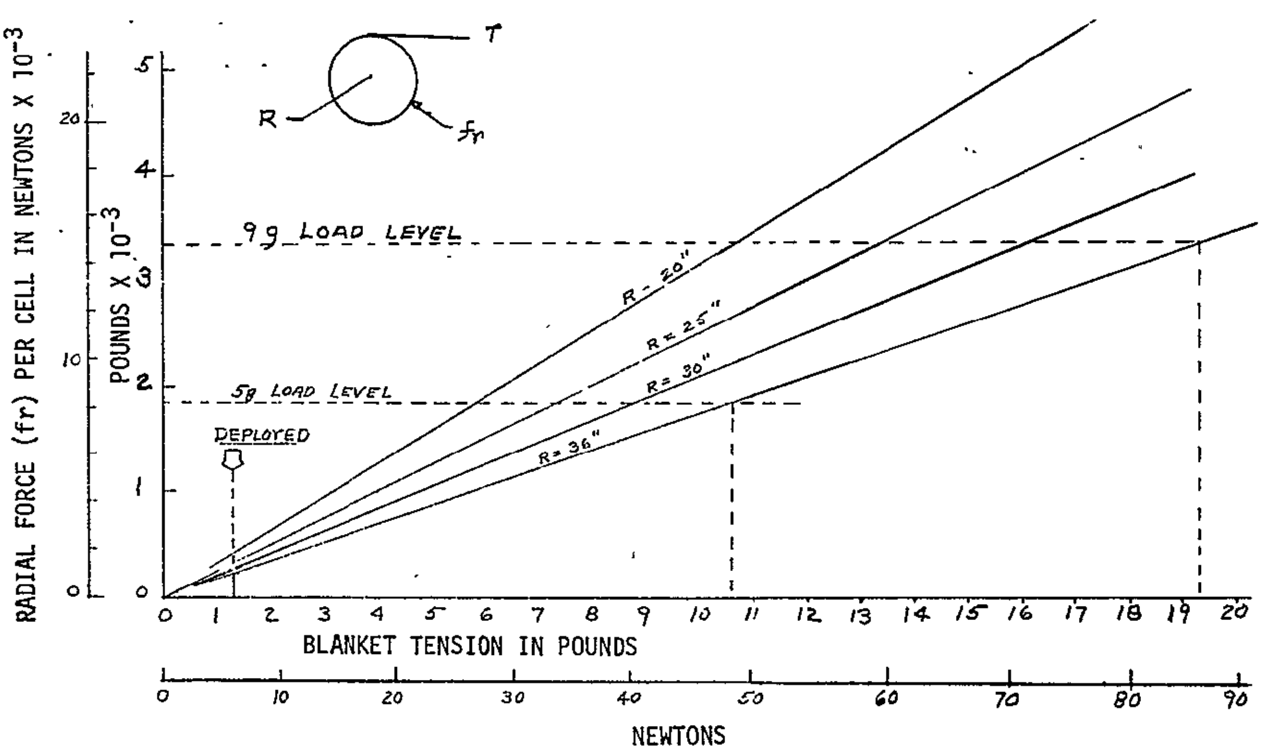


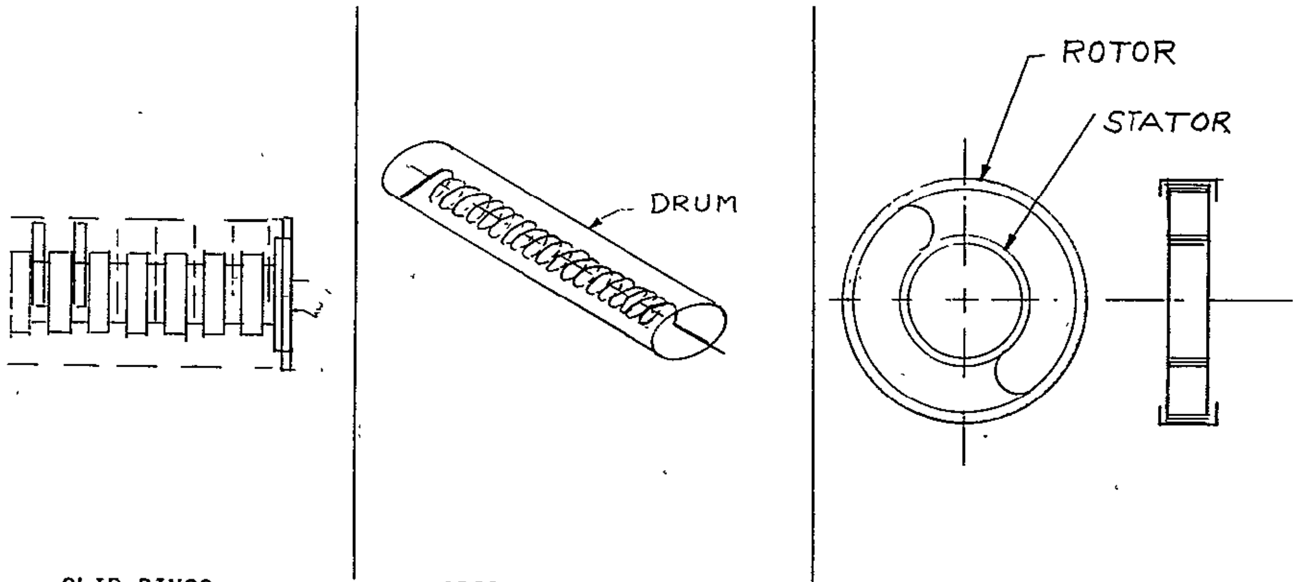
Figure 2-17. Blanket Stowage Tension

2.2.4 POWER TRANSFER

The flat pack power transfer device may be a simple section of ribbon flex cable. In the case of roll-up systems, a device which will permit rotary motion of the drum is required. Four basic approaches are being considered for this function, namely, slip rings, spiral twist cable, ribbon cable roll-up (shown in Figure 2-18), and a motorized connector. A comparison of the first three methods is given in Table 2-10. Slip rings are a state-of-the-art device which are flight proven and are not critically affected by temperature variations. The only precaution required is adequate lubrication for bearings, brush and ring assemblies. The probable characteristics of a suitable slip ring assembly to bring off the power individually from 42 power modules have been predicted by Polyscientific-Litton as follows:

Volts	200 Vdc
Rings	42 @ 0.6 Amps rated current 2 @ 25 Amps rated current
Brushes	
Quantity	2 per ring
Pressure	42 small rings = 1 oz 2 large rings = 8 oz
Materials	
Rings	Cu-plated with nickel and hard silver
Brushes	Ag/moly/graphite
Housing	Aluminum
Size	11.5 in. Lg x 2 in. dia
Weight	1.5 - 2.0 pounds
Starting Torque	0.90 in-lb. in air 0.18 in-lb. in vacuum

The spiral twist concept and ribbon roll-up concept will also be evaluated. A prime concern with these approaches is with the dependence of flexibility upon temperature. Increased stiffness at low temperatures may develop torques which are prohibitive.



SLIP RINGS | SPIRAL TWIST CABLE | RIBBON CABLE ROLL-UP

Figure 2-18. Power Transfer Devices

Table 2-10. Power Transfer Trades

TYPE	PRO	CON
SLIP RINGS	• SPACE PROVEN APPROACH • OPERABLE OVER WIDE TEMPERATURE RANGE WITH ESSENTIALLY CONSTANT TORQUE • STATE OF ART DEVICE	• REQUIRE LUBRICATION OF BRUSHES & BEARINGS
SPIRAL TWIST CABLE	• SIMPLE MECHANISM	• REQUIRES LONG LEAD • TORQUE VARIES TEMPERATURE • REQUIRES SOME DEVELOPMENT
RIBBON CABLE ROLL-UP	• CONSTANT TORQUE OVER ROTARY TRAVEL RANGE	• LONG LEADS • TORQUE VARIES WITH TEMPERATURE • REQUIRES SOME DEVELOPMENT

The motor driven connector shown in Figure 2-19 is a fourth attractive concept. The device is equipped with guide pins which could serve not only to line up the two halves of the connector for insertion, but also to lock the drum at full extension if desired. In this concept, the array is connected electrically at the end of the deployment phase. Just before reaching full extension, the motor driven connector is energized, causing the guide pins to be ligthly spring loaded against the end plate of the drum. Final extension of the boom rotates the drum until the guide pins fall into matching holes in the connector. An interlock switch then causes the motor to fully engage the connector. The action is reversible, and the connector can be engaged remotely at any desired extension of the array within an integral number of revolutions of the drum. This concept will be evaluated in respect to availability and relative merits during the third quarter of the study.

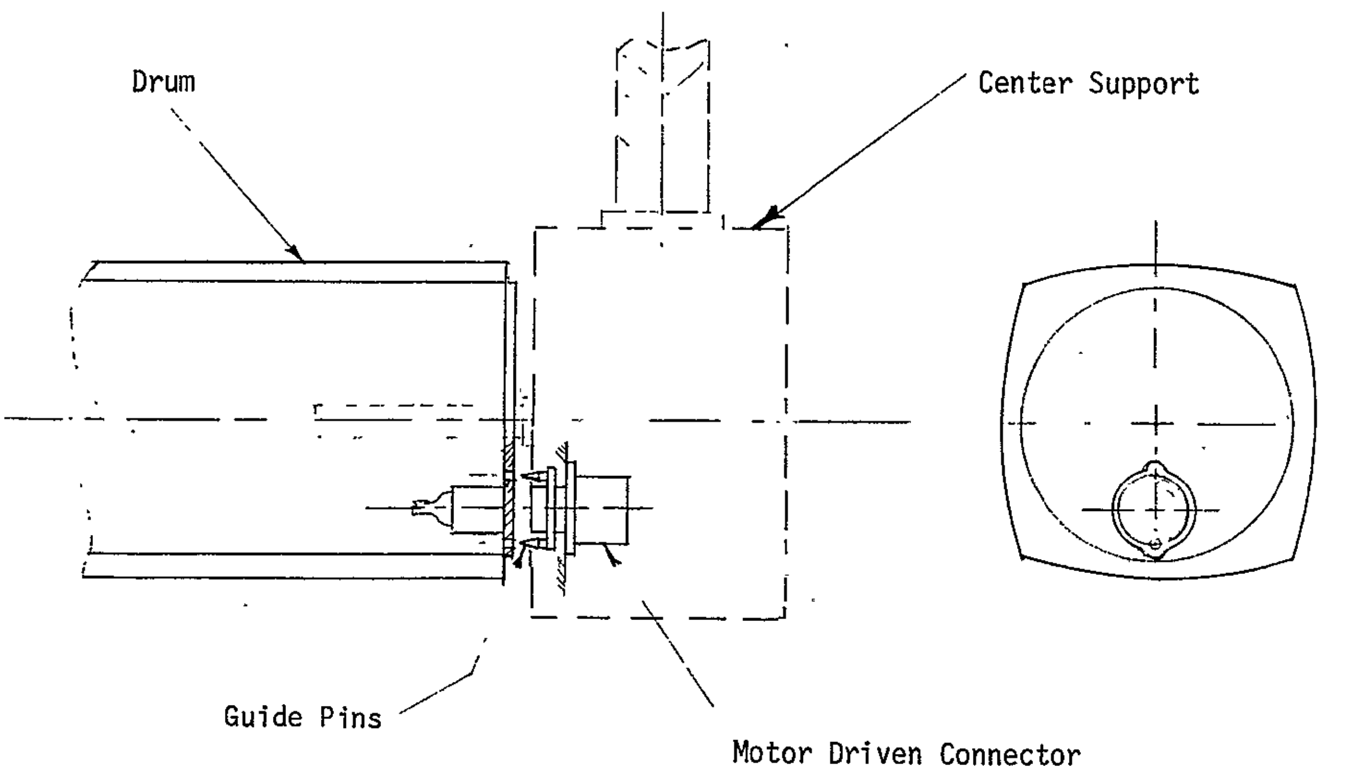


Figure 2-19. Power Transfer Concept

2.2.5 TENSIONING MECHANISMS

A flexible blanket must be maintained at a fixed level of tension throughout mission life to keep the natural frequency at the specified value. Tension is also beneficial during extension or retraction to prevent random slack in the array.

For the flat pack concept, adjustable tension springs at the bottom end of the array (as shown in Figure 2-20) are being considered. In this case, the springs are adjusted for proper tension when the boom is at the end of travel. The springs are designed for a low gradient so that stretch of the blanket with time does not drastically change the tension level.

