CR 151670

BOEING

D180-22876-6

NAS9-15196
DRL T-1346
DRD MA-664T
LINE ITEM 3

Volume VI
Evaluation Data Book

(NASA-CR-151670) SOLAR POWER SATELLITE SYSTEM DEFINITION STUDY. PART 2, VOLUME 6: EVALUATION DATA BOOK Final Report (Boeing Aerospace Co., Seattle, Wash.) 307 p HC A14/MF A01 CSCL 10A G3/15

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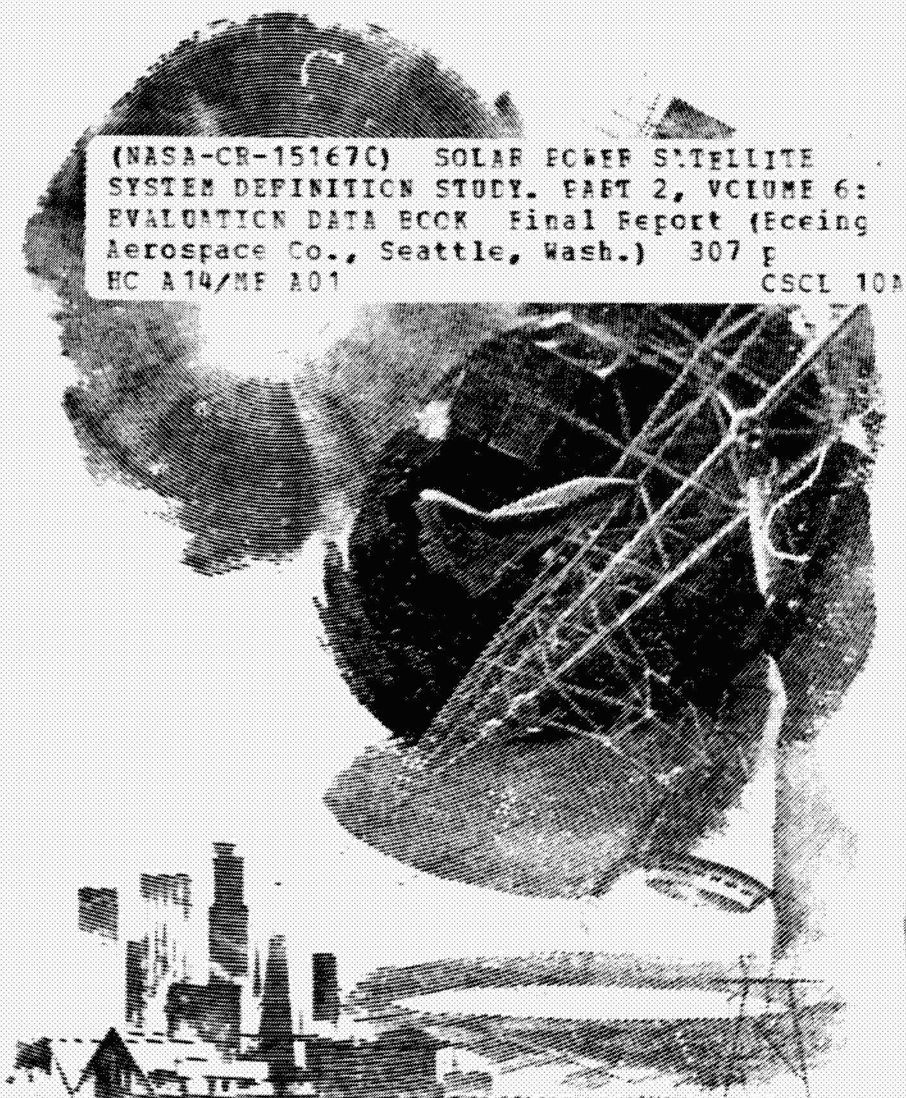

Solar Power Satellite

SYSTEM DEFINITION STUDY
PART II

D180-22876-6

CONTRACT NAS9-15196
DRL T-1346
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LINE ITEM 3

Solar Power Satellite

SYSTEM DEFINITION STUDY
PART II

VOLUME VI
EVALUATION DATA BOOK
D180-22876-6
DECEMBER 1977

Submitted To
The National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
in Fulfillment of the Requirements
of Contract NAS9-15196

Approved:

G. R. Woodcock
Study Manager

BOEING AEROSPACE COMPANY
MISSILES AND SPACE GROUP–SPACE DIVISION
P.O. BOX 3999
SEATTLE, WASHINGTON

D180-22876-6

FOREWORD

The SPS system definition study was initiated in December 1976. Part I was completed on May 1, 1977. Part II technical work was completed October 31, 1977.

The study was managed by the Lyndon B. Johnson Space Center (JSC) of the National Aeronautics and Space Administration (NASA). The Contracting Officer's Representative (COR) was Clarke Covington of JSC. JSC study management team members included:

Dickey Arndt	Microwave System Analysis	Andrei Konradi	Space Radiation Environment
Harold Benson	Cost Analysis	Jim Kelley	Microwave Antenna
Bob Bond	Man-Machine Interface	Don Kessler	Collision Probability
Jim Cioni	Photovoltaic Systems	Lou Leopold	Microwave Generators
Hu Davis	Transportation Systems	Lou Livingston	System Engineering and
R. H. Dietz	Microwave Transmitter and Rectenna	Jim Meany	MPTS Computer Program
		Stu Nachtwey	Microwave Biological Effects
Bill Dusenbury	Energy Conversion	Sam Nassiff	Construction Base
Bob Gundersen	Man-Machine Interface	Bob Ried	Structure and Thermal Analysis
Alva Hardy	Radiation Shielding		
Buddy Heineman	Mass Properties	Jack Seyl	Phase Control
Lyle Jenkins	Space Construction	Bill Simon	Thermal Cycle Systems
Jim Jones	Design	Fred Stebbins	Structural Analysis
Dick Kennedy	Power Distribution		

The study was performed by the Boeing Aerospace Company. The Boeing study manager was Gordon Woodcock. Boeing Commercial Airplane Company assisted in the analysis of launch vehicle noise and overpressures. Boeing technical leaders were:

Ottis Bullock	Structural Design	Don Grim	Electrical Propulsion
Vince Caluori	Photovoltaic SPS's	Henry Hillbrath	Propulsion
Bob Conrad	Mass Properties	Dr. Ted Kramer	Thermal Analysis and Optics
Eldon Davis	Construction and Orbit-to-Orbit Transportation	Frank Kilburg	Alternate Antenna Concepts
		Walt Lund	Microwave Antenna
Rod Darrow	Operations	Keith Miller	Human Factors and Construction Operations
Owen Denman	Microwave Design Integration		
		Dr. Ervin Nalos	Microwave Subsystem
Hal DiRamio	Earth-to-Orbit Transportation	Jack Olson	Configuration Design
		Dr. Henry Oman	Photovoltaics
Bill Emsley	Flight Control	John Perry	Structures
Dr. Joe Gauger	Cost	Scott Rathjen	MPTS Computer Program Development
Jack Gewin	Power Distribution		
Dan Gregory	Thermal Engine SPS's		

The General Electric Company Space Division was the major subcontractor for the study. Their contributions included Rankine cycle power generation, power processing and switchgear, microwave transmitter phase control and alternative transmitter configurations, remote manipulators, and thin-film silicon photovoltaics.

Other subcontractors were Hughes Research Center–gallium arsenide photovoltaics; Varian–klystrons and klystron production; SPIRE–silicon solar cell directed energy annealing.

This report was prepared in 8 volumes as follows:

- I – Executive Summary
- II – Technical Summary
- III – SPS Satellite Systems
- IV – Microwave Power Transmission Systems
- V – Space Operations
- VI – Evaluation Data Book
- VII – Study Part II Final Briefing Book
- VIII – SPS Launch Vehicle Ascent and Entry Sonic Overpressure and Noise Effects

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APPENDICES

ENCLOSURES

D180-22876-6

SPS SYSTEMS DEFINITION STUDY
Part II Final Report
Volume 6
Evaluation Data Book

1.0 INTRODUCTION

This volume has been prepared to provide a permanent record of the actual calculations of mass properties, costs, and uncertainties for the Part II final reference designs. The data are presented with only the necessary amount of exploratory text. The analysts' original notes have been used whenever adequately legible in order to preserve authenticity.

2.0 MASS PROPERTIES

2.1 SILICON PHOTOVOLTAIC REFERENCE SYSTEM

This weight definition and uncertainty notebook for the photovoltaic reference configuration is a supplement to the formal documentation provided in support of the Part II final review.

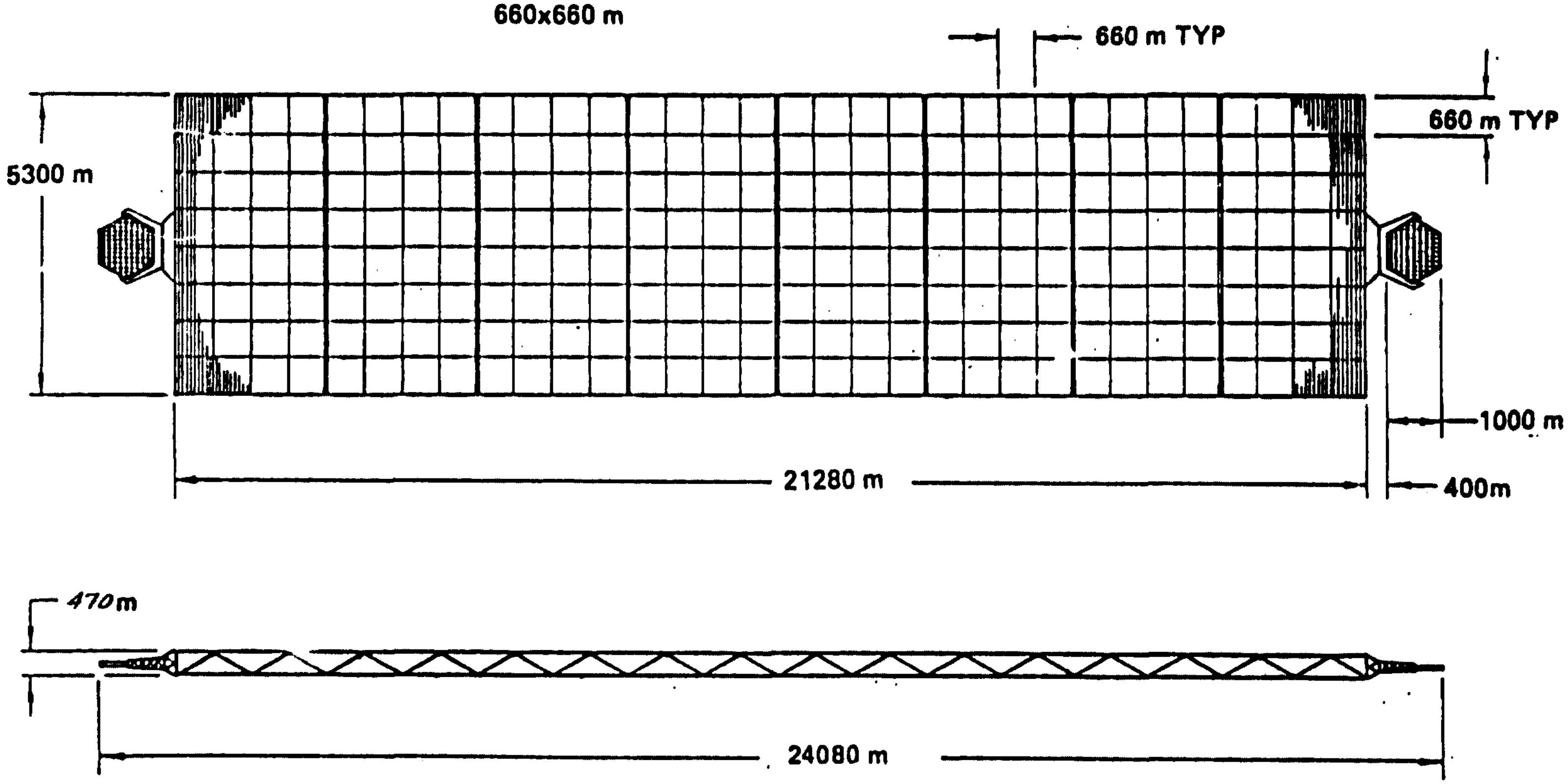
The weight definition part of this notebook provides weight data to a lower level of detail than was presented at the final review. Included in the weight definition are semi-detailed weight summaries, weight calculations, drawings and sketches, and results of weight analysis studies. A preliminary loads and stress analysis for the critical beams in the basic structural frame is also provided.

The weight uncertainty part of this notebook provides the base data pertinent to the establishment of the satellite weight/size tolerance ellipses. Subjects addressed are 1) the variation of satellite weight with array planform area, and 2) the effect of tolerances on the weight of the reference configuration.

Analyst: Bob Conrad

Photovoltaic Reference Configuration

SPS-1004



TOTAL SOLAR CELL AREA: 97.34 Km^2
TOTAL ARRAY AREA: 102.51 Km^2
TOTAL SATELLITE AREA: 112.78 Km^2
OUTPUT: 16.43 GW MINIMUM. TO SLIPRINGS

2.1.1 SUMMARY WEIGHT STATEMENT
(WEIGHT IN KILOGRAMS)

2.1.1-1.0	SOLAR ENERGY COLLECTION SYSTEM		51,782,300
2.1.1-1.1	PRIMARY STRUCTURE	5,385,000	
2.1.1-1.2	SECONDARY STRUCTURE	▷1	
2.1.1-1.3	MECHANICAL ROTARY JOINT	66,800	
2.1.1-1.4	MAINTENANCE STATION	—	
2.1.1-1.5	CONTROL	178,100	
2.1.1-1.6	INSTRUMENTATION/COMMUNICATIONS	4,000	
2.1.1-1.7	SOLAR CELL BLANKETS	43,750,000	
2.1.1-1.8	SOLAR CONCENTRATORS	—	
2.1.1-1.9	POWER DISTRIBUTION	2,398,400	
2.1.1-2.0	MICROWAVE POWER TRANSMISSION SYSTEM		25,212,200
	(TOTAL - LESS GROWTH)		(76,994,500)
2.1.1-3.0	WEIGHT GROWTH ALLOWANCE ~ 26.6%		20,505,500
	(TOTAL - WITH GROWTH)		(97,500,000)

▷1 DISTRIBUTED TO OTHER WBS ITEMS.

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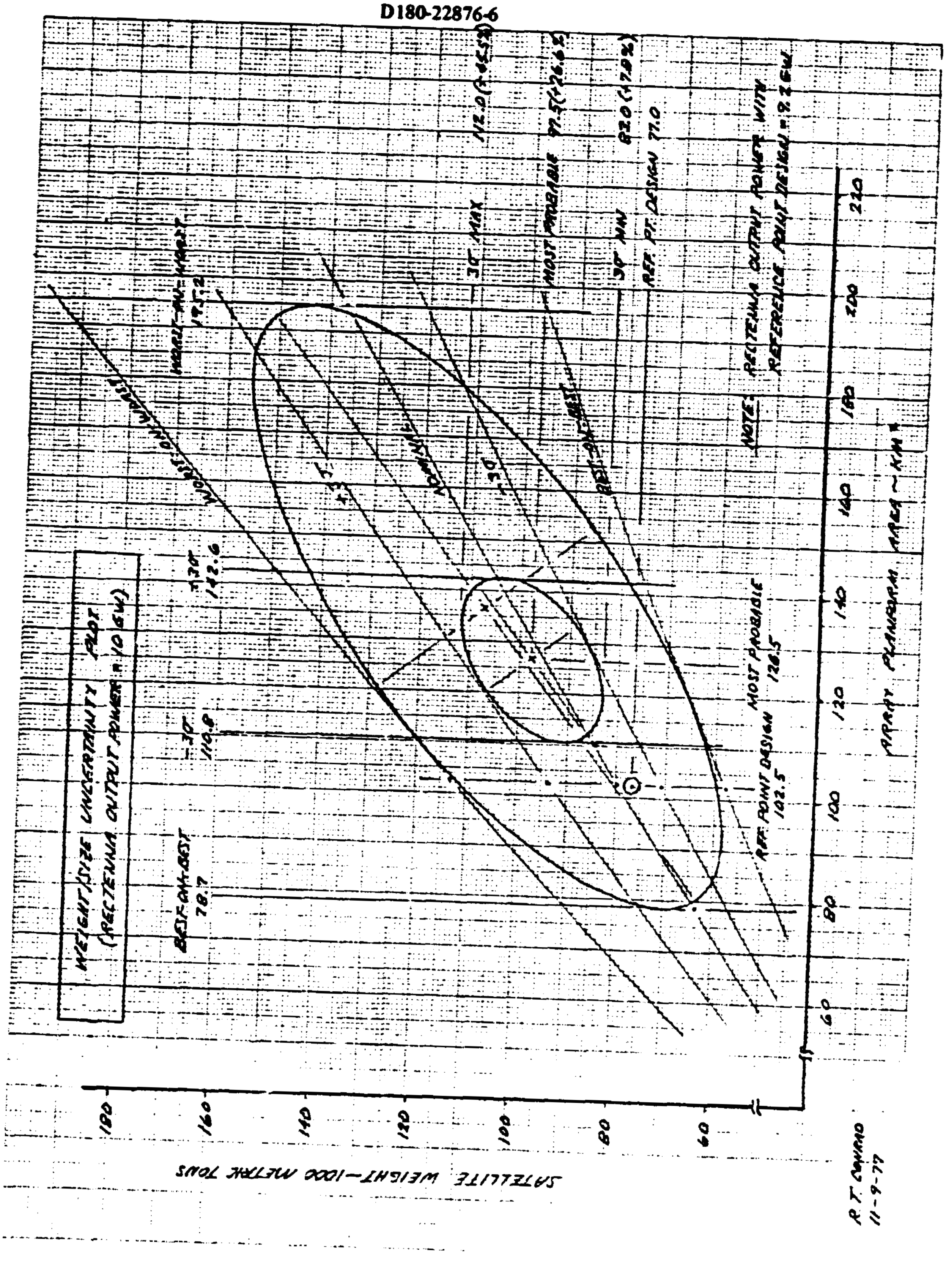

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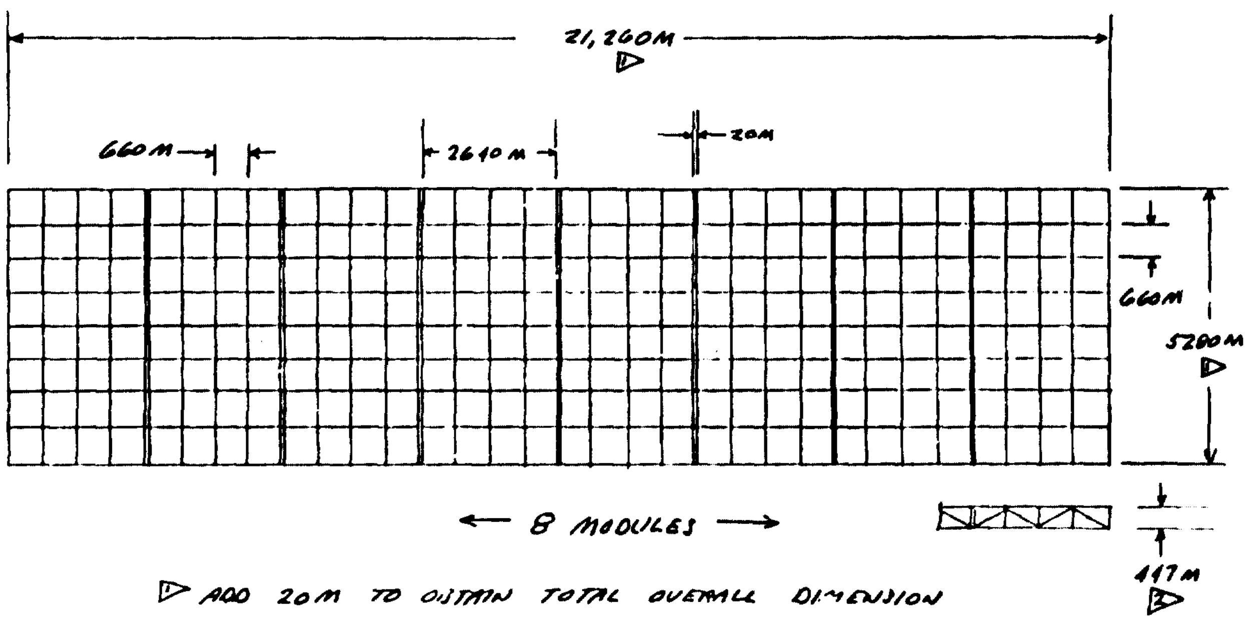
2.1.1 - 1.1 PRIMARY STRUCTURE 5,385,000 kg

MODULE NO. 1				755,400
BASIC FRAME			636,700	
20M BEAMS		604,730		
TENSION CABLES		1,680		
ASSEMBLY ALLOWANCE ~ 5%		30,290		
DOCKING PROVISIONS (18 PLACES)			4,500	
ANTENNA SUPPORT STRUCTURE			53,000	
EXTERNAL FRAME		43,000		
20M BEAMS	40,900			
ASSEMBLY ALLOWANCE ~ 5%	2,100			
ADDITIONS TO MODULE FRAME		10,000		
ROTARY JOINT			▷	
ANTENNA YOKE STRUCTURE			41,200	
FRAME		36,200		
5M BEAMS	34,500			
ASSEMBLY ALLOWANCE ~ 5%	1,700			
ROTATION JOINTS/PITCH CONTROLS		5,000		
ANTENNA SUPPORT STRUCTURE (LEO-TO-GEO)			20,000	
MODULE NO. 2				645,700
BASIC FRAME			636,700	
20M BEAMS		604,730		
TENSION CABLES		1,680		
ASSEMBLY ALLOWANCE ~ 5%		30,290		
DOCKING PROVISIONS (36 PLACES)			9,000	
MODULE NO. 3				645,700
MODULE NO. 4				645,700
MODULE NO. 5				645,700
MODULE NO. 6				645,700
MODULE NO. 7				645,700
MODULE NO. 8				755,400

▷ INCLUDED ELSEWHERE IN WEIGHT STATEMENT UNDER "MECHANICAL ROTARY JOINT" AND "ELECTRICAL ROTARY JOINT."

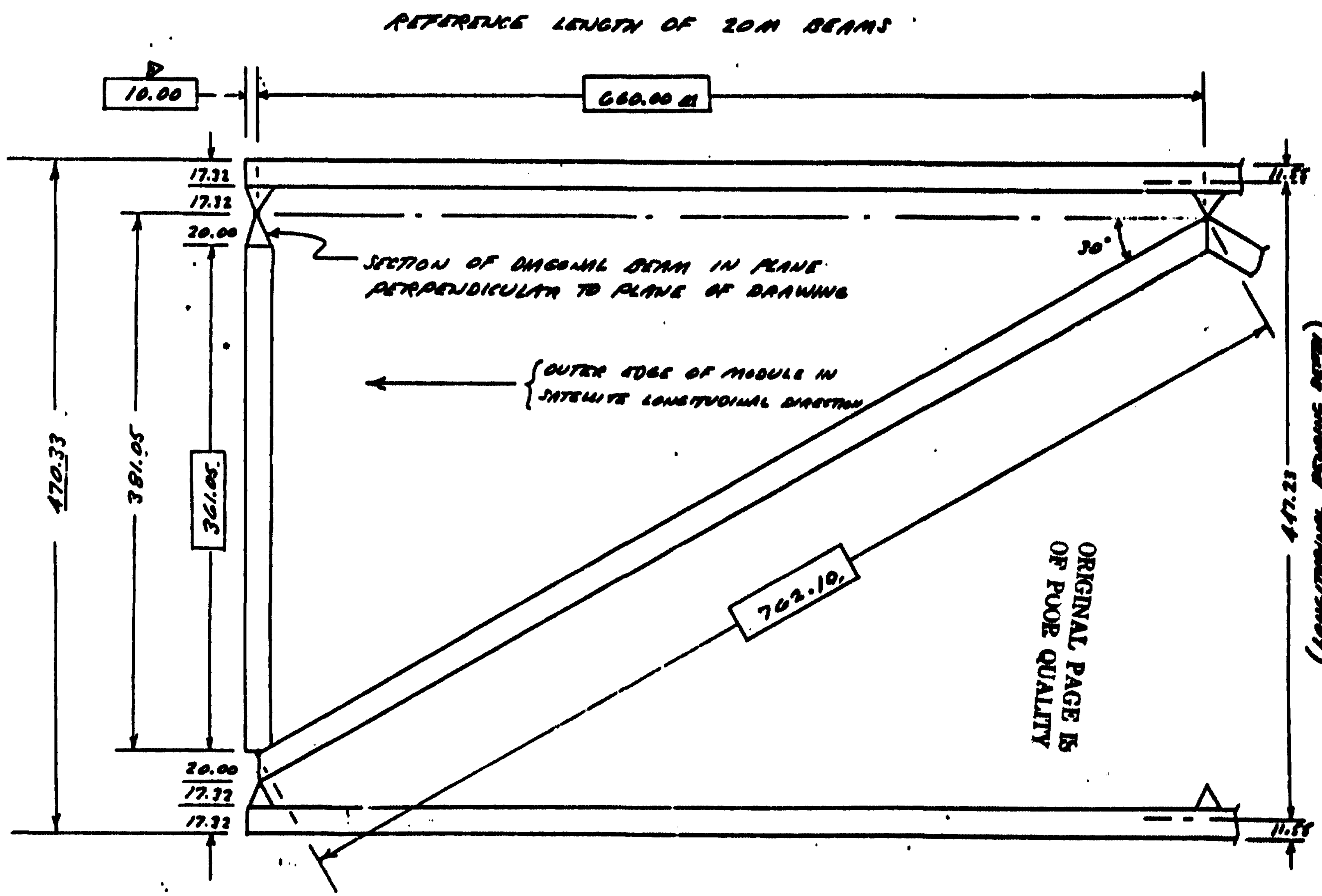
REFERENCE CONFIGURATION
(ALL DIMENSIONS ARE BEAM ℄ TO BEAM ℄)



1 ADD 20M TO OBTAIN TOTAL OVERALL DIMENSION

2 ADD 23M TO OBTAIN TOTAL OVERALL DIMENSION

STRUCTURAL PLANFORM AREA = 112.25 km^2



▷ DELTA LENGTH AT EDGE. (28 PLACES/SURFACE/MODULE, INCLUDING 2 PLACES/CORNER/SURFACE)

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20M BEAMS (PER MODULE) 604,730 Kg

LOCATION/BEAMS	▷ LENGTH OF BEAM PER MODULE (M)	▷ UNIT WT. OF BEAM (kg/m)	WT. OF BEAM PER MODULE (kg)
UPR. SURFACE/LONGITUDINALS	(9×4)×660 = 23,760	4.24	100,742
" " /LATERALS	(5×8)×660 = 26,400	"	111,936
" " /EDGE DELTAS	(28)×10 = 280	"	1,187
	(50,440)		(213,865)
LWR. SURFACE/LONGITUDINALS	(9×4)×660 = 23,760	3.34	79,358
" " /LATERALS	(5×8)×660 = 26,400	"	88,176
" " /EDGE DELTAS	(28)×10 = 280	"	935
INTRA SURF./LONG. DIAGONALS	(9×4)×762.1 = 27,436	"	91,636
" " /LATERAL DIAGONALS	(5×8)×762.1 = 30,484	"	101,816
" " /VERTICALS ▷	(24)×361.1 = 8666	"	28,944
	(117,026)		(390,865)
TOTAL - PER MODULE	167,466	—	604,730

▷ SEE SKETCH (PREVIOUS PAGE) FOR REFERENCE BEAM LENGTHS.

▷ SEE 20M BEAM WEIGHT ANALYSIS FOR DETAILS. (APPENDIX D)

▷ LOCATED AROUND PERIPHERY OF MODULE ONLY.

KEVLAR TENSION CABLES (PER MODULE) 1680. kg

"X" CABLES IN LOWER SURFACE PERIPHERAL BAYS.

DATA PER CABLE:

$$L = (660-20)/\sin 45° = 905 \text{ m}$$

$$D = 6.3 \text{ mm} = 0.0063 \text{ m}$$

$$V_{KEVLAR} = \frac{\pi}{4} D^2 L$$

$$= \frac{\pi}{4}(0.0063)^2(905) = 0.028 \text{ m}^3$$

$$W_{KEVLAR} = \rho V$$

$$= (1400 \text{ kg/m}^3)(0.028 \text{ m}^3)$$

$$= 39 \text{ kg}$$

$W_{\text{END FITTINGS, TURNBUCKLES, CONSTANT FORCE SPRINGS, ETC}} = 3$ kg

} 42 kg/CABLE

CABLE WT. PER MODULE = (42 kg/CABLE)(2 CABLES/BAY)(20 BAYS)

= 1680 kg

DOCKING PROVISIONS (PER LONGITUDINAL BEAM END) 250 kg

DOCKING PROVISIONS REQUIRED AT EACH BREAK IN EACH LONGITUDINAL BEAM (UPPER AND LOWER SURFACE).
18 PLACES PER END MODULE.
36 PLACES PER INTERMEDIATE MODULE.
ESTIMATE 250 kg OF DOCKING PROVISIONS ON EACH SIDE OF A BREAK IN A LONGITUDINAL BEAM.

<u>ANTENNA SUPPORT STRUCTURE</u> (PER ANTENNA) 53,000 kg

REF: SPS-LO-48 AND ISOMETRIC SKETCH ON NEXT PAGE

ALL BEAMS ARE 20 M BEAMS @ 4.24 kg/m [1]

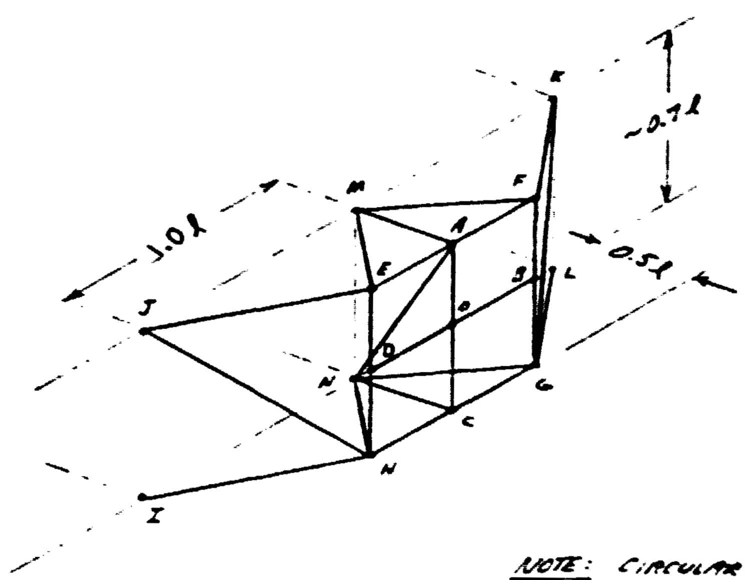
TOTAL LENGTH OF BEAM = 14.62 [2] x 660 M = 9649 M

EXTERNAL SUPPORT FRAME		43,000
20 M BEAMS	40,900	
ASSEMBLY ALLOWANCE ~5%	2,100	
ADDITIONS/CHANGES TO MODULE STRUCTURE		10,000 (EST)
TOTAL - PER ANTENNA		53,000 kg

[1] SAME 20 M BEAM AS USED ON UPPER SURFACE OF TRUSS STRUCTURE.

[2] SEE TABLE ON NEXT PAGE.

ANTENNA SUPPORT STRUCTURE
(EXTERNAL SUPPORT FRAME)



NOTE: CIRCULAR BEAM SHOWN ON SPS-LO-48 IS CONSIDERED PART OF "MECHANICAL ROTARY JOINT".