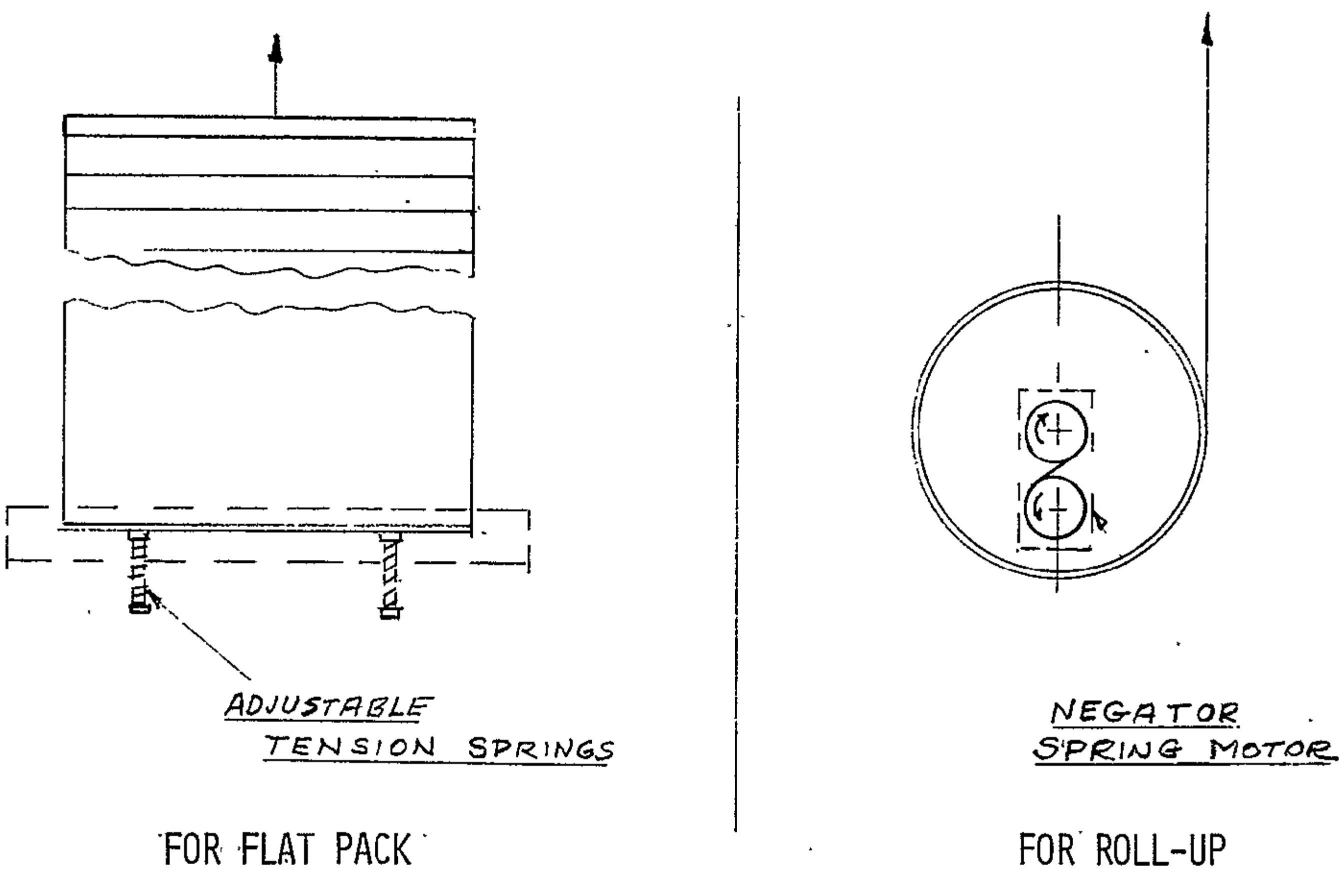


Figure 2-20. Tensioning Mechanism

In the case of the roll-up approach, a single negator motor on the drum serves to maintain nearly a constant tension at all times on the blanket. If a four-sided drum is used, this torque must be modulated $\pm$ 15% 4 cycles per revolution to compensate for the effective radius variation. A four-lobed cam used as the output reel of the negator motor tends to produce up to $\pm$ 10% variation in output torque which may be sufficient compensation for this purpose.

2.2.6 SOLAR ARRAY CONCEPTS

At this point in the study, four system concepts have been generated for comparison.

Concept No.	Type	Figure Ref.
1	Flexible Array/Lattice Boom Roll-up/ Retractable	2-21
2	Flexible Array/Lattice Boom Flat Pack/ Non-Retractable	2-22
3	Semi-rigid Array/Isogrid Flat Pack/ Retractable	2-23
4	Flexible Array (Stiffened) Lattice Boom Flat Pack/Retractable	2-24

Concept No. 1 is a roll-up approach which combines some of the advantages of both roll-up and flat pack. The drum has four sides which are slightly curved to provide some radial compression force under wrap without excessive cell bending. The drum, constantly torqued by a negator spring motor, places the blanket under constant tension during both extension and retraction contributing reliability to these functions. The mast is a 5-inch diameter coilable lattice boom as discussed in paragraph 2.2.2. The drums are canted at an angle of 8.25 degrees to add a V-stiffening effect to system structure. The mechanical interface with the spacecraft is a flange which mates with a flange on the array shaft making the array completely orientable as may be required.

Concept No. 2 is similar to concept no. 1 except that a flat pack approach is used for stowage. Because of the highly flexible nature of the blanket defined in paragraph 2.1, this array is considered to be non-retractable. The configuration is shown in its stowed condition in Figure 2-22.

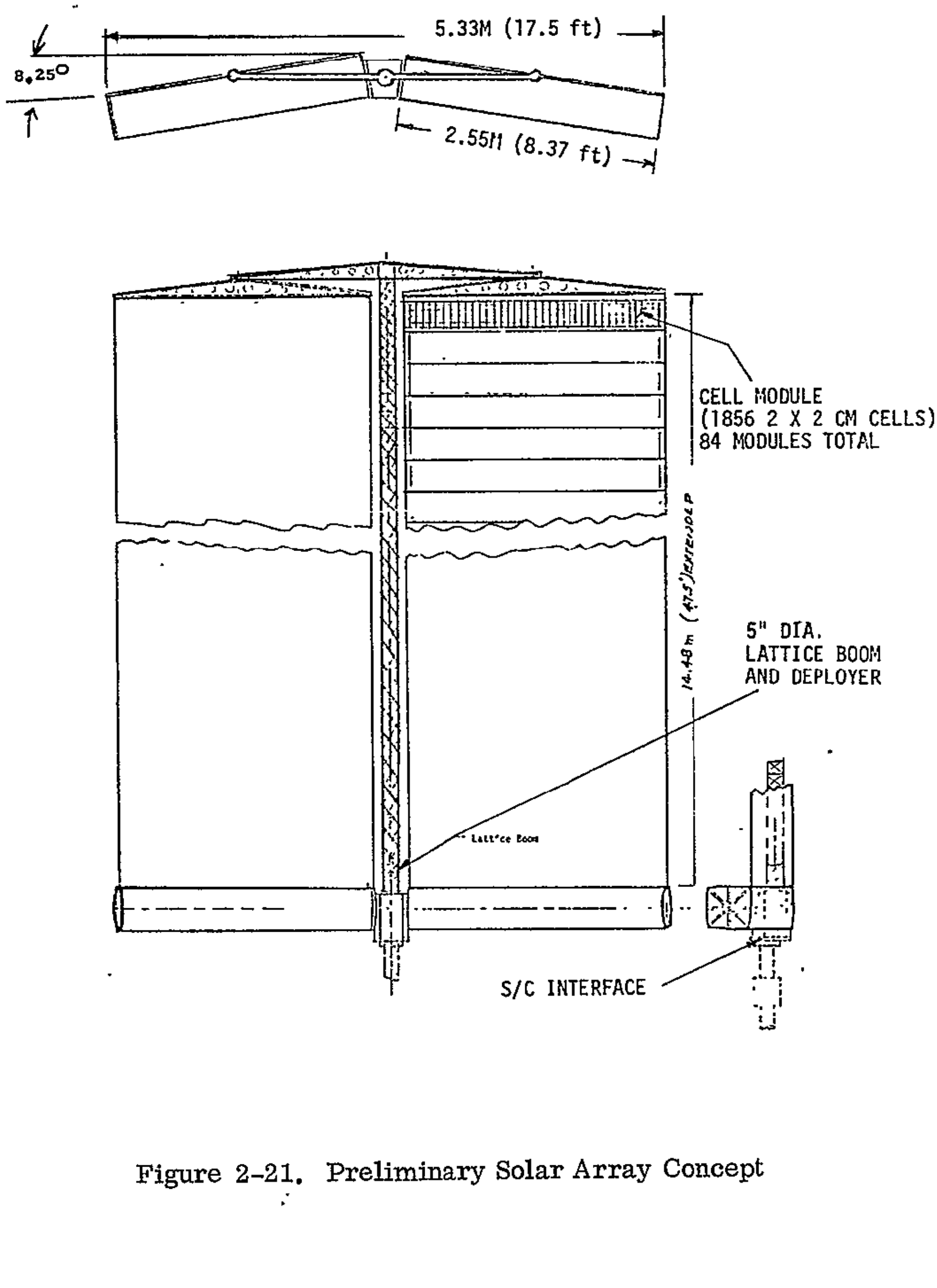


Figure 2-21. Preliminary Solar Array Concept

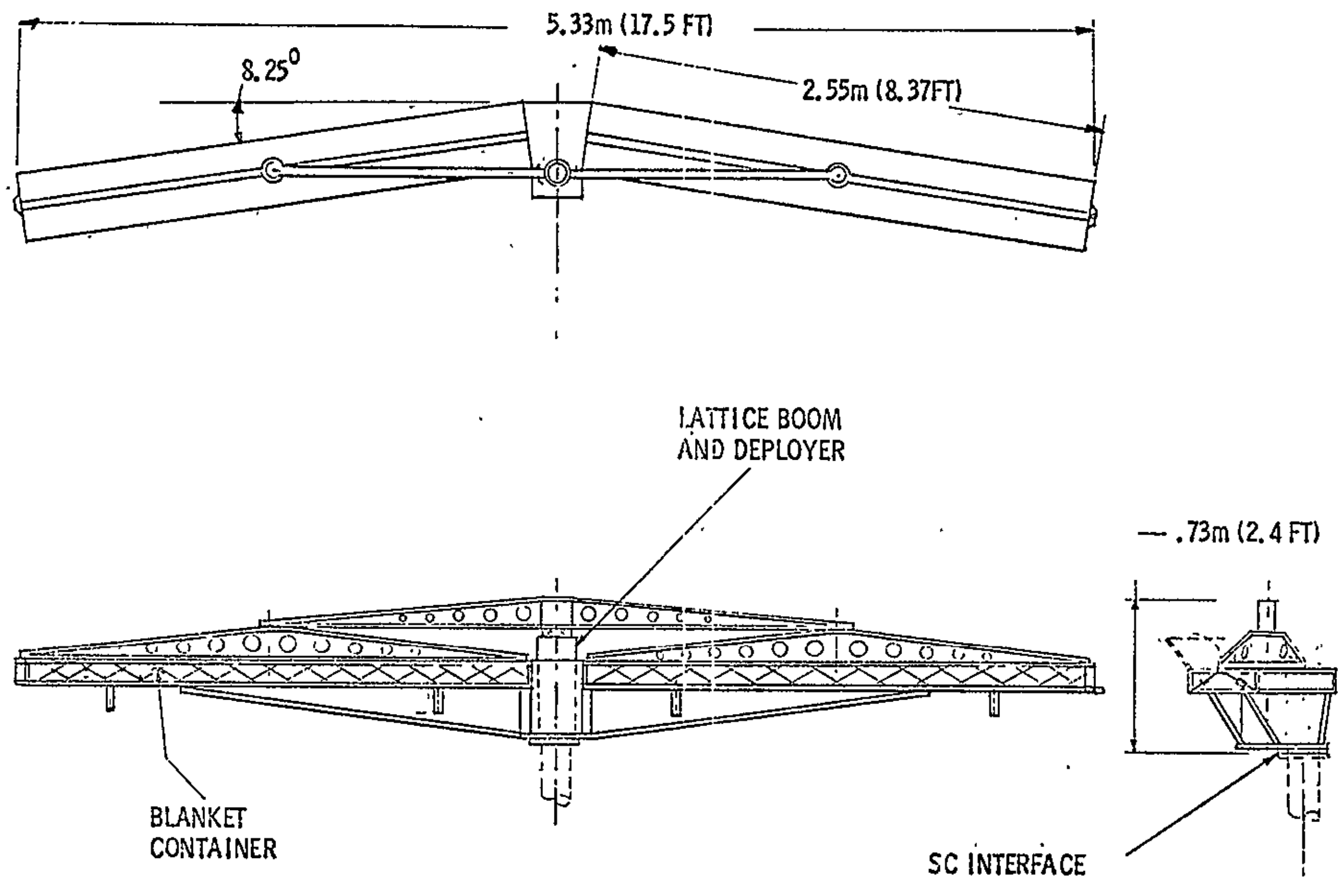


Figure 2-22. Flat Pack Stowage Concept

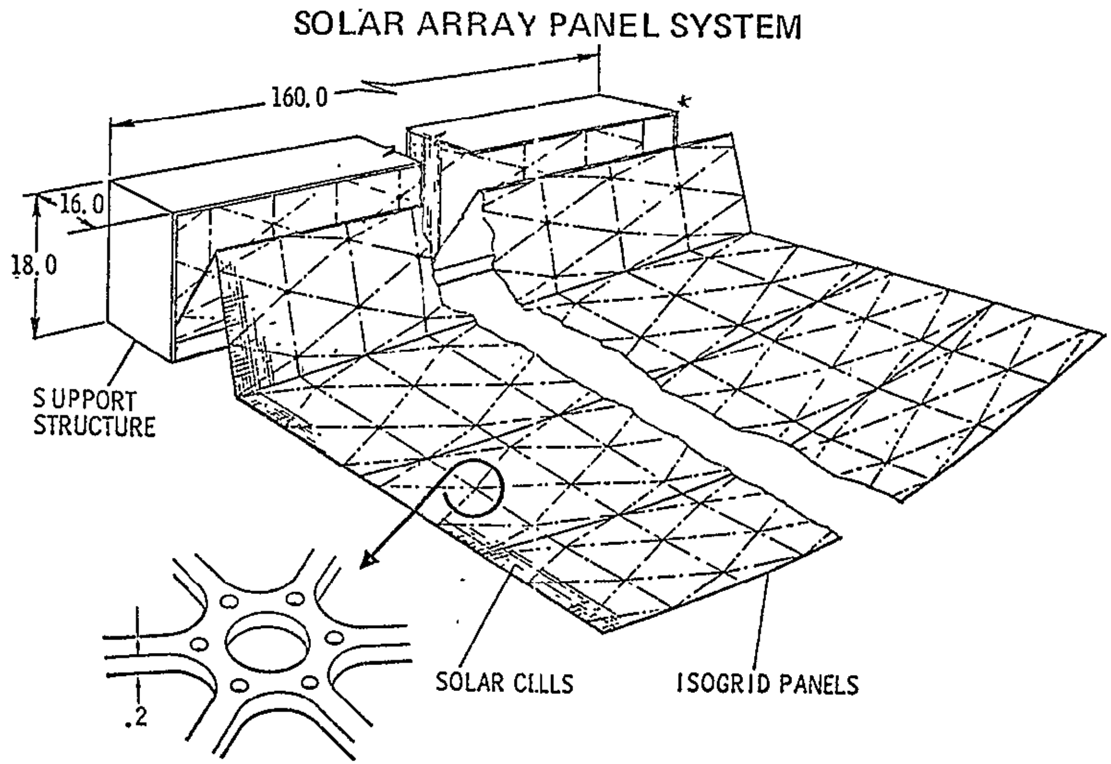


Figure 2-23. Semi-Rigid Solar Array Panel System

Concept No. 3 utilizes a semi-rigid lightweight structure to which the blanket is bonded as the net support structure. Evaluation of this approach is based upon the General Dynamics proposal for SEPS of March 1974 (Ref. No. 3). This array is very representative of a semi-rigid type. Although it is retractable, it is somewhat handicapped by the deployment mechanism which is both complex and relatively heavy compared with other deployment methods.

In Concept No. 4, module stiffening, has been applied to Concept No. 2 to provide potential for retraction capability. The stiffening of the module is accomplished by placing a framework of very lightweight isogrid structure on the back of the blanket in the cell area. Small torsion springs at each hinge-line provide memory to cause the module to fold properly at the hinge line when the mast is retracted.

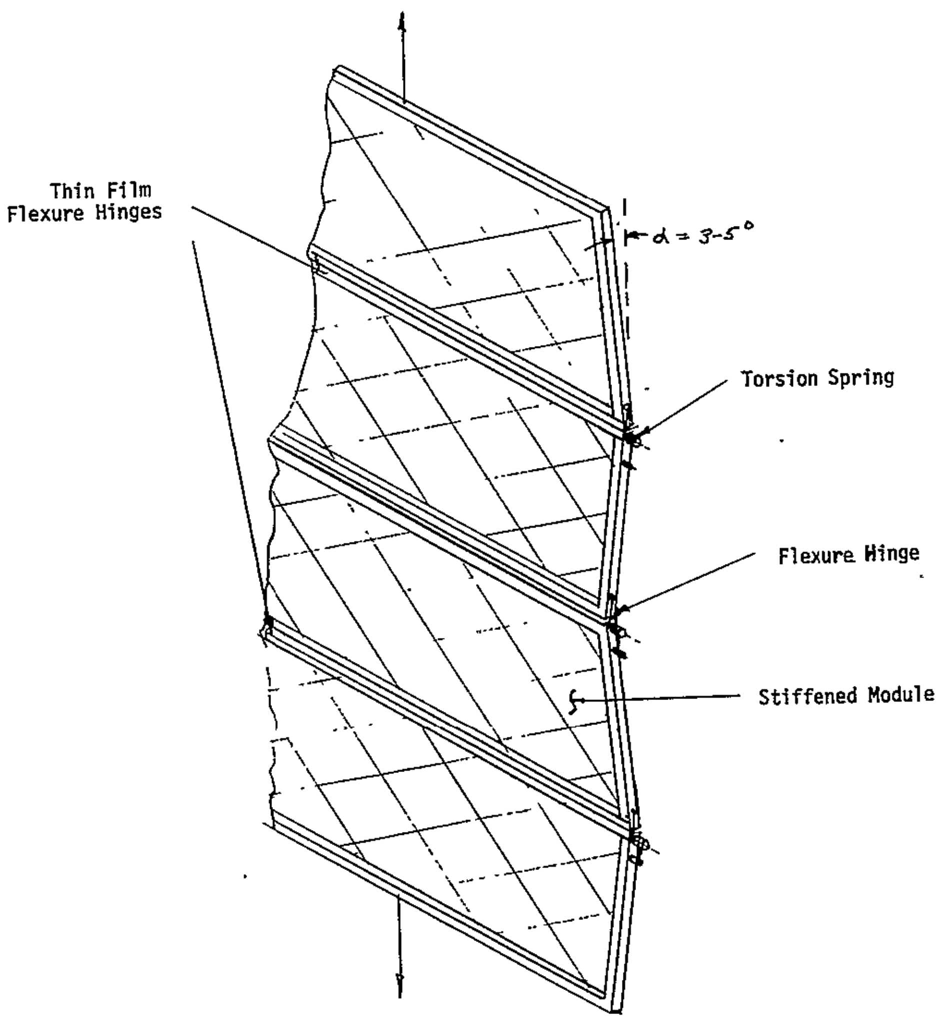


Figure 2-24. Stiffened Module Concept

2.2.7 LAUNCH RETENTION

During launch it is expected that the drum or box container for the stowed array will be secured by additional brackets and pyro release devices. These elements may be anchored to the spacecraft as illustrated in Figure 2-25, in which case they are calculated as a portion of the array weight.

As an alternate approach, the extremities of the stowage structure may be tied down to the shuttle cradle members. The bracket and release mechanism can then stay with the shuttle and are not counted as array mass. This approach will be considered during the third quarter study period.

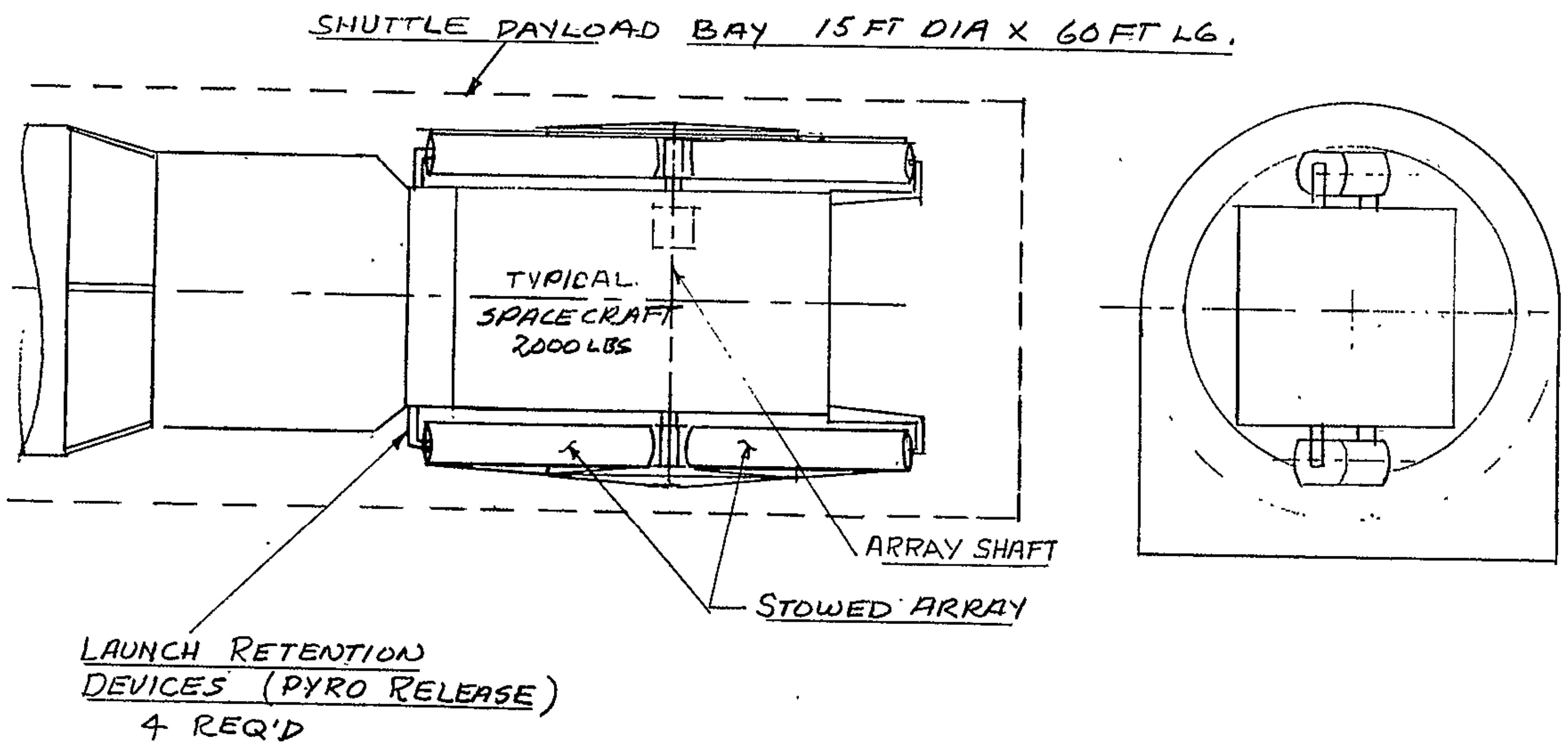


Figure 2-25. Launch Retention

2.3 PARAMETRIC ANALYSES

Analysis of the array during this quarter has been directed toward the array blanket. This effort has been initiated in the areas of stress and thermal aspects of the cell assembly construction and will be continued in our third quarter activity.

2.3.1 STRESS ANALYSIS

The stress analysis of the array will entail the following considerations:

1. Thermal compatibility stress
2. Axial loading stresses
3. Bending stress in stowage

Calculation of stresses from thermal sources has been completed this quarter on the present candidate blanket assembly. The typical cross section investigated is shown in Figure 2-26. A temperature change of 220°C from room temperature (20°C) to -200°C was assumed as worst case. A computer program was written for ease in evaluating the effect of thickness and material iterations.

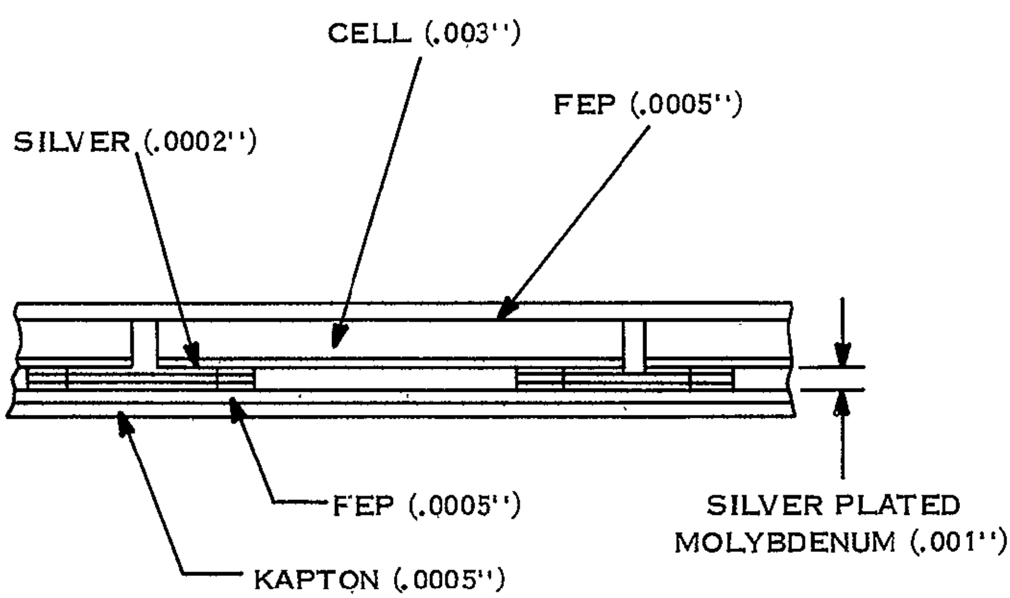


Figure 2-26. Typical Blanket Cross Section

From this analysis it is concluded that, at the low temperature extreme, a negative margin exists on the yield point of the silver material. The silver is stressed in tension due to the large difference between the thermal coefficients of expansion between silver and silicon. It is probable that in the standard cell utilizing silver as the contact material, the silver yields at low temperature without degrading its conductive properties. With the very thin cell conditions which exist on this proposed array, these thermal stress effects may give rise to some bowing (buckling) of the cells at both temperature extremes. It will be important to test representative sections of blanket for mechanical stability at an early stage of the experimental phase of the program. For a more detailed discussion of stresses derived from thermal compatibility factors, refer to Reference 4 included in Appendix A, Section 7.

2.3.2 ABSORBENCE/EMITTANCE

In compliance with the baseline requirements that the solar array equilibrium temperature not exceed 85°C at a solar irradiance power density of 135 mW/cm^2, we have made a preliminary evaluation of the materials properties necessary to perform this temperature regulatory function. Figure 2-27 is a plot of the equation

$$T_{cell}\ (^{\circ}K) = \left[\frac{\alpha\ (1-\eta)\ S}{\sigma\,(E_F + E_B)}\right]^{1/4} \text{ where}$$

T_{cell} ($^{\circ}$K) is the Cell Temperature

S - solar illumination power density of 135 mW/cm^{-2}

η - solar cell efficiency of 0.13

σ - Stephen-Boltzman constant; 5.668 x 10^{-9} mW/cm^{-2} . $^{\circ}K^{-4}$

E_F - Front surface emissivity

E_B - Back surface emissivity

α - solar absorptance of 0.84

Using the above relationship, it is determined that an equilibrium temperature of 55°C is achievable at a total emissivity (i.e., [$E_F + E_B$]) of ~1.558.

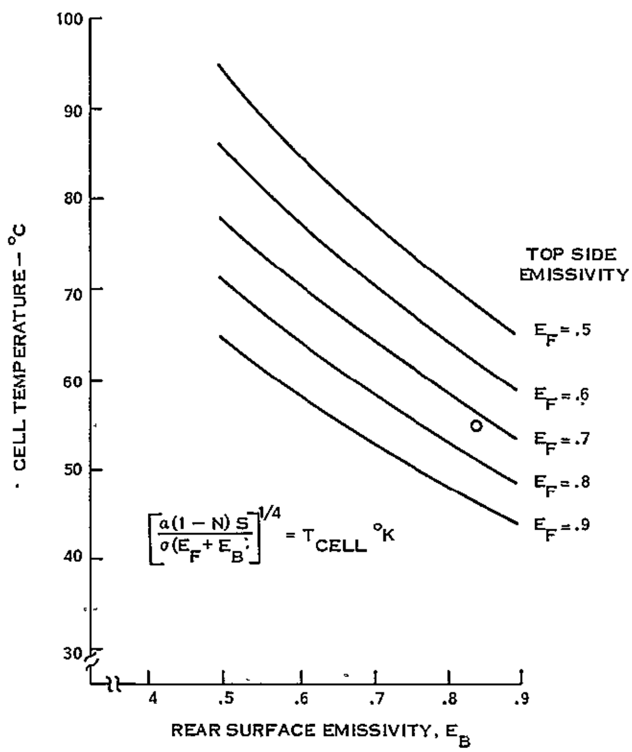


Figure 2-27. Influence of Optical Properties or Cell Temperatures

Table 2-11 is a summary of measurements made at General Electric Space Division of front and rear surface emissivity and resultant cell equilibrium temperature for several different rear surface materials combinations. Materials were heat and pressure bonded to silver-backed solar cells.

The data thus far indicates that 0.5 mil teflon substrates will not give optimal rear surface thermal rejection. We do, however, feel confident that a front surface emissivity of .730 will satisfy requirements for the front surface.

The rear surface bonded to a 1 mil FEP/2 Mil Kapton composite film will adequately satisfy the thermal rejection criteria mentioned above, but at the expense of additional weight.