BEAM	LENGTH
EAF	1.00ℓ
DOB	"
NCG	"
EDH	0.70ℓ
FBG	"
AO	0.35ℓ
OC	"
EJ	0.71ℓ
EM	"
FM	"
FK	"
HI	"
HN	"
GN	"
GL	"
MA	0.50ℓ
NC	"
JH	0.99ℓ
KG	"
AN	0.86ℓ

TOTAL LENGTH OF BEAM = 14.62ℓ

ANTENNA YOKE STRUCTURE (PER ANTENNA) 41,200 kg

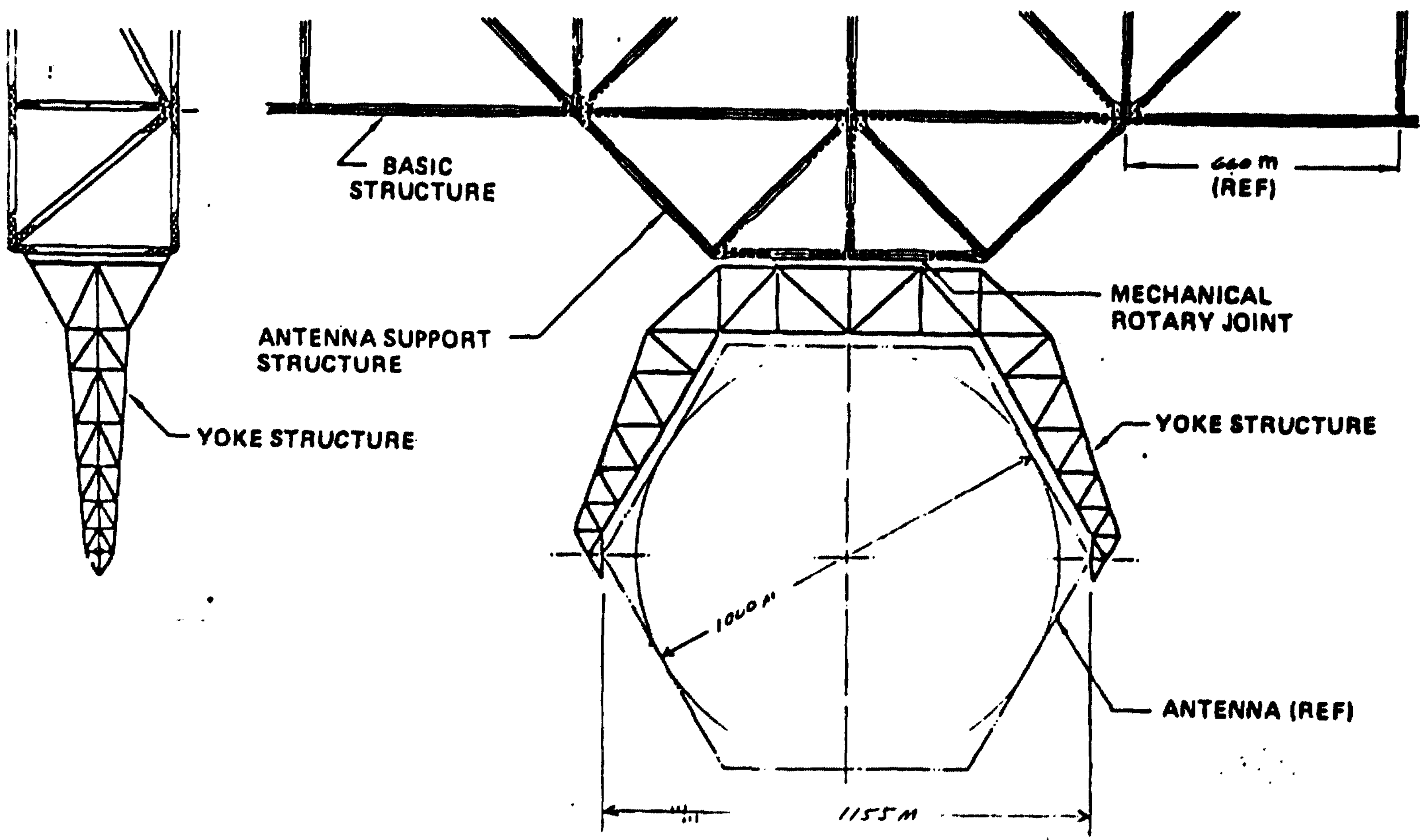
REF: SPS-20-98 AND ATTACHED DRAWING AND ISOMETRIC SKETCHES

ALL BEAMS ARE 5M BEAMS @ 1.61 kg/m [1]

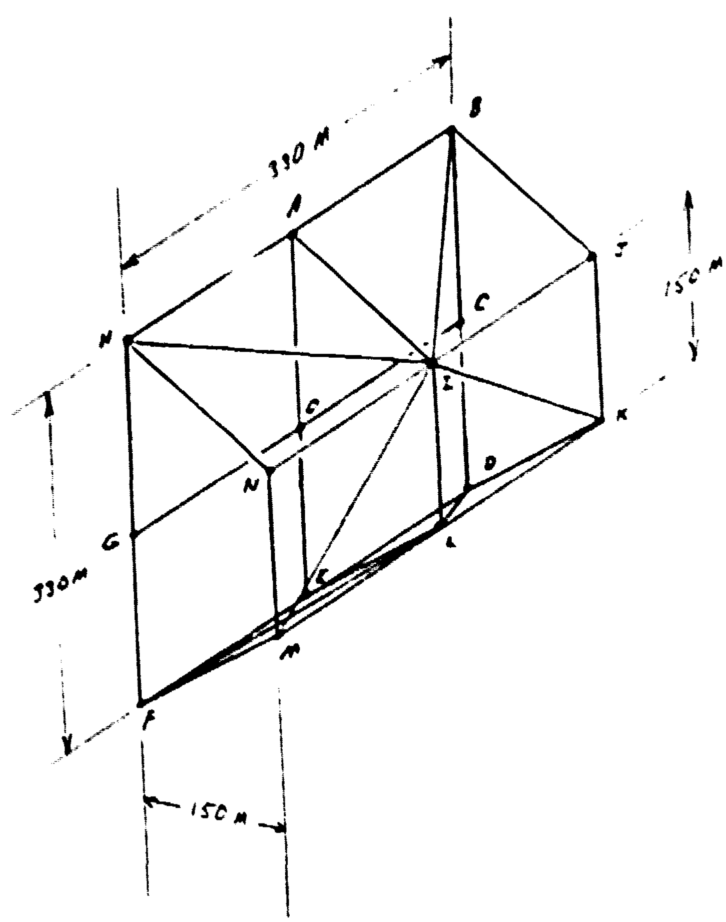
FRAME:		36,200
CENTER SECTION (5774 m) [2]	9296	
SIDE SECTION - RH (2732 m) [2]	4398	
SIDE SECTION - LH (2732 m) [2]	4398	
ARM SECTION - RH (5085 m) [2]	8187	
ARM SECTION - LH (5085 m) [2]	8187	
ASSEMBLY ALLOWANCE ~5%	1734	
ROTATION JOINTS (2):		5000 (EST.)
TOTAL - PER ANTENNA		41,200 kg

[1] SEE 5M BEAM WEIGHT ANALYSIS (APPENDIX D) FOR DETAILS.

[2] DETAILS ON FOLLOWING PAGES.


BASIC STRUCTURE
660 m (REF)
ANTENNA SUPPORT STRUCTURE
MECHANICAL ROTARY JOINT
YOKE STRUCTURE
YOKE STRUCTURE
1000 m
ANTENNA (REF)
1155 M

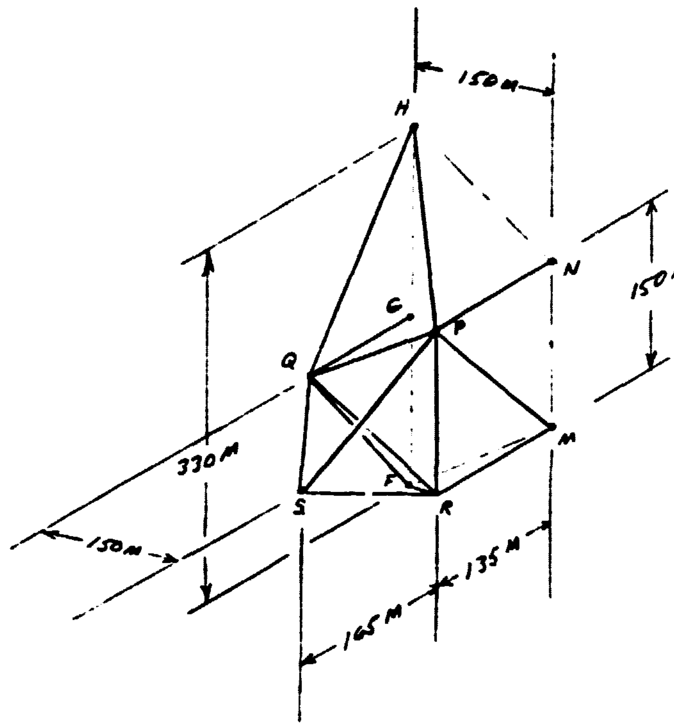
ANTENNA YOKE STRUCTURE
(CENTER SECTION)



JOINTS IN REAR PLANE: OABCDEFGH

JOINTS IN FRONT PLANE: IJKLMN

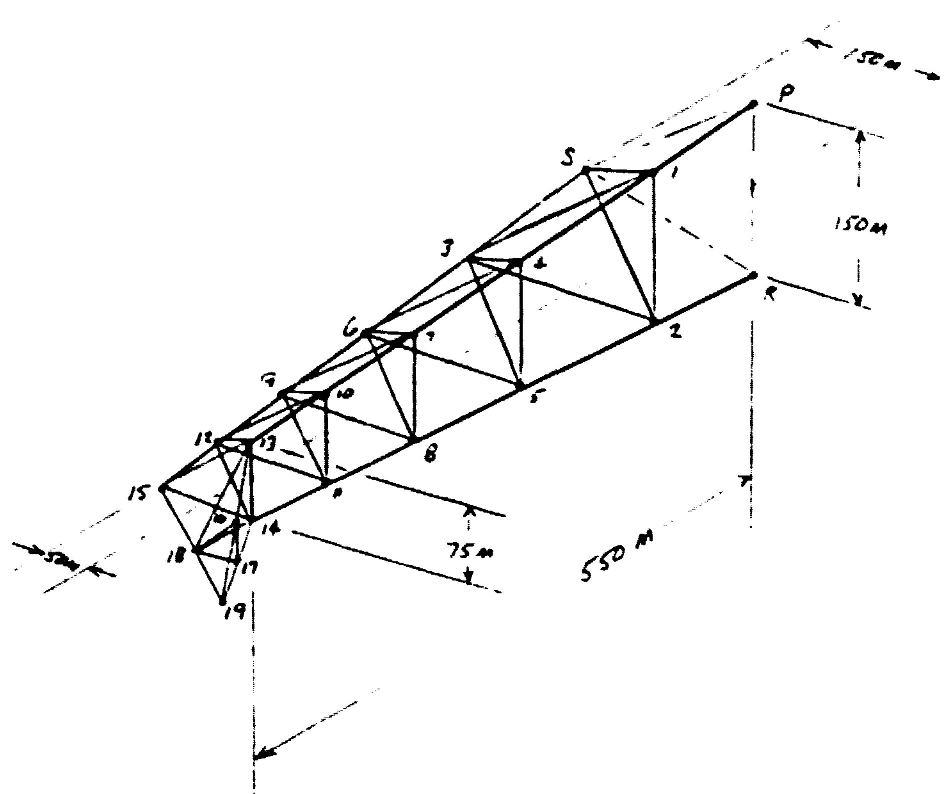
ANTENNA YOKE STRUCTURE
(SIDE SECTION-RH)



JOINTS IN REAR PLANE: HGFQ

JOINTS IN FRONT PLANE: MNPRS

ANTENNA YOKE STRUCTURE
(ARM SECTION-RH)



JOINTS IN REAR PLANE: S, 3, 6, 9, 12, 15

JOINTS IN FRONT PLANE: P, R, 1, 2, 4, 5, 7, 8, 10, 11, 13, 14, 18

ANTENNA YOKE STRUCTURE (CONT'D)

LOCATION/BEAM	LENGTH OF BEAM (m)
CENTER SECTION:*	
BEAM HAB	330
GOC	"
FED	"
HGF	"
BCD	"
AO	165
DE	"
NIJ	330
MLK	"
NM	150
IL	"
JK	"
MI	223
KI	"
HN	175
AI	"
BJ	"
FN	"
EL	"
DK	"
HI	297
BI	"
FL	"
DL	"
	(5774 m)

ANTENNA YOKE STRUCTURE (CONT'D)

LOCATION / BEAM	LENGTH OF BEAM (M)
SIDE SECTION - RH: *	
BEAM GO	135
HQ	213
FQ	"
NP	135
MR	"
PR	150
MP	202
PS	181
RS	"
PQ	168
RQ	"
SO	223
PH	314
RF	"
	(2732 M)

ANTENNA YOKE STRUCTURE (CONT'D)

LOCATION / BEAM	LENGTH OF BEAM (m)
ARM SECTION – RH: *	
BEAM P-1-4-7-10-13	550
R-2-5-8-11-14	"
1-2	130
4-5	110
7-8	95
10-11	85
13-14	75
13-18	70
14-18	"
S-3-6-9-12-15	500
S-1	163
S-2	"
1-3	163
2-3	"
3-4	160
3-5	"
4-6	132
5-6	"
6-7	129
6-8	"
7-9	111
8-9	"
9-10	109
9-11	"
10-12	86
11-12	"
12-13	84
12-14	"
13-15	79
14-15	"
13-16-19	107
14-17-19	"
16-17	38
16-18	40
17-18	"
	(5085 m)

2 1.1 - 1.2 SECONDARY STRUCTURE

DISTRIBUTED TO OTHER WBS ITEMS.

2.1.1-1.3 MECHANICAL ROTARY JOINT (1) 33,400 kg

CIRCULAR RING BEAMS (2)		9640
RING BEAMS (2)	8790	
TENSION CABLES (24)	250	
BEAM INSTALLATION PROVISIONS	600	
DRIVE RING		18,380
ROLLER ASSEMBLIES (48)		670
ASSEMBLY FITTINGS (48)	550	
GUIDE WHEEL INSTALLATIONS (192)	120	
ROLLER/DRIVE ASSEMBLIES (12)		950
ASSEMBLY FITTINGS (12)	550	
GUIDE WHEEL INSTALLATIONS (24)	60	
DRIVE WHEEL INSTALLATIONS (24)	40	
D.C. DRIVE MOTORS, MOUNTS (12)	240	
SPRING INSTALLATIONS-DRIVE WHEELS (12)	60	
SUPPORT FITTINGS (120)		600
DRIVE RING SUPPORT FTG (60)	300	
ROLLER ASSEMBLY SUPPORT FTG (48)	240	
ROLLER/DRIVE ASSY SUPPORT FTG (12)	60	
ASSEMBLY & INSTALLATION HARDWARE		160
CONTINGENCY ~ 10%		3000

CIRCULAR RING BEAM (PER RING) — 4395 kg

REF: ATTACHED SKETCH

USE A BEAM WITH A WEIGHT OF 4.0 kg/METER.

$$W_{RING\ BEAM} = (\pi\ D_{MEAN}) \times 4.0\ kg/m$$

$$= (\pi \times 350\ m) \times 4.0\ kg/m$$

$$= 4395\ kg$$

TENSION CABLE (PER CABLE) — 10.5 kg

REF: ATTACHED SKETCH

DATA PER CABLE:

$L = 170\ m$

$D = 6.3\ mm = 0.0063\ m$

$$V_{KEVLAR} = \frac{\pi}{4} D^2 L$$

$$= \frac{\pi}{4} (0.0063)^2 (170) = 0.0053\ m^3$$

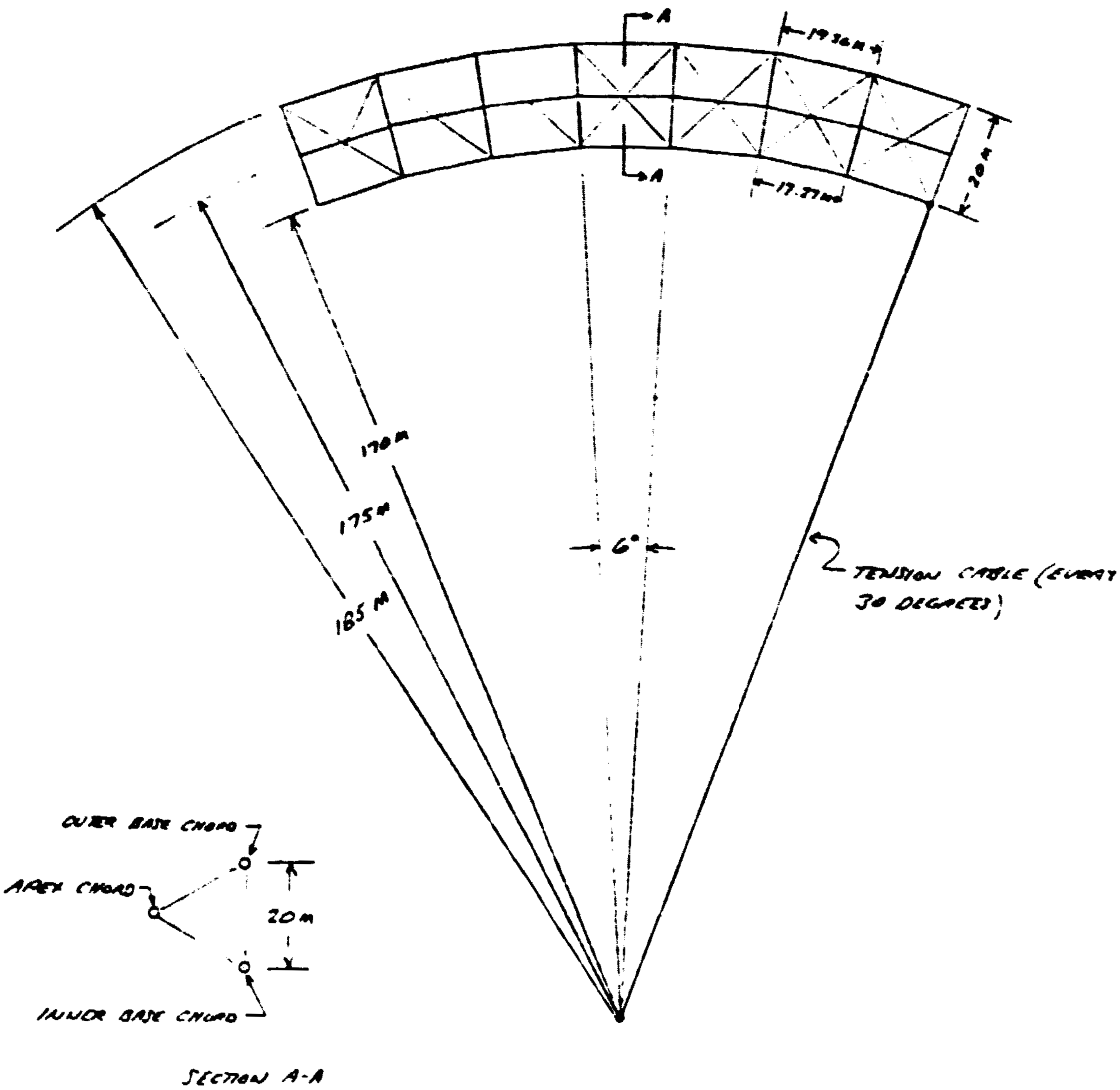
$$W_{KEVLAR} = \rho V$$

$$= (1400\ kg/m^3)(0.0053\ m^3) = 7.5\ kg$$

$W_{END\ FITTINGS,\ TURNBUCKLE,\ CONSTANT\ FORCE\ SPRING,\ INSTALLATION\ PROVISIONS} = 3.0\ kg$

(Total: 10.5 kg)

CIRCULAR RING BEAM GEOMETRY



DRIVE RING — 18,380 kg

REF: ATTACHED SKETCHES

USE SEGMENTED RING OF GRAPHITE/EPOXY

RING X-AREA = 16.2 IN² = 0.01045 m²

$W_{RING} = \pi D A \rho \times k_{JOINTS}$

$= \pi (350\ m)(0.01045\ m^2)(1600\ kg/m^3) \times 1.05$

$= 18,380\ kg$

ROLLER ASSEMBLY (PER ASSEMBLY) — 14 kg

REF: ATTACHED SKETCH

a. ASSEMBLY FITTING

USE ALUMINUM FITTING
X-AREA = 28 IN² = 0.01806 m²
LENGTH = 9" - 0.23 m

$W_{FITTING} = A L \rho$

$= (0.01806\ m^2)(0.23\ m)(2770\ kg/m^3) = 11.5\ kg$

b. GUIDE WHEELS

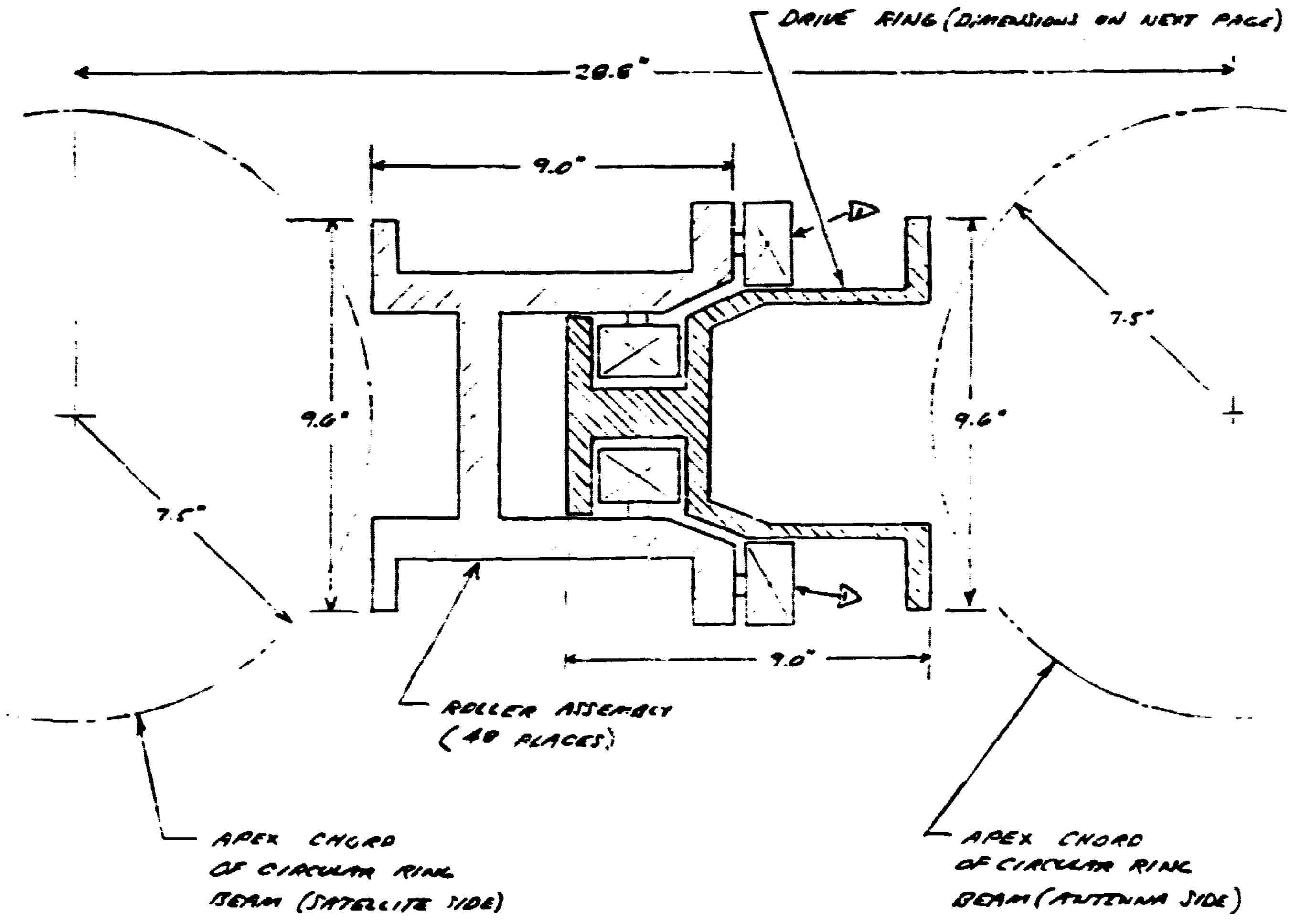
USE STEEL WHEELS/SHAFTS/BEARINGS, ETS
WHEEL DIA = 2 IN = 5.1 CM
WHEEL WIDTH = 1.25 IN = 3.2 CM
SHAFT DIA = 0.5 IN = 1.3 CM
SHAFT LENGTH = 3.0 IN = 7.6 CM
} VOL = 4.5 IN³ = 0.000074 m³

$W_{GUIDE\ WHEELS} = \rho V \times 4$ PER FTG

$= (8000\ kg/m^3)(0.000074\ m^3) \times 4$

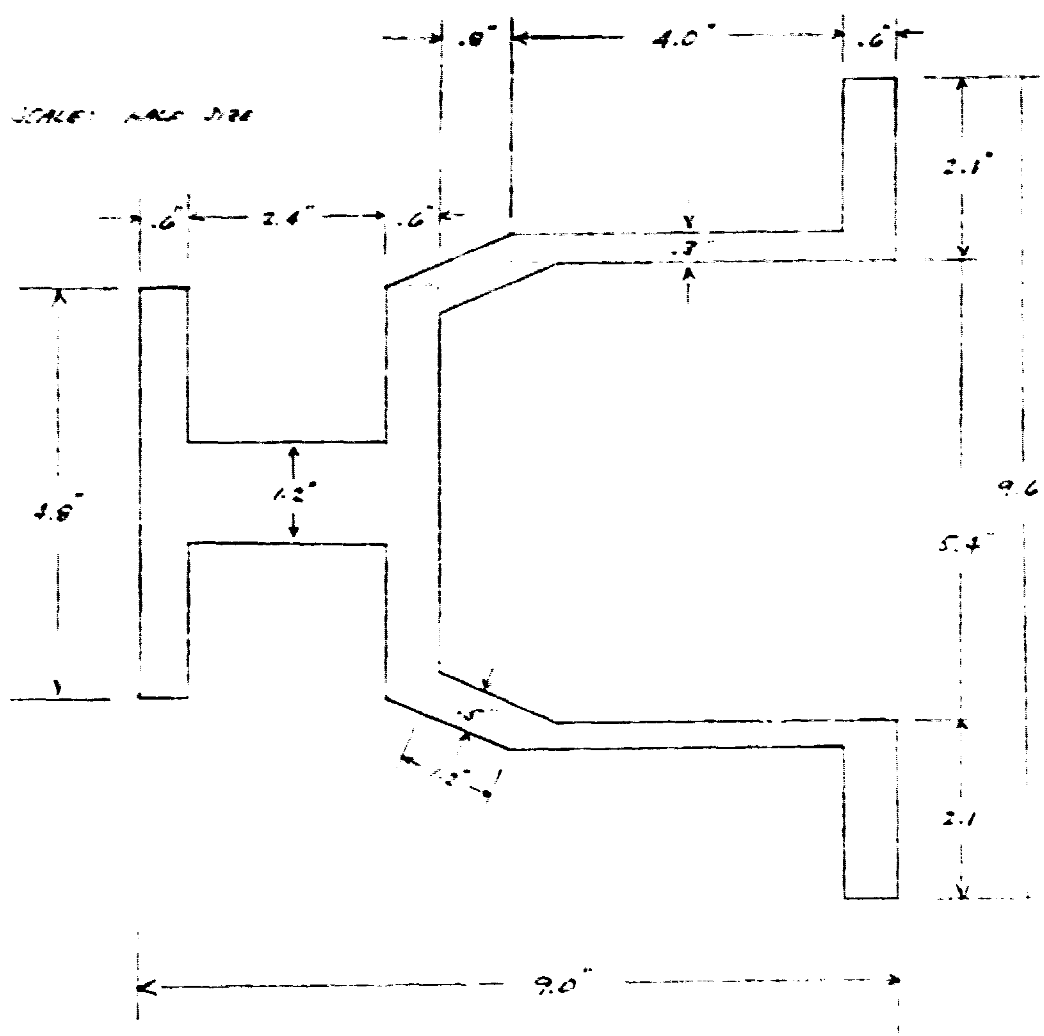
$= 0.6 \times 4 \approx 2.5\ kg$

DRIVE RING AND ROLLER ASSEMBLY
LOCATION RELATIVE TO OUTER BASE
CHORDS OF CIRCULAR RING BEAMS



▷ A ROLLER/DRIVE ASSEMBLY IS LOCATED AT 12 PLACES (EVERY TENSION CABLE) AROUND THE PERIPHERY OF THE CIRCULAR BEAM (SATELLITE SIDE). THIS ASSEMBLY IS SIMILAR TO THAT SHOWN EXCEPT THAT THE WHEELS INDICATED BY FLAG ▷ ARE MOTOR DRIVEN FRICTION WHEELS WHICH ARE SPRING LOADED ACROSS THE ASSEMBLY.

DRIVE RING GEOMETRY



CROSS SECTION AREA = [(4.8 × .6) + (2.4 × 1.2) + (4.8 [illegible]) + 2(1.2 × .5) + 2(4.0 × .3) + 2(2.1 × .6)] 1.10 = 16.2 in²

TOLERANCES & FILLETS (1.10)

2.1.1- 1.4 MAINTENANCE STATION

NOT APPLICABLE

2.1.1-1.5 CONTROL 178,100 kg

THRUST PRODUCTION EQUIPMENT	23,300	*
POWER PROCESSORS	90,000	
INSTALLATION HARDWARE	16,800	
(TOTAL DRY WEIGHT)	(130,100)	
ANNUAL PROPELLANT (ARGON)	48,000	
(1-YEAR TOTAL)	(178,100)	

* ESTIMATES PER G. WOODCOCK

2.1.1-1.6 INSTRUMENTATION/COMMUNICATIONS 4000 kg

USE THE JSC "GREEN BOOK" VALUE OF 4000 kg

2.1.1-1.7 SOLAR CELL BLANKETS 43,750,000 kg

SOLAR CELL PANELS		43,191,350
COVER GLASS - FUSED SILICA	16,987,940	
CELLS - SILICON	11,670,850	
INTERCONNECTS - COPPER	1,150,160	
SUBSTRATE - FUSED SILICA	11,325,290	
TOLERANCES ALLOWANCE (5%)	2,057,110	
JOINT/SUPPORT TAPES		300,360
CATENARY STYSTEM		258,290

PHOTOVOLTAIC BLANKET WEIGHT BUILDUP

ITEM	DENSITY (S.G.)	DENSITY (g/m²/mil)	THICKNESS (mils)	AREA FACTOR	WEIGHT (g/m²)
COVERS - FUSED SILICA	2.20	55.88	3.0	1.0	167.64
CELLS - SILICON	2.36	57.94	2.0	0.4607	115.17
INTERCONNECTS - COPPER	8.94	227.08	0.5	0.100	11.35
SUBSTRATE - FUSED SILICA	2.20	55.88	2.0	1.0	111.76

THEORETICAL PANEL WEIGHT	405.92
TOLERANCES ALLOWANCE (5%)	20.30
ESTIMATED PANEL WEIGHT	426.22
PANEL AREA FACTOR (.9913)	422.51
SEGMENTS AREA FACTOR (.9978)	421.33
JOINT/SUPPORT TAPES	2.93
CATENARY SYSTEM	2.52
ESTIMATED ARRAY WEIGHT	426.78

CELL AREA = 380,264 m²/BAY

PANEL AREA = 395,843 m²/BAY

ARRAY AREA = 400,474 m²/BAY

NO. OF BAYS = 256

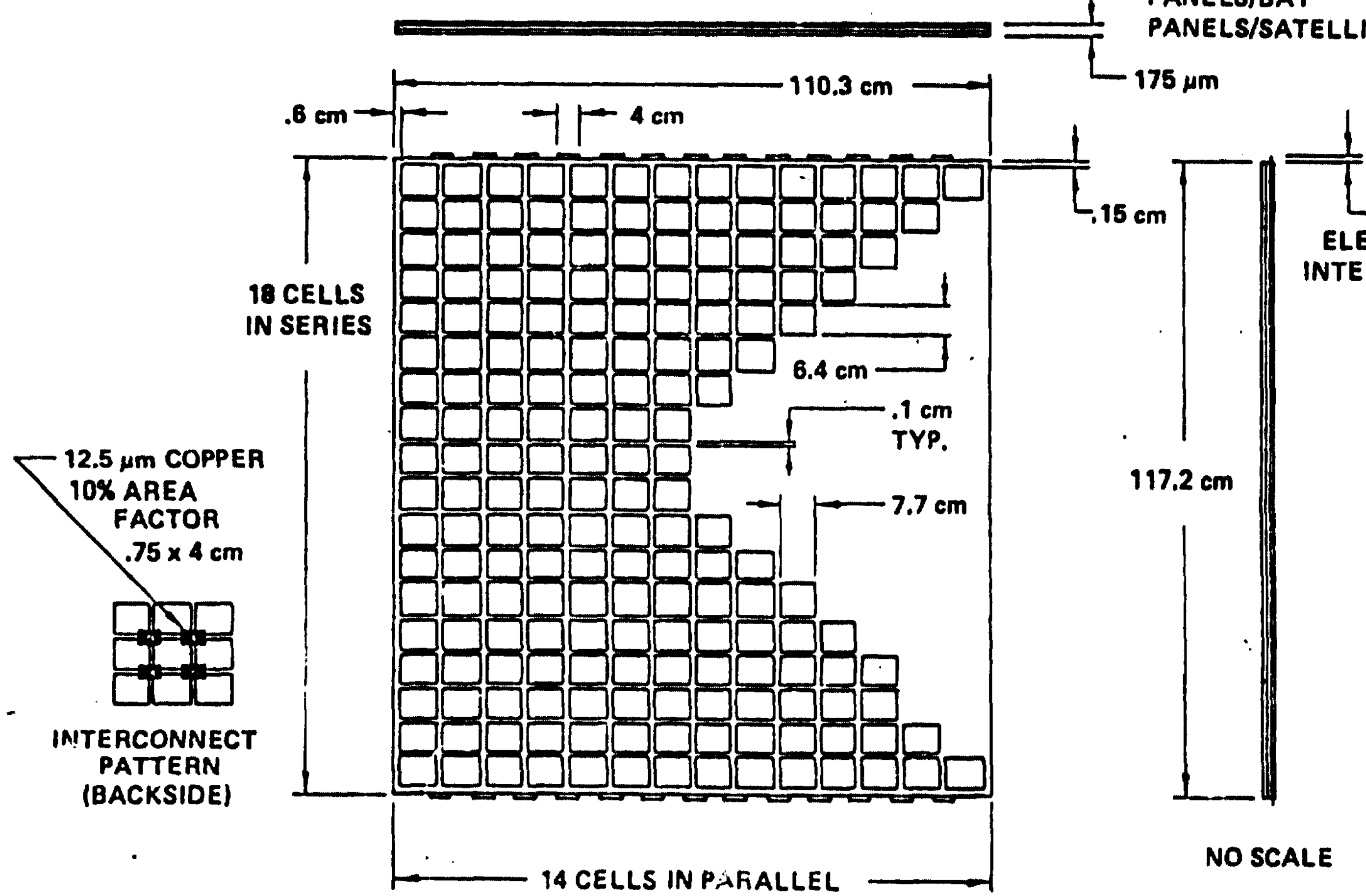
Photovoltaic Reference Configuration
Solar Array Fundamental Element
"Blanket Panel"

BOEING

SPS-1390

- 14 CELLS IN PARALLEL WILL TOLERATE 4 CELL FAILURES IN ANY ROW

# CELLS/PANEL	: 252
WGT/PANEL	: 426 GRAMS
PANELS/BAY	: 306,206
PANELS/SATELLITE	: 78,388,736

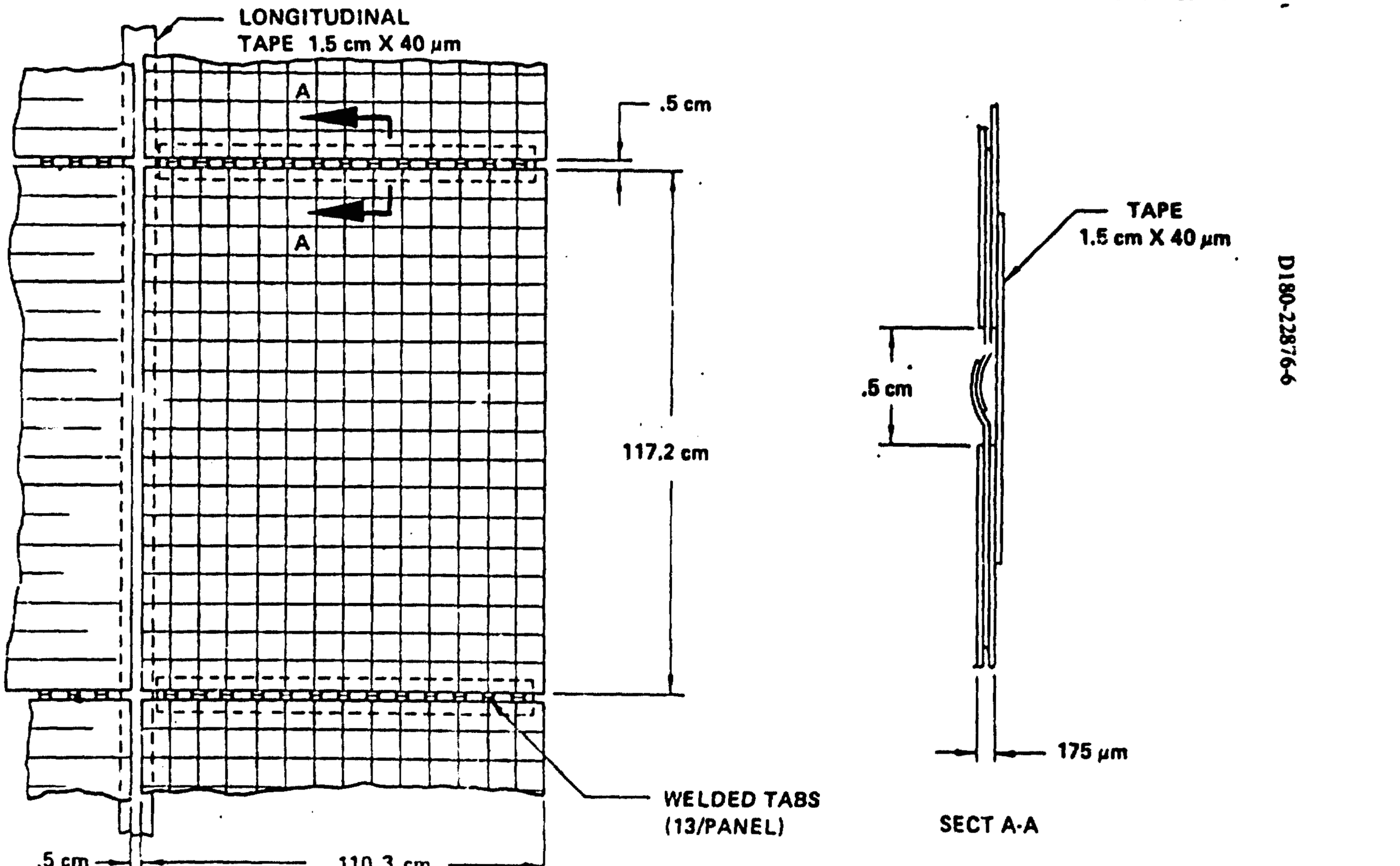


D180-22876-6

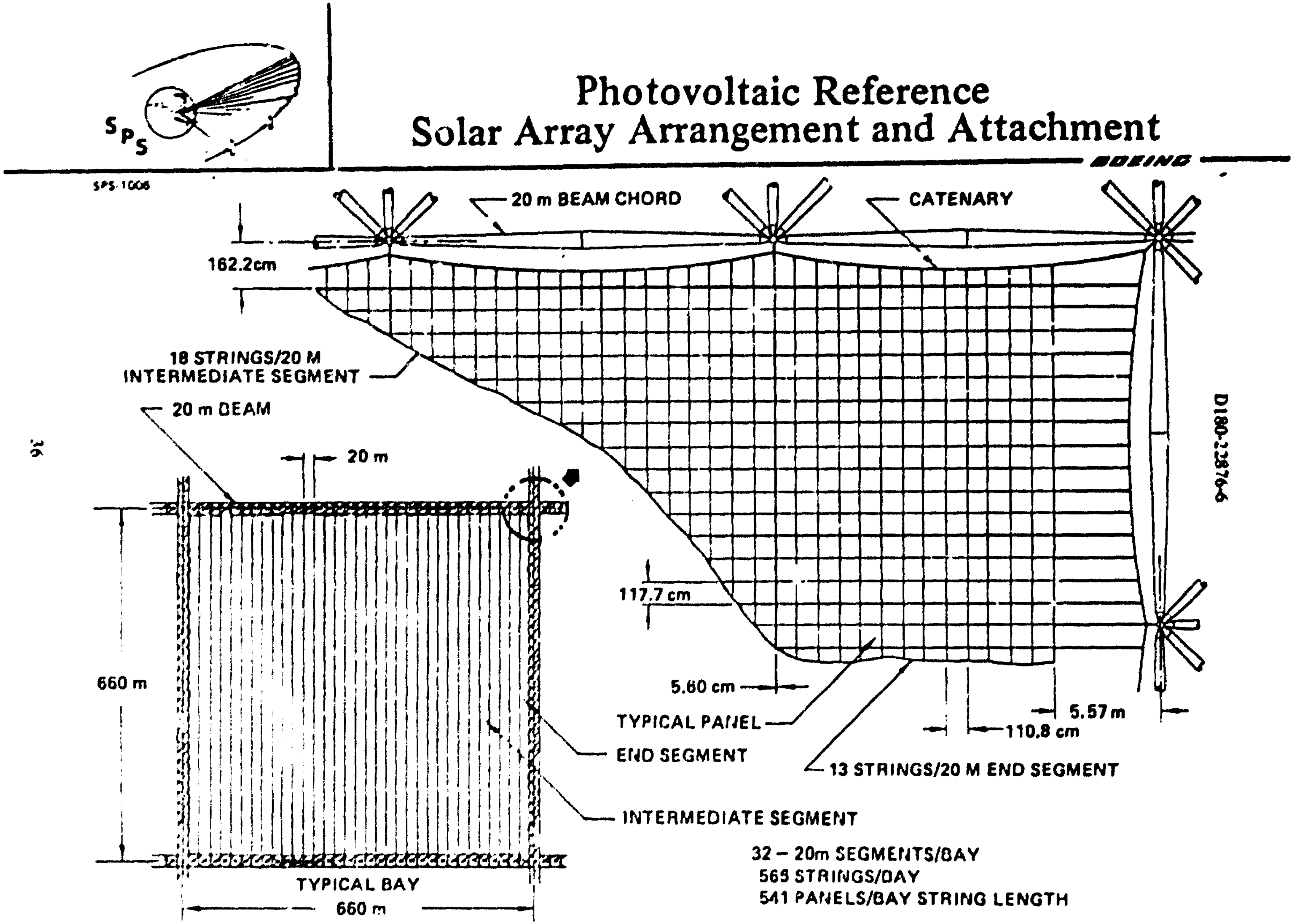
Photovoltaic Reference Panel to Array Assembly

BOEING

SPS-1391



Photovoltaic Reference Solar Array Arrangement and Attachment

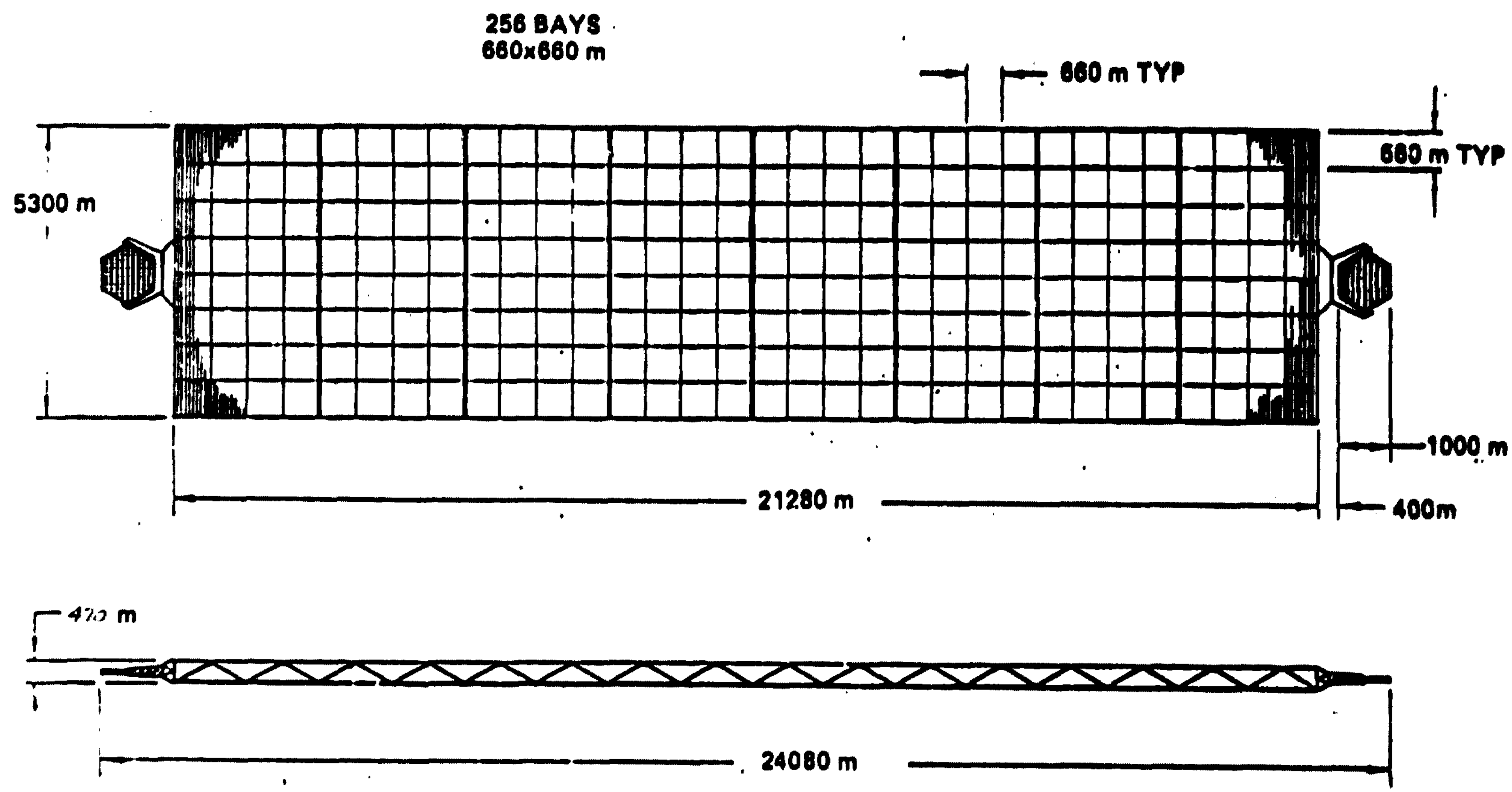


D180-22876-6

36

Photovoltaic Reference Configuration

SPS-1004



TOTAL SOLAR CELL AREA: 97.34 Km^2
TOTAL ARRAY AREA: 102.51 Km^2
TOTAL SATELLITE AREA: 112.78 Km^2
OUTPUT: 16.43 GW MINIMUM TO SLIPRINGS

D180-22876-6

AREA FACTORS

$$\text{SOLAR CELL AREA FACTOR (PER PANEL)} = \frac{\text{AREA OF 252 SOLAR CELLS}}{\text{AREA OF 1 PANEL (LESS INTERCONNECTS)}}$$

$$= \frac{252\,(6.40\text{ cm} \times 7.70\text{ cm})}{117.2\text{ cm} \times 110.3\text{ cm}} = 0.96066$$

$$\text{PANEL AREA FACTOR} = \frac{\text{AREA OF 1 PANEL (LESS INTERCONNECTS)}}{\text{AREA OF 1 PANEL (INSTALLED)}}$$

$$= \frac{117.2\text{ cm} \times 110.3\text{ cm}}{117.7\text{ cm} \times 110.8\text{ cm}} = 0.99126$$

$$\text{20m SEGMENT AREA FACTOR} = \frac{\text{AREA OF 9738 PANELS (INSTALLED)}}{\text{AREA OF 20m SEGMENT}}$$

$$= \frac{9738\,(117.7\text{ cm} \times 110.8\text{ cm})}{2000\text{ cm} \times 63{,}675.7\text{ cm}} = 0.99720$$

$$\text{END SEGMENT AREA FACTOR} = \frac{\text{AREA OF 7033 PANELS (INSTALLED)}}{\text{AREA OF END SEGMENT}}$$

$$= \frac{7033\,(117.7\text{ cm} \times 110.8\text{ cm})}{1443.2\text{ cm} \times 63{,}675.7\text{ cm}} = 0.99806$$

$$\text{SEGMENT AREA FACTOR (NET)} = \frac{(30 \times 0.99720) + (2 \times 0.99806)}{32} = 0.99725$$

$$\text{ARRAY AREA FACTOR (PER BAY)} = \frac{\text{AREA OF 30 20m + 2 END SEGMENTS}}{\text{AREA OF 660m BAY}}$$

$$= \frac{62{,}886.4\text{ cm} \times 63{,}675.7\text{ cm}}{66{,}000\text{ cm} \times 66{,}000\text{ cm}} = 0.91927$$

(CONT'D)

AREA FACTORS (CONT'D)

$$\text{SOLAR CELL AREA FACTOR (PER BAY)} = \frac{\text{AREA OF 77,163,912 SOLAR CELLS}}{\text{AREA OF 660 M BAY}}$$

$$= \frac{77,163,912\,(6.40\text{ CM} \times 7.70\text{ CM})}{66,000\text{ CM} \times 66,000\text{ CM}}$$

$$= 0.87297 \triangleright$$

$$\text{SOLAR CELL AREA FACTOR (PER SATELLITE)} = \frac{\text{AREA OF 19,753,961,472 SOLAR CELLS}}{\text{AREA OF SATELLITE}}$$

$$= \frac{19,753,961,472\,(.064\text{ M} \times .077\text{ M})}{21,280\text{ M} \times 5300\text{ M}} = 0.86313$$

$$\text{ARRAY AREA FACTOR (PER SATELLITE)} = \frac{\text{AREA OF 256 BAY ARRAYS}}{\text{AREA OF SATELLITE}}$$

$$= \frac{256\,(628.864\text{ M} \times 636.757\text{ M})}{21,280\text{ M} \times 5300\text{ M}} = 0.90891$$

$\triangleright$ OR,

$$\text{SOLAR CELL AREA FACTOR (PER BAY)} = \left(\begin{array}{c}\text{SOLAR CELL}\\ \text{AREA FACTOR}\\ \text{(PER PANEL)}\end{array}\right) \times \left(\begin{array}{c}\text{PANEL}\\ \text{AREA}\\ \text{FACTOR}\end{array}\right) \times \left(\begin{array}{c}\text{SEGMENT}\\ \text{AREA}\\ \text{FACTOR}\end{array}\right) \times \left(\begin{array}{c}\text{ARRAY}\\ \text{AREA}\\ \text{FACTOR}\end{array}\right)$$

$$= 0.96066 \times 0.99126 \times 0.99725 \times 0.91927$$

$$= 0.87297$$

WEIGHT FACTOR FOR JOINT/SUPPORT TAPES
(FIBERGLASS TYPE TAPE PLUS ADHESIVE)

REF: SEE JOINT TAPE CONFIGURATIONS ON FOLLOWING PAGE

LENGTH OF 1.5 CM WIDE TAPE PER BAY $= (598 \times 636.8\,m) + (542 \times 628.9\,m)$

$= 721{,}670\ m$

LENGTH OF 5.1 CM WIDE TAPE PER BAY $= (31 \times 636.8\,m) = 19{,}741\ m$

TOTAL AREA OF TAPE PER BAY $= (721{,}670 \times .015) + (19{,}741 \times .051)$

$= 11{,}832\ m^2$

WEIGHT OF TAPE (PLUS ADHESIVE) PER BAY $= (11{,}832\ m^2 \times 1.6\ MIL \times 50.8\ g/m^2/MIL)_{TAPE}$

$+ (11{,}832\ m^2 \times 0.5\ MIL \times 35.56\ g/m^2/MIL)_{ADHESIVE}$

$= 1{,}172{,}078\ g$

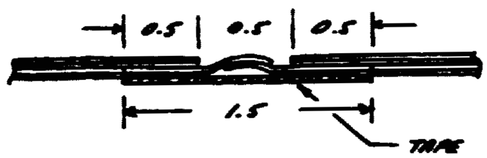
TAPE (PLUS ADHESIVE) WEIGHT FACTOR $= \dfrac{\text{WEIGHT OF TAPE (PLUS ADHESIVE) PER BAY}}{\text{ARRAY AREA PER BAY}}$

$= \dfrac{1{,}172{,}078\ g}{636.8\ m \times 628.9\ m}$

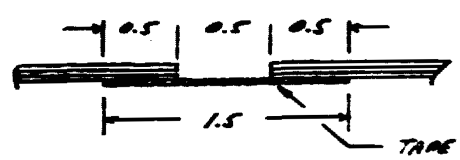
$= 2.927\ g/m^2$

JOINT TAPE CONFIGURATIONS
(ALL DIMENSIONS IN CENTIMETERS)

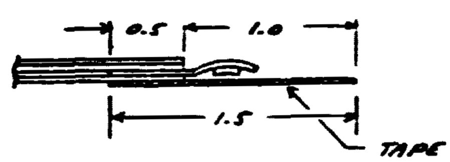
a) PANEL-TO-PANEL (WITH INTERCONNECTS)



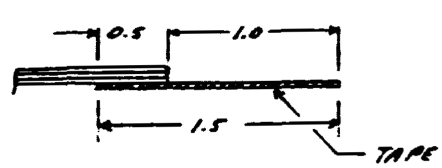
b) PANEL-TO-PANEL (NO INTERCONNECTS)



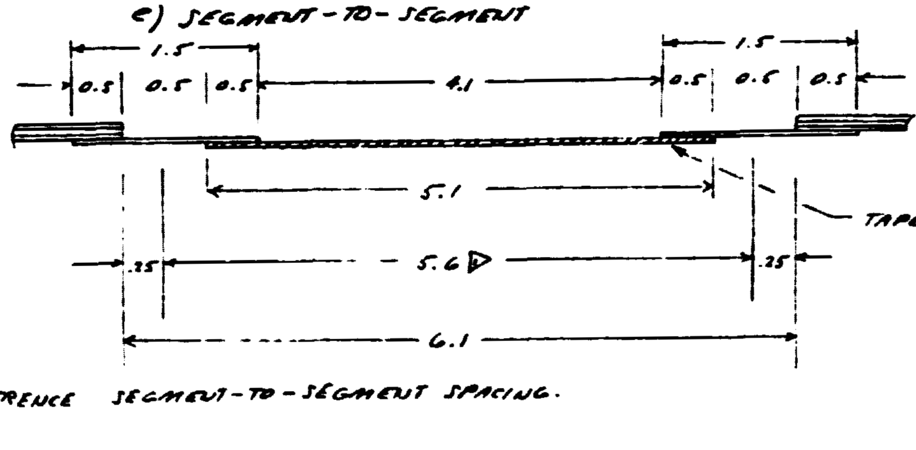
c) SEGMENT OUTER EDGE (WITH INTERCONNECTS AND CABLE)



d) SEGMENT OUTER EDGE (NO INTERCONNECTS)



e) SEGMENT-TO-SEGMENT



▷ REFERENCE SEGMENT-TO-SEGMENT SPACING.

WEIGHT FACTOR FOR CATENARY SYSTEM

NO. OF CATENARIES PER BAY $= 4\left(\frac{660}{20} - 1\right) = 128$

WEIGHT PER CATENARY INSTALLATION $= \underset{\text{EST.}}{\underline{17.5 \text{ LB}}} = 7900 \text{ g}$

$$\text{CATENARY WEIGHT FACTOR} = \frac{\text{WEIGHT OF CATENARIES PER BAY}}{\text{ARRAY AREA PER BAY}}$$

$$= \frac{128 \times 7900 \text{ g}}{636.8 \text{ m} \times 628.9 \text{ m}}$$

$$= 2.525 \text{ g/m}^2$$

2.1.1-1.8 SOLAR CONCENTRATORS

NOT APPLICABLE

2.1.1-1.9 POWER DISTRIBUTION — 2,398,400 kg

POWER BUSES	2,030,000	*
CELL STRING FEEDERS	38,800	*
DISCONNECTS (384)	78,000	*
IN-LINE SWITCH GEAR (192)	78,000	*
DC-DC CONVERTERS	200	*
ENERGY STORAGE	20,000	*
ELECTRICAL ROTARY JOINT (2)	39,200	**
SUPPORT STRUCTURES ~5%	114,200	

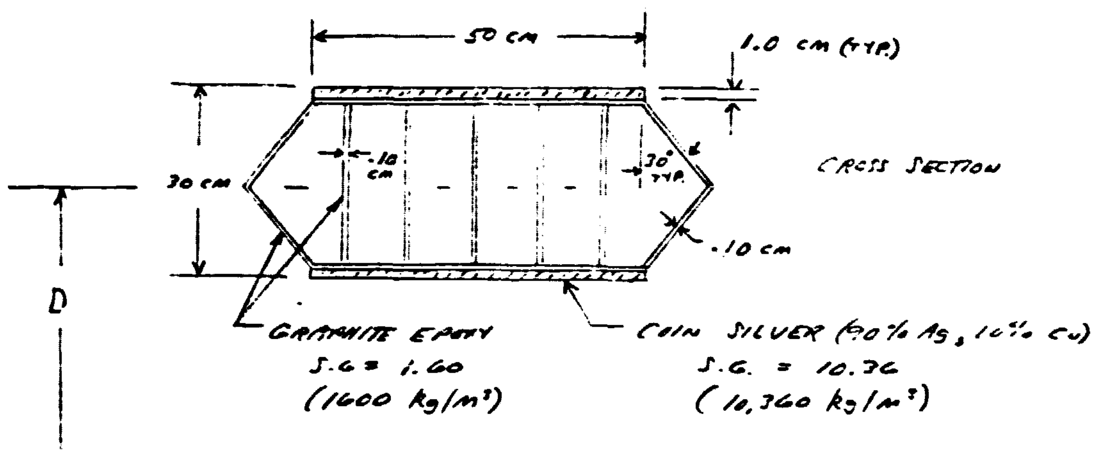
* USED MASS ESTIMATES DEVELOPED BY JACK GEWIN OF THE ELECTRICAL POWER STAFF.

** ELECTRICAL ROTARY JOINT WEIGHT BASED ON MASS CALCULATIONS OF CONCEPTUAL DESIGN. (DETAILS ON FOLLOWING PAGES).

ELECTRICAL ROTARY JOINT (1) 19,600 kg

SLIP RINGS		11,810
INNER RING	2510	
MIDDLE RING	3940	
OUTER RING	5360	
BRUSHES (832)		540
BRUSH WIRE (1664)		270
BRUSH HOLDERS		1160
16-BRUSH HOLDER (8)	216	
20-BRUSH HOLDER (16)	448	
24-BRUSH HOLDER (16)	496	
FEEDERS (2 SIDES)		3840
INNER FEEDERS (16)	896	
MIDDLE FEEDERS (16)	1536	
OUTER FEEDERS (16)	1408	
STRUCTURAL SUPPORT FRAME ~5%		900
ASSEMBLY & INSTALLATION HARDWARE ~1%		180
CONTINGENCY ~5%		900

<u>SLIP RINGS (3)</u> <u>11,810 kg</u>



X-AREA OF COIN SILVER = $2(50 \times 0.5) = 50\ cm^2 = 0.0050\ m^2$

X-AREA OF GRAPHITE EPOXY = $2(50 \times .1) + 5(26.6 \times .1)$

$+ 4(17.3 \times .1) \approx 31\ cm^2 \approx 0.0031\ m^2$

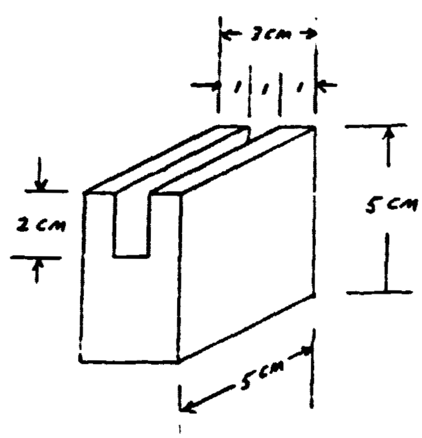
RING	DIA. (m)	VOL. OF Ag (m^3)	VOL OF G/E (m^3)	WT OF Ag (kg)	WT OF G/E (kg)
INNER	7	0.220	0.068	2280	110
MIDDLE	11	0.346	0.107	3580	170
OUTER	15	0.472	0.146	4880	230
				10,740	510

$$W_{SLIP\ RINGS} = 1.05\,(W_{SILVER} + W_{G/E})$$

$$= 1.05\,(10{,}470 + 510)$$

$$= 11{,}810\ kg$$

BRUSH (1) — 0.65 kg



85% Ag, 3% C, 12% MoS_2
S.G = 9.57
(9570 kg/m³)

VOLUME = (5 × 5 × 3) − (5 × 2 × 1) = 65 cm³ = 0.000,065 m³

WEIGHT = 1.05(9570 kg/m³)(0.000,065 m³)

= 0.65 kg/BRUSH

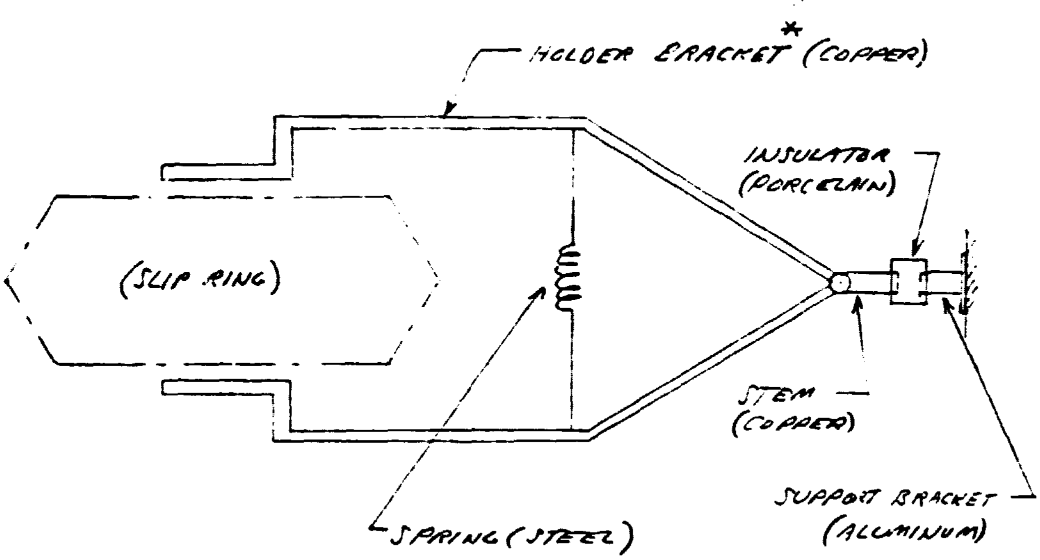
BRUSH WIRE (1) — 0.16 kg

2 WIRES/BRUSH
L = 0.2 m
#000 COPPER BRAID WIRE @ 578 LB/1000 FT (0.77 kg/m)

WEIGHT = 1.05(0.77 kg/m)(0.2 m)

= 0.16 kg/WIRE

BRUSH HOLDER, 16-BRUSH/20-BRUSH/24 BRUSH (1 EA.) 27 kg/28 kg/31 kg



* GEOMETRY ON NEXT PAGE

ITEM	ITEM VOLUME (m^3)	DENSITY kg/m^3	WEIGHT (kg)
UPR HOLDER ARM, 16-BRUSH	0.00122	8980	11.0
LWR " " "	"	"	11.0
UPR HOLDER ARM, 20-BRUSH	0.00127	"	11.5
LWR " " "	"	"	11.5
UPR HOLDER ARM, 24-BRUSH	0.00143	"	13.0
LWR " " "	"	"	13.0
STEM	0.00008	"	1.0
SPRING	—	8030	2.0
INSULATOR	0.00010	2960	0.5
SUPPORT BRACKET	—	2770	1.5

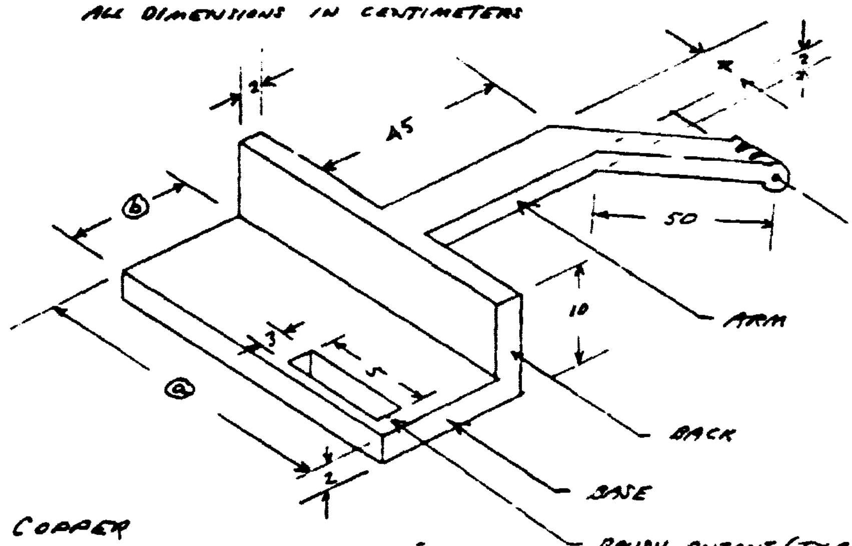
$$W_{16\text{-BRUSH HOLDER}} = (2 \times 11.0) + 1.0 + 2.0 + 0.5 + 1.5 = 27 \text{ kg}$$

$$W_{20\text{-BRUSH HOLDER}} = (2 \times 11.5) + 1.0 + 2.0 + 0.5 + 1.5 = 28 \text{ kg}$$

$$W_{24\text{-BRUSH HOLDER}} = (2 \times 13.0) + 1.0 + 2.0 + 0.5 + 1.5 = 31 \text{ kg}$$

HOLDER BRACKET GEOMETRY

ALL DIMENSIONS IN CENTIMETERS

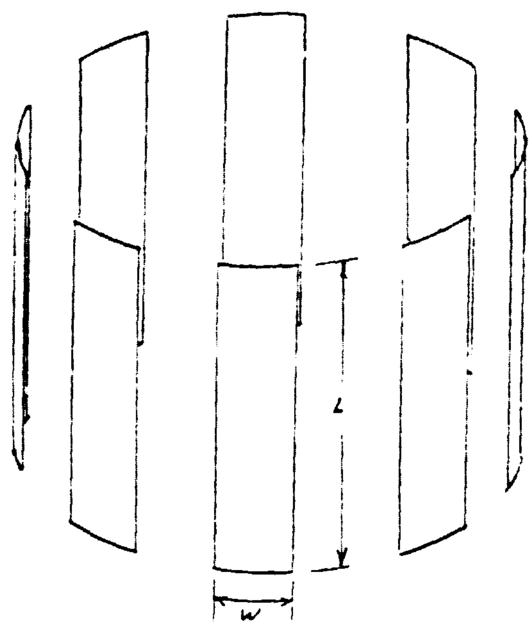


COPPER
S.G. = 8.78
(8780 kg/m³)

$$\text{VOL. OF ARM} = 95 \times 4 \times 2 = 760\ cm^3$$
$$\text{VOL. OF BACK} = ⓐ \times 10 \times 2 = 20ⓐ\ cm^3$$
$$\text{VOL. OF BASE} = [ⓐ \times ⓑ \times 2] - [(5 \times 3 \times 2)\ \text{NO. OF BRUSHES}]$$
$$= 2ⓐⓑ - 30 N_{BRUSHES}$$

TYPE HOLDER	BRUSH CONFIG.	ⓐ (cm)	ⓑ (cm)	$N_{BRUSHES}$	V_{ARM} (cm^3)	V_{BACK} (cm^3)	V_{BASE} (cm^3)	V_{TOTAL} (cm^3)
16-BRUSH	4×2	13	17	8	760	260	202	1222
20-BRUSH	5×2	13	21	10	760	260	246	1266
24-BRUSH	4×3	19	17	12	760	380	286	1426

FEEDERS (PER SIDE) 1920 kg



8 FEEDERS/RING

ALUMINUM
S.G = 2.77
(2770 kg/m³)

LOCATION	L (m)	W (m)	t (cm)	PER FEEDER: VOL (m^3)	PER FEEDER: DENSITY (kg/m^3)	PER FEEDER: WT (kg)	$WT_{8\ FEEDERS}$ (kg)
INNER RING	11	0.92	0.20	0.0202	2770	56	448
MIDDLE RING	8	1.44	0.30	0.0346	"	96	768
OUTER RING	5	1.96	0.32	0.0316	"	88	704

TOTAL: 1920 kg

2.1.1-2.0 MICROWAVE POWER TRANSMISSION SYSTEM (1) 12,606,100 kg

PRIMARY STRUCTURE			52,500
SECONDARY STRUCTURE			197,500
ANTENNA CONTROL SYSTEMS			(TBD)
POWER DISTRIBUTION SYSTEM - EXCL. SUBARRAYS			2,933,100
POWER BUSES		380,300	
ROTARY JOINT TO PWR SECTOR CONTROL	270,600		
SECTOR CONTROL TO SUBARRAYS	109,700		
SWITCH GEAR / DISCONNECTS		136,600	
DC-DC CONVERTERS		1,241,000	
THERMAL CONTROL (ACTIVE)		736,000	
ENERGY STORAGE		299,300	
SUPPORT STRUCTURES ~ 5%		139,700	
ANTENNA COMMUNICATIONS/DATA SYSTEM			(TBD)
ANTENNA SUBARRAYS			9,423,000
TYPE 1 (272)		839,000	
TYPE 2 (580)		1,506,000	
TYPE 3 (612)		1,305,000	
TYPE 4 (612)		1,122,000	
TYPE 5 (756)		1,154,000	
TYPE 6 (864)		1,043,000	
TYPE 7 (628)		614,000	
TYPE 8 (576)		508,000	
TYPE 9 (1032)		760,000	
TYPE 10 (1000)		581,000	

PRIMARY STRUCTURE 52,520 kg

USED MASS ESTIMATE DEVELOPED BY STRUCTURES RESEARCH STAFF GROUP.