Table 2-11. Summary of Emissivity Values for Various Samples of FEP Teflon and Kapton Bonded to Silver Backed Solar Cells

Sample	Solar Cell Surface	E		Cell Temperature with 0.5 Mil Front Cover of FEP and Back as Indicated by Sample Line (°C)
		37.78°C	100°C	
0.5 Mil FEP	Front	.730	.721	
0.5 Mil FEP	Back	.491	.467	72.5
1 Mil FEP/ 2 Mil Kapton	Back	.843	-	51.3
1 Mil FEP/ 2 Mil Kapton	Back	.851	-	50.9
1 Mil FEP/ 2 Mil Kapton	Back	.851	-	50.9
2 Mil FEP	Back	.645		62.4

Figure 2-28 (this curve agrees with our data at higher values of film thickness) indicates that about 5 mils of FEP Teflon will be necessary in order to achieve our equilibrium temperature goal of 55°C at 135 mV/cm^{-2} solar illumination power density. Clearly this additional weight penalty is unacceptable. Also, it is apparent that substrate films other than FEP Teflon will yield superior emissive characteristics.

Follow-on efforts in this regard will address themselves to further study of the heat rejection characteristics of different thermal-plastic compound materials in different thickness ranges.

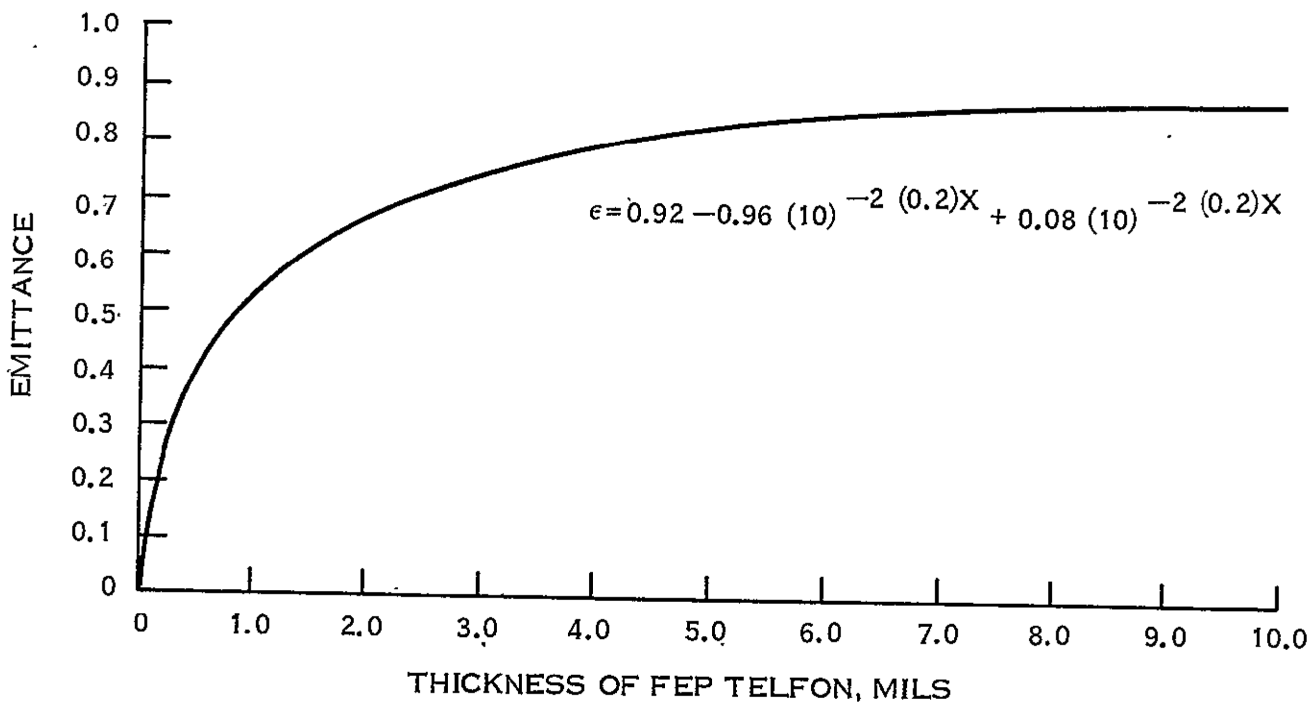


Figure 2-28. Thickness of FEP Teflon vs. Emittance

2.4 MASS SUMMARY

In this section, the four array concepts are compared on the basis of their respective power to mass ratios as can best be estimated at this stage of the study. This mass evaluation is subject to change as more accurate numbers are generated through the coming design layout phase of the program.

The basic description of the four candidate systems is listed for reference in Table 2-12. The mass comparison of the first three concepts is shown in Table 2-13 along with the Lockheed SEPS array which is considered state-of-the-art, and the proposed General Electric array which resulted from the 110 watt/kg study performed by General Electric in 1973. Changes which have contributed greatly to the mass reduction accomplishments are also indicated in the columns under the arrows.

Table 2-12. Description of Array Concepts

CONCEPT NO.	TYPE	ELEMENTS
1	ROLL-UP (RETRACTABLE)	• FLEXIBLE ARRAY • LATTICE BOOM & DEPLOYER • CURVED SIDE DRUM
2	FLAT PACK (NON RETRACTABLE)	• FLEXIBLE ARRAY • LATTICE BOOM & DEPLOYER • BOX CONTAINER
3	SEMI RIGID (RETRACTABLE)	• SEMI RIGID ARRAY STRUCTURE • DEPLOYER MECHANISM • BOX CONTAINER
4	FLAT PACK (STIFFENED MODULE) (RETRACTION POTENTIAL)	• FLEXIBLE (WITH STIFFENED MODULES) • LATTICE BOOM & DEPLOYER • BOX CONTAINER

Table 2-13. Mass Summary Chart

	ITEM	STATE OF ART LMSC SEPS ARRAY			110 W/KG ARRAY GE STUDY			200 WATT/KG ARRAY								
								PREL BASELINE			CURRENT ESTIMATES					
											① ROLL-UP		② FLAT PACK		③ SEMI-RIGID	
	POWER (KW) EFFICIENCY (W/KG)	12.5 66		⇨	10 110		⇨	10 186		⇨	10 202		10 227		10 177	
		WT (KG)	%	• CELL THICKNESS 8 TO 5 MILS	WT (KG)	%	• CELL THICKNESS 5 TO 3 MILS	WT (KG)	%		WT (KG)	%	WT (KG)	%	WT (KG)	%
1	BLANKET ASSY.	122.45	64	• COVERGLASS THICKNESS 6 TO 1.5 MILS	48.5	55	• CELL EFFICIENCY 11 TO 13%	25.8	48	• PROJECTED ESTIMATE OF DECREASE IN MASS OF ELECTRICAL CONNECTIONS	24.	54	22.58	46	22.58	40
2	STOWAGE & SUPPORT SUPPORT	25.88	13		30.6	35		18.25	35	• ULTRA LOW MASS STORAGE STRUCTURE (ISOGRID)	20.04	32	15.93	36	13.38	24
3	RETENTION & RELEASE	-			-		• V STIFFENED	2.4	5		2.4	5	2.4	5	-	-
4	DEPLOY & RETRACT MECHANISMS	43.96	23	• ASPECT RATIO 7.9:1 TO 3.14:1 o MAST DIA. 39.6 TO 19 CM	8.4	10	• STIFFNESS REQ'D. 14 x 10^5 LB-IN^2 TO 1 x 10^5 LB-IN^2 o MAST DIA. 19 CM LATTICE TO 3.4 CM TUBULAR o MAST LENGTH 18.4 TO 1[illegible] M	7.25	12	• OPTIMIZED BOOM & DEPLOYER CONSTRUCTION	3.09	9	3.09	13	20.6	36
	TOTAL WT (KG)	192.29	100		87.5	100		53.7	100		49.53	100	44	100	56.56	100

NOTES

① Roll-up, 5" Dia. Lattice Boom, Retractable

② Flat Pack, 5" Dia. Lattice Boom; Non-retractable

③ Semi-Rigid, Isogrid Substructure, Retractable

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From these preliminary mass estimates, it appears that the power/mass requirement can be met by both the roll-up and flat-pack concepts with the latter being limited to a non-retractable category for the 44 kg mass shown. Note that the semi-rigid approach is very competitive in the array support structure area, but has a heavy deployment mechanism which results in a power/mass ratio of only 177 watts/kg.

A further mass breakdown is shown in Table 2-14 which also includes Concept 4 for comparison. The amount of module stiffening that is required to make a highly flexible array automatically foldable is difficult to analyze on paper and may even be impractical to implement. Concept 4 takes a conservative approach and mounts the thin array on a lightweight isogrid framework to establish a feel for the mass effects of the added structure. Further analysis of this approach is needed to establish feasibility.

In summary, the roll-up concept (Concept 1) shows the most promise at this juncture in time. It meets the goal of 200 watts/kg and has high potential for being fully retractable. Further study and evaluation of all concepts will continue through the third quarter preliminary designs phase.

Table 2-14. Mass Summary - 200 Watt/kg Solar Array Candidates

FUNCTION	1 ROLL-UP/LATTICE FLEXIBLE WT IN KG	%	2 FLAT PACK/LATTICE FLEXIBLE WT IN KG	%	3 ISOGRID SUBSTRUCTURE SEMI-RIGID ARRAY WT IN KG	%	4 FLAT PACK/LATTICE SEMI-RIGID MODULE WT IN KG	%
ELECTRICAL								
SOLAR CELLS	14.67		14.67		14.67		14.67	
SUBSTRATE	3.33		3.33		3.33		3.33	
ADHESIVE	-		-		-		.2	
COVER MATERIAL	2.02		2.02		2.02		2.02	
BUS STRIPS	.12		.12		.12		.12	
INTERCONNECTS	2.08		2.08		2.08		2.08	
BLANKET TOTAL	22.22		22.22		22.22		22.22	
SLIP RINGS	1.43		-		-		-	
CABLE	.3		0.3		.30		.30	
CONNECTORS	.06		.06		.06		.06	
TOTAL	24.01	49	22.58	52	22.58	41	22.58	51
MECHANICAL								
STOWAGE & SUPPORT — DRUMS	5.6		-		-		-	
CONTAINER	-		6.11		2.0		6.11	
CENTER SUPPORT	8.6		3.75		3.75		3.75	
STRUTS	-		.23		.23		.23	
	14.2	32	10.09	23	5.98	10	10.09	22
ARRAY SUB STRUCTURE								
BOOM	.91		.91		-		.91	
HEADER	1.82		1.82		-		1.82	
LEADING EDGE MEMBER	3.11		3.11		-		3.11	
CELL SUBSTRUCTURE	-		-		7.4		7.4	
	5.84	12	5.84	13	7.4	13	13.24	13
ACTUATION								
DEPLOY MECHANISM	2.49		2.49		15.2		2.49	
TENSION MOTOR	.60		-		-		-	
TENSION SPRINGS	-		.60		-		.60	
ACTUATOR MOTORS	-		-		5.4			
	3.09	6	3.09	7	20.6	36	3.09	7
RETENTION & RELEASE								
BRACKETS	1.0		1.0		INC. IN DEPLOY MECH. MASS.		2.0	
CABLES	.4		.4				.4	
PYRO DEVICES	1.0		1.0				1.0	
	2.4	1	2.4	5			3.4	7
TOTAL MASS	49.54		44.00		56.56		52.4	
WATTS/KG	202		227		177		191	

NOTES:
1. CONCEPT NOS 1 & 3 ARE RETRACTABLE. CONCEPT NOS 2 & 4 ARE NOT RETRACTABLE.
2. CONCEPT NOS 1, 2, & 4 EMPLOY 5" DIA. LATTICE TYPE BOOM.

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CONCLUSIONS

SECTION 3
CONCLUSIONS

Out of four ultra-lightweight solar array concepts that have been analysed to date, two offer specific power in excess of the 200 W/kg goal of this program. Of the two, the flexible roll-up concept, is retractable, the flexible flat pack, is not. Both of these concepts are predicted on the use of a sheet thermoplastic (FEP-Teflon) as a heat-sealed coverglass and substrate laminate material. Kapton would be the other component of the substrate laminate.

The principal areas of concern regarding these conceptual designs lie with the physical and thermal properties in the interplanetary radiation environment. More information and data will be sought regarding the resistance of FEP Teflon to the defined high energy particle and UV electromagnetic radiation environments. Techniques for the enhancement of thermal emittance of these ultra-thin plastics will be sought.

RECOMMENDATIONS

SECTION 4
RECOMMENDATION

The principal area of criticism identified at the Mid-Term report in June was the selection of the interplanetary mission for the establishment of the radiation environment requirements. It is recommended that the present conceptual designs be evaluated against both the low earth and synchronous earth orbit radiation environments.

This analysis would show the potential of the interplanetary design to reach the specific power and end-of-life power goals in these adverse environments.

NEW TECHNOLOGY

SECTION 5
NEW TECHNOLOGY

5.1 EXPANDED TEMPERATURE RANGE LATTICE BOOM

A lattice type boom with structural members of composite materials has been tentatively chosen as the preferred mast for the 200 Watt/kg array. These extendible booms are normally made with fiberglass material using standard S-class epoxy as the bonding resin. This material starts to soften at about 120°C, thus loosing strength at the top of our specified operating temperature range of -130°C to 140°C. Therefore, a composite material with a range which exceeds the 140°C value, with some comfortable margin, is needed.

It is significant to note that some development work in being done in this area by Able Engineering Co. for Lockheed and NASA at the present time. Sample members have been made using a polymide resin and are currently on test for physical and thermal properties. The results of this development will be of direct interest to the 200 W/kg study.

5.2 PHYSICAL AND THERMAL PROPERTIES OF POLYMER MATERIALS

FEP Teflon and Kapton have been selected for coverglass/substrate material in the above identified conceptual designs. The amount and kind of data available to this study leaves some doubt concerning the high energy particle radiation resistance and UV radiation resistance of these materials. A need exists for further data on these materials to enhance the confidence factor in their selection.

REFERENCES

SECTION 6

REFERENCES

1. "Solar Array Technology Evaluation Program for SEPS", Final Report by LMSC, NAS8-30315.

2. "Feasibility Study of a 110 watt/Kilogram Lightweight Solar Array." GE Co. under contract 953387 to JPL, 25 May 1973.

3. "Solar Cell Coverglass Development", Final Report, A.R. Kirkpatrick Simulation Physics Inc. NAS5-10236, March 1971.