SECONDARY STRUCTURE 197,500 kg

USED MASS ESTIMATE DEVELOPED BY STRUCTURES RESEARCH STAFF GROUP.

ANTENNA CONTROL SYSTEMS (TBD)

POWER DISTRIBUTION SYSTEM - EXCL. SUBARRAYS 2,519,000 kg

USED MASS ESTIMATE DEVELOPED BY JACK GELWIN OF ELECTRICAL PWR STAFF

OF THE TOTAL MASS, THE HEAVIEST ITEMS ARE THE DC-DC CONVERTERS AND ASSOCIATED THERMAL CONTROL, WHICH COMPRISE 47.3% AND 29.2%, RESPECTIVELY.

(CONT'D)

POWER DISTRIBUTION SYSTEM (CONT'D)

THE RATIONALE FOR THE MASS OF THE DC-DC CONVERTERS AND ASSOCIATED THERMAL CONTROL ARE GIVEN BELOW:

a) DC-DC CONVERTERS

- 228 CONVERTERS PER ANTENNA.
- EACH CONVERTER SUPPLIES POWER TO APPROXIMATELY 425 KLYSTRONS.
- POWER OUTPUT OF EACH CONVERTER IS 5443 KW.
- ESTIMATED SPECIFIC MASS IS 1.0 kg/KW
- ESTIMATED TOTAL MASS = 228 × 5443 × 1.0 = 1,241,000 kg.

b) THERMAL CONTROL

- DC-DC CONVERTER EFFICIENCY IS 96.0%
- ESTIMATED RADIATOR AREA = 323 m²/CONVERTER
- ESTIMATED SPECIFIC MASS OF ACTIVE THERMAL CONTROL SYSTEM = 10 kg/m² OF RADIATOR AREA
- ESTIMATED TOTAL MASS = 228 × 323 × 10 = 736,000 kg

ANTENNA COMMUNICATIONS/DATA SYSTEM (TBD)

ANTENNA SUBARRAYS 9,423,000 kg

OF THE TOTAL MASS, THE HEAVIEST ITEMS ARE THE KLYSTRONS, THERMAL CONTROL, AND RADIATING WAVEGUIDES, WHICH COMPRISE 49.5%, 22.1%, AND 15.8%, RESPECTIVELY. (SEE ATTACHED TABLES). THE UNIT MASS DATA FOR INDIVIDUAL ITEMS ARE: KLYSTRON, 48 kg EACH; THERMAL CONTROL, 21.6 kg/KLYSTRON; RADIATING WAVE GUIDE, 214 kg/SUBARRAY.

THE RATIONALE FOR THE UNIT MASS DATA ARE GIVEN BELOW:

a) KLYSTRON

- PERFORMED A MASS ANALYSIS OF A CONCEPTUAL DESIGN OF A 70KW KLYSTRON. (SEE APPENDIX E)

b) THERMAL CONTROL

- KLYSTRON EFFICIENCY IS 85%.
- COLLECTOR SECTION HEAT PIPE/RADIATOR DISSIPATES 8.0 KW AT 500°C. RF SECTION HEAT PIPE/RADIATOR DISSIPATES 5.2 KW AT 300°C.
- MERCURY WORKING FLUID
- ESTIMATED MASS-OPTIMIZED HEAT PIPE/RADIATOR MASS AT 6.2 kg FOR COLLECTOR SECTION AND 12.7 kg FOR RF SECTION. ADDED MULTI-LAYER INSULATION AT 2.7 kg.

ANTENNA SUBARRAYS (CONT'D)

c) RADIATING WAVE GUIDE

- PERFORMED A MASS ANALYSIS OF A CONCEPTUAL DESIGN. (SKETCH AND CALCULATIONS ATTACHED).

SUBARRAY MASS MATRIX BASED ON MASS DATA OF EACH GROUP OF IDENTICAL SUBARRAYS

SUBARRAYS	KLYSTRONS PER SUBARRAY	SUBARRAYS PER ANTENNA	KLYSTRON MASS (kg)	DISTRIBUTION WAVEGUIDE MASS (kg)	RADIATING WAVEGUIDE MASS (kg)	SOLID STATE CONTROL MASS (kg)	PWR. DISTR. CABLING MASS (kg)	THERMAL CONTROL MASS (kg)	SUBARRAY STRUCTURE MASS (kg)	TOTAL (MT)
TYPE 1	36	272	470,016	16,864	58,208	48,960	3536	211,344	24,208	833
TYPE 2	30	580	835,200	30,160	124,120	87,000	5800	375,260	48,720	1506
TYPE 3	24	612	705,024	25,704	130,968	73,440	5508	317,016	47,736	1305
TYPE 4	20	612	587,520	32,436	130,968	61,200	4896	263,772	41,004	1122
TYPE 5	16	756	580,608	31,752	161,784	60,480	4536	260,820	50,652	1151
TYPE 6	12	864	497,664	27,648	184,896	51,840	3456	223,776	53,568	1043
TYPE 7	9	628	271,296	20,096	134,392	28,260	1884	121,932	35,796	614
TYPE 8	8	576	221,184	12,096	123,264	23,040	1728	93,888	32,832	508
TYPE 9	6	1032	297,216	21,672	220,848	30,960	3096	133,128	52,632	760
TYPE 10	4	1000	192,000	21,000	214,000	20,000	2000	86,000	46,000	581
TOTAL (MT)			4658	239	1485	485	36	2087	433	9423
% GRAND TOTAL			49.5%	2.5%	15.8%	5.1%	0.4%	22.1%	4.6%	100.0%

TOTAL NUMBER OF 70KW KLYSTRONS = 97,036 PER ANTENNA

SUBARRAY MASS MATRIX BASED ON MASS DATA OF INDIVIDUAL SUBARRAYS

SUBARRAY	KLYSTRONS PER SUBARRAY	KLYSTRON MASS (kg)	DISTRIBUTION WAVEGUIDE MASS (kg)	RADIATING WAVEGUIDE MASS (kg)	SOLID STATE CONTROL MASS (kg)	PWR. DISTR. CABLING MASS (kg)	THERMAL CONTROL MASS (kg)	SUBARRAY STRUCTURE MASS (kg)	SUBTOTAL (kg)	SUBARRAYS PER ANTENNA	TOTAL (MT)
TYPE 1	36	1728	62	214	180	18	777	89	3063	272	833
TYPE 2	30	1440	52	214	150	10	647	84	2597	580	1506
TYPE 3	24	1152	42	214	120	9	578	78	2133	612	1305
TYPE 4	20	960	53	214	100	8	431	67	1833	612	1122
TYPE 5	16	768	42	214	80	6	345	67	1522	756	1151
TYPE 6	12	576	32	214	60	4	259	62	1207	864	1043
TYPE 7	9	432	32	214	45	3	194	57	977	620	614
TYPE 8	8	384	21	214	40	3	163	57	882	576	508
TYPE 9	6	288	21	214	30	3	129	51	736	1032	760
TYPE 10	4	192	21	214	20	2	86	46	581	1000	581
										6932	9423

PERTINENT UNIT MASS DATA:

KLYSTRON (70 KW)	48 kg EACH
RADIATING WAVE GUIDE	214 kg / SUBARRAY
THERMAL CONTROL	21.6 kg / KLYSTRON
SOLID STATE CONTROL	5.0 kg / KLYSTRON

RADIATING WAVE GUIDE (PER SUMMARY) 214.0 kg

a. GRAPHITE EPOXY STRUCTURE

SEE ATTACHED SKETCH

$V_{G/E} = \left(S_{UPR \,\&\, LWR\ SURFACES} + S_{RIBS} + S_{END\ CLOSEOUTS}\right) t$

$= \left[(11.464 \times 9.728)2 + (9.728 \times 0.06)121 \right.$

$\left. + (0.09325 \times 0.06)(120)2 \right] 0.00041$

$= (227.63 + 72.08 + 1.34)0.00041$

$= 0.1234\ m^3$

$W_{G/E} = 1.05 \rho V$

$= 1.05\,(1580\ kg/m^3)(0.1234\ m^3)$

$= 204.7\ kg$

b. ALUMINUM COATING

SEE ATTACHED SKETCH

$V_{ALUM} = \left(S_{INTERNAL, TOP, BOTTOM \,\&\, SIDES} + S_{INTERNAL, ENDS} + S_{EXTERNAL, LWR SURF}\right) t$

$= \left[(0.09325 + 0.09325 + 0.06 + 0.06)(9.728)120 \right.$

$\left. + (0.09325 \times 0.06)(120)(2) + (11.464 \times 9.728) \right] 0.000,006,67$

$= (305.15 + 1.34 + 111.81)0.000,006,67$

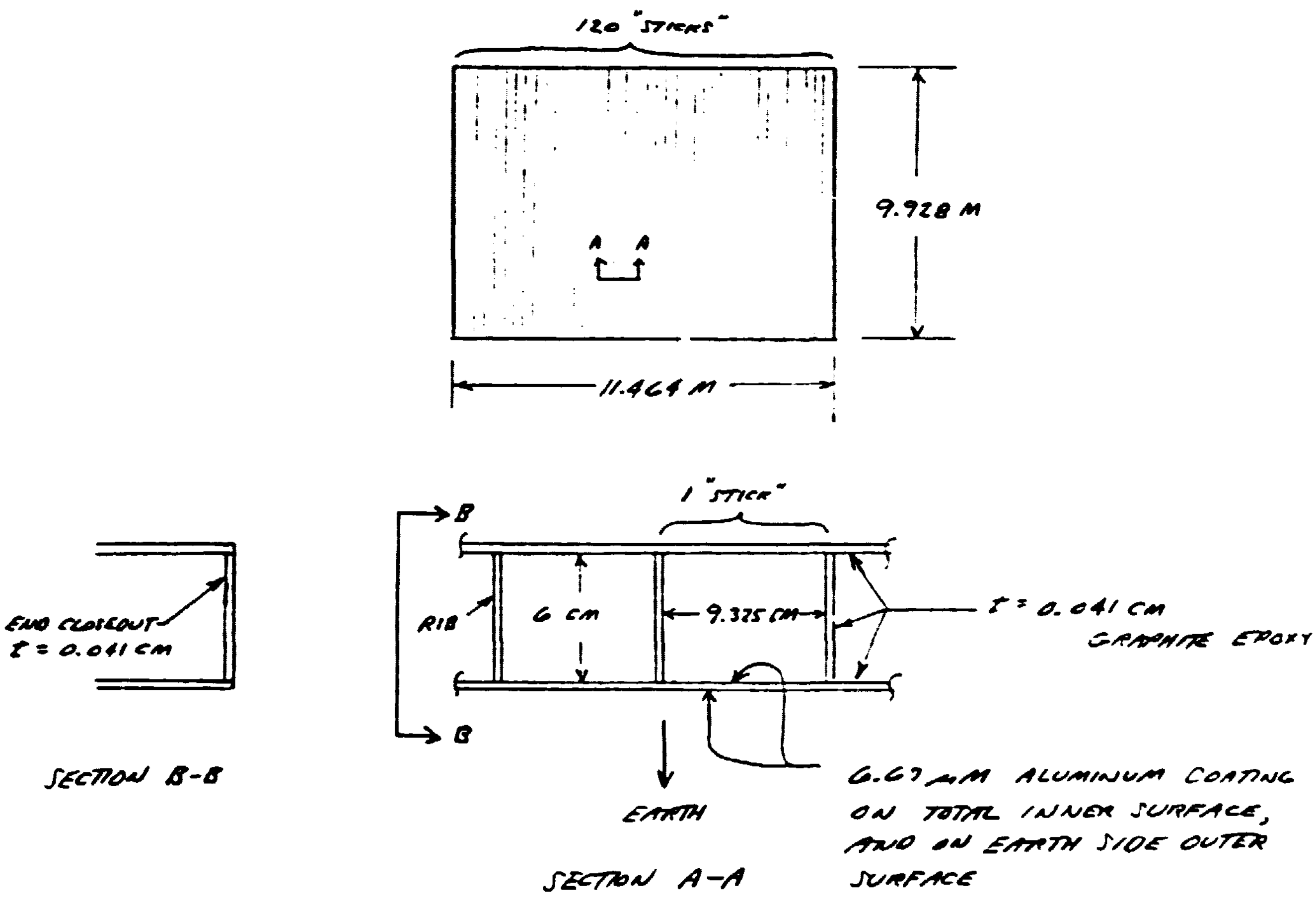
$= 0.00320\ m^3$

$W_{ALUM} = 1.05 \rho V$

$= 1.05\,(2770\ kg/m^3)(0.00320\ m^3)$

$= 9.3\ kg$

RADIATING WAVE GUIDE



NOTE: INTERNAL CLOSEOUTS ARE KEVLAR SHEET. (WEIGHT IS NEGLIGIBLE)

2.1.1-3.0 WEIGHT GROWTH ALLOWANCE 20,505,500 kg

THE RESULTS OF THE WEIGHT/SIZE UNCERTAINTY ANALYSIS ARE PRESENTED ON PAGE vi. AS INDICATED, THE REFERENCE POINT DESIGN WEIGHS 77.0 $\times 10^3$ METRIC TONS AND HAS AN ARRAY AREA OF 102.5 KM^2. ALSO, AS NOTED, THE RECTENNA OUTPUT POWER WITH THE REFERENCE POINT DESIGN IS 9.2 GW. THE MOST PROBABLE DESIGN HAS A PREDICTED WEIGHT OF 97.5 $\times 10^3$ METRIC TONS AND A PREDICTED ARRAY AREA OF 126.5 KM^2. THE RECTENNA OUTPUT POWER WITH THE MOST PROBABLE DESIGN IS PREDICTED AT 10.0 GW. THE WEIGHT AND SIZE GROWTH IN GOING FROM THE REFERENCE POINT DESIGN TO THE MOST PROBABLE DESIGN ARE 20.5 $\times 10^3$ METRIC TONS AND 24.0 KM^2, RESPECTIVELY.

FIGURE 3-1 PROVIDES SOME DETAILS ON THE PREDICTED WEIGHT/SIZE GROWTH IN GOING FROM THE REFERENCE POINT DESIGN TO THE MOST PROBABLE DESIGN. THE FIRST STEP IS TO GO FROM THE REFERENCE POINT DESIGN TO THE CURRENT NOMINAL CONFIGURATION. THE CHANGES (+7.9 $\times 10^3$ METRIC TONS, +7.6 KM^2) REFLECT THE IMPACT OF NORMALIZING THE REFERENCE POINT DESIGN TO A RECTENNA OUTPUT POWER OF 10.0 GW, USING AN UPDATED POWER EFFICIENCY STRING (A MAJOR IMPACT OF THE UPDATED POWER EFFICIENCY STRING IS AN INCREASE IN ANTENNA DIAMETER FROM 1.0 KM TO 1.2 KM) AND NOMINAL UNIT WEIGHTS. THE SECOND STEP IS TO GO FROM THE CURRENT NOMINAL CONFIGURATION TO THE MOST PROBABLE CONFIGURATION. THE CHANGES (+13.6 $\times 10^3$ METRIC TONS, +16.4 KM^2) REFLECT ANTICIPATED OVERALL DEGRADATION IN THE POWER EFFICIENCY STRING AND IN THE NOMINAL UNIT WEIGHTS. AS INDICATED, OF THE 13.6 $\times 10^3$ METRIC TON WEIGHT INCREASE, 10.1 $\times 10^3$ METRIC TON IS PREDICTED TO OCCUR DUE TO CHANGES IN POWER EFFICIENCIES, AND ONLY 2.5 $\times 10^3$ METRIC TON IS PREDICTED TO OCCUR DUE TO CHANGES IN NOMINAL UNIT WEIGHTS.

IN CONCLUSION, THE POWER EFFICIENCY STRING, BECAUSE ITS CONTROLS ARRAY SIZE AND ANTENNA SIZE, WILL BE THE MAJOR WEIGHT DRIVER. DEGRADATION OF NOMINAL UNIT WEIGHTS WILL BE A SECONDARY WEIGHT DRIVER.

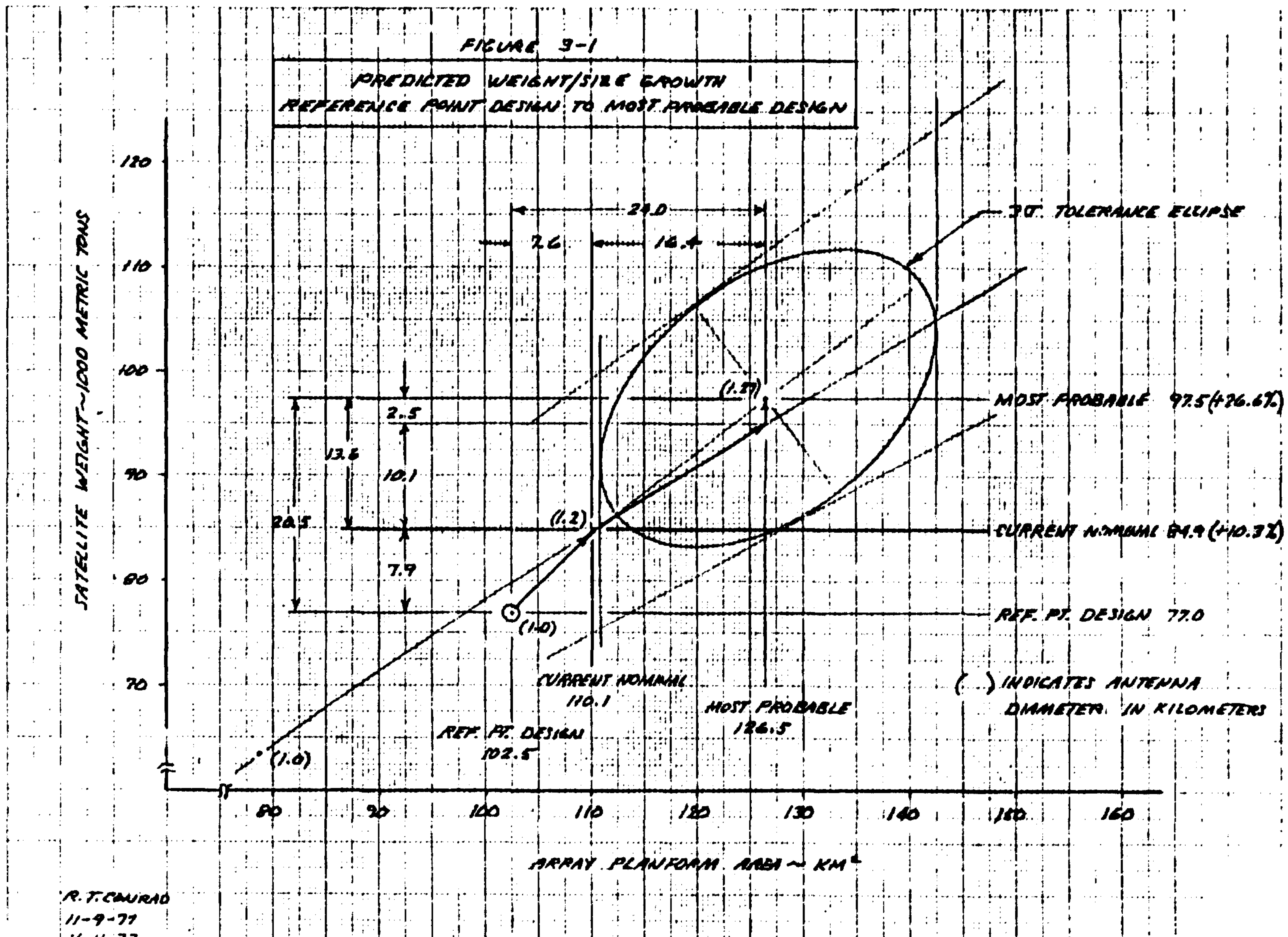


FIGURE 3-1

PREDICTED WEIGHT/SIZE GROWTH
REFERENCE POINT DESIGN TO MOST PROBABLE DESIGN

2.1.1

APPENDIX A

SIZING DATA FOR A 20 METER LONG TAPERED TUBE OF GRAPHITE/EPOXY

SIZING DATA FOR A 20 METER LONG TAPERED TUBE OF GRAPHITE/EPOXY

a. PHYSICAL CHARACTERISTICS/PROPERTIES OF TUBE

AS A COMPRISE BETWEEN FAILURE MODES OF LONG COLUMN BUCKLING AND LOCAL CRIPPLING, THE FOLLOWING GRAPHITE/EPOXY TUBE DEFINITION HAS BEEN SELECTED.

3 LAYER TUBE OF GY-70/904 { OUTER LAYER IS 0.2 t @ 90°; MIDDLE LAYER IS 0.6t @ 0°; INNER LAYER IS 0.2t @ 90° }

THE PHYSICAL CHARACTERISTICS/PROPERTIES OF THE TUBE ARE

$E_x = 25.57 \times 10^6$ PSI

$E_y = 17.34 \times 10^6$ PSI

$G_{xy} = 0.60 \times 10^6$ PSI

$\nu_{xy} = 0.0124$

$\nu_{yx} = 0.0084$

$\rho = 0.061$ LB/IN³

$\alpha = -0.2486 \times 10^{-6}$ IN/IN/°F

b. CRIPPLING COEFFICIENT

FROM DM 84-A?, SECTION 311.5.?.B, CRIPPLING STRESS FOR A FILAMENTARY COMPOSITE TUBE IS GIVEN AS

$$F_{CR} = K \phi \alpha \frac{t}{R} \quad (1)$$

WHERE

$$K = 1 - 0.901\left(1 - e^{-\frac{1}{16}\sqrt{\frac{R}{t}}}\right) \quad (2)$$

$$\phi \begin{cases} = 1.0 & (3a) \\ = \left[\dfrac{2 G_{xy}\left(1 + \sqrt{\nu_{xy}\,\nu_{yx}}\right)}{\sqrt{E_x E_y}}\right]^{1/2} & (3b) \end{cases} \quad \text{WHICHEVER IS LESS}$$

$$\alpha = \left[\frac{E_x E_y}{3\left(1 - \nu_{xy}\,\nu_{yx}\right)}\right]^{1/2} \quad (4)$$

6. CRIPPLING COEFFICIENT (CONT'D)

THE CLASSIC EXPRESSION FOR CRIPPLING STRESS IN TERMS OF A CRIPPLING COEFFICIENT IS

$$F_{CR} = C \, E_x \, \frac{t}{R} \qquad (5)$$

EQUATING EQUATIONS (1) AND (5) AND SOLVING FOR THE CRIPPLING COEFFICIENT YIELDS

$$C = \frac{K \, \phi \, \alpha}{E_x} \qquad (6)$$

SOLVING FOR K FROM EQTN (2):

R/t	K
10	0.838
100	0.583
250	0.434
500	0.321
750	0.262
1000	0.223

(7)

SOLVING FOR ϕ FROM EQTN'S (3a) AND (3b):

EQTN (3b) GOVERNS,

$$\phi = 0.240 \qquad (8)$$

SOLVING FOR α FROM EQTN (4):

$$\alpha = 12.16 \times 10^{6} \qquad (9)$$

b. CRIPPLING COEFFICIENT (CONT'D)

SUBSTITUTING EQTN'S (7), (8), AND (9) INTO EQTN (6) YIELDS

SEE FIG. A-1

R/t	C
10	0.096
100	0.067
250	0.050
500	0.037
750	0.030
1000	0.025

(10)

AN APPROXIMATE EQUATION FOR C FOR R/t VALUES BETWEEN 150 AND 1500 IS

$$C = \frac{0.8}{(R/t)^{0.50}} \qquad (11)$$

c. OPTIMUM TUBE DEFINITION FOR 20m TAPERED STRUT

- LONG COLUMN BUCKLING

FOR LOW STRESS LEVELS, SHEAR DEFLECTION EFFECTS ARE NEGLIGIBLE, AND THE EULER EQUATION APPLIES:

$$F_{CR} = \frac{c\, m\, E_x}{(L/\rho)^2} \qquad (12)$$

SUBSTITUTING

$c = 1$ FOR PINNED ENDS

$m = 2.75$ FOR $R_1/R_2 = 1/3$

$E_x = 25.57 \times 10^6$ PSI

L 787.4 IN

$\rho = 0.707\, R_2$ FOR THIN WALLED TUBE

YIELDS

$$F_{CR} = 77.30\; R_2^2 \qquad (13)$$

F. OPTIMUM TUBE DEFINITION FOR 20M TAPERED STRUT (CONT'D)

- LONG COLUMN BUCKLING (CONT'D)

$$P_{CR} = 2\pi R_2 t F_{CR}$$

$$= 2\pi R_2 t (77.30 R_2^2)$$

$$= 485.4 R_2^3 t \qquad (14)$$

FROM WHICH

$$t = \frac{P_{CR}}{485.4 R_2^3} \qquad (15)$$

- CRIPPLING AT MIDSPAN — NOMINAL CRIPPLING COEFFICIENT

$$F_{CR} = C E_x \left(\frac{t}{R_2}\right) \qquad (5)$$

WHERE, FOR THE SPS COMPOSITE TUBE, THE NOMINAL CRIPPLING COEFFICIENT CAN BE APPROXIMATED AS

$$C = \frac{0.8}{\left(\frac{R_2}{t}\right)^{0.50}} \quad ; \quad 150 \le \frac{R}{t} \le 1500 \qquad (11)$$

THUS

$$F_{cr} = 0.8 E_x \left(\frac{t}{R_2}\right)^{1.5} \qquad (16)$$

SUBSTITUTING

$$E_x = 25.57 \times 10^6 \text{ psi}$$

YIELDS

$$F_{CR} = 20.46 \times 10^6 \left(\frac{t}{R_2}\right)^{1.5} \qquad (17)$$

THUS

$$P_{CR} = 2\pi R_2 t F_{CR}$$

$$= 2\pi R_2 t \left[20.46 \times 10^6 \left(\frac{t}{R_2}\right)^{1.5}\right]$$

$$= 128.5 \times 10^6 \frac{t^{2.5}}{R_2^{0.5}} \qquad (18)$$

C. OPTIMUM TUBE DEFINITION FOR 20M TAPERED STRUT (CONT'D)

- CRIPPLING AT MIDSPAN — NOMINAL CRIPPLING COEFFICIENT (CONT'D)

FROM WHICH

$$t = \frac{P_{CR}^{\,0.4} R_2^{\,0.2}}{1752} \qquad (19)$$

- LONG COLUMN BUCKLING AND LOCAL CRIPPLING

LETTING EQTN (15) EQUAL EQTN (19) AND SOLVING FOR R_2 YIELDS

$$R_2 = 1.49 \; P_{CR}^{\,0.1875} \qquad (20)$$

SEE FIG. A-2

P_{CR} (LB ULT.)	R_2 ▷ (IN.)	t ⊳⊳ (IN)	R_2/t (IN/IN)
500	4.78	.0094	509
1000	5.44	.0127	428
1500	5.87	.0152	386
2000	6.20	.0172	360
2500	6.46	.0190	340
3000	6.69	.0205	326
3500	6.88	.0220	313
4000	7.06	.0233	303
4500	7.21	.0245	294
5000	7.36	.0257	286

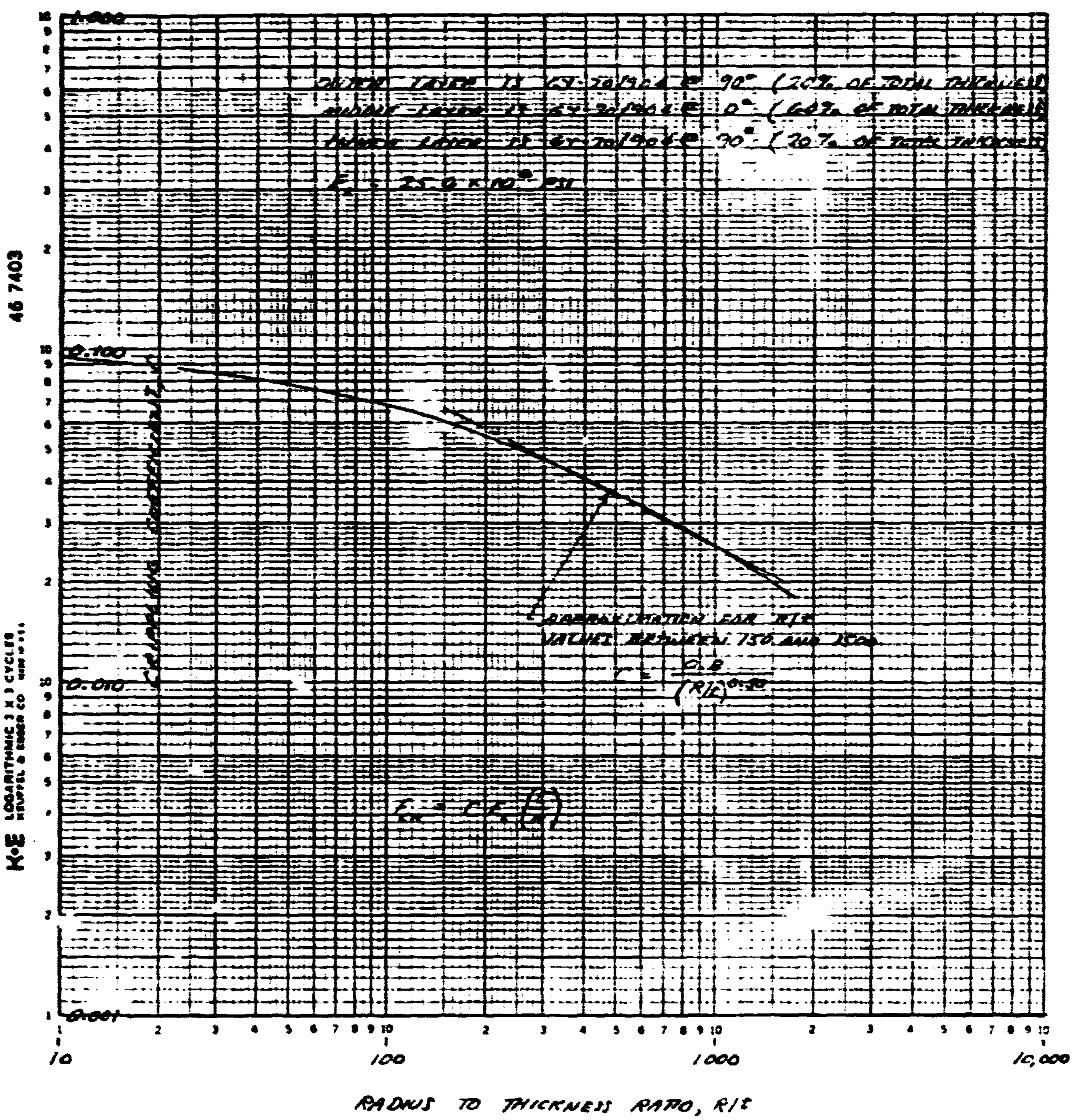
(21)

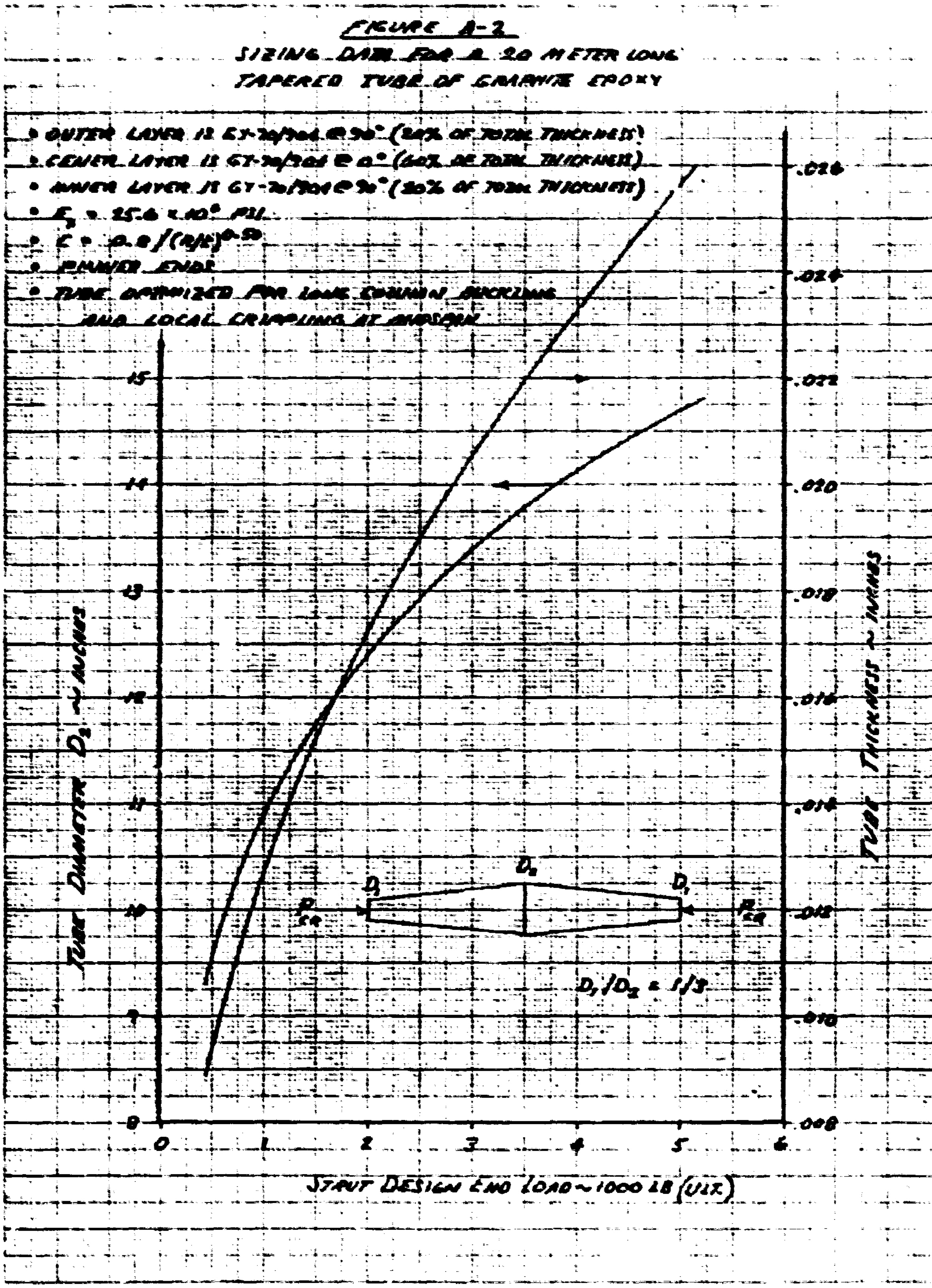
▷ FROM EQTN (20)

⊳⊳ FROM EITHER EQTN (15) OR (19)

FIGURE A-1

CRIPPLING COEFFICIENT FOR TYPICAL COMPOSITE TUBE OF GRAPHITE/EPOXY





R.T. Conaro
9/15/77

2.1.1

APPENDIX B

ARRAY EDGE LOADING ANALYSIS

ARRAY EDGE LOADING ANALYSIS

STIFFNESS COMPARISONS FOR STRUCTURAL CONCEPTS FOR SPS ARE SUMMARIZED IN FIGURE B-1. CONCEPT #2 IS THE STRUCTURAL CONCEPT "MOST-LIKE" THE CURRENT REFERENCE CONFIGURATION. FOR CONCEPT #2, THE FIRST MODE FREQUENCY OF THE TRUSS WITH SOLAR CELLS AND ANTENNAS IS 0.0012 HZ.

TO PREVENT COUPLING OF THE SOLAR ARRAYS AND TRUSS, THE FIRST MODE FREQUENCY OF EACH ARRAY INSTALLATION SHOULD BE HIGHER THAN THE FIRST MODE FREQUENCY OF THE TRUSS BY A FACTOR OF AT LEAST 2 TO 3. THE RESULTANT FIRST MODE FREQUENCY RANGE OF 0.0024 HZ TO 0.0036 HZ CORRESPONDS TO AN HOURLY CYCLE RATE RANGE OF 8.6 TO 13.0.

FOR THE PURPOSE OF ESTABLISHING EDGE LOADING ON EACH ARRAY, AN ARRAY FIRST MODE FREQUENCY OF 12 CYCLES PER HOUR (0.0033 HZ) HAS BEEN SELECTED.

THE EQUATION FOR THE FIRST MODE FREQUENCY OF VIBRATION FOR A SQUARE MEMBRANE IS

$$\omega = \frac{\pi}{L}\sqrt{\frac{2T}{w}} \qquad \sim \text{RADIANS/SECOND}$$

OR

$$f = \frac{3600}{2\pi}\,\frac{\pi}{L}\sqrt{\frac{2T}{w}} \qquad \sim \text{CYCLES/HOUR}$$

FROM WHICH

$$T = \frac{2f^2L^2w}{(3600)^2}$$

WHERE

T = TENSION LOADING ALONG EDGE OF MEMBRANE IN NEWTONS/METER

f = FIRST MODE FREQUENCY IN CYCLES/HOUR

L = LENGTH OF SIDE OF SQUARE MEMBRANE IN METERS

w = UNIT WEIGHT OF MEMBRANE IN KILOGRAMS/METER^2

FIGURE B-2 PRESENTS ARRAY EDGE LOADING DATA FOR SPS.

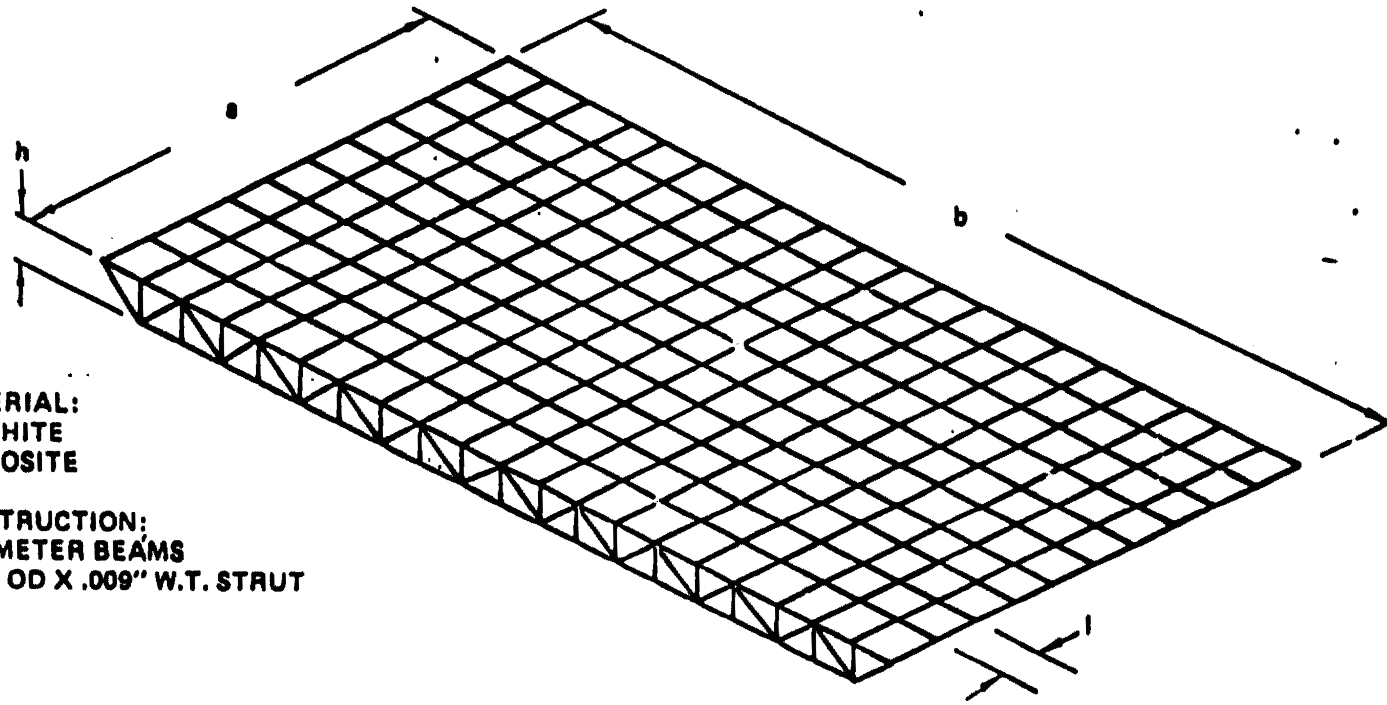
SPS

FIGURE B-1

Stiffness Comparisons For Structural Concepts For SPS

BOEING

SPS-960



GIVEN:

(1) MATERIAL:
GRAPHITE
COMPOSITE

(2) CONSTRUCTION:
. 20 METER BEAMS
. 12" OD X .009" W.T. STRUT

TRUSS ANGLE θ	CONCEPT NO.	a IN METERS	b IN METERS	l IN METERS	h IN METERS	MASS (Kg)	AREA IN M^2	TRUSS f_1 (Hz) ONLY	WITH SOLAR CELLS f_1 (Hz)	WITH SOLAR CELLS AND ANTENNAS f_1 (Hz)
30°	1	10240	10240	640	406	4.16×10^6	1.05×10^8	.0130	.0035	.0032
30°	2	5120	20480	640	406	4.19×10^6	1.05×10^8	.0052	.0014	.0012
45°	3	6240	16640	520	566	5.81×10^6	1.04×10^8	.0100	.0032	(NOT DETERMINED)
90°	4	6080	18240	380	683	10.30×10^6	1.11×10^8	.0094	.0037	(NOT DETERMINED)

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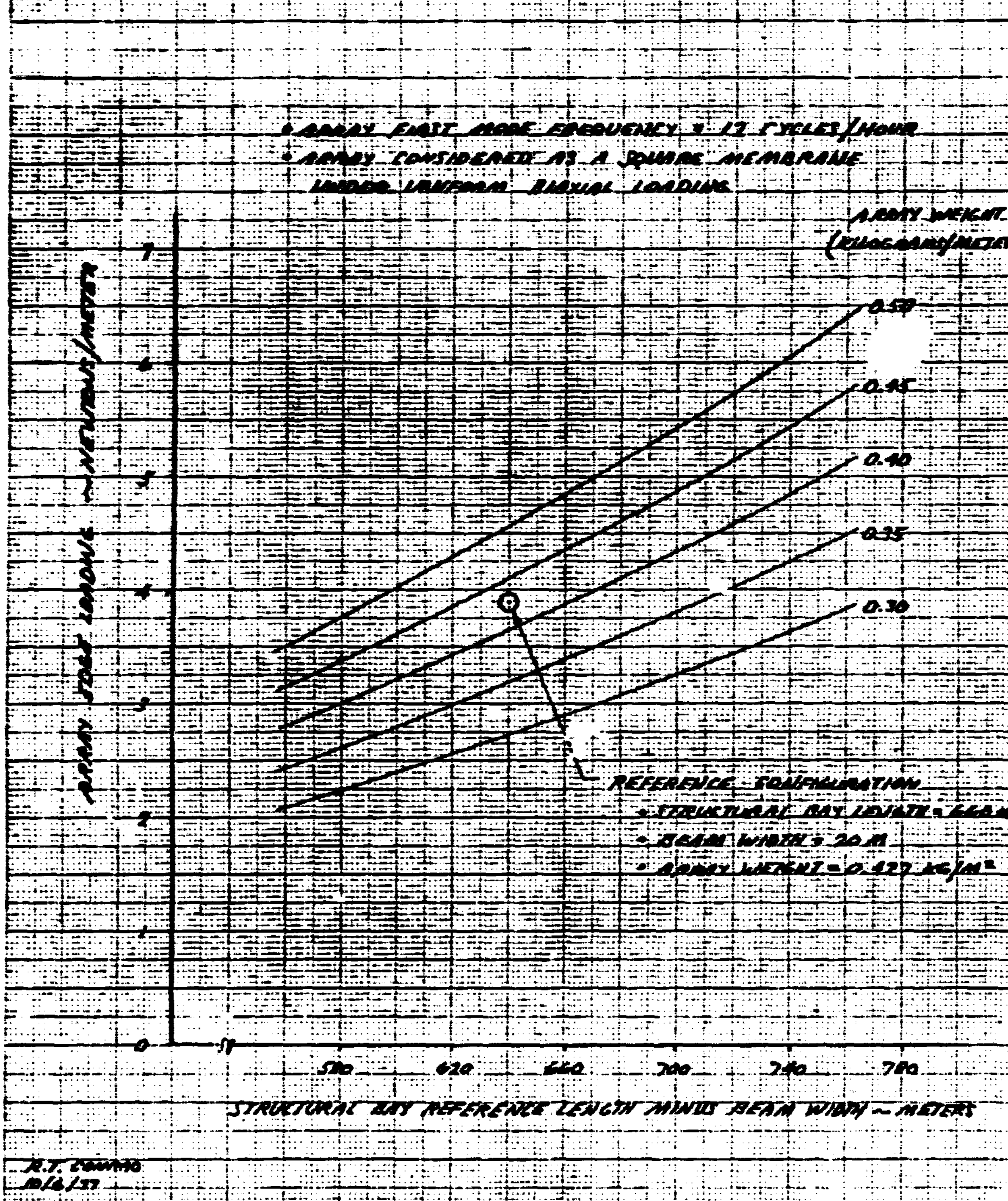
FIGURE 8-2 ARRAY EDGE LOADING

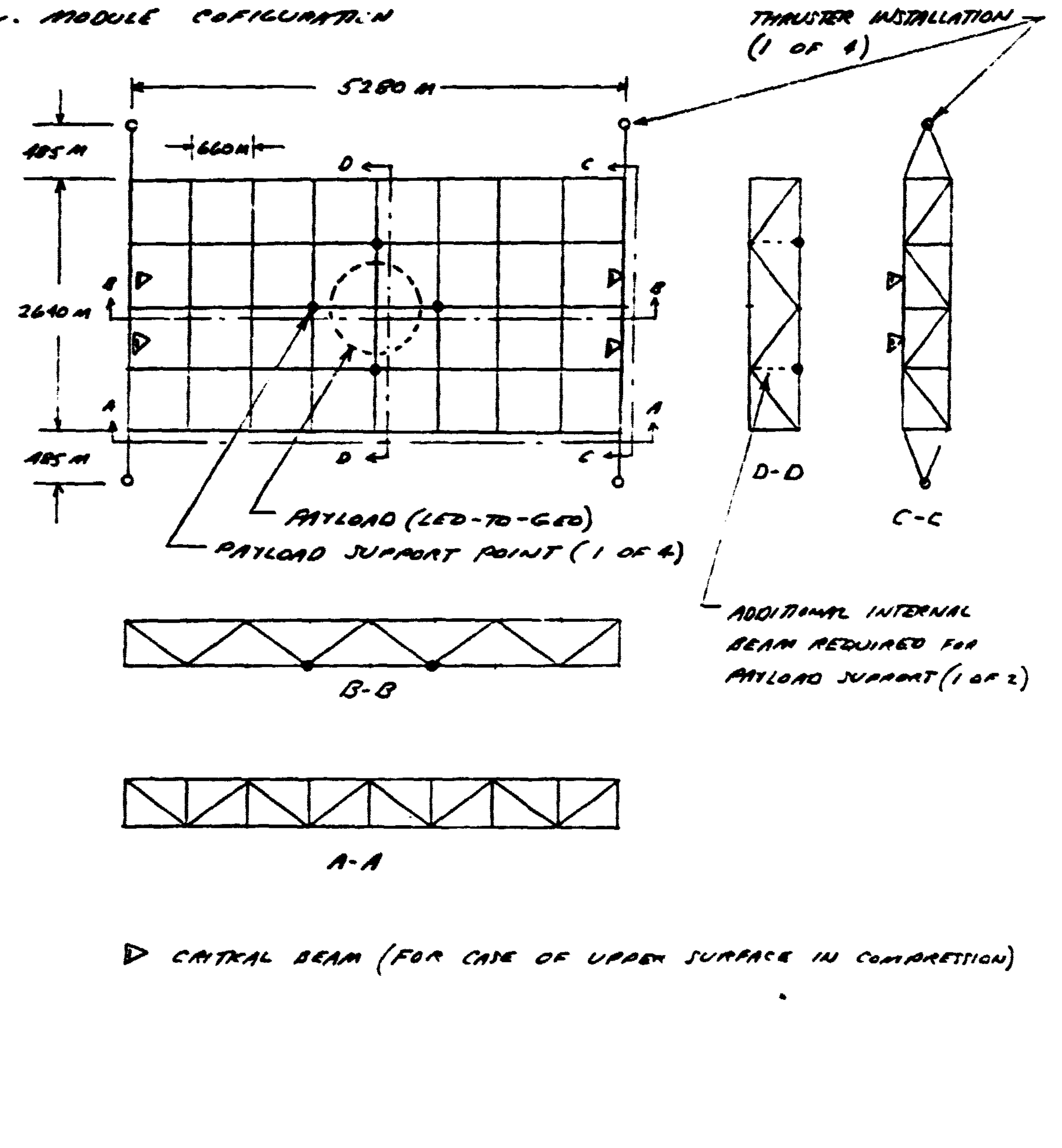


2.1.1
APPENDIX C

LOAL ANALYSIS AND LOADS/SIZING SUMMARY FOR CRITICAL BEAM IN UPPER SURFACE

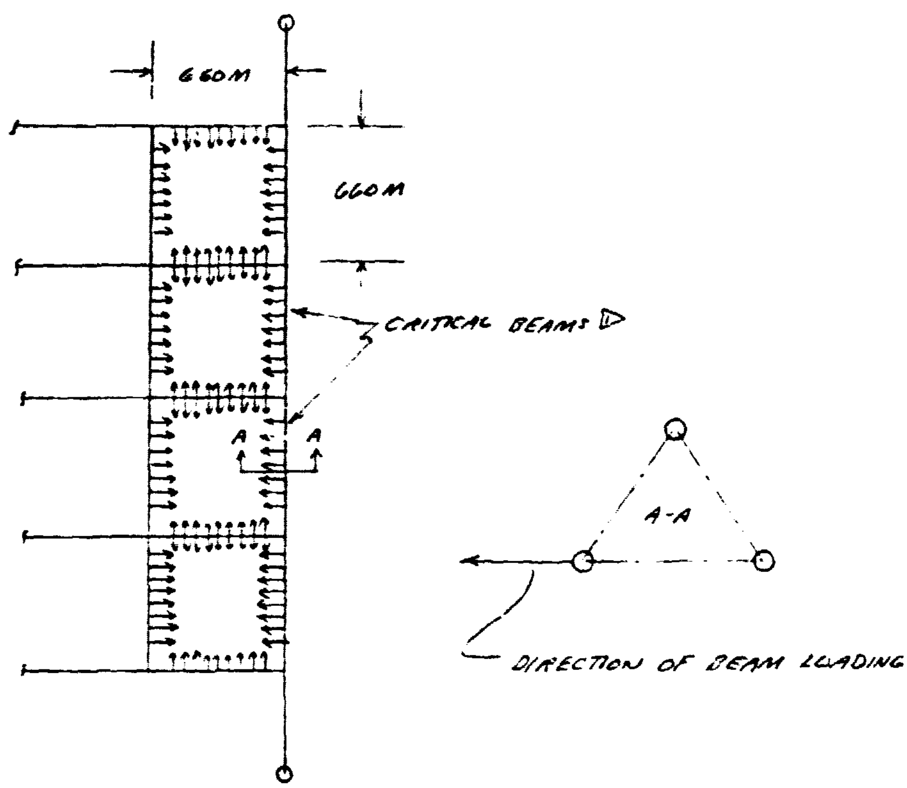
LOADS ANALYSIS AND LOADS/SIZING SUMMARY
FOR
CRITICAL BEAM IN UPPER SURFACE

a. MODULE COFIGURATION



▷ CRITICAL BEAM (FOR CASE OF UPPER SURFACE IN COMPRESSION)

b. LOADS ON CRITICAL BEAM DUE TO PRETENSION IN ARRAY



- ARRAY PRETENSION LOADING ALONG EDGE = 3.9 N/M [2]
- LOADS IN CRITICAL BEAM

  BEAM LOADING = 3.9 N/M = .0223 LB/IN

  COLUMN LOAD = $-(3.9\ N/M)(\frac{1}{2} \times 660\ M)$

  = −1287 N = −289 LB

  [3]

[1] PART OF SATELLITE LONGITUDINAL BEAM SYSTEM/MODULE LATERAL BEAM SYSTEM.

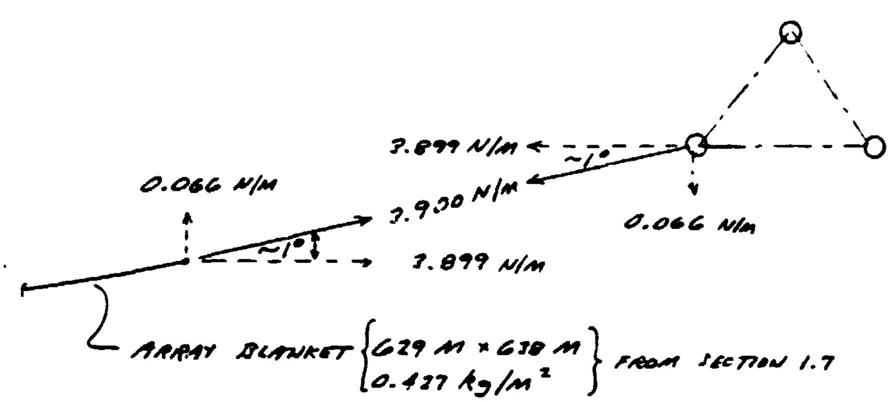
[2] FROM APPENDIX A, FIGURE A-2.

[3] APPLIED (LIMIT) LOADS.

c. LOADS ON CRITICAL BEAM DUE TO PRETENSION IN ARRAY DURING LEO TO GEO TRANSFER

- ASSUME THAT THE ARRAY CATENARY SUPPORT SYSTEM ATTACHES TO THE BEAM (AT 20M INTERVALS) BY MEANS OF CONSTANT FORCE SPRINGS. THE LOAD IN A SPRING IS 78 N (3.9 N/M × 20 M).

- THEN, SHOULD THE T/W DURING LEO TO GEO REACH THE MAXIMUM CAPABILITY OF 0.0001, THE VERTICAL AND HORIZONTAL COMPONENTS OF THE ARRAY PRETENSION LOADING (AND THE ARRAY BLANKET SAG ANGLE AT OUTER EDGE), ARE AS SHOWN BELOW



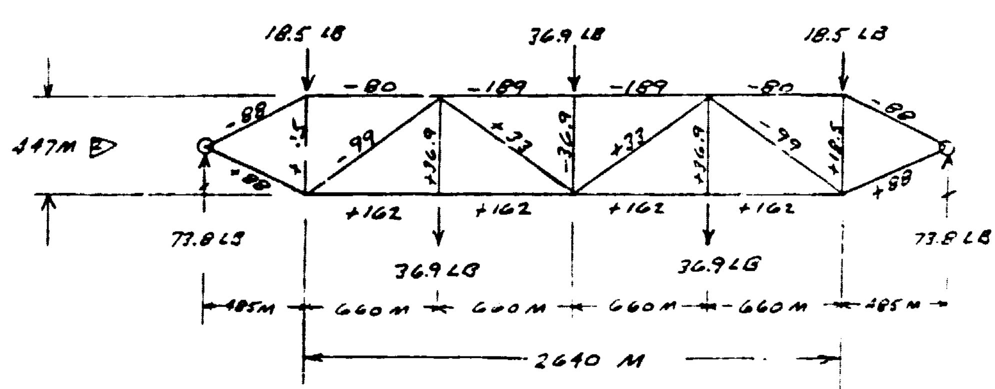
- THE CORRESPONDING LOADS IN THE CRITICAL BEAM ARE

BEAM LOADING (HORIZ.) = 3.899 N/M = 0.0223 LB/IN
BEAM LOADING (VERT.) = 0.066 N/M = 0.0004 LB/IN
COLUMN LOAD = $-(3.899\ N/M)(\frac{1}{2} \times 660\ M)$
= −1287 N = −289 LB ▷

▷ APPLIED (LIMIT) LOADS

d. DELTA LOAD ON CRITICAL BEAM DUE TO MODULE SELF TRANSPORT FROM LEO TO GEO, NO PAYLOAD CASE

- TYPICAL MODULE WEIGHT = 6,500,000 kg ▷
- APPLIED THRUST AT EACH OF FOUR THRUSTER INSTALLATIONS (BASED ON MAX T/W CAPABILITY = 0.0001) ≈ 162.5 kg_f ≈ 73.8 LB_f
- WORST CASE LOADS ACTING ON SECTION CC TRUSS:



- Δ COLUMN LOAD ON CRITICAL BEAM = -189 LB ▷

▷ $\frac{\text{SOLAR ENERGY COLLECTION SYSTEM WT}}{\text{NUMBER OF MODULES}} = \frac{\sim 52,000,000 \text{ kg}}{8} = 6,500,000 \text{ kg}$

▷ $470.33 - 2\left(\frac{2}{3} \times 17.32\right) = 447.24 \text{ M}$ ▷ APPLIED (LIMIT) LOAD

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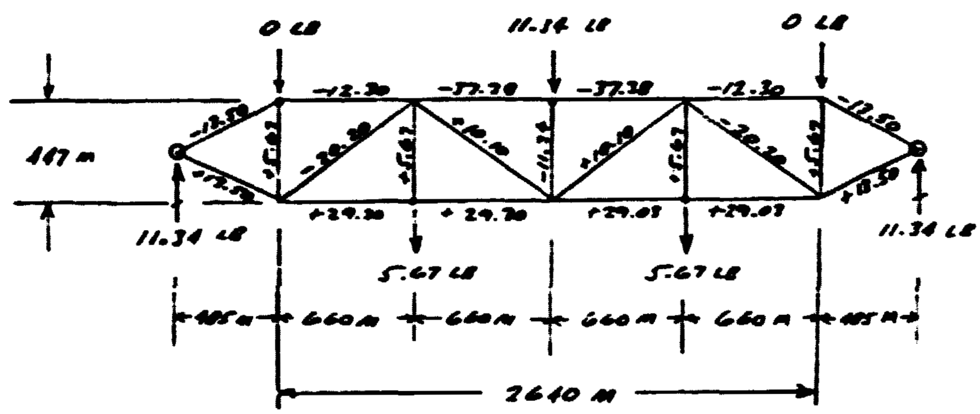
e. DELTA LOAD ON CRITICAL BEAM PER 1,000,000 kg OF PAYLOAD TRANSPORTED FROM LEO TO GEO

- DELTA APPLIED THRUST AT EACH OF FOUR THRUSTER INSTALLATIONS (BASED ON MAX T/W CAPABILITY = 0.0001) = 25 kg_f = 11.34 LB_f

- WORST CASE LOADS ACTING ON SECTION C-C TRUSS:

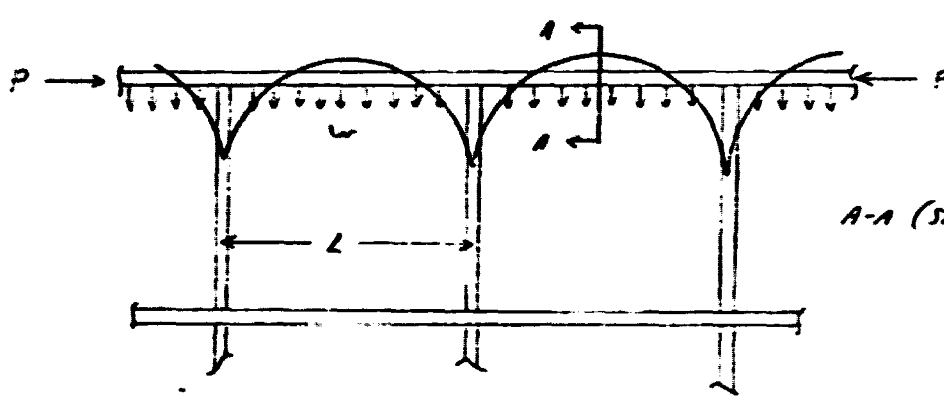


- ΔCOLUMN LOAD ON CRITICAL BEAM = - 37.38 LB / 1,000,000 kg P/L ▷

▷ APPLIED (LIMIT) LOAD

f. EQUATION FOR COLUMN LOAD ON CRITICAL STRUT IN CRITICAL BEAM

TREATING THE CRITICAL BEAMS AS BEING CONTINUOUSLY SUPPORTED, IT FOLLOWS THAT THE MOMENT DIAGRAM IS AS SHOWN BELOW:



A-A (SEE NEXT PAGE)

WHERE

$$M_{MIDSPAN} = \frac{wL^2}{24}$$

AND

$$M_{BEAM\ INTERSECT} = -\frac{wL^2}{12}$$

} ASSUMES BEAM-COLUMN IMPACT ON M.MENTS IS NEGLIGIBLE. ▷

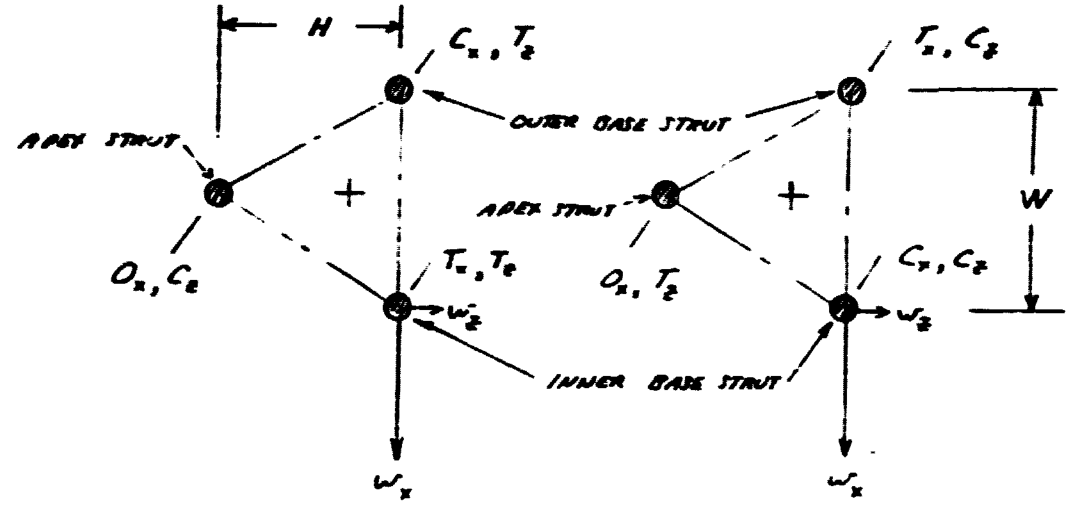
THUS, THE MAXIMUM MOMENT IN THE CRITICAL BEAM OCCURS AT A BEAM INTERSECT LOCATION.

(CONT'D)

▷ THIS ASS[illegible]ON IS VALID SO LONG AS $P/P_{EULER} \approx 1$, WHERE P IS THE APPLIED COMPRESSIVE LOAD ON THE BEAM AND P_{EULER} IS THE EULER LOAD, $k\pi^2 EI/L^2$, CAPABILITY OF THE BEAM. BEAM-COLUMN EFFECTS HAVE BEEN FOUND TO BE NEGLIGIBLE IN ALL BEAM CONFIGURATIONS CONSIDERED TO DATE.

f. (CONT'D)

SECTION A-A IS SHOWN BELOW WITH THE LOAD IN THE STRUTS INDICATED AS COMPRESSION (C), TENSION (T), OR NO LOAD (O).



AS INDICATED, THE CRITICAL STRUT IS THE INNER BASE STRUT AT THE BEAM INTERSECT LOCATION.

THE EQUATION FOR THE DESIGN (ULTIMATE) COLUMN LOAD ON THIS STRUT IS

$$P = \left[\left(\frac{W_x L^2}{12\,W} + \frac{1}{2}\left(\frac{W_z L^2}{12\,H}\right) + \frac{P}{3}\right) \times U.F.S.\right]_{\text{AT BEAM INTERSECT}}$$

WHERE THE $\frac{1}{2}$ FACTOR ACCOUNTS FOR THE COMPRESSION LOAD IN THE BEAM DUE TO THE W_z LOADING BEING CARRIED EQUALLY IN THE TWO BASE STRUTS.

f. LOADS/SIZING SUMMARY

A LOADS/SIZING SUMMARY FOR THE CRITICAL BEAM IN THE UPPER SURFACE IS PRESENTED IN FIGURE C-1. THE SIZING DATA FOR THE CRITICAL STRUT (D_{max} AND t) ARE PER APPENDIX A.

NOTICE, FOR THE FOUR DESIGN CONDITIONS CONSIDERED, THAT THE DESIGN (ULTIMATE) COLUMN LOADS ON THE CRITICAL STRUT ALL FALL WITHIN A FAIRLY NARROW RANGE. THIS SITUATION INDICATES THAT THE ARRAY PRETENSION IS THE MAJOR DRIVER WITH RESPECT TO LOADS.

THE BASELINE DESIGN CONDITION IS: ARRAY PRETENSION, MODULE SELF TRANSPORT, P/L = ANTENNA.

FIGURE C-1

LOADS/SIZING SUMMARY FOR CRITICAL BEAM IN UPPER SURFACE

DESIGN CONDITION	APPLIED (LIMIT) LOADS ON CRITICAL BEAM — UNIFORM LOADING ALONG BEAM		APPLIED (LIMIT) LOADS ON CRITICAL BEAM — COLUMN LOAD ON BEAM	DESIGN (ULTIMATE) COLUMN LOAD ON CRITICAL STRUT	SIZE DATA FOR 20 METER LONG TAPERED TUBE ▷		
	w_x (LB/IN)	w_z (LB/IN)	P (LB)	P ▷ (LB)	D_{max} (IN)	t (IN)	$A_{AVE.}$ (IN²)
• ARRAY PRETENSION	.0223	—	289	2536	12.96	.0191	.510
• ARRAY PRETENSION, MODULE SELF TRANSPORT, NO PAYLOAD	.0223	.0004	478	2655	13.07	.0195	.534
• ARRAY PRETENSION, MODULE SELF TRANSPORT, P/L = 1/4 ANTENNA	.0223	.0004	592	2712	13.12	.0197	.541
→ • ARRAY PRETENSION, MODULE SELF TRANSPORT, P/L = ANTENNA ←	.0223	.0004	934	2883	13.27	.0202	.561

ARRAY PRETENSION = 3.9 NEWTONS/METER
MAX T/W CAPABILITY DURING SELF TRANSPORT = 0.0001
MODULE WEIGHT ≈ 6,500,000 kg
ANTENNA WEIGHT ≈ 12,200,000 kg

→ ← INDICATES BASELINE DESIGN CONDITION

▷ $$P = \left[\left(\frac{w_x L^2}{12\,W} + \frac{1}{2}\left(\frac{w_z L^2}{12\,H}\right) + \frac{P}{3}\right) \times U.F.S.\right]$$

WHERE

$L = 660$ M $= 25{,}984$ IN.
$W = 20$ M $= 787$ IN.
$H = 17.3$ M $= 682$ IN.
U.F.S. $= 1.5$

▷ $D_{MIN} / D_{MAX} = 1/3$

2.1.1

APPENDIX D

WEIGHT ANALYSIS OF 20M BEAM AND 5M BEAM

WEIGHT ANALYSIS OF 20 M BEAM AND 5 M BEAMS

THE GEOMETRY AND COMPONENT NOMENCLATURE FOR THE 20M BEAMS ARE PRESENTED IN FIGURE D-1. THE DATA ALSO APPLIES TO THE 5M BEAMS USED IN THE ANTENNA YOKE ASSEMBLY.