4. SEPS - Solar Array Deployment System, P. Slysch and L. Siden, General Dynamics Document No. P.D. 74-0014, March 1974.

5. Solar Panel Array Thermal Compatibility Stress Analysis, Don Fox, GE Document PIR U-1R53-477.

APPENDIX A

SOLAR ARRAY THERMAL COMPATIBILITY STRESS ANALYSIS

APPENDIX A

GENERAL ELECTRIC

SPACE DIVISION
PHILADELPHIA

PROGRAM INFORMATION REQUEST / RELEASE

PIR NO.	*CLASS. LTR.	OPERATION	PROGRAM	SEQUENCE NO.	REV. LTR.
	U	— 1R53 —	—	477	

*USE "C" FOR CLASSIFIED AND "U" FOR UNCLASSIFIED

FROM	TO
Don Fox - U2407	Rae Stanhouse - M4018 George Rayl - M2101

DATE SENT	DATE INFO. REQUIRED	PROJECT AND REQ. NO.	REFERENCE DIR. NO.
7/1/76			

SUBJECT

SOLAR ARRAY THERMAL COMPATIBILITY STRESS ANALYSIS

INFORMATION REQUESTED/RELEASED

1.0 PURPOSE

To present the solar panel array thermal compatibility stress analysis results and to suggest a design modification.

2.0 SUMMARY

A thermal/stress analysis was undertaken for a specified cross section of materials. A computer program was written to facilitate analysis. Loads, stresses, and margins of safety were calculated for all eight components. The silver material exhibited a negative margin of safety. The analysis was rerun with molybednum substituted for silver. All margins of safety were then positive.

3.0 DISCUSSION

This array consists of 8 material layers of varying cross section (see Figure 2-26 in Section 2). The array is assembled at room temperature (~20C) but is used in space where the low temperature limit is ~ -180C. The array is, therefore, forced to go through severe temperature cycling of 200C. The materials, making up the array, have greatly different coefficients of thermal expansion, and, hence, the array is highly stressed due to the ΔT of 200C.

The stress analysis was first done by hand, see Section 4.0.

A computer program was then written to calculate the loads, stresses, and margins of safety. This program checked the hand solution and allows easy component sizing alteration if re-analysis is desired. This program is an out-growth of the one written for Reference 1.

The properties of the various materials were taken from References 2-5 except for molybdenum. Molybdenum properties are taken from References 6 and 8.

The problem solution method is illustrated in Reference 7. It is based on the fact that the sum of external forces is always zero, $\Sigma F = 0 = P_1 + P_2 + \ldots + P_i$ and that the deflection of each material can be calculated by $\delta_p = PL/AE$. As each material is rigidly fastened to its neighbor, $(\delta_T + \delta_p)_1 = (\delta_T + \delta_p)_2 = \ldots = (\delta_T + \delta_p)_8$, or the total growth of each material must be equal.

D. Anderson - M4214

PAGE NO. ____ OF ____

RETENTION REQUIREMENTS

COPIES FOR	MASTERS FOR
☐ 1 MO.	☐ 3 MOS.
☐ 3 MOS.	☐ 6 MOS.
☐ 6 MOS.	☐ 12 MOS.
☐ MOS.	☐ MOS.
☐	☐ DO NOT DESTROY

FORM 1020B REV. (9-70)

4.0 CONCLUSIONS

Negative margins of safety have again been calculated as in the previous analysis, Reference 1.

Silver and silicon do not work well together in thermal cycling.

A model with molybdenum substituted for silver was run. This model exhibited good margins of safety for all materials.

The layers of the array must be bonded continuously to prevent buckling as they are all susceptable.

References

1. PIR, U-1R53-474A, "Solar Panel Array Stress Analysis", Author: D. T. Fox

2. "Thermoelastic Analysis of Solar Cell Arrays and Their Material Properties", Authors: M. A. Salama, W. M. Rowe, R. K. Yasui.

3. Bulletin T-2E, Teflon FEP Fluorocarbon Film Physical Thermal Properties.

4. Polymide Plastics, Hughes Aircraft Co., 28 October, 1965.

5. PIR, U-1P10-KLH-001, "Results of Measurements of Low Temperature Coefficient of Thermal Expansion of Kapton", Author: K. L. Hanson.

6. "Materials Selector 76", Materials Engineering.

7. "Strength of Materials", Author: F. L. Singer.

8. "Metals Handbook, Vol. 1, Properties and Selection." Eighth Edition, American Society for Metals.

9. "Aircraft Structures", Author: D. J. Peery.

5.0 THERMAL COMPATIBILITY STRESS ANALYSIS OF SOLAR PANEL ARRAY

A thermal stress analysis was performed by hand on a typical solar panel array containing FEP, silicon, silver, kapton and molybdenum.

The assembly was analyzed for a temperature excursion of 220 degrees centigrade, from 20C (room temperature) to -200C.

One of the materials exhibited a negative margin of safety.

A computer program was written to repeat these calculations. This allowed the parameters to be changed and the solutions to be altered.

Molybdenum was substituted for silver and the analysis rerun. This resulted in all positive margins of safety.

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SOLAR PANEL ARRAYS

MATERIAL PROPERTIES

VARIATION OF α & E WITH TEMPERATURE, REF 1-4

TEMPERATURE	$\alpha \times 10^6$ (IN/IN/C)				$E \times 10^{-6}$ (LB/IN²)			
C	FEP	SILVER	SILICON	KAPTON	FEP	SILVER	SILICON	KAPTON
-200	8.1	13.0	-1.5	12.7	100.	12.2		
-180	7.1	13.9	-1.1	11.96	48.	12.12		
-160	6.5	14.8	-.7	11.22	38.	12.09		
-140	5.5	15.7	-.3	10.48	32.	11.96		
-120	5.0	16.6	.1	9.74	28.	11.88		
-100	4.7	17.5	.5	9.0	25.	11.8		
-80	4.4	17.74	.8	8.26	21.	11.74		
-60	4.25	17.98	1.1	7.52	19.	11.68		
-40	4.05	18.22	1.4	6.78	14.	11.62		
-20	4.00	18.46	1.7	6.04	11.	11.56		
0	3.96	18.7	2.0	5.3	6.	11.5		
R.T. 20	4.00	18.8	2.2	4.56	4.5	11.24		
40	4.05	18.9	2.4	3.82	3.8	10.98		
60	4.25	19.0	2.6	3.08	3.2	10.72		
80	4.4	19.1	2.8	2.34	2.8	10.46		
100	4.7	19.2	3.0	1.6	.5	10.2		
120	5.0	19.3	3.2	.86	.4	9.94		
140	5.5	19.4	3.4	.12	.33	9.68		

FORM 1-8136 B (9 56)

The solar panels are made of layers of different materials. A typical assembly has the cross section shown in Figure 1 on the next page.

During a thermal cycle the panels grow due to α, the coefficient of thermal expansion. Each material, however, grows at a different rate because of the different α's for each material. Stresses are induced in the materials because they are bonded together. Two assumptions can validly be made, Reference 7. Since the materials are bonded together, each material grows the same amount.

$$(\delta_T + \delta_P)_1 = (\delta_T + \delta_P)_2 = \dots = (\delta_T + \delta_P)_8$$

Since the materials are a closed system

$$\Sigma F = 0 = P_1 + P_2 + \dots + P_8$$

where $\delta_T = \alpha L \Delta T$

and $\delta_P = PL/AE$

SOLAR PANEL ARRAYS

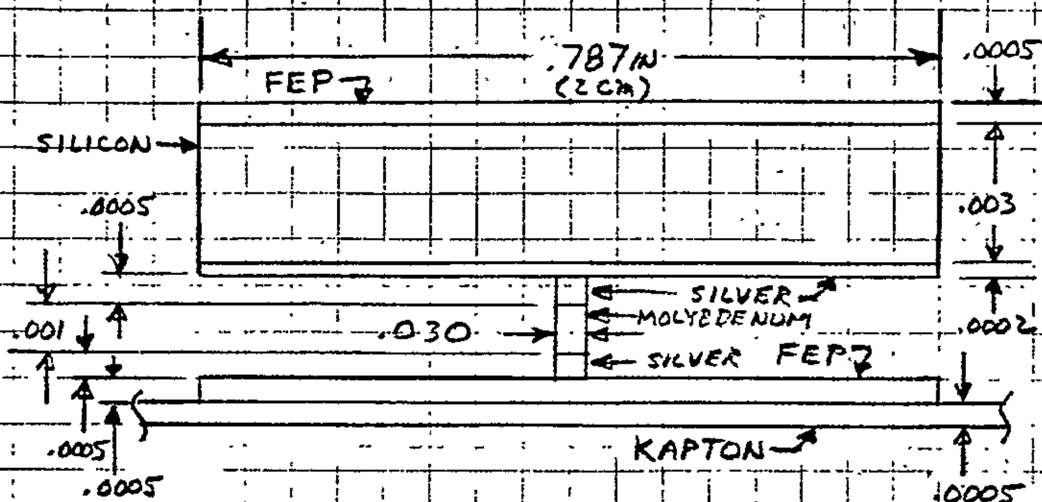

FIGURE 1

LAYER	MATERIAL	b (IN)	t (IN)	L (IN)
1	FEP	.787	.0005	.787
2	SILICON	.787	.0030	
3	SILVER	.787	.0002	
4	SILVER	.030	.0005	
5	MOLYBDENUM	.030	.0010	
6	SILVER	.030	.0005	
7	FEP	.787	.0005	
8	KAPTON	.787	.0005	.787

SOLAR PANEL ARRAYS

δ_p CALCULATIONS

$$\delta_p = \frac{PL}{AE}$$

L = LENGTH = .787 IN (2 cm)
A = bt = AREA (IN^2)
E = MODULUS OF ELASTICITY (LB/IN^2)
P = UNKNOWN LOAD (LBS)

THE L/AE CALCULATIONS ARE SHOWN IN THE FOLLOWING FIGURE

LAYER	MATERIAL	E X 10^{-6} (1) (LBS/IN^2)	A X 10^6 (IN)^2	AE (LB)	(L/AE) X 10^6 (IN/LB)
1	FEP	1.0	393.7	393.7	2000.0
2	SILICON	18.1	2362.2	42755.9	18.4
3	SILVER	12.2	157.5	1921.3	409.8
4	SILVER	12.2	15.0	183.0	4302.7
5	MOLYBDENUM	50.0 (2)	30.0	1500.0	524.5
6	SILVER	12.2	15.0	183.0	4302.7
7	FEP	1.0	393.7	393.7	2000.0
8	KAPTON	3.0	393.7	1181.1	666.7

(1) REF 2, 3, 4
(2) REF 8

SOLAR PANEL ARRAYS

δ_T CALCULATIONS

THE SOLAR PANELS WERE BUILT AT ROOM TEMPERATURE BUT HAD TO BE SAFE AT -190 C, A TEMPERATURE RANGE OF 210 DEGREES. THE VARIOUS MATERIALS MAKING UP THE ARRAY ALL ELONGATE AT A DIFFERENT RATE DURING CHANGES OF TEMPERATURE. THIS DIFFERENCE RATE CAUSES INDUCED LOADS WHICH WERE STUDIED IN THIS TOPIC.

THE GROWTH DUE TO TEMPERATURE IS CALCULATED BY THE FOLLOWING EXPRESSION:

$$\delta_T = \alpha L \Delta T$$

δ_T = CHANGE IN LENGTH (IN)
α = COEFFICIENT OF THERMAL EXPANSION (IN/IN/C)
L = ORIGINAL LENGTH (IN)
ΔT = CHANGE IN TEMPERATURE (C)

THIS CAN BE WRITTEN IN THE FORM

$$\delta_T / L = \alpha \Delta T$$

AS α VARIES WITH TEMPERATURE ITS VALUE AT EVERY 20 DEGREES WAS USED AND MULTIPLIED WITH A $\Delta T = 20$. THE SUM OF ALL THESE VALUES GAVE THE TOTAL δ/L GROWTH FOR THE TOTAL TEMPERATURE CHANGE. THIS WAS DONE FOR ALL FOUR MATERIALS.

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SOLAR PANEL ARRAYS

δ_T / L CALCULATIONS

	FEP		SILVER		SILICON		KAPTON	
TEMPERATURE	$\alpha \times 10^6$	$\delta_T/L \times 10^6$	$\alpha \times 10^6$	$\delta_T/L \times 10^6$	$\alpha \times 10^6$	$\delta_T/L \times 10^6$	$\alpha \times 10^6$	$\delta_T/L \times 10^6$
C	IN/IN/C	IN/IN	IN/IN/C	IN/IN	IN/IN/C	IN/IN	IN/IN/C	IN/IN
-200	8.1		13.0		-1.5		12.7	
		152		269		-26		246.6
-180	7.1		13.9		-1.1		11.96	
		136		287		-18		231.8
-160	6.5		14.8		-.7		11.22	
		120		305		-10		217.0
-140	5.5		15.7		-.3		10.48	
		105		323		-2		202.2
-120	5.0		16.6		.1		9.74	
		97		341		6		187.4
-100	4.7		17.5		.5		9.0	
		91		352.4		13		172.6
-80	4.4		17.74		.8		8.26	
		86.5		357.2		19		157.8
-60	4.25		17.98		1.1		7.52	
		83		362.0		25		143.0
-40	4.05		18.22		1.4		6.78	
		80.5		366.8		31		128.2
-20	4.0		18.46		1.7		6.04	
		79.6		371.6		37		113.4
0	3.96		18.7		2.0		5.3	
		79.6		375.0		42		98.6
20	4.0		18.8		2.2		4.56	
	Σ =	1110.2		3710.0		117.0		1898.6

TYPICAL CALCULATION

$$\frac{\delta_T}{L} = \frac{(\alpha_i + \alpha_{i+1})}{2}\Delta T = \frac{(8.1 \times 10^{-6} + 7.1 \times 10^{-6})(20C)}{2} = 152 \times 10^{-6} \frac{IN}{IN}$$

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FORM 1 6136 8 (9 58)

δ_T CALCULATIONS

$\alpha_{MOLY}(70°F) = 2.7 \times 10^{-6}$ IN/IN/°F (REF 6)

THERE WAS NO LOW TEMPERATURE DATA AVAILABLE. THE DATA THAT WAS AVAILABLE FROM 32°F UP INDICATES THAT THE COEFFICIENT OF THERMAL EXPANSION FOR MOLYBDENUM IS CONSTANT.