THE WEIGHT DEFINITION FOR A SECTION OF UPPER SURFACE 20M BEAM IS GIVEN IN FIGURE D-2. THE CHORD DIA AND THICKNESS VALUES (D/d/t = 13.3/4.4/.020 IN.) ARE PER APPENDIX C. THE DESIGN CONDITION FOR THE CHORDS IS: ARRAY PRETENSION, MODULE SELF TRANSPORT, P/L = ANTENNA. ALL OTHER TUBE MEMBERS HAVE BEEN SELECTED AS HAVING THE SAME MAXIMUM AND MINIMUM DIAMETERS AS THE CHORDS, BUT A MINIMUM THICKNESS OF .010 IN. THE BEAM UNIT WEIGHT OF 4.24 kg/m CORRESPONDS TO A CHORD STRUT DESIGN END LOAD OF 2003 LB(ULT). FOR THE LOWER SURFACE AND INTRA SURFACE BEAMS, THE CHORD STRUT THICKNESS IS REDUCED TO THE MINIMUM GAGE OF 0.010 IN. THE CORRESPONDING BEAM UNIT WEIGHT IS 3.24 kg/m.

THE VARIATION OF 20M BEAM UNIT WEIGHT WITH CHORD STRUT DESIGN COLUMN LOAD IS PRESENTED IN FIGURE D-3

THE WEIGHT DEFINITION FOR A SECTION OF 5M BEAM IS GIVEN IN FIGURE D-4. THE 5M BEAM IS THE BASIC ELEMENT OF THE ANTENNA YOKE ASSEMBLY. TUBE SIZING IS A GUESSESTIMATE.

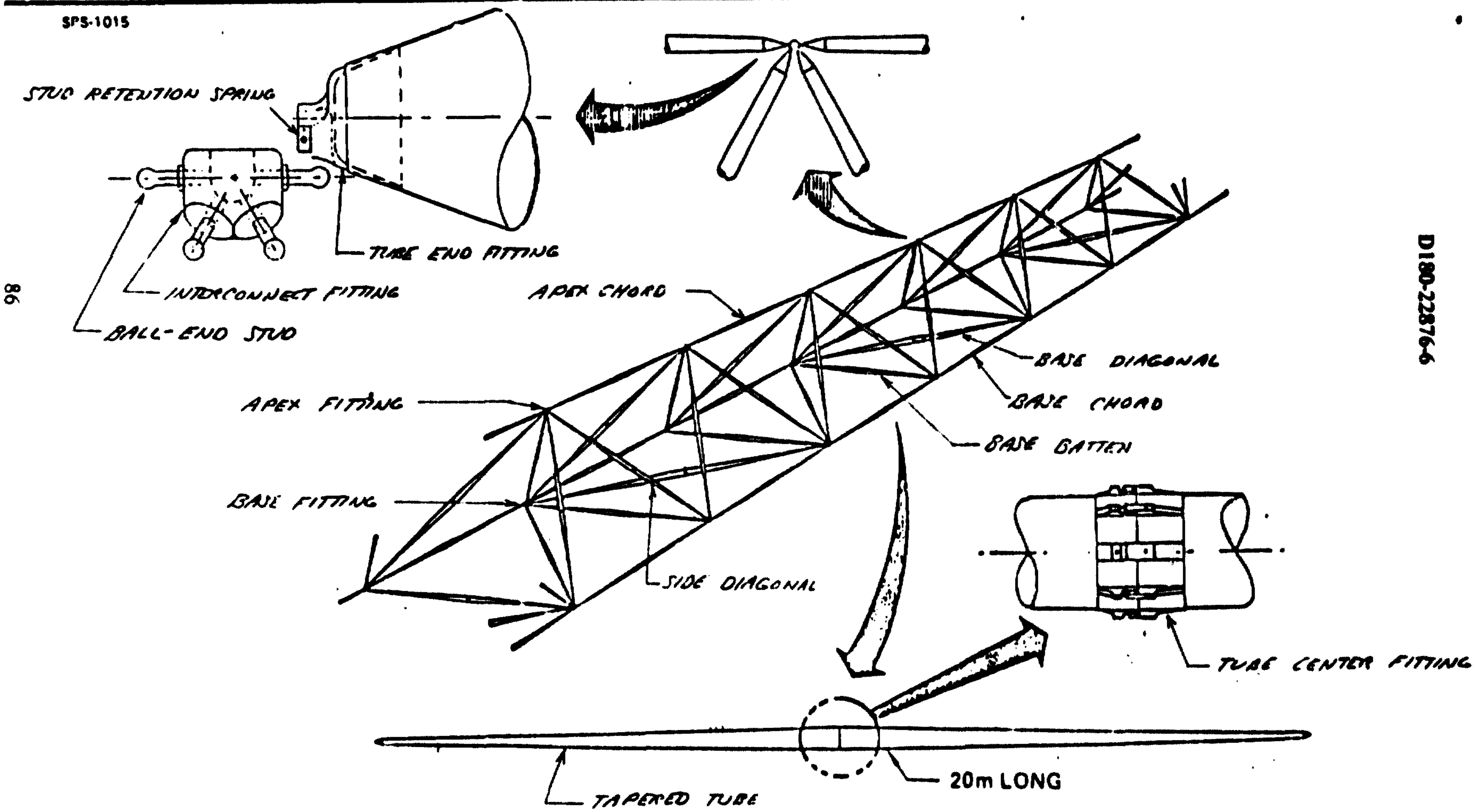
GEOMETRY AND VOLUME DATA FOR THE COMPONENTS OF THE 20M BEAM AND 5M BEAM ARE PRESENTED ON PAGES D.7 THRU D.17.

FIGURE D-1

Photovoltaic Reference
20 Meter Beam Structure

BOEING

SPS-1015



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87

FIGURE D-2
WEIGHT DEFINITION FOR 20M BEAM SECTION
(UPPER SURFACE BEAMS)

CHORD STRUT DESIGN END LOAD = 2883 LB (ULT.)

ITEM	MATERIAL	PRINCIPAL DIMENSIONS (IN.)	WT/ITEM (LB)	NO. OF ITEMS	TOTAL WT (LB)
TAPERED TUBES:					(169.20)
CHORD HALF SECTION	G/E	D = 13.3, d = 4.4, L = 386.9, t = .020	13.12	6	78.72
SIDE DIAGONAL HALF SECTION	"	" " 433.4 t = .010	7.34	8	58.72
BASE DIAGONAL HALF SECTION	"	" " 549.9 "	9.32	2	18.64
BASE BATTEN HALF SECTION	"	" " 386.9 "	6.56	2	13.12
TUBE CENTER JOINTS					(10.98)
CHORD CTR. JOINT HALF SECTION	ALUM	FITS TUBE END WITH D = 13.3	0.61	6	3.66
DIAG./BATTEN CTR. JT. HALF SECTION	"	" " " " "	"	12	7.32
TUBE END FITTINGS					(5.18)
CHORD END FITTING	ALUM	FITS TUBE END WITH d = 4.4	0.28	6	1.68
DIAG./BATTEN END FITTING	"	" " " " "	"	12	3.36
STUD RETENTION SPRING	INCONEL		0.002	36	0.07
SPRING INSTALLATION BOLT	STEEL		0.0009	72	0.06
SPRING INSTALLATION NUT	"		0.0003	36	0.01
STRUT INTERCONNECT FITTINGS					(1.40)
APEX FITTING	ALUM	L = 2.25, W = 2.25, H = 1.65	0.35	1	0.35
BASE FITTING	"	" W = 1.65 "	0.30	2	0.60
BALL-END STUD	STEEL	D_{BALL} = 0.375, L = 1.35	0.025	18	0.45
				219	186.76 LB (4.24 kg/m)

NOTE: FOR LOWER SURFACE BEAMS AND INTRA SURFACE BEAMS, USE 147.40 LB (3.34 kg/m) BASED ON CHORD THICKNESS = 0.010 IN.

FIGURE D-3 VARIATION OF 20 METER BEAM UNIT WEIGHT WITH CHORD STRUT DESIGN END LOAD

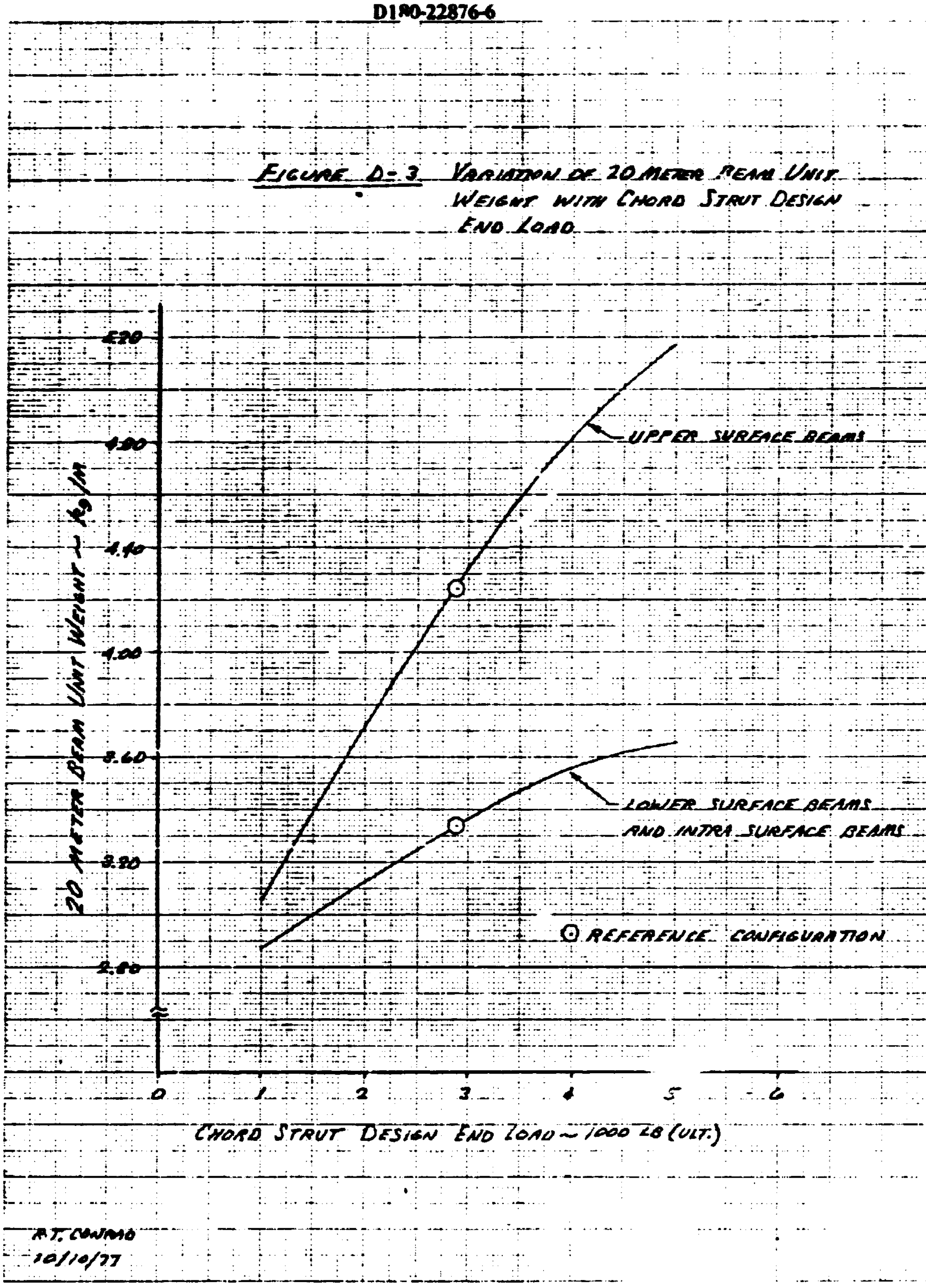


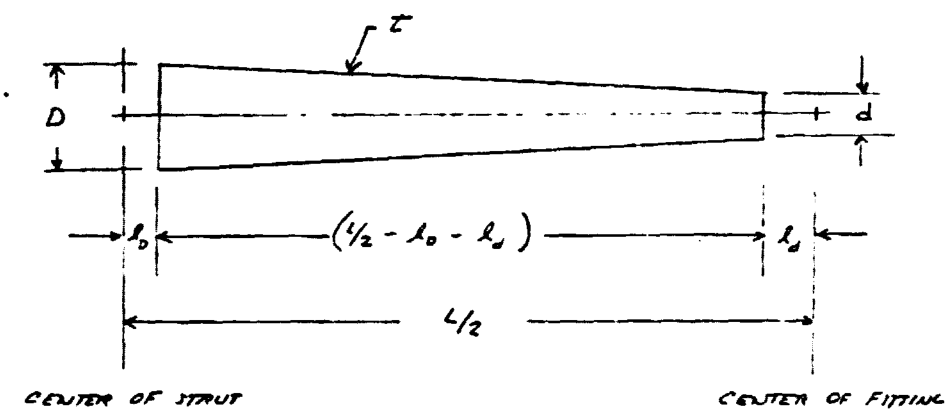
FIGURE D-3

WEIGHT DEFINITION FOR 5M BEAM SECTION
(BEAMS FOR ANTENNA YOKE ASSEMBLY)

ITEM	MATERIAL	PRINCIPAL DIMENSIONS (IN.)	WT/ITEM (LB)	NO. OF ITEMS	TOTAL WT (LB)
TAPERED TUBES					(10.10)
CHORD HALF SECTION	G/E	D = 5.0, d = 1.7, L = 95, t = .008	0.51	6	3.06
SIDE DIAGONAL HALF SECTION	"	" " L = 107 "	0.57	8	4.56
BASE DIAGONAL HALF SECTION	"	" " L = 136 "	0.73	2	1.46
BASE BATTEN HALF SECTION	"	" " L = 95 "	0.51	2	1.02
TUBE CENTER JOINTS					(4.14)
CHORD CTR. JOINT HALF SECTION	ALUM	FITS TUBE END WITH D = 5.0	0.23	6	1.38
DIAG./BATTEN CTR. JT. HALF SECTION	"	" " " " "	"	12	2.76
TUBE END FITTINGS					(2.12)
CHORD END FITTING	ALUM	FITS TUBE END WITH d = 1.7	0.11	6	0.66
DIAG./BATTEN END FITTING	"	" " " " "	"	12	1.32
STUD RETENTION SPRING	INCONEL		0.002	36	0.07
SPRING INSTALLATION BOLT	STEEL		0.0009	72	0.06
SPRING INSTALLATION NUT	"		0.0003	36	0.01
STRUT INTERCONNECT FITTINGS					(1.40)
APEX FITTING	ALUM	L = 2.25, W = 2.25, H = 1.65	0.35	1	0.35
BASE FITTING	"	" W = 1.65 "	0.30	2	0.30
BALL-END STUD	STEEL	D_{BALL} = 0.375, L = 1.35	0.025	18	0.45
				219	17.76 LB

(1.61 kg/m)

GEOMETRY AND VOLUME OF TUBE HALF SECTION

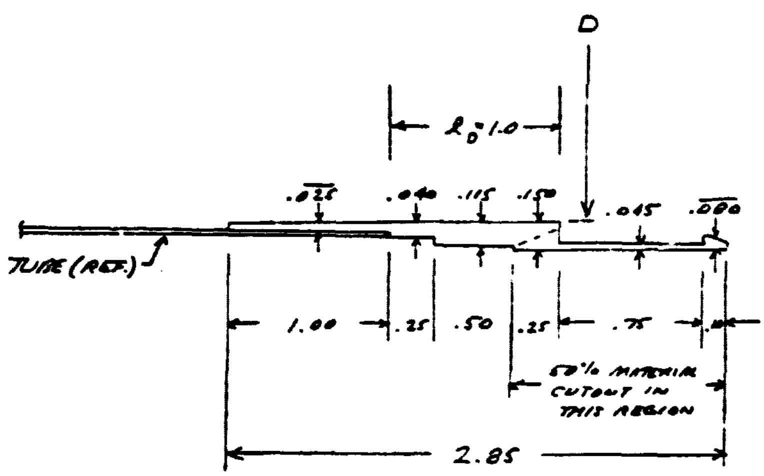


$$\text{MAT'L VOLUME} = \pi \left(\frac{D+d}{2} \right) \left(\frac{L}{2} - \ell_D - \ell_d \right) t$$

	TUBE	D (IN)	d (IN)	L (M)	L (IN)	ℓ_D (IN)	ℓ_d (IN)	$(L/2-\ell_D-\ell_d)$ (IN)	t (IN)	V (IN³)
20M BEAM	CHORD*	▷1 13.3	4.4	20.00	787.4	1.0	5.8	386.9	▷1 .020	215.0
	CHORD	13.3	4.4	20.00	787.4	1.0	5.8	386.9	.010	107.5
	SIDE DIAGONAL	13.3	4.4	22.36	880.3	1.0	5.8	433.4	.010	120.4
	BASE DIAGONAL	▷2 13.3	4.4	28.28	1113.4	1.0	5.8	549.9	▷2 .010	152.8
	BASE BATTEN	13.3	4.4	20.00	787.4	1.0	5.8	386.9	.010	107.5
5M BEAM	CHORD	5	1.7	5.00	196.9	1.0	2.5	95.0	.008	8.79
	SIDE DIAGONAL	5	1.7	5.59	220.1	1.0	2.5	106.6	.008	9.87
	BASE DIAGONAL	▷2 5	1.7	7.07	278.3	1.0	2.5	135.7	▷2 .008	12.56
	BASE BATTEN	5	1.7	5.00	196.9	1.0	2.5	95.0	.008	8.79

* UPPER SURFACE ONLY. ▷1 SIZING PER APPENDIX C. ▷2 SIZING ESTIMATED.

GEOMETRY OF TUBE CENTER JOINT HALF SECTION



* SAME CROSS SECTION AS USED ON 4.00 DIA (REF) SNAP LOCK DEMONSTRATION FITTING (SEE ATTACHED DRAWING)

VOLUME OF TUBE CENTER JOINT HALF SECTION

$$\text{AVE. CROSS SECTION AREA} = (1.00 \times .\overline{025}) + (.25 \times .040) + (.50 \times .115) + \tfrac{1}{2}(.25 \times .150) + \tfrac{1}{2}(.75 \times .045) + \tfrac{1}{2}(.10 \times .\overline{080})$$

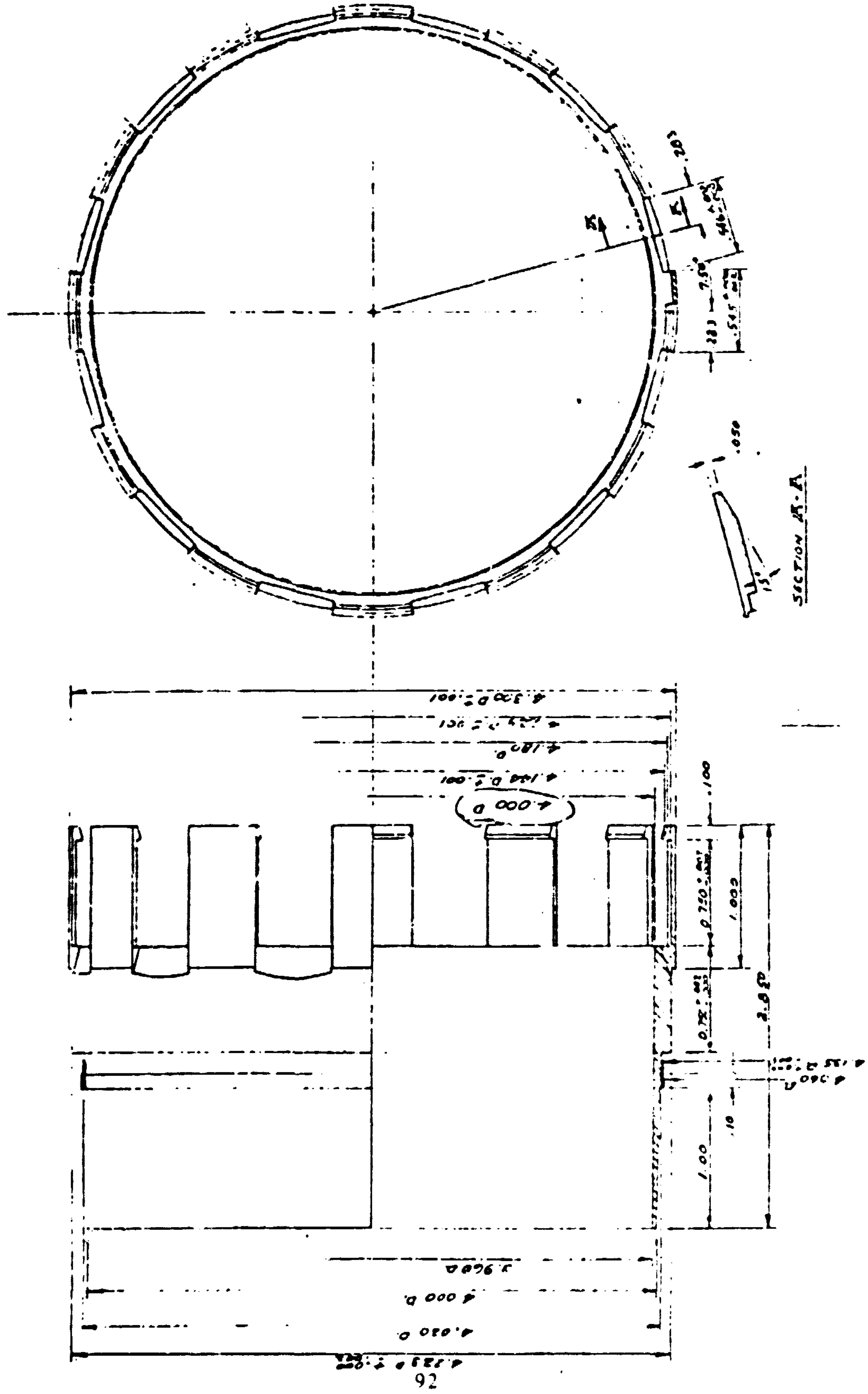
$$= .0250 + .0100 + .0575 + .0188 + .0169 + .0040$$

$$= 0.1322 \text{ IN}^2$$

$$\text{MAT'L VOLUME} \approx \pi \, D \, A \times k_{\text{TOLERANCES}}$$

→ USE 1.10

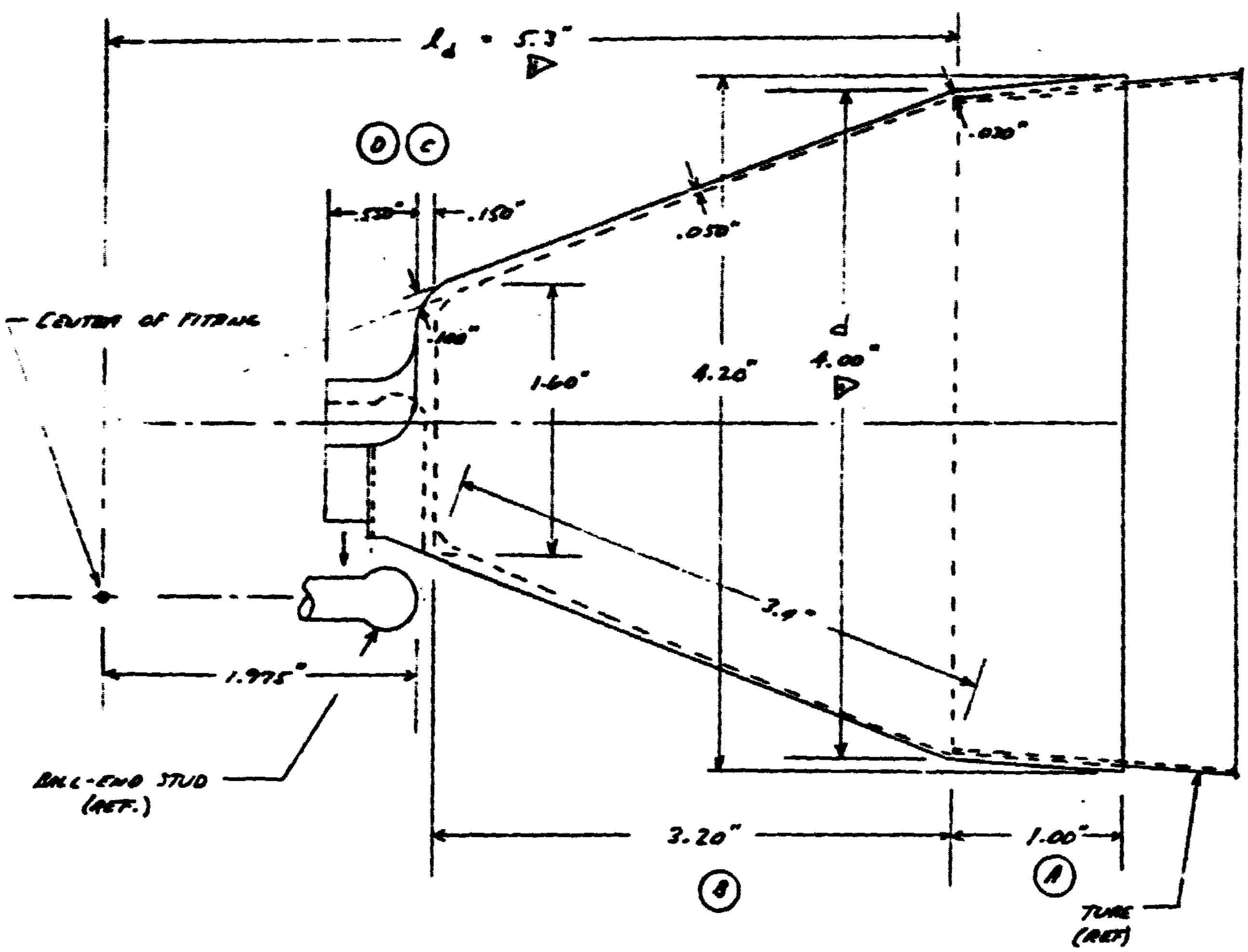
$$\approx \pi \, D \, (0.1322) \times 1.10 \approx 0.46 \, D$$



TUBE CENTER JOINT HALF SECTION

GEOMETRY OF TUBE END FITTING (4")

SCALE: FULL SIZE



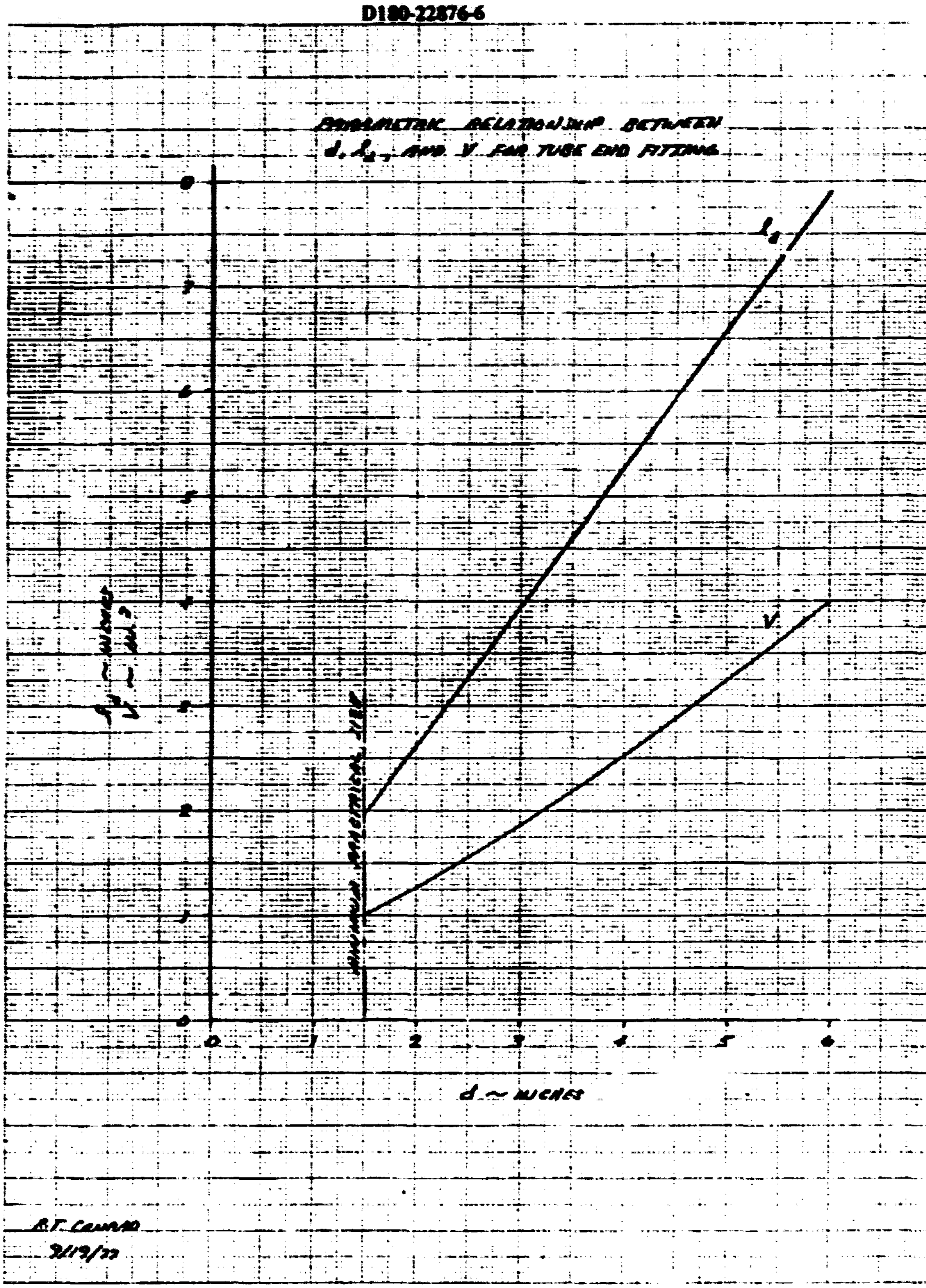
VOLUME OF TUBE END FITTING (4")

$$V = (V_A + V_B + V_C + V_D) \times k_{\text{TOLERANCES \& FILLETS}} \quad (\rightarrow \text{USE } 1.10)$$

$$= \left\{ (\pi \times 4.1 \times .020)(1.00) + \pi \left[\frac{(4 \times .030) + (2.8 \times .050) + (1.6 \times .100)}{3} \right] (3.4) + \frac{\pi}{4}(1.6)^2(.150) + 0.30_{\text{EST.}} \right\} 1.10$$

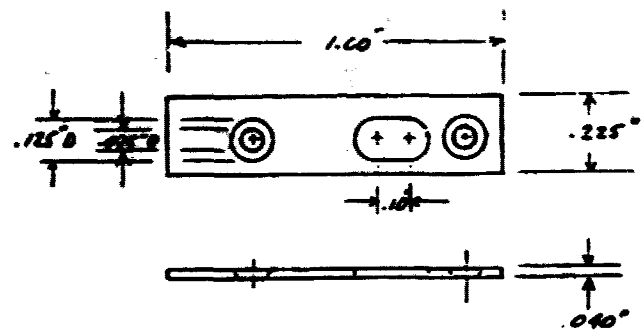
$$= (0.39 + 1.49 + 0.30 + 0.30)1.10 = 2.53 \text{ IN}^3$$

PARAMETRIC RELATIONSHIP BETWEEN d, ℓ_d, AND V GIVEN ON NEXT PAGE.