$\alpha = 4.86 \times 10^{-6}$ IN/IN/C

$\delta_T/L = \alpha \Delta T = (4.86 \times 10^{-6}$ IN/IN/C$)(200C) = 972 \times 10^{-6}$ IN/IN

THE δ_T CALCULATIONS ARE SHOWN IN THE FOLLOWING FIGURE.

MATERIAL	$(\delta_T/L) \times 10^6$ (IN/IN)	L (IN)	$\delta_T \times 10^6$ (IN)
FEP	1110.2	.787	874.2
SILICON	117.0	↓	92.1
SILVER	3710.0		2921.3
MOLYBDENUM	972.0		765.3
KAPTON	1898.6	.787	1495.0

SOLAR PANEL ARRAYS

FINDING P

SOLVING EQUATION (1)

$$(\delta_T+\delta_P)_1=(\delta_T+\delta_P)_2=\ldots=(\delta_T+\delta_P)_8$$

LAYER	MATERIAL	$(\delta_T+\delta_P)\times10^6$	SOLVE FOR P_i IN TERMS OF P_1 USING EQUATION (1)
1	FEP	874.2 + 2000.0 P_1	$P_1 = P_1$
2	SILICON	92.1 + 18.4 P_2	P_2 = 108.696 P_1 + 42.505
3	SILVER	2921.3 + 409.8 P_3	P_3 = 4.880 P_1 − 4.995
4	SILVER	2921.3 + 4302.7 P_4	P_4 = .465 P_1 − .476
5	MOLYBDENUM	765.3 + 524.5 P_5	P_5 = 3.813 P_1 + .208
6	SILVER	2921.3 + 4302.7 P_6	P_6 = .465 P_1 − .476
7	FEP	874.2 + 2000.0 P_7	$P_7 = P_1$
8	KAPTON	1495.0 + 666.7 P_8	P_8 = 3.000 P_1 − .931

BUT $\Sigma F = 0 = P_1+P_2+\ldots+P_8$ = 123.319 P_1 + 35.835 (2)

P_1 = −35.835/123.319 = − 0.291 LBS

P_2 = 108.696 (−.2906) + 42.505 = 10.918 LBS

P_3 = 4.880 (−.2906) − 4.995 = − 6.413 LBS

P_4 = .465 (−.2906) − .476 = − 0.611 LBS

P_5 = 3.813 (−.2906) + .208 = − 0.898 LBS

P_6 = .465 (−.2906) − .476 = − 0.611 LBS

P_7 = −35.835/123.319 = − 0.291 LBS

P_8 = 3.000 (−.2906) − .931 = − 1.803 LBS

"CHECK" ΣP = 0.000 LBS ✓

SOLAR PANEL ARRAYS

MARGIN OF SAFETY CALCULATIONS

THE STRESS IN EACH MATERIAL IS CALCULATED BY THE FOLLOWING EXPRESSION.

$$\sigma = P/A$$

σ = STRESS (LBS/IN²)
P = LOAD (LBS)
A = AREA (IN)²

THE MARGIN OF SAFETY IS FOUND BY DIVIDING THE ALLOWABLE STRESS (ULTIMATE) BY THE APPLIED STRESS (ULTIMATE) AND SUBTRACTING 1.

$$M.S. = \frac{\sigma_{ULT\ ALLOW}}{\sigma_{ULT\ APPLIED}} - 1$$

$$\sigma_{ULT_{APPLIED}} = 1.5\,\sigma$$

THE MARGIN OF SAFETY CALCULATIONS ARE SHOWN IN THE FOLLOWING FIGURE

LAYER	MATERIAL	A X 10⁶ (IN²)	P (LBS)	σ (LBS/IN²)	$\sigma_{ULT\ ALLOW}$ (1) (LBS/IN²)	MARGIN OF SAFETY
1	FEP	393.7	.2906	738	3000	1.709
2	SILICON	23622	-10.919	-4622	20000	1.884
3	SILVER	157.5	6.415	40730	52000	NEG
4	SILVER	15.0	.611	40730	52000	NEG
5	MOLYBDENUM	30.0	.901	30033	95000	1.108
6	SILVER	15.0	.611	40730	52000	NEG
7	FEP	393.7	.2906	738	3000	1.709
8	KAPTON	393.7	1.804	4582	25000	2.637

(1) COMPRESSION ALLOWABLES ASSUMED EQUAL TENSION ALLOWABLES

The computer program run and its listing are shown on the following three pages:

B = width (in)

T = thickness (in)

A = area $(in)^2$

P = load (lb)

Stress (PSI)

```
THIS PROGRAM COMPUTES SOLAR PANEL CRYSTAL
STACKUP LOADS, STRESSES, AND MARGINS OF SAFETY.

ENTER THE MATERIAL THICKNESSES. 1: FEP 1
2: SILICON, 3: SILVER 1, 4: SILVER 2, 5: MOLYBDENUM,
6: SILVER 3, 7: FEP 2, 8: KAPTON
=.0005,.003,.0002,.0005,.001,.0005,.0005,.0005

MATERIAL  B         T          A          P        STRESS  ALLOWABLE SAFETY
                                                           STRESSES  MARGIN
   1      0.787  0.00050.000394    +0.290   +737.861   3000.0    1.711
   2      0.787  0.00300.002362   -10.917 -4621.637  20000.0    1.885
   3      0.787  0.00020.000157    +6.413+40719.463  52000.0   -0.149
   4      0.030  0.00050.000015    +0.611+40719.463  52000.0   -0.149
   5      0.030  0.00100.000030    +0.899+29983.047  95000.0    1.112
   6      0.030  0.00050.000015    +0.611+40719.463  52000.0   -0.149
   7      0.787  0.00050.000394    +0.290   +737.861   3000.0    1.711
   8      0.787  0.00050.000394    +1.803 +4578.783  25000.0    2.640

*
```

LIST

```
C    PROGRAM NAME: DFSOLAR2
C
C    THIS PROGRAM COMPUTES SOLAR PANEL CRYSTAL STACKUP STRESSES.
C
       IMPLICIT REAL*8(A-H,P-Z)
       DIMENSION A(8),T(8),B(8),D(8),E(8)
       DIMENSION AM(8),S(8),P(8),SA(8),SM(8)
       JJ=8
       PRINT 2
     2 FORMAT('THIS PROGRAM COMPUTES SOLAR PANEL CRYSTAL'/
&      'STACKUP LOADS, STRESSES, AND MARGINS OF SAFETY.'/)
     3 PRINT 4
C      ENTER THE MATERIAL THICKNESSES
     4 FORMAT(/' ENTER THE MATERIAL THICKNESSES. 1: FEP 1'/
&      ' 2: SILICON, 3: SILVER 1, 4: SILVER 2, 5: MOLYBDENUM,'/
&      ' 6: SILVER 3, 7: FEP 2, 8: KAPTON')
       READ:(T(K),K=1,JJ)
       AL=2/2.54
       B(1)=AL
       B(2)=AL
       B(3)=AL
       B(4)=.03
       B(5)=.03
       B(6)=.03
       B(7)=AL
       B(8)=AL
       DO 7 I1=1,JJ
     7 A(I1)=B(I1)*T(I1)
C      THE ELONGATION DUE TO DELTA T FROM 20C TO -200C FOR
C      THE VARIOUS MATERIALS FOLLOWS:
       AM(1)=(.0011102)*AL
       AM(2)=(117E-6)*AL
       AM(3)=(3710E-6)*AL
       AM(4)=AM(3)
       AM(5)=(972E-6)*AL
       AM(6)=AM(3)
       AM(7)=AM(1)
       AM(8)=(1898.6E-6)*AL
C      THE MODULUS OF ELASTICITY OF THE VARIOUS MATERIALS FOLLOWS:
C      E1=E7=FEP, E2=SILICON, E3=E4=E6=SILVER, E5=MOLYBDENUM, E8=KAPTON
       E(1)=1E6
       E(2)=18.1E6
       E(3)=12.2E6
       E(4)=E(3)
       E(5)=50E6
       E(6)=E(3)
       E(7)=E(1)
       E(8)=3E6
C      THE ELOGATION DUE TO LOAD IS EQUAL TO PL/AE
       DO 1 I3=1,JJ
       D(I3)=AL/(A(I3)*E(I3))
     1 CONTINUE
       P(1)=-((AM(1)-AM(2))/D(2)+(AM(1)-AM(3))/D(3)+(AM(1)-AM(4))/D(4)
&      +(AM(1)-AM(5))/D(5)+(AM(1)-AM(6))/D(6)+(AM(1)-AM(7))/D(7)
&      +(AM(1)-AM(8))/D(8))/(D(1)/D(1)+D(1)/D(2)+D(1)/D(3)+D(1)/D(4)
&      +D(1)/D(5)+D(1)/D(6)+D(1)/D(7)+D(1)/D(8))
       PP=D(1)*P(1)+AM(1)
       P(2)=(PP-AM(2))/D(2)
       P(3)=(PP-AM(3))/D(3)
       P(4)=(PP-AM(4))/D(4)
       P(5)=(PP-AM(5))/D(5)
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      P(7)=(PP-AM(7))/D(7)
      P(8)=(PP-AM(8))/D(8)
      DO 5 I2=1,JJ
    5 S(I2)=P(I2)/A(I2)
C     THE ALLOWABLE STRESSES ARE AS FOLLOWS:
      SA(1)=3000
      SA(2)=20000
      SA(3)=52000
      SA(4)=52000
      SA(5)=95000
      SA(6)=52000
      SA(7)=3000
      SA(8)=25000
C     MARGIN OF SAFETY CALCULATIONS: MS=(S-ALLOW/S-APPLIED)-1
      DO 6 I=1,JJ
    6 SM(I)=ABS(SA(I)/(S(I)*1.5))-1
      PRINT 10
   10 FORMAT(//'MATERIAL',2X,'B',8X,'T',7X,'A',7X,'P',6X,'STRESS'
&     ,2X,'ALLOWABLE',1X,'SAFETY'/51X,'STRESSES',2X,'MARGIN')
      DO 8 KK=1,JJ
      WRITE(6,9)KK,B(KK),T(KK),A(KK),P(KK),S(KK),SA(KK),SM(KK)
    9 FORMAT(3X,I2,2X,F8.3,F8.4,F8.6,2F10.3,F8.1,F8.3)
    8 CONTINUE
      STOP
      END

ready

*
```

The second computer run and its listing are shown on the following three pages.

Molybdenum has been substituted for silver in all cases.

```
THIS PROGRAM COMPUTES SOLAR PANEL CRYSTAL
STACKUP LOADS, STRESSES, AND MARGINS OF SAFETY.
THIS PROGRAM HAS SUBSTITUTED MOLYDENUM FOR SILVER.

ENTER THE MATERIAL THICKNESSES. 1: FEP 1
2: SILICON, 3: MOLYBDENUM 1, 4: MOLYBDENUM 2, 5: MOLYBDENUM 3,
6: MOLYBDENUM 4, 7: FEP 2, 8: KAPTON
=.0005,.003,.0002,.0005,.001,.0005,.0005,.0005

MATERIAL  B        T         A         P       STRESS   ALLOWABLE SAFETY
                                                         STRESSES  MARGIN
   1      0.787  0.00050.000394     +0.305   +774.065   3000.0   1.584
   2      0.787  0.00300.002362     -9.369  -3966.351  20000.0   2.362
   3      0.787  0.00020.000157     +5.007+31793.231  95000.0   0.992
   4      0.030  0.00050.000015     +0.477+31793.231  95000.0   0.992
   5      0.030  0.00100.000030     +0.954+31793.231  95000.0   0.992
   6      0.030  0.00050.000015     +0.477+31793.231  95000.0   0.992
   7      0.787  0.00050.000394     +0.305   +774.065   3000.0   1.584
   8      0.787  0.00050.000394     +1.845  +4687.394  25000.0   2.556

*
```

LIST

```
C    PROGRAM NAME: DFSOLAR3
C
C    THIS PROGRAM COMPUTES SOLAR PANEL CRYSTAL STACKUP STRESSES.
C    THIS PROGRAM HAS SUBSTITUTED MOLYDENUM FOR SILVER.
       IMPLICIT REAL*8(A-H,P-Z)
       DIMENSION A(8),T(8),B(8),D(8),E(8)
       DIMENSION AM(8),S(8),P(8),SA(8),SM(8)
       JJ=8
       PRINT 2
     2 FORMAT('THIS PROGRAM COMPUTES SOLAR PANEL CRYSTAL'/
&      'STACKUP LOADS, STRESSES, AND MARGINS OF SAFETY.'/
&      'THIS PROGRAM HAS SUBSTITUTED MOLYDENUM FOR SILVER.')
     3 PRINT 4
C      ENTER THE MATERIAL THICKNESSES
     4 FORMAT(/' ENTER THE MATERIAL THICKNESSES. 1: FEP 1'/
&      ' 2: SILICON, 3: MOLYBDENUM 1, 4: MOLYBDENUM 2, 5: MOLYBDENUM 3,
&      ' 6: MOLYBDENUM 4, 7: FEP 2, 8: KAPTON')
       READ:(T(K),K=1,JJ)
       AL=2/2.54
       B(1)=AL
       B(2)=AL
       B(3)=AL
       B(4)=.03
       B(5)=.03
       B(6)=.03
       B(7)=AL
       B(8)=AL
       DO 7 I1=1,JJ
     7 A(I1)=B(I1)*T(I1)
C      THE ELONGATION DUE TO DELTA T FROM 20C TO -200C FOR
C      THE VARIOUS MATERIALS FOLLOWS:
       AM(1)=(.0011102)*AL
       AM(2)=(117E-6)*AL
       AM(3)=(972E-6)*AL
       AM(4)=AM(3)
       AM(5)=AM(3)
       AM(6)=AM(3)
       AM(7)=AM(1)
       AM(8)=(1898.6E-6)*AL
C      THE MODULUS OF ELASTICITY OF THE VARIOUS MATERIALS FOLLOWS:
C      E1=E7=FEP, E2=SILICON, E3=E4=E5=E6=MOLYBDENUM, E8=KAPTON
       E(1)=1E6
       E(2)=18.1E6
       E(3)=50E6
       E(4)=E(3)
       E(5)=E(3)
       E(6)=E(3)
       E(7)=E(1)
       E(8)=3E6
C      THE ELOGATION DUE TO LOAD IS EQUAL TO PL/AE
       DO 1 I3=1,JJ
     1 D(I3)=AL/(A(I3)*E(I3))
       P(1)=-((AM(1)-AM(2))/D(2)+(AM(1)-AM(3))/D(3)+(AM(1)-AM(4))/D(4)
&      +(AM(1)-AM(5))/D(5)+(AM(1)-AM(6))/D(6)+(AM(1)-AM(7))/D(7)
&      +(AM(1)-AM(8))/D(8))/(D(1)/D(1)+D(1)/D(2)+D(1)/D(3)+D(1)/D(4)
&      +D(1)/D(5)+D(1)/D(6)+D(1)/D(7)+D(1)/D(8))
       PP=D(1)*P(1)+AM(1)
       P(2)=(PP-AM(2))/D(2)
       P(3)=(PP-AM(3))/D(3)
       P(4)=(PP-AM(4))/D(4)
```