PARAMETRIC RELATIONSHIP BETWEEN
d, ℓ, AND V FOR TUBE END FITTING
ℓ
V
ℓ ~ INCHES
V ~ IN.³
MINIMUM PRACTICAL SIZE
d ~ INCHES
0
1
2
3
4
5
6
7
8
R.T. CONRAD
9/19/77

GEOMETRY OF STUD RETENTION SPRING

SCALE: TWICE SIZE, FLAT PATTERN



VOLUME OF STUD RETENTION SPRING

$$V = V_{ENCLOSED} - V_{BOLT\ INSTALLATION\ HOLE} - V_{COUNTERSUNK\ HOLES}$$

$$= (1.00 \times 0.225)(.040)$$

$$- \left(\frac{\pi}{4}(.125)^2 + (.225 \times .10)\right)(.040)$$

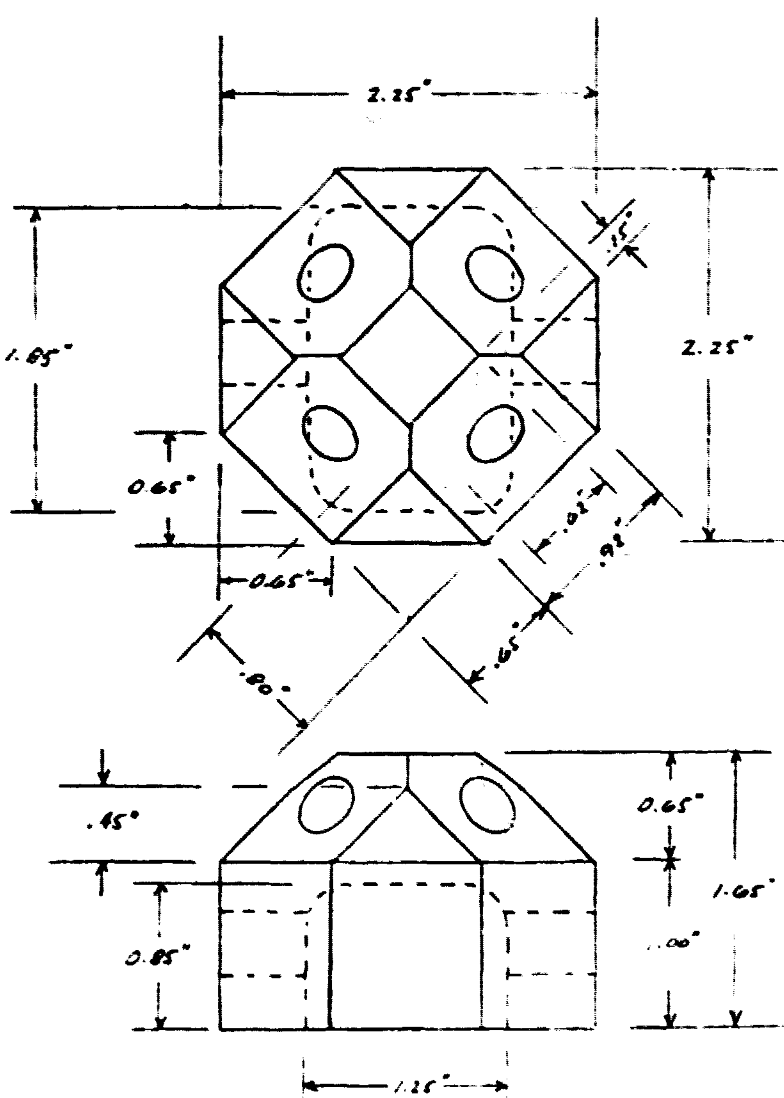
$$- \left(\frac{\pi}{4}(.\overline{10})^2 \times 2\right)(.040)$$

$$= 0.0090 - 0.0014 - 0.0006$$

$$= 0.0070\ IN^3$$

GEOMETRY OF APEX CHORD FITTING

SCALE: FULL SIZE



INSIDE FILLET RADIUS = 0.25"

HOLE DIAMETER = 0.250"

VOLUME OF APEX CHORD FITTING

$$V_{LOWER\ SECTION} = \left[(2.25 \times 2.25 \times 1.00) - 4\left(\tfrac{1}{2} \times .65 \times .65 \times 1.00\right)\right]_{ENCLOSED\ VOLUME}$$

$$- \left[(1.85 \times 1.25 \times .85) - 2\left((1.85 - .25) + (1.25 - .25)\right)\left(1 - \tfrac{\pi}{4}\right)(.25)^2\right]_{CUTOUT}$$

$$- \left[\left(\tfrac{\pi}{4}(.250)^2 \times .\overline{50}\right) \times 2\right]_{STUD\ HOLES}$$

$$= 4.22 - 1.90 - 0.05$$

$$= 2.27\ IN^3$$

$$V_{UPPER\ SECTION} = \left[(.62 \times .62 \times .65)\right.$$

$$+ 4\left(\tfrac{1}{2} \times .80 \times .45 \times .92\right) - 4\left(\tfrac{1}{2} \times .15 \times .15 \times .\overline{60}\right)$$

$$\left. + 4\left(\tfrac{1}{4} \times .65 \times .65 \times .45\right)\right]_{ENCLOSED\ VOLUME}$$

$$- \left[\tfrac{\pi}{4}(.250)^2 \times .\overline{50}) \times 4\right]_{STUD\ HOLES}$$

$$= 1.37 - 0.10$$

$$= 1.27\ IN^3$$

$$V_{TOTAL} = V_{LOWER\ SECTION} + V_{UPPER\ SECTION}$$

$$= 2.27 + 1.27$$

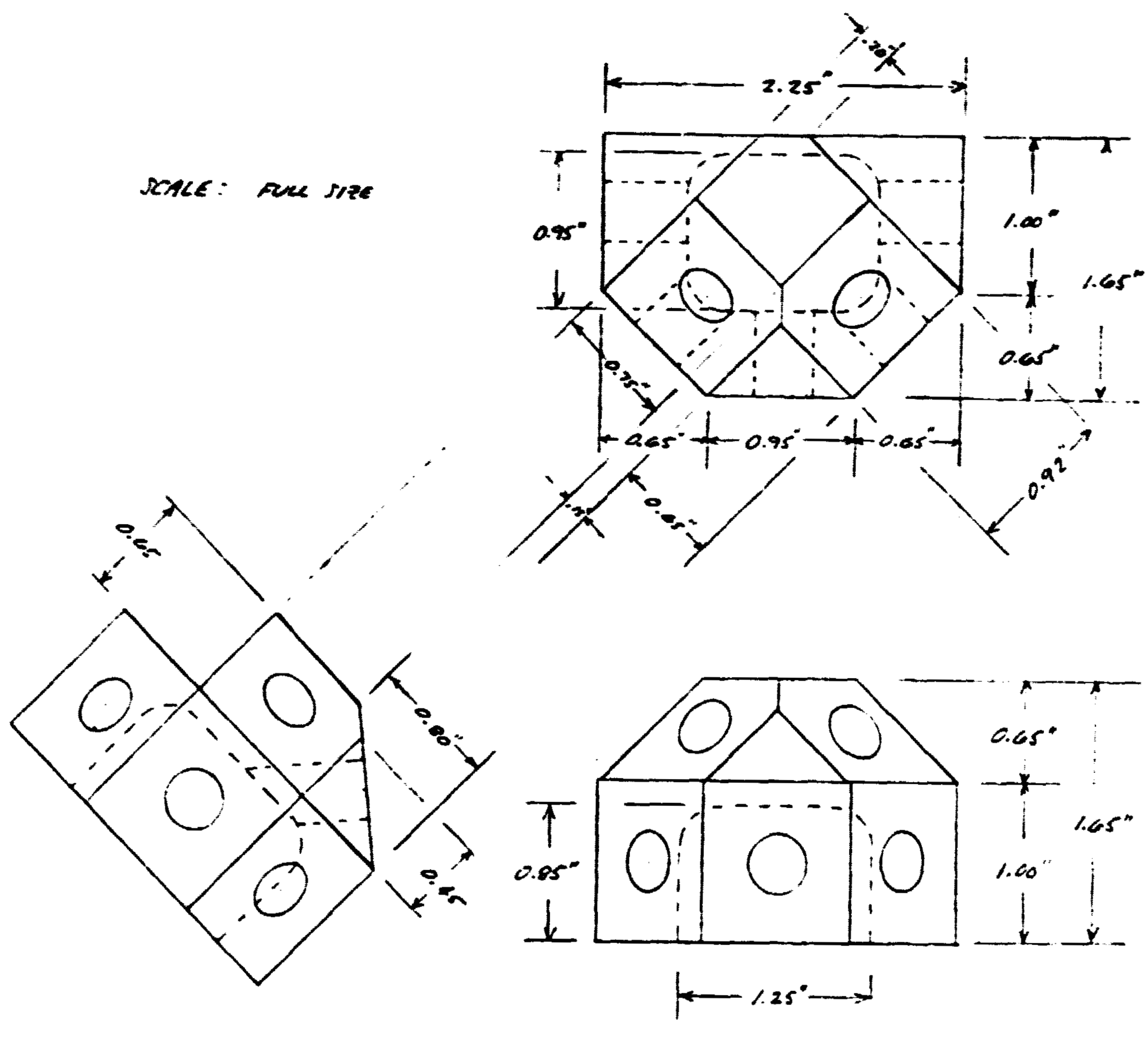
$$= 3.54\ IN^3$$

$$\frac{V_{MATERIAL}}{V_{ENVELOPE}} = \frac{3.54}{2.25 \times 2.25 \times 1.65} = \frac{3.54}{8.35} = 42\%$$

ORIGINAL PAGE IS
OF POOR QUALITY

GEOMETRY OF BASE CHORD FITTING

SCALE: FULL SIZE



INSIDE FILLET RADIUS = 0.25"

HOLE DIAMETER = 0.250"

VOLUME OF BASE CHORD FITTING

$$V_{LOWER\ SECTION} = \left[(2.25 \times 1.65 \times 1.00) - 2\left(\tfrac{1}{2} \times .65 \times .65 \times 1.00\right)\right]_{\substack{ENCLOSED\\VOLUME}}$$

$$- \left[(1.25 \times 0.95 \times 0.85) - \left(4 \times (1.25 - .25) \times \left(1 - \tfrac{\pi}{4}\right)(.25)^2\right)\right]_{CUTOUT}$$

$$- \left[\left(\tfrac{\pi}{4}(.250)^2 \times .\overline{40}\right) \times 5\right]_{\substack{STUD\\HOLES}}$$

$$= 3.29 - 0.96 - 0.10$$

$$= 2.23 \quad IN^3$$

$$V_{UPPER\ SECTION} = \left[(.75 \times .75 \times 0.65) - \left(\tfrac{1}{2} \times .20 \times .20 \times .65\right)\right.$$

$$+ 2\left(\tfrac{1}{2} \times .80 \times .65 \times .72\right) - 2\left(\tfrac{1}{2} \times .15 \times .15 \times .\overline{60}\right)$$

$$\left. + \left(\tfrac{1}{4} \times .65 \times .65 \times .45\right)\right]_{\substack{ENCLOSED\\VOLUME}}$$

$$- \left[\left(\tfrac{\pi}{4}(.250)^2 \times .\overline{50}\right) \times 2\right]_{\substack{STUD\\HOLES}}$$

$$= 0.87 - 0.05$$

$$= 0.82 \quad IN^3$$

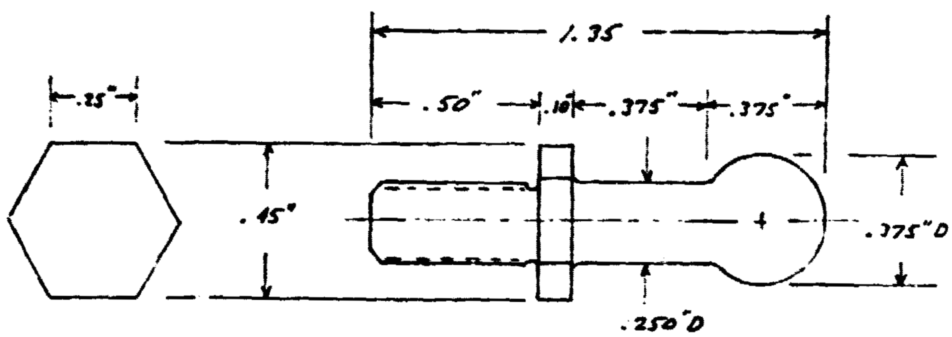
$$V_{TOTAL} = V_{LOWER\ SECTION} + V_{UPPER\ SECTION}$$

$$= 2.23 + 0.82$$

$$= 3.05 \quad IN^3$$

$$\frac{V_{MATERIAL}}{V_{ENVELOPE}} = \frac{3.05}{2.25 \times 1.65 \times 1.65} = \frac{3.05}{6.13} = 50\%$$

GEOMETRY OF BALL-END STUD



SCALE: TWICE SIZE

VOLUME OF BALL-END STUD

$$V = V_{\text{THREADED SECTION}} + V_{\text{HEX NUT SECTION}} + V_{\text{SHANK SECTION}} + V_{\text{BALL SECTION}}$$

$$= 0.9\left(\frac{\pi}{4}\right)(.25)^2(.50) + 6\left(\frac{1}{2} \times .25 \times .225\right)(.10) + \frac{\pi}{4}(.25)^2(.375) + \frac{\pi}{6}(.375)^3$$

= $0.022 + 0.017 + 0.018 + 0.0$[illegible]

$$= 0.085 \text{ IN}^3$$

2.1.1

APPENDIX E

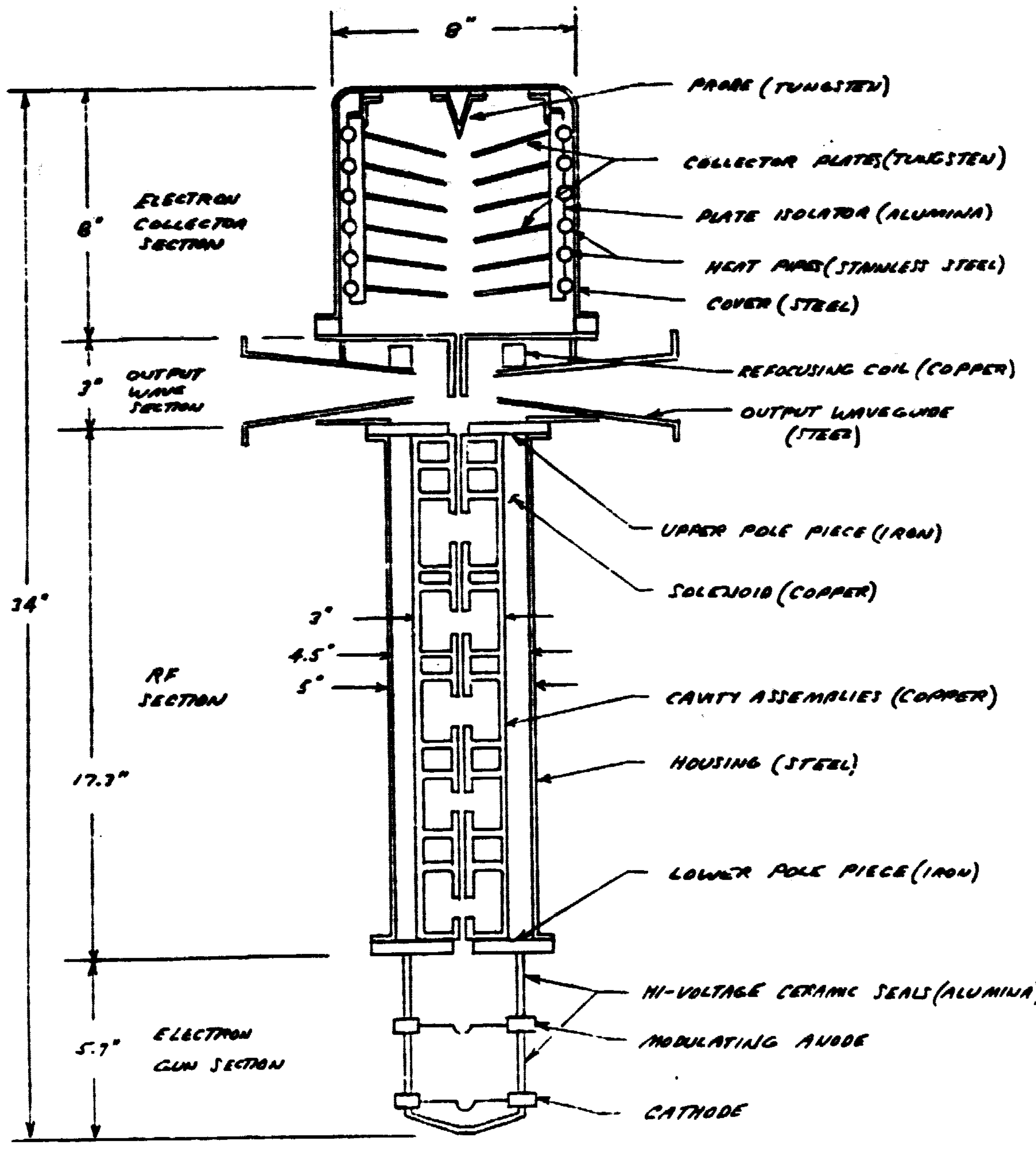
WEIGHT ANALYSIS OF 70KW KLYSTRON

WEIGHT ANALYSIS OF 70KW KLYSTRON

THE GEOMETRY AND COMPONENT NOMENCLATURE FOR A CONCEPTUAL VERSION OF A 70 KW KLYSTRON ARE PRESENTED IN FIGURE E-1. A WEIGHT DEFINITION FOR THE TUBE IS GIVEN IN FIGURE E-2. SUPPORTING DETAILS ARE PROVIDED ON PAGE E.5 THRU E.11.

FIGURE E-1

CROSS SECTION VIEW OF CONCEPTUAL VERSION OF 70KW KLYSTRON



R.T. Conrad
7/20/77

FIGURE E-2

WEIGHT DEFINITION FOR 70 KW KLYSTRON

ITEM	MAT'L	PRINCIPAL DIMENSIONS (IN.)	WEIGHT (LB)	
SOLENOID		OD = 4.5, ID = 3.0, L = 16.5		36.1
WIRE	COPPER	(75% OF SOLENOID VOLUME)	35.3	
INSULATION	ALUMINA	(5% OF SOLENOID VOLUME)	0.8	
CAVITIES ASSEMBLY	COPPER	D = 7.0, L = 16.5, $\bar{t}$ = 0.375		16.4
POLE PIECES (2)	IRON	D = 6.0, d = 1.0, $\bar{t}$ = 0.40		6.2
SOLENOID SHELL	STEEL	D = 5.0, L = 16.5, $\bar{t}$ = 0.125		9.3
COLLECTOR PLATES, PROBE				10.2
PLATE NO. 1 (LWR)	TUNGSTEN	D = 6.0, d = 2.0, H = 0.3, t = 0.210	3.7	
PLATE NO. 2	"	" " H = 0.4, t = 0.120	2.1	
PLATE NO. 3	"	" " H = 0.5, t = 0.060	1.1	
PLATE NO. 4	"	" " H = 0.6, t = 0.030	0.5	
PLATE NO. 5	"	" " H = 0.7, t = 0.030	0.6	
PLATE NO. 6 (UPR)	"	" " H = 0.8, t = 0.110	2.1	
PROBE	"	D = 1.0, d = 0, H = 1.5, t = 0.060	0.1	
COLLECTOR PLATE ISOLATOR	ALUMINA	OD = 7.2, ID = 6.0, H = 6.1, $\bar{t}$ = 0.48		6.4
COLLECTOR SECTION COVER	STEEL	D = 8.0, H = 7.5, t = 0.050		4.4
OTHER COMPONENTS: REFOCUSING COIL, HEAT PIPES, HI-VOLTAGE CERAMIC SEALS, MODULATING ANODE/CONNECTOR, CATHODE/CONNECTOR, HEATER, OUTPUT WAVE GUIDES (2), VAC. ION CONNECTOR, CAVITY TUNING PROVISIONS, INTERNAL CABLING, ETC., AND ASSEMBLY AND INSTALLATION HARDWARE.				17.0
				(106 LB)

PRELIMINARY WEIGHT ESTIMATE
FOR 70KW KLYSTRON

SOLENOID (COPPER WIRE + ALUMINA INSULATION) — 36.1 LB

OD = 4.5", ID = 3.0", L = 16.5"

VOLUME DISTRIBUTION IS 75% COPPER,
5% ALUMINA INSULATION, 20% EMPTY SPACE.

$$VOL = \frac{\pi}{4}(D^2 - d^2)L$$

$$= \frac{\pi}{4}(4.5^2 - 3.0^2)\,16.5$$

$$= 146 \text{ IN}^3$$

$$W_{COPPER} = (0.322 \text{ LB/IN}^3)(0.75 \times 146 \text{ IN}^3) = 35.3 \text{ LB}$$

$$W_{ALUMINA} = (0.107 \text{ LB/IN}^3)(0.05 \times 146 \text{ IN}^3) = 0.8 \text{ LB}$$

CAVITIES ASSEMBLY (COPPER) — 16.4 LB

OD = 3.0", L = 16.5", $\bar{t}$ = 0.375

$$VOL = \frac{\pi}{4}(D^2 - d^2)L$$

$$= \frac{\pi}{4}(3.0^2 - 2.25^2)\,16.5$$

$$= 51 \text{ IN}^3$$

$$W = (0.322 \text{ LB/IN}^3)(51 \text{ IN}^3) = 16.4 \text{ LB}$$

POLE PIECES (IRON) 6.2 LB

$OD = 6''$, $ID = 1''$, $t = 0.4''$

$VOL = \frac{\pi}{4}(D^2 - d^2)t$

$= \frac{\pi}{4}(6^2 - 1^2)0.4$

$= 11\ IN^3$ / POLE PIECE

$WT = (0.283\ LB/IN^3)(11\ IN^3) \times 2 = 6.2\ LB$

SOLENOID SECTION OUTER SHELL (STEEL) 9.3 LB

$OD = 5.0$, $L = 16.5$, $t = 0.125''$

$VOL = \frac{\pi}{4}(D^2 - d^2)L$

$= \frac{\pi}{4}(5.00^2 - 4.75^2)16.5$

$= 32\ IN^3$

$WT = (0.29?\ LB/IN^3)(32\ IN^3) = 9.3\ LB$

COLLECTOR PLATES/PROBE (TUNGSTEN) 10.2 LB

PLATE SHAPE IS FRUSTRUM OF CIRCULAR CONE
PROBE SHAPE IS CIRCULAR CONE

SURFACE AREA OF PLATE/PROBE = $\pi\left(\frac{D+d}{2}\right)\sqrt{H^2+\left(\frac{D-d}{2}\right)^2}$

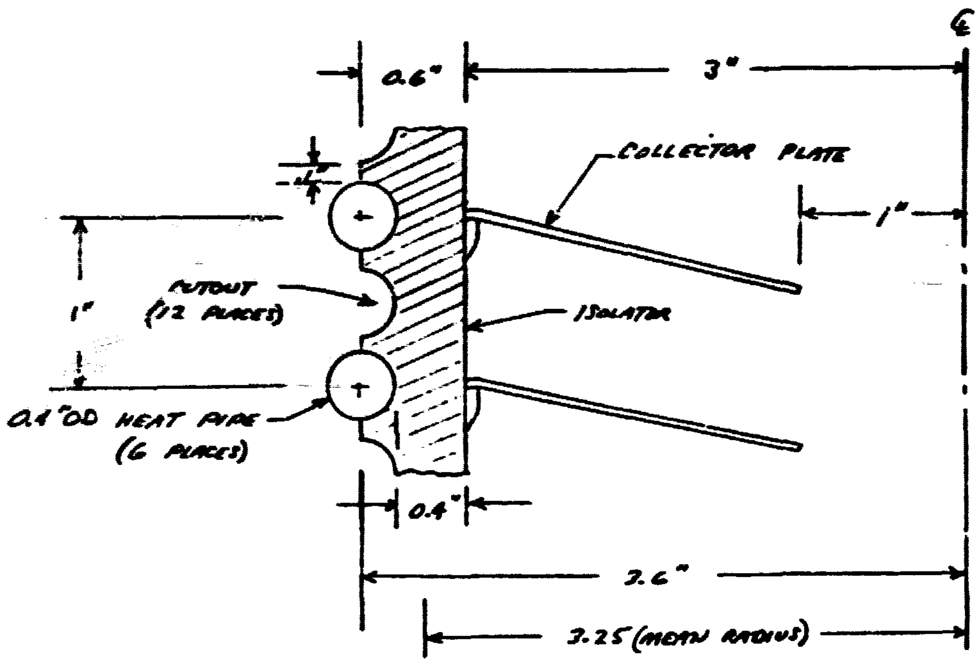
TUNGSTEN DENSITY IS 0.697 LB/IN³

	ITEM	D (IN)	d (IN)	H (IN)	S (IN²)	T (IN)	WT (LB)
(BOTTOM)	PLATE 1	6	2	0.3	25.4	0.210	3.7
	PLATE 2	✓	✓	0.4	25.6	0.120	2.1
	PLATE 3	✓	✓	0.5	25.9	0.060	1.1
	PLATE 4	✓	✓	0.6	26.2	0.030	0.5
↓	PLATE 5	✓	✓	0.7	26.6	0.030	0.6
(TOP)	PLATE 6	✓	✓	0.8	27.1	0.110	2.1
	PROBE	1	0	1.5	2.5	0.060	0.1

TOTAL = 10.2 LB

<u>COLLECTOR PLATE ISOLATOR (ALUMINUM)</u> <u>6.4 LB</u>

ASSUME CROSS SECTION GEOMETRY AS SHOWN BELOW



CROSS SECTION AREA THRU ISOLATOR = (HEIGHT × WIDTH) − (SCALLOPING)

$= (6.1^{▷} \times 0.6) - \left[\frac{\pi}{8}(0.4)^2 \times 12\right]$

$= 3.66 - 0.75$

$= 2.91 \text{ IN}^2$ $\qquad \bar{\varepsilon} = \frac{2.91}{3.66} \times .60 = .48$

$WT = \rho A$ (MEAN CIRCUMFERENCE)

$= (0.107 \text{ LB/IN}^3)(2.91 \text{ IN}^2)(2\pi \times 3.25 \text{ IN.}) = 6.4 \text{ LB}$

▷ $H = (12 \times .4) + (13 \times .1) = 6.1"$

<u>COLLECTOR SECTION COVER</u> (STEEL) — <u>4.4 LB</u>

OD = 8"; L = 7.5", ATTACH FLANGE WIDTH = .75"

USE 0.050 STAINLESS STEEL

$S = S_{TOP} + S_{SIDES} + S_{ATTACH\ FLANGE}$

$= \frac{\pi}{4}(8)^2 + \pi(8)(7.5) + \frac{\pi}{4}(9.5^2 - 8^2)$

$= 50 + 188 + 21$

$= 259 \text{ IN}^2$

$WT = k \rho t S$

$= 1.15(0.290)(.050)(259)$

$= 4.4 \text{ LB}$

<u>REFOCUSING COIL</u> (COPPER WIRE + ALUMINA INSULATION) — <u>2.2 LB</u>

OD = 4.5", ID = 3.0", L = 1"

VOLUME DISTRIBUTION IS 75% COPPER,
5% ALUMINA INSULATION, 20% EMPTY SPACE.

$VOL = \frac{\pi}{4}(4.5^2 - 3.0^2)1.0$

$= 8.8 \text{ IN}^3$

$W_{COPPER} = (0.322)(.75 \times 8.8) = 2.2$

$W_{ALUMINA} = (0.107)(.05 \times 8.8) = \text{NEG}$

COLLECTOR SECTION HEAT PIPES (STAINLESS STEEL/MERCURY) 2.6 LB

a. STRUCTURE

USE 316 STAINLESS STEEL (ANNEALED CONDITION) TUBING WITH 0.40" O.D AND 0.036" I.D.

$$W = k \rho A L \times 6$$

$$= 1.33\,(0.290)\,\frac{\pi}{4}\,(.40^2 - .36^2)\,\big[(\pi \times 7.2) + 10\big] \times 6$$

(bracketed term $= 32.6$; ▷ on the 10)

$$= 1.8 \text{ LB}$$

b. WICKS

USE STAINLESS STEEL WIRE MESH (20 MESH) WITH 12 MIL THICKNESS AND 80% POROSITY.

$$W = k \rho S t (1 - F_{POROSITY}) \times 6$$

$$= 1.0 (0.290)(\pi \times 0.35 \times 32.6)(.012)(1 - 0.80) \times 6$$

($\pi \times 0.35 \times 32.6 = 35.8$)

$$= 0.15 \text{ LB}$$

c. MERCURY

MERCURY IN WICKS. WICKS ARE 12 MIL THICK AND 80% POROUS. ASSUME 60% OF THIS VOLUME IS FILLED WITH MERCURY

$$W = k \rho S t (F_{POROSITY})(F_{MERCURY}) \times 6$$

$$= 1.0 (0.490)(35.8)(0.012)(0.8)(0.6) \times 6$$

$$= 0.6 \text{ LB}$$

▷ LENGTH OF PIPE SECTION EXTENDING FROM HOUSING.

<u>OUTPUT GAP AND BODY HEAT PIPES</u> (STAINLESS STEEL/MERCURY) **<u>1.7 LB</u>**

USE 4 PIPES SIMILAR TO COLLECTOR SECTION PIPES

STRUCTURE	4 × 0.3	= 1.2
WICKS	4 × 0.025	= 0.1
MERCURY	4 × 0.1	= 0.4

<u>HI-VOLTAGE CERAMIC SEALS</u> (ALUMINA) **<u>0.5 LB</u>**

O.D. = 3.5, I.D. = 3.3, L = 2.0"

$VOL = \frac{\pi}{4}(3.5^2 - 3.3^2)\,2.0 = 2.1\ IN^3/SEAL$

$WT = (0.107)(2.1) \times 2\ SEALS = 0.5\ LB$

<u>OTHER COMPONENTS</u> **<u>10.0 LB</u>**

MODULATING ANODE/CONNECTOR
CATHODE/CONNECTOR
HEATER/CONNECTOR
OUTPUT WAVEGUIDES (2)
VAC. ION CONNECTOR
CAVITY TUNING PROVISIONS
ELECTRICAL CABLING - INTERNAL
ASSEMBLY AND INSTALLATION HARDWARE

2.1.1

APPENDIX F

SCALING RELATIONSHIPS FOR COLUMN LOAD ON CRITICAL STRUT IN CRITICAL BEAM

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SCALING RELATIONSHIPS FOR COLUMN LOAD ON CRITICAL STRUT IN CRITICAL BEAM

FROM APPENDIX C, THE DESIGN (ULTIMATE) COLUMN LOAD ON THE CRITICAL STRUT IN THE CRITICAL BEAM CAN BE EXPANDED AND EXPRESSED AS

$$P = \left(\frac{w_x L_B^2}{12 W_B} + \frac{w_z L_B^2}{24 H_B} + \frac{P}{3} + \frac{\Delta P_1}{3} + \frac{\Delta P_2}{3} \right) \times UFS$$

WHERE

w_x = APPLIED LOADING ALONG BEAM DUE TO ARRAY PRETENSION

w_z = APPLIED LOADING ALONG BEAM DUE TO MODULE SELF-TRANSPORT

P = APPLIED COLUMN LOAD ON BEAM DUE TO ARRAY PRETENSION, NO P/L

ΔP_1 = DELTA APPLIED COLUMN LOAD ON BEAM DUE TO SELF TRANSPORT FROM LEO TO GEO, NO P/L

ΔP_2 = DELTA APPLIED COLUMN LOAD ON BEAM DUE TO ANTENNA TRANSPORT

L_B, W_B, H_B = BEAM LENGTH, WIDTH, HEIGHT

UFS = ULTIMATE FACTOR OF SAFETY

FOR A FIXED FREQUENCY OF VIBRATION FOR THE ARRAY, IT FOLLOWS THAT (FROM APPENDIX B).

$$w_x \propto (L_A^2)(w_A) \propto (L_B - W_B)^2 (w_A)$$

WHERE

L_A = LENGTH OF SIDE OF SQUARE ARRAY $\simeq (L_B - W_B)$

w_A = ARRAY WEIGHT PER UNIT AREA

FOR A FIXED MAX T/W CAPABILITY DURING LEO-TO-GEO SELF TRANSPORT, IT FOLLOWS THAT (FROM APPENDIX C)

$$w_z \propto (L_A)(w_A) \propto (L_B - W_B)(w_A)$$

(CONT'D)

THE RELATIONSHIP FOR THE COLUMN LOAD ON THE BEAM DUE TO ARRAY PRETENSION IS (FROM APPENDIX C)

$$P \propto (w_x)(L_B) \propto (L_B - W_B)^2 (w_A)(L_B)$$

FOR A FIXED MAX T/W CAPABILITY DURING LEO-TO-GEO SELF TRANSPORT, AND FOR A FIXED RELATIVE LOCATION FOR THE THRUSTERS, IT FOLLOWS THAT (FROM APPENDIX C)

$$\Delta P_1 \propto \frac{(W_m)(L_m)}{(H_m)} \propto \frac{(w_m)(L_m)(W_m)}{(H_m)}$$

AND

$$\Delta P_2 \propto \frac{(W_{ANT.})(L_m)}{(H_m)}$$

WHERE

W_m = MODULE WEIGHT
w_m = MODULE WEIGHT PER UNIT AREA
L_m = MODULE LENGTH
W_m = MODULE WIDTH
H_m = MODULE HEIGHT

2.2 RANKINE THERMAL ENGINE REFERENCE SYSTEM

This section provides a record of mass estimation calculations for the thermal engine SPS. Calculations for the thermal engine SPS. Calculations were made by Dan Gregory and Jim Jenkins. Assumptions, methodology, and key results were reviewed by Bob Conrad.

Mass Summary – Potassium Rankine SPS

Power generation system

		10^6 kg
Structure		
facet support		5.370
edge beams		0.309
cavity support arms		0.517
cavity to cavity struts		0.192
antenna supports		0.094
ACS supports		0.050
steel tip frames		0.450
		6.976
facets		1.837
radiators (without potassium but with heat pipe sodium)		10.768
power distribution		4.760
switch gear		0.218
generators, accessories		2.508
generator radiators		1.140
turbines		13.755
pumps and their radiators		0.984
boilers and manifolds (feeders)		3.296
cavity assembly (with cpc frame)		1.000
Compound parabolic concentrators (cpc) skin		0.299
light doors (cpc apertures)		0.025
monitor, command & control		0.100
ACS (attitude control system)		1.200
Turbine Start loops & Controls		0.250
Antenna support (skp rings, turntables)		0.286
potassium inventory	radiators	4.634
	boilers	0.402
	feeders	1.015
	turbines, misc.	0.006
		6.058
misc, including energy storage		0.200
Power generation		55.660
Antennas		24.384
		80.044

SYNOPSIS "FINAL" CONFIGURATION MASS ESTIMATION

TURBINES: ORIGINAL GE MASS WAS 12.991 X10^6 FOR 544 turbines
FOR 576 turbines 13.755 X10^6 +20% −40%
(G.E. estimates)

FACETS ACTUAL TOTAL DISH AREA ON CURVE = 1.221X10^8 m^2
THE "GAP FACTOR" IS 0.95, HENCE 1.16 X10^8 m^2 FACET:
ACTUAL AREA IS 1000 m^2/FACET, HENCE 116,000 FACETS

FACETS & ASSOCIATED ROCKER ARMS 15.84 kg EACH

1.837 X10^6 kg

FACET SUPPORT FRAMEWORK (8/1/77) 46.3 kg/facet

5.370 X10^6 kg.

EDGE BEAMS OF SUPT. FRAMEWORK

1.75 kg/m OF EDGE, EDGE IS 2763 m, X64 = 1.768X10^5 m,

0.309X10^5 kg

GRAPHITE SUPPORT ARMS (20 m) 2760 m EACH, X64 = 1.766 X10^5 m
2.93 kg/m

0.517 X10^5 kg

RADIATORS, PRIMARY

INLET MANIFOLD		1240
THROAT/ARMS		790
VALVES (1 KG EACH)		710
RET MAN		216
BUMPERS	IN	481
	OUT	208
HEAT PIPES		13,299
		16,694

(RAD. POTASSIUM is 6046 kg/eng = 4.63 X10^6 kg/spr)
(FOR 3.21 X10^6 m^2 radiating, spread over 6.84X10^6 projected.

16,694, X576 10.769 X10^6

GENERATOR RADIATORS
on fractional area basis, rel. to primary 1.80 X10^6

GENERATORS 4.066 X10^6
(0.227 kg/kWe)

POWER DISTRIBUTION

from J. Gowin

main busses		4.600 ×10^6
SWITCHGEAR		0.218 ×10^6
cavity busses		0.160 ×10^6
		~4978 ×10^6

BOILER AND FEEDERS

BOILER:	INLET MANIFOLD	39.1	
	OUTLET MANIFOLD	1063	
	TUBES	1210	
		2312	1.332 ×10^6
FEEDERS			
	INLET	123	
	RETURN	3288	
		3411	1.964 ×10^6
			3.296 ×10^6

PUMPS & PUMP RADIATORS — 0.984 ×10^6

POTASSIUM

RADIATOR	8046	
BOILER	698	
FEEDERS	1763	
TURBINE	10	
	10 517	6059 ×10^6

CAVITY

INSULATION	0.937 ×10^6	
FRAME	0.055 ×10^6	
	0.992 ×10^6	— 1 ×10^6

ADDITIONAL STRUCTURES

CAVITY-TO-CAVITY STRUTS	0.192 ×10^6
ANTENNA SUPPORTS	0.094 ×10^6
ACS SUPPORTS	0.050 ×10^6
STEEL TOP FRAMES	0.450 ×10^6
	0.786 ×10^6

CPC — 0.3 ×10^6

LIGHT DUCK, 425 Kg, 25μm Al +20% — 0.024 ×10^6

ACS (extrapolation/modification to self power thruster concept — Prop. tankage for one year) — 1.20 ×10^6

RADIATORS (PRIMARY)

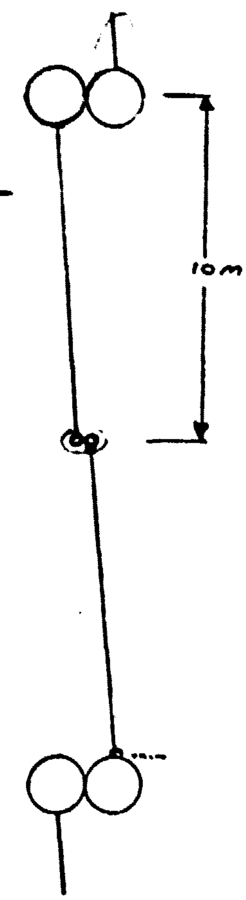
1) POWER REJECTED = 96.115×10^6 − 18.166×10^6 = 77.949×10^6 kW.

2) ALLOWING FOR REJECTION BY VAPOR MANIFOLD, USE 77×10^6 kW.

3) REJECTION TEMPERATURE = 932 − 4 = 928 K.

4) CONCENTRATOR BLOCKAGE IS INSIGNIFICANT.

5) RADIATOR MANIFOLDS ON 10M CENTERS →



6) SURFACE $\epsilon = 0.90$

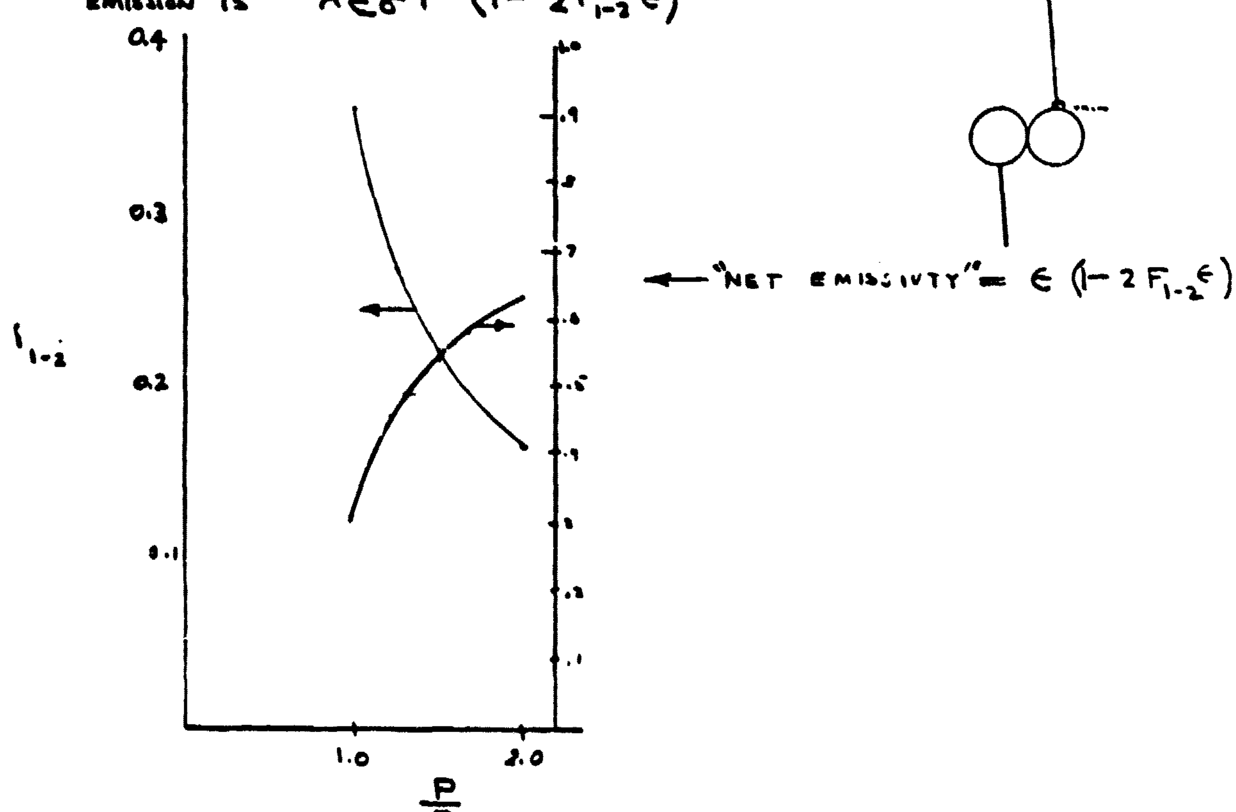
7) HEAT PIPE SPACING EFFECT: SPACE = P, DIA = D

$$F_{1-2} = \frac{2}{\pi}\left\{2\left[\left(\frac{\alpha}{360°}\right)\pi + \frac{P\cos\alpha}{2D}\right] - \frac{P}{D}\right\}$$

WHERE $\alpha = \sin^{-1}\frac{D}{P}$

$$F_{1-space} = 1 - 2F_{1-2}$$

EMISSION IS $A\epsilon\sigma T^4(1 - 2F_{1-2}\epsilon)$



8) HEAT PIPE SPACING SET AT $\frac{P}{D} = 1.6$.

9) NET $\epsilon = 0.57$, $Q/A = 24.0\ kW/m^2$.

10) RADIATING AREA $= \frac{77 \times 10^6\ kW}{24.0\ kW/m^2} = 3.21 \times 10^6\ m^2$

11) THE PROJECTED AREA IS $\frac{3.21 \times 10^6\ m^2}{\pi} = 1.02 \times 10^6\ m^2$

12) ALLOW 10% OVERSIZE FOR HEAT PIPE PENETRATIONS, 3% FOR THRU PIPES,

TOTAL PROJECTED AREA $= 1.15 \times 10^6\ m^2$.

13) BASELINE H.P. HAS $D = 0.006\ m$, $L_{cond} = 0.5\ m$, PROJECTED AREA $= 3 \times 10^{-3}\ m^2$;

$$\#\ \text{TOTAL PIPES} = \frac{1.15 \times 10^6\ m^2}{3 \times 10^{-3}\ m^2} = 3.83 \times 10^8$$

$$\#\ \text{FUNCTIONAL PIPES}\ \frac{3.83 \times 10^8}{113} = 3.39 \times 10^8$$

10% HITS ← FACTOR FOR FLYING RADIATOR EDGE-ON TO METEOR "STREAM"

$$\frac{3.83 \times 10^7 \times 0.399}{1.15 \times 10^6 \times 9.5 \times 10^8\ sec} = 1.4 \times 10^{-8}\ HITS/m^2/SEC$$

PARTICLE MASS $= 2.6 \times 10^{-7}\ gm = 2.6 \times 10^{-10}\ kg$

$$r = \left(\frac{3 \times 2.1 \times 10^{-10}}{2000\,\pi}\right)^{\frac{1}{3}} = 4.77 \times 10^{-5}\ m$$

$t = 1.97\,d = 1.77 \times 10^{-4}\ m$ (SHELL THICKNESS) $\approx 0.008''$

14) LET $L_{evap} = 0.12\ M$ (TO MAKE $\frac{1}{2}$ WRAP ON 8 cm THRU PIPE)

$L_{cond} = 0.5\ M$

$L_{TOT} = 0.62\ M$

15) HEAT PIPE SHELL MASS:

$$0.62\ m \times 0.006\ m \times \pi \times 1.77 \times 10^{-4} \times 7800\ kg/m^3 = 0.0163\ kg$$

16) SCREEN WICK (SEE 8/3/77), $t = 1 \times 10^{-4}\ m$, POROSITY $= 0.7$

$$0.62\ m \times 0.0056\ m \times \pi \times 1 \times 10^{-4} \times 0.3 \times 7800 = 0.0026\ kg$$

17) SODIUM, MENISCUS ALLOWS FILL OF 80% OF SCREEN VOID

$$0.62\ m \times 0.0056\ m \times \pi \times 1 \times 10^{-4} \times 0.7 \times 0.8 \times 790 = 0.00049\ kg$$

18) INDIVIDUAL HEAT PIPE MASS $= 1.93 \times 10^{-2}\ kg = 0.019\ kg$ —

ROUND-UP TO $0.02\ kg$/PIPE

$\times 3.83 \times 10^8 = 7.66 \times 10^6\ kg$/SPS

Length check - 355 × 8 m = 2840 m
heat pipe D = 0.006 m P = 1.6 → 0.0096, lines $\frac{2940}{.0096} = 306{,}250$
[illegible]

3

19) DUE TO THE SPACING ($\frac{P}{D} = 1.6$) THE ACTUAL PROJECTED AREA OF THE RADIATOR $= 1.15 \times 10^6 \times 1.6 = 1.84 \times 10^6\ m^2$

20) WITH 576 ENGINES, THIS IS 3194 m^2/ENG —

21) PER 5), THE THRUPIPE $L \approx 9\ m$, & A "PANEL IS 9×1 M, HENCE 355 THRUPIPES, ACTIVE MANIFOLD LENGTH = 355 M.

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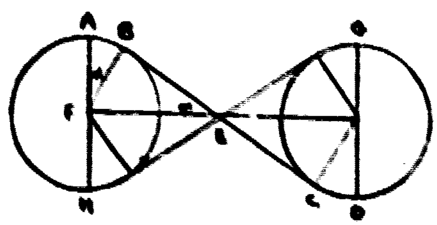
VIEW FACTOR – PARALLEL TUBES



$\overline{AH} = D$

$\overline{AG} = P$

$$A_1F_{1-2} = \frac{(\widehat{AD} + \widehat{GH}) - (\overline{AG} + \overline{DH})}{2} = \frac{(4\,\widetilde{AE}) - 2P}{2} = 2\widetilde{AE} - P$$

$$\alpha = \sin^{-1}\frac{\overline{FB}}{\overline{FE}} = \sin^{-1}\frac{D/2}{P/2} = \sin^{-1}\frac{D}{P}$$

$$\widehat{AB} = \left(\frac{\alpha}{360°}\right)\pi D$$

$$\overline{BE} = \overline{EF}\cos\alpha = \frac{P}{2}\cos\alpha$$

$$A_1F_{1-2} = 2\widetilde{AE} - P = 2(\widehat{AB} + \overline{BE}) - P = 2\left[\left(\frac{\alpha}{360°}\right)\pi D + \frac{P}{2}\cos\alpha\right] - P$$

LET $P = XD$ (X = PITCH / DIAMETER)

THEN

$$A_1F_{1-2} = 2\left[\left(\frac{\alpha}{360°}\right)\pi D + \frac{XD}{2}\cos\alpha\right] - XD$$

$$= D\left\{2\left[\left(\frac{\alpha}{360°}\right)\pi + \frac{X}{2}\cos\alpha\right] - X\right\}$$

BUT $A_1 = \frac{\pi D}{2}$

THUS

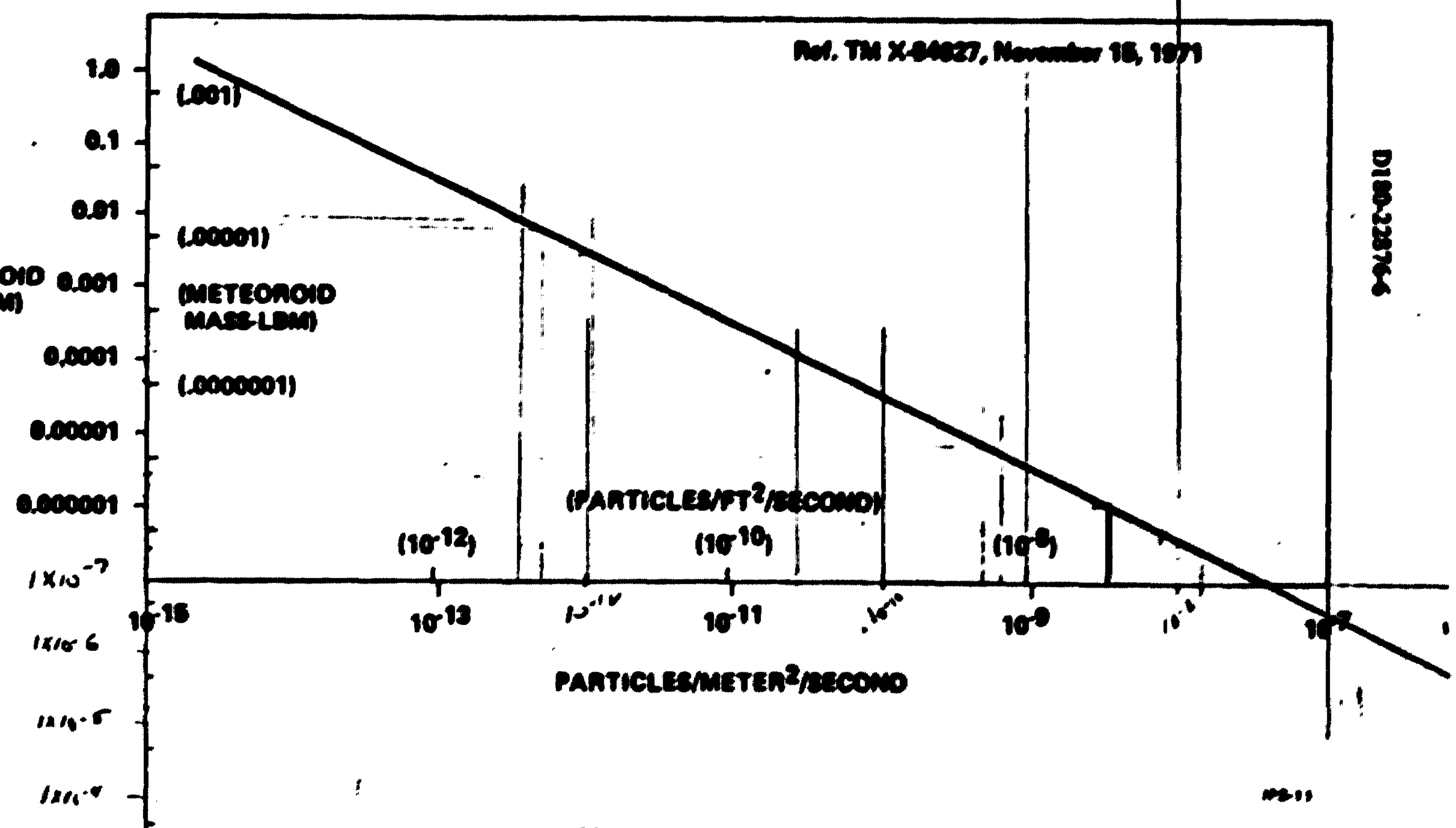
$$F_{1-2} = \frac{D}{\frac{\pi D}{2}}\left\{2\left[\left(\frac{\alpha}{360°}\right)\pi + \frac{X}{2}\cos\alpha\right] - X\right\}$$

$$= \frac{2}{\pi}\left\{2\left[\left(\frac{\alpha}{360°}\right)\pi + \frac{X}{2}\cos\alpha\right] - X\right\}$$

SPACE
BASED
POWER

Sporadic & Stream
Average Total Meteoroid Environment
(Omnidirectional)

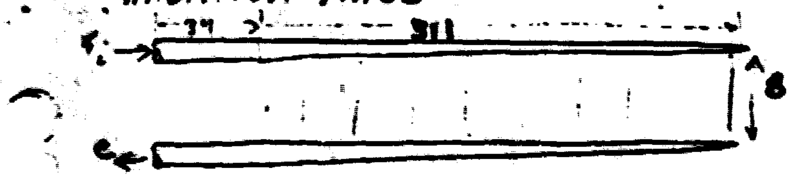
BOEING



D180-22876-6

123

RADIATOR MASS D180-22876-6 9/13/77 6



$\dot{m}$ = .89 × 83.9 kg/sec = 74.67 kg/sec

T_i = 932°K X_i = .786 P_i = 5.504 PSIA

sl. properties

ρ_ℓ = 688 kg/m^3 ρ_v = .202 kg/m^3 μ_ℓ = 130×10^{-6} nt sec/m^2

μ_v = 18.8×10^{-6} nt sec/m^2

$$\rho_i = \left(\frac{x}{\rho_v} + \frac{(1-x)}{\rho_\ell}\right)^{-1} = .257 \text{ kg m}^3$$

μ_i = 4.26×10^{-5} nt sec/m^2

inlet header & manifold 34 m header 311 m manifold

D inlet = 1.60 m const $\frac{\Delta P}{\Delta L}$ manifold

$$N_{Re} = \frac{4\dot{m}}{\pi \mu D_i} = 1.39 \times 10^6 \qquad f = .011$$

$$\Delta P = \frac{8 f L \dot{m}^2}{D^5 \pi^2 \rho} = 6421 \text{ nt/m}^2 \quad , .9312 \text{ PSIA}$$

THROUGH PIPE

$\dot{m}$/pipe = .276 kg/sec 811 through pipes 87% in quality

D = .09 m L = 8 m $\bar{\mu}$ = 8.63×10^{-5} nt sec/m^2 $\bar{\rho}$ = .314 kg/m^3

Pres. recovery $\Delta P_r = \rho_2 V_2^2 - \rho_1 V_1^2 = \frac{\dot{m}^2}{A^2}\left(\frac{1}{\rho_\ell} - \frac{1}{\rho_{(x=.786)}}\right)$

ΔP_r = −11,727 nt/m^2 , −1.701 PSIA pressure increase

Press drop

N_R = 50,900 f = .022

ΔP = 6452 nt/m^2 , .936 PSIA

assume get ½ press. recovery

net ΔP = .936 − .851 = .086

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RETURN HEADER & MANIFOLD

D_{exit} = .278 m   const $\frac{\Delta P}{\Delta L}$ manifold

ρ = 688 kg/m³ μ = 130×10⁻⁶ nt sec/m²

N_{Re} = 2.631 ×10⁶   f = .0099

ΔP = 13516 nt/m², 1.960 PSIA

Total pressure drop

.9312 + .086 + 1.960 = 2.977 PSIA

5.404 PSIA − 2.977 PSIA = 2.427 PSIA   need 1.5 PSIA NPSH o.k. ✓

MASSES

INLET HEADER & MAN.   min gage all pipe 1.27×10⁻⁴ m (.005 in)

$M = [34 \times \pi \times 1.6 + 311 \times \pi \times 1.131] \times 1.27\times10^{-4} \times 7750 =$ **1256 kg** ✓

THROUGH PIPE

$M = 311 \times \pi \times .08 \times 8 \times 1.27\times10^{-4} \times 7750 =$ **615 kg**

RETURN HEADER & MAN

$M = [34 \times \pi \times .278 + 311 \times \pi \times .197]\, 1.27\times10^{-4} \times 7750 =$ **218 kg** ✓

POTASSIUM MASSES

INLET $M = [34 \times \pi \times (\frac{1.6}{2})^2 + 311 \times \pi\, (\frac{1.131}{2})^2] \times .257 =$ **98 kg** ✓

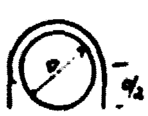
THROUGH PIPES $M = 311 \times \pi \times (\frac{.08}{2})^2 \times 8 \times .514 =$ **6 kg** ✓

RETURN $M = [34 \times \pi\, (\frac{.278}{2})^2 + 311 \times \pi\, (\frac{.197}{2})^2] \times 688 =$ **7942 kg** ✓

BUMPERS

INLET   .16 m spacing   .0004 thick   890 kg/m³

$M = [34.(\frac{\pi D}{2} + D + .16\pi) + 311\, (.707\frac{\pi D}{2} + .707D + .16\pi)] \times .0004 \times 890$



= **434 kg** ✓

RETURN   .08 m spacing   3 × .0028 thick

$M =$ **2004 kg** ✓

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TOTAL RADIATOR MASS, 1 ENGINE = **12 573 kg**
(less heat pipes 16,115 kg

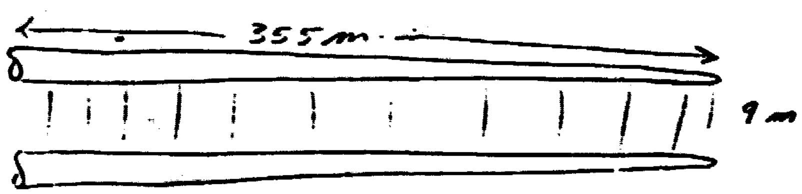
Manifolds & Throughpipes 7/20/77

Revised Radiator 355. throughpipes

$\dot{m}$ = 74.67 kg/sec T_i = 932°K x_i = .786 P_i = 5.504 PSIA

ρ_ℓ = 680 kg/m³ ρ_v = .202 kg/m³ μ_ℓ = 130×10⁻⁶ nt sec/m² μ_v = 18.5×10⁻⁶ nt sec/m²

ρ_i = .257 kg/m³ μ_i = 4.26×10⁻⁵ nt sec/m²



inlet man. $N_{Re} = \frac{4\dot{m}}{\pi \mu D_i} = 1.39\times10^6$ f = .011 D_m = 1.6 m

$$\Delta P = \frac{8 \times .011 \times 355 \times 74.67^2}{(1.6)^5 \pi^2 \, .257} = 6{,}607 \text{ nt/m}^2 \,,\ .958 \text{ PSIA}$$

Through pipe $\dot{m}$/pipe = .210 kg/sec

D = .08 L = 9 m $\bar{\mu}$ = 2.63×10⁻⁵ nt sec/m² $\bar{\rho}$ = .514 kg/m³

Press recovery $\Delta P_r = \frac{\dot{m}^2}{A^2}\left(\frac{1}{\rho_\ell} - \frac{1}{\rho(x=.786)}\right)$

ΔP_r = −6,811 nt/m² ; −.988 PSIA

Press drop
$$\Delta P = \frac{8 \times .022 \times 9 \times .210^2}{(.08)^5 \times \pi^2 \times .514} = 4202 \text{ nt/m}^2 ;\ .609 \text{ PSIA}$$

assume ½ ΔP_r available net .609 − .494 = .115 PSIA

Return man. D_{ex} = .278 m ρ = 682 kg/m³ μ = 130×10⁻⁶ nt sec/m²

N_{Re} = 2.631×10⁶ f = .0099 L = 355 m

ΔP = 13,908 nt/m² 2.017 PSIA

Total ΔP = .958 + .115 + 2.017 = 3.090 PSIA

MPSH available 5.404 − 3.090 = 2.314 PSIA

Masses

INLET MAN min gage 1.27×10^{-4} m $\bar{D} = 1.13$ m

$M = [355 \times \pi \times 1.13 \times 1.27\times10^{-4} \times 7750] = 1240$ kg

Throughpipes

$M = 355 \times \pi \times .08 \times 9 \times 1.27\times10^{-4} \times 7750 = 790$ kg

return man $\bar{D} = .197$ m

$M = 355 \times \pi \times .197 \times 1.27\times10^{-4} \times 7750 = 216$ kg

K masses

INLET $M = 355 \times \pi \left(\frac{1.13}{2}\right)^2 \times .257 = 91$ kg

THROUGH PIPES $M = 355 \times \pi \times \left(\frac{.08}{2}\right)^2 \times 9 \times .514 = 8$ kg

return $M = 355 \times \pi \left(\frac{.197}{2}\right)^2 \times 688 = 7444$ kg

Bumpers

INLET $M = 355 \times \left(\frac{.707\pi 1.60}{2} + .707 \times 1.60 + .16\pi\right) \times .0004 \times 890 = 431$ kg

Return $M = 355 \times \left(\frac{.707\pi}{2} .278 + .707 \times .278 + .08\pi\right) \times 3 \times .0027 \times 890 =$

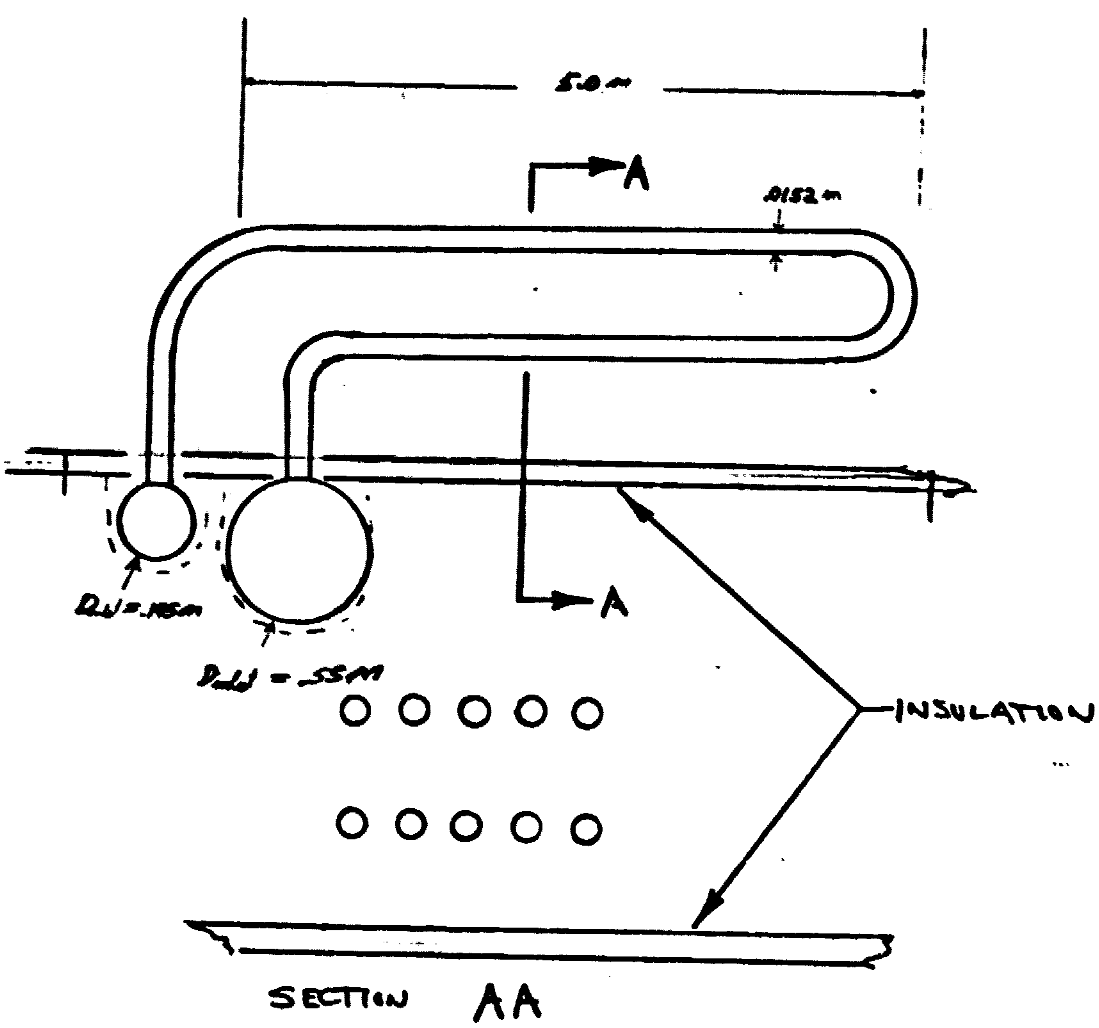
$= 2008$ kg

TOTAL MASS

	PER ENGINE	PER SPS
PIPING	2246 kg	1.294×10^6 kg
K	7543 kg	4.345×10^6 kg
BUMPERS	2439 kg	1.405×10^6 kg
TOTAL	12,228 kg ←	7.043×10^6 kg ←

less heat pipes

BOILER TUBES



3 panels/engine: 20 m long X 6 m wide

ENGINE TO BOILER EXTENSION PIPES

70m ave

liquid: .145 m DIA

$f = .009$

$$\Delta P = \frac{8 \times .009 \times 70 \times 81.5^2}{\pi^2 \times 688 (.145)^5} = 7.692 \times 10^4 \ nt/m^2$$ 11.16 PSIA

too high
total outlet

$$\Delta P = \frac{8 \times .010 \times 130.96 \times 81.5^2}{\pi^2 \times 688 (D)^5} = \frac{12.248}{D^5}$$ desire ~ 9 PSIA ; 6.206 nt/m²

$$D^5 = \frac{12.248}{6.206 \times 10^4} \qquad D = .175 \ m$$

vapor:

$$\Delta P = \frac{8 \times .010 \times 130.96 \times 81.5^2}{\pi^2 \times 2.263 \times D^5} = \frac{3.116 \times 10^3}{D^5}$$ need 4 PSIA ; 2.758×10⁴ nt/m²

$$D^5 = \frac{3.116 \times 10^3}{2.758 \times 10^4} = .647$$ use .65 m

Masses

liquid:

$$m_m = (70 \times \pi \times .175 + 60.96 \times \pi \times .124)\ 2.2 \times 10^{-4} \times 7{,}910 = 123 \ kg$$

$$m_A = (70 \times \pi \left(\frac{.175}{2}\right)^2 + 60.96 \times \pi \times \left(\frac{.124}{2}\right)^2) \times 688 = 1{,}665 \ kg$$

vapor

$$m_m = (70 \times \pi \times .65 + 60.96 \times \pi \times .460) \times 1.58 \times 10^{-3} \times 7910 = 3288 \ kg$$

liq:

$$m_A = (70 \times \pi \left(\frac{.65}{2}\right)^2 + 60.96 \times \pi \left(\frac{.460}{2}\right)^2) \times 2.263 = 98 \ kg$$

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CAVITY ANALYSIS

$\dot{q}_I$: flux on tubes = $\dot{Q}_I / A_T$

$A_T = \frac{\pi}{2} A_C$

$\dot{Q}_I$: net input to working fluid

A_T : tube area

A_C : cavity wall area

(loss factor; re-radiation)

$$\dot{q}_I = \frac{.93\,(I_S\, C_{r_{eff}}) - \sigma T_T^{\,4}}{\pi/2 \; A_C/A_A}$$

I_S : insolation

$C_{r_{eff}}$: effective conc. ratio to cavity aperture

A_A : aperture area

loss factor accounts for reflection from cavity and wall losses.

$$\dot{Q}_I = \dot{m}\,(c_{p_L} \Delta T_f + h_{fg})$$

THERMAL BALANCE

POWER TO APERTURE :	7.050×10^6 KW	
RE-RAD LOSS :	$-\ .551 \times 10^6$ KW	7.8 %
WALL & REFLECTION LOSS :	$-\ .493 \times 10^6$ KW	7.0 %
NET POWER TO ENGINES :	6.006×10^6 KW	85.2 %

BOILER & CAVITY ANALYSIS

9/19/77 ①

$\dot{m}$ = 83.9 kg/sec , 185 lb/sec

T_e = 1242°K , 2236°R

T_i = 932°K , 1678°R

P_{SAT} = 75.5 PSIA

Vapor region (2236°R)

c_p = .2755 BTU/LBM °R

μ = .0522 lbm/hr ft

$k \approx \mu(c_p + 2.48) =$ .144 BTU/lbm °R

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ρ = .1413 lb/ft³

$N_{Re} = \frac{\rho V D}{\mu} = \frac{.1413}{.0522} VD = 2.707\ VD$

$N_{Pr} = \frac{\mu c_p}{k} = \