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      [illegible]
      P(6)=(PP-AM(6))/D(6)
      P(7)=(PP-AM(7))/D(7)
      P(8)=(PP-AM(8))/D(8)
      DO 5 I2=1,JJ
    5 S(I2)=P(I2)/A(I2)
C     THE ALLOWABLE STRESSES ARE AS FOLLOWS:
      SA(1)=3000
      SA(2)=20000
      SA(3)=95000
      SA(4)=95000
      SA(5)=95000
      SA(6)=95000
      SA(7)=3000
      SA(8)=25000
C     MARGIN OF SAFETY CALCULATIONS: MS=(S-ALLOW/S-APPLIED)-1
      DO 6 I=1,JJ
    6 SM(I)=ABS(SA(I)/(S(I)*1.5))-1
      PRINT 10
   10 FORMAT(/'MATERIAL',2X,'B',8X,'T',7X,'A',7X,'P',6X,'STRESS'
&     ,2X,'ALLOWABLE',1X,'SAFETY'/51X,'STRESSES',2X,'MARGIN')
      DO 8 KK=1,JJ
      WRITE(6,9)KK,B(KK),T(KK),A(KK),P(KK),S(KK),SA(KK),SM(KK)
    9 FORMAT(3X,I2,2X,F8.3,F8.4,F8.6,2F10.3,F8.1,F8.3)
    8 CONTINUE
      STOP
      END

ready

*
```

SOLAR PANEL ARRAYS

BUCKLING CHECK

$$P_{cr} = \frac{\pi^2 EI}{L^2} = \frac{\pi^2 E b t^3}{12 L^2}$$ (REF. 9)

FIRST: ASSUME L = .5 IN AND CALCULATE $P_{CRITICAL}$

SECOND: USE $P_{APPLIED}$ AND CALCULATE $L_{MINIMUM}$

LAYER AND MATERIAL	$E \times 10^{-6}$ (PSI)	t (IN)	b (IN)	P_{cr} (LBS)
1. FEP	1.0	.0005	.787	3.236×10^{-4}
2. SILICON	18.1	.003	.787	1.265
3. SILVER	12.2	.0002	.787	2.525×10^{-4}
4. SILVER	12.2	.0005	.030	1.505×10^{-4}
5. MOLYBDENUM	50.0	.0010	.030	4.935×10^{-3}
6. SILVER	12.2	.0005	.030	1.505×10^{-4}
7. FEP	1.0	.0005	.787	3.236×10^{-4}
8. KAPTON	3.0	.0005	.787	9.709×10^{-4}

$$L_{MIN} = \sqrt{\frac{\pi^2 E b t^3}{12 P}}$$

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APPENDIX B

AN EVALUATION OF ULTRA-LIGHTWEIGHT SOLAR CELL COVERGLASS MATERIALS

APPENDIX B

GENERAL ELECTRIC
SPACE DIVISION
PHILADELPHIA

PROGRAM INFORMATION REQUEST / RELEASE

PIR NO.	*CLASS. LTR.	OPERATION	PROGRAM	SEQUENCE NO.	REV. LTR.
	200W/Kg-6.76-016			—	

*USE "C" FOR CLASSIFIED AND "U" FOR UNCLASSIFIED

FROM	TO
W. Wilson	G. J. Rayl

DATE SENT	DATE INFO. REQUIRED	PROJECT AND REQ. NO.	REFERENCE DIR. NO.
6/10/76	6/10/76		

SUBJECT

An Evaluation of Ultra-lightweight Solar Cell Coverglass Materials

INFORMATION REQUESTED/RELEASED

The search for an ultra-lightweight coverglass is complicated by the necessity to trim as much weight as possible and at the same time retain those thermal, physical and radiation resistant properties that are required to preserve the integrity of the coverglass/cell combination. Integral glasses (a coverglass that is formed in place) and heat-sealed thermoplastic materials appear to offer the only hope of achieving the necessary performance at a minimum weight penalty.

FEP Teflon is a prime candidate because of its optical properties and heat-sealability. From mass range considerations alone, 13 μm of FEP will be an effective shield against 1 Mev electron damage equivalent proton particles up to a fluency of $2(10^{12})$ particles/cm^2.

PAGE NO. ___ OF ___

✓ RETENTION REQUIREMENTS

COPIES FOR	MASTERS FOR
☐ 1 MOS.	☐ 3 MOS.
☐ 3 MOS.	☐ 6 MOS.
☐ 6 MOS.	☐ 12 MOS.
☐ MOS.	☐ MOS.
☐	☐ DO NOT DESTROY

FORM 1020 B REV. (9-75)

1.0 INTRODUCTION

A. PURPOSE AND USES OF STATE-OF-THE-ART Si SOLAR CELL COVER SLIPS

State-of-the-art solar arrays are typically composed of several layers. Progressing from top to bottom through the array, one finds: (1) cover slip, (2) cover-to-cell adhesive, (3) Si solar cell, (4) interconnect, (5) assembly adhesive, if array is of the independent interconnect type, and (6) the substrate or array blanket. Coverslips are used as particle shields to protect solar cells from the damaging effects of the space radiation environment. They are also useful in regulating array temperature. It is the intent of this study to make the necessary trade-offs to achieve the goal of designing an array with a specific power output of 200 W/Kg (BOL). The array should be capable of operating in the radiation and thermal environment specified in our Baseline Requirement, Document No. 200 W/Kg-2.76-004, dated 15 April 1976. We have identified the choice of an appropriate coverslip as a crucial step toward the realization of the goal of our conceptual design.

B. A CONSIDERATION OF PERTINENT PARAMETERS

The space thermal environment imposes on us the necessity to design a Coverslip/Solar Cell assembly which can withstand thermal shock between temperature extremes of -190°C to +140°C without damage to the structural integrity of the assembly. This requirement can be met by either designing for a close coefficient of linear thermal expansion match between the coverslip and solar cell (in integral coverslip configurations), or by letting built-up stress (caused by differences in relative thermal expansion) be taken up by a flexible adhesive between cell and coverslip.

The emittance of the coverslip material becomes the important parameter since it is necessary to regulate the array temperature in order to maintain efficient array operation.

Transmittance of cover, both un-irradiated and after particulate and UV irradiation is important to optimal array performance. Any absorption, within the cover material or adhesive, which falls within the spectral response bandwidth of the solar cell will limit its output.

Particulate radiation is also capable of degrading the coverslip's mechanical strength, thus resistance to radiation induced embrittlement becomes a parameter of interest in the selection of coverslip materials. UV stability of cover adhesive materials is another concern of the so solar array designer since the organic polymers normally used ad adhesives may darken as a result of UV induced photo-polymeric mechanisms of chemical change.

The complete evaluation of candidate materials requires empirical data or theoretical predictions for the following material properties.

1. Transmittance of coverslip and adhesive

    a. in the as-fabricated state

    b. After UV irradiation

c. After 2×10^{12} P/Cm^2 irradiation at 1 MeV

2. Coefficient of linear thermal expansion

3. Resistance to radiation induced embrittlement

4. Emissivity

5. Density

6. Stress in integral covers

7. Flexibility

C. CHARACTERISTICS OF AN IDEAL COVERSLIP FOR USE IN A 200 W/Kg SOLAR ARRAY

If reference is now made to the previously identified pertinent materials properties and consideration given to the requirements of a 200 W/Kg array, one can conceptualize a set of array characteristics possessed by the "ideal" solar array. Such an array might have the following properties:

Coverslip Materials Properties of the Ideal
Lightweight Solar Array

1. Transmittance = 100% over the spectral response range of the solar cells used (pre and post-irradiated)

2. Identical match between coefficient and thermal expansion of coverslip and solar cell (no stress situation).

3. 100% resistance to radiation induced embrittlement (i.e., no UV induced photo-polymeric reactions).

4. 100% high emissivity since it is desirable to maintain the solar array at as low a temperature as possible.

5. The coverslip material should have zero density.

A variety of fused silica type glass compounds including cerium-stabilized ones have been either used or proposed as radiation shields for Silicon Solar Cell arrays. These glasses can be sputter applied or vacuum evaporated by one of several techniques. Microsheet material is also available; however, it is not considered here due to the inability to fabricate and handle thin (< 1.5-2.0 mil) samples of these materials. Microsheet glasses, in addition, are usually bonded to the solar cell with an adhesive. This causes an additional weight penalty. The other leading space solar array coverslip candidate material is FEP teflon which is heat and pressure sealed.

At this point, several trades can already be made. The selection of integral covers over adhesively-bonded configurations has the advantage of lighter weight and better transmittance of the UV due to the elimination of the adhesive. In addition, significant weight savings can be achieved by reductions in cover cell thickness. Figure 1 shows the gain in specific power to weight ratio that is possible by reducing cell and coverslip thicknesses. Particular attention should be given the two curves for 4 mil thick silicon cells. Achievable gains in reducing coverslip thickness from 1.3 to 0.5 mils result in a 32.5% increase in specific power for the covered cell case. A prior study (110 W/Kg) has identified 37 μm as the necessary coverslip thickness to adequately shield against solar flare protons in the energy range from 1 to 100 MeV. If less severe proton radiation environments are expected for certain missions, coverslips as thin as 0.0005 inch should be adequate. Reference to the curve shown in Figure 2 shows the range of 1-100 MeV protons in SiO_2. Data is given for SiO_2 because its density (2.2 gm-cm^{-3}) is typical of the densities of solar cell coverslip materials. From the curve it can be seen that about 0.54 mils of coverslip material is required to stop 1 MeV protons.

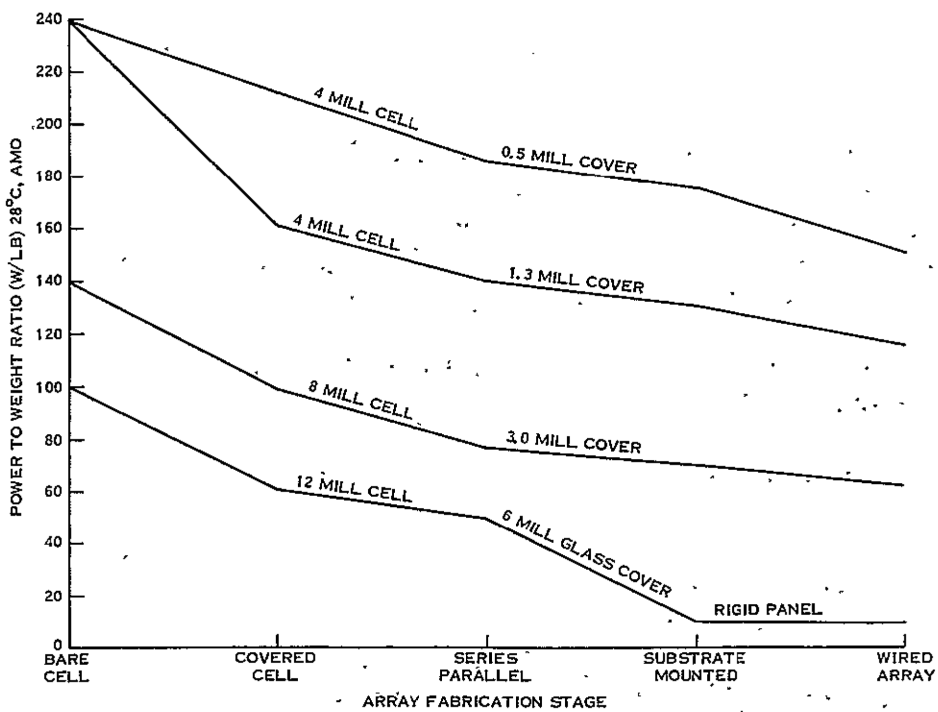

Figure 1. Power-to-Weight Ratio for Various Solar Cell Array Designs (Ref 1).

2.0 A CONSIDERATION OF GLASS COVERSLIP MATERIALS

Glass materials have been prime candidates for use as solar cell radiation shields. Various compositions have been formulated which attempt to improve both initial and post irradiation transmittance and where integral covers are concerned, several deposition techniques are currently available. An in-depth comparison of several integral coverglass materials and

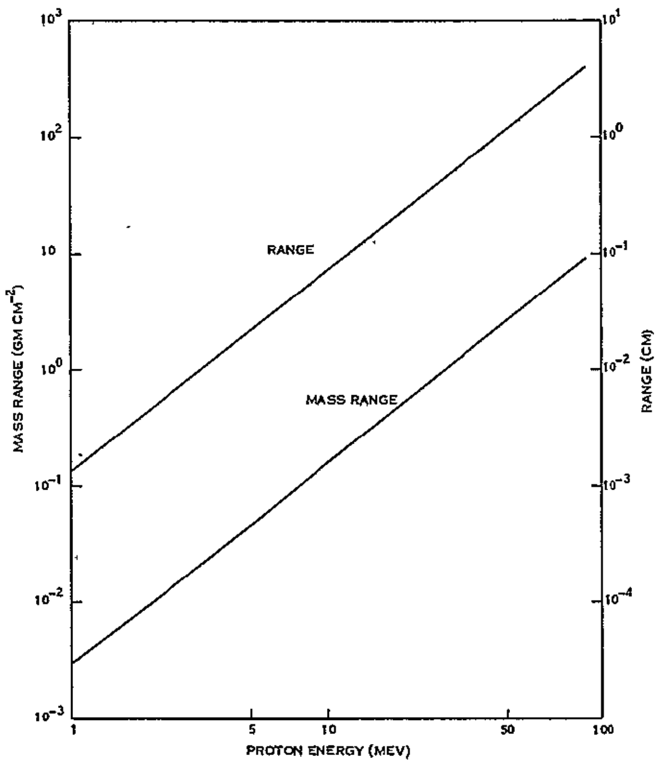

Figure 2. Mass Range and Range vs. Proton Energy (Ref 2)

methods of deposition was conducted by the General Electric Company in 1973. At that time, consideration was given to the following deposition techniques:

1. High Vacuum Ion Sputtering (HVIBS)

2. Electron beam evaporation

3. Radio frequency sputtering

4. Fusion

Some of the results of that study are presented here since the status of integral glass covers for solar cells has not changed considerably since that time. For purposes of the present study, results of prior studies will be viewed in relation to the requirements for a 200 W/Kg array. The May 25, 1973 study, (Reference 3), gives a summary of materials for various glasses deposited by HVIBS as shown in Table 1.

From Table 1 it can be seen that integral covers of Corning 7070 glass out rank all other materials considered. Its low deposited stress is of considerable importance especially when deposited on thin solar cells. Figure 3 shows the average bow in integrally covered cell vs integral coverslip thickness.

Table 1. Summary of Integral Cover Materials Deposited by HIBS (from Reference 3)

Material	Deposited Stress	Integral Coating Physical Quality	Integral Coating Optical Quality
7940 fused silica	High	Excellent	Excellent
SiO_2/Si_3N_4	Very High	Poor	Poor
7740	Moderate	Excellent	Excellent
7740 + CeO_2 doping	Low	Excellent	Good
0211 + CeO_2 doping	Very Low	Excellent	Good
7070	Low	Initially fair, improved to excellent	Excellent

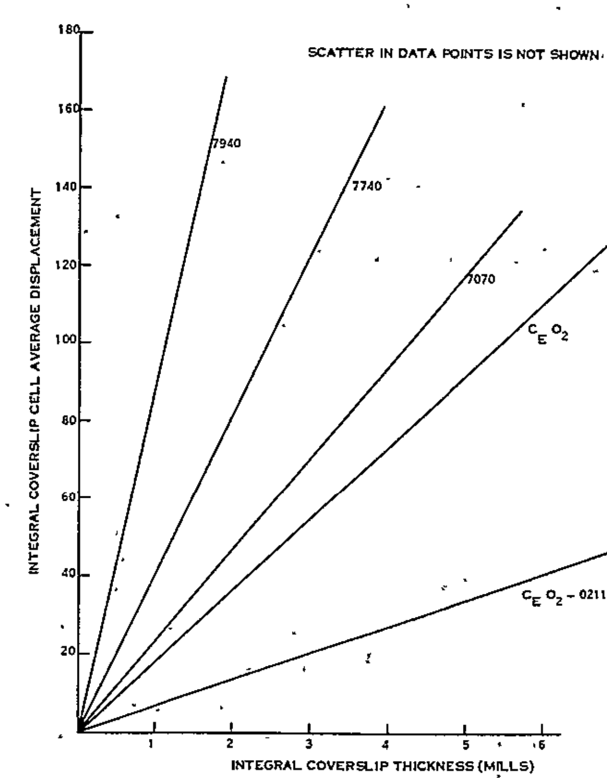

Figure 3. Integral Coverslip Cell Bow vs Integral Coverslip Thickness (Ref. 3)

Though cerium doped 0211 HVIBS covers show superior performance in achieving low deposited stress levels, one must take into consideration its poorer transmission in the ultraviolet. Cerium doping was originally intended to stabilize glass materials against particulate radiation induced darkening effects and its success in that regard is well established. Its function as a UV rejection filter is considered to be a plus in its favor when used in conjunction with organic adhesives which must be shielded against UV radiation. This UV rejection property of Cerium-stabilized glass compounds becomes unnecessary when integrally bonded coverslip/solar cell assemblies are used. It also has the deleterious effect of "neutralizing" the advantage in broadband conversion efficiency gained through use of recently developed violet cells. A trade-off study will be conducted to determine whether the low stress levels achievable with Cerium stabilized 7740 and 0211 glasses (a very desirable quality for glasses deposited on 3 mil solar cells) is preferred over use of the higher transmission of 7070 glass (a quality which enables the use of solar cells with enhanced violet response).

HVIBS Corning 7070 glass also emerges as an attractive cover material for silicon solar cells when consideration is given to its linear coefficient of thermal expansion and relative radiation resistance.

Integral covers of 7070 deposited by RF sputtering at room temperature show similar good characteristics as those deposited by HVIBS. Brackley, Lawson and Satchell (Reference 4) report the following results on their evaluation of RF sputtered 7070 glass on solar cells:

1. Intrinsic coverslip stress $< 3 \times 10^{-7}$ dynes/cm^2 (the lower limit of their measurement capability). This stress value was an order of magnitude lower than intrinsic stress levels in Corning 7740 and Schott 8330 glass films. They also report negligible bowing even when 300 μm are deposited on cells as thin as 125 μm.

2. No delamination when immersed in boiling water for periods of weeks.

3. Excellent UV transmittance falling only to 95% at 350 nm from 99% between 1200 nm and 400 nm.

4. Negligible change of transmission after exposure to 1 MeV electrons to a total fluence of 10^{15} e/cm^2. By comparison, films of 7740 and 8330 glass were found to darken severely.

5. Typical deposition rates for this process are about 2.6 μm/hour.

NOTE

This deposition rate is rather slow and may effect cost.

Work in the area of electron-beam evaporation of dielectric materials onto solar cells was carried out by Stella and Somberg and reported in Reference 5. These investigators report the following results of their investigation:

1. Demonstration of the feasibility of achieving evaporation processes capable of providing 50-100 μm thick transparent (0.5-1.0% absorption per mil), low stress integral glass covers on Titanium oxide antireflection coated solar cells.

C-2

2. Extremely fast deposition rates (72-108 μm/hr).

3. Most successful were depositions achieved with Corning 1720 aluminosilicate glass as the source material.

4. Integral coverglass stress was found to be inversely related to deposition rate.

Frit and fuse methods of integral coverglass deposition have not yielded encouraging results. Investigators Rauch and Ulrich (Reference 6) report unacceptably high losses in solar cell efficiency as a result of the elevated temperature steps used in the bonding process.

Perhaps the most interesting new development in the area of integrally bonded coverglass materials and processes is reported by Kirpatrick (Reference 7). The new technology involves bonding Corning 7070 glass to solar cells in a virtually unstressed condition by use of electrostatic-field-assisted and temperature-assisted sealing. Temperatures used in this technique are ≥ 400°C, but well below the softening point of the glass. Process times of a few minutes are reported. Sample thicknesses used in this study were 72 mils. This study also reported a slight darkening of 7070 glass by 1 MeV electrons and the subsequent bleaching (almost back to the un-irradiated state) of this material by UV. The data is presented in Figure 4.

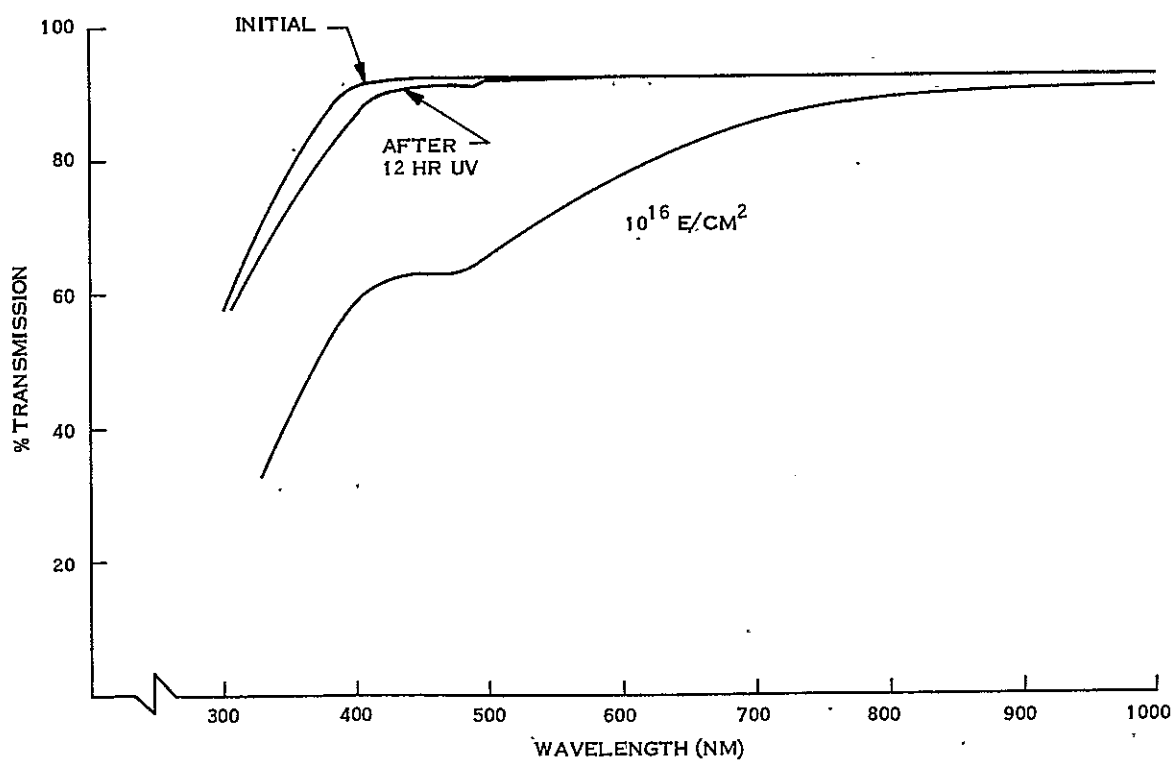

Figure 4. Ultraviolet Bleaching of Irradiated 7070 Glass (Ref 7)

FEP TEFLON AS A COVERSLIP MATERIAL

Besides the glass materials mentioned above, the other leading candidate material considered for solar cell cover application is the "clear" plastic fluorocarbon film, Fluorinated Ethylene Propylene (FEP Teflon). This material is amenable to integral bonding to solar cells with AR coatings. Thus adhesives need not be used in FEP encapsulated arrays. As in the case of glass cover materials, the elimination of adhesives also obviates the need for a UV filter on one side of the cover to protect the adhesive. The resultant gain in blue-light generated cell current must be considered significant both because of the initial cell output and because the blue (0.4 μm) wavelength generated solar cell surrent is the least affected by radiation damage to the cell and makes up a larger proportion of the total current available as the damage to the cell increases (Reference 8). Two types of FEP material, Type A and Type C, have been proposed as solar cell integral covers. Test results reveal little difference between the two materials as regards crucial performance factors, however FEP-A material requires an adhesion promoter. It has been found (Reference 8) that FEP as a cover material is compatible with SiO, Ta_2O_5, and Si_3N_4 coated cells.

Several authors (References 10 & 11) have reported UV darkening and charged particle induced embrittlement of FEP films. A 10% loss in cell power after 4000 hours of equivalent sun exposure to UV is reported by Rauschenbuch and Cammady (Reference 10). Figure 5 shows their results for UV irradiation from a shoot-arc, high pressure Xenon lamp at an intensity of 2.0 UV suns in the wavelength range from 0.25 to 0.38 μm. These investigators traced fatigue cracking of FEP, after particulate irradiation, to an inherent fatigue sensitivity of FEP in general, and partially to the cell interconnect design and solar cell contact choice.

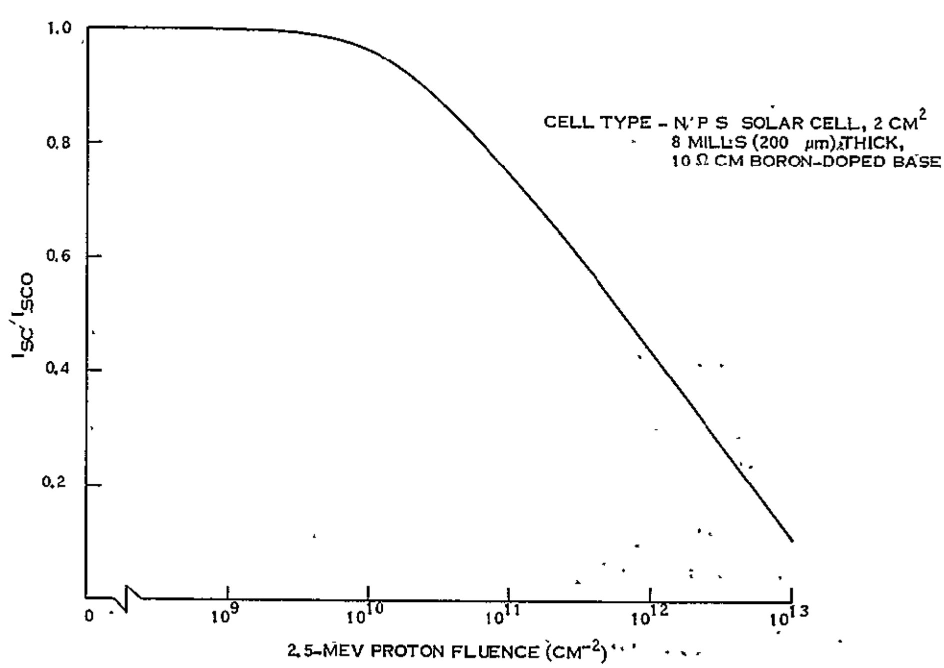

Figure 5. Short-Circuit Current Degradation Due to Ultraviolet Irradiation

S.K. Marsik and J.D. Broder (Reference 11) tested FEP-A covers on silicon solar cells that had been irradiated with 1-MeV electrons, in vacuum, to a total fluence of 2.5×10^{16} $\bar{e}/cm^2$ (6.75×10^8 rad of absorbed dose for FEP-A material). They found FEP-A to darken at the blue end of the spectrum (0.4 and 0.45 μm range). They postulate than an active form of fluorine created in the FEP-A material by breaking of long chain molecules after electron irradiation might react with SiO AR coatings to change its color and optical properties. This effect, if substantiated, might possibly be eliminated by the use of non-oxide AR coatings such as Si_3N_4.

Marsik and Broder also found that a 1-MeV electron fluence of 2.5×10^{15} $\bar{e}/cm^2$ makes FEP-A too brittle to sustain at least two flexes comparable to those typical of a "rollup" array.

Evaluation of the radiation resistance properties of plastic materials is complicated by the fact that for some materials (FEP Teflon is one) degradation is a much stronger function of UV-spectral content than intensity, Reference 8. Caution, therefore, must be used in interpreting study results since not all solar simulators create a uniform UV spectrum and the spectrum that is produced does not accurately reproduce the solar UV spectrum.

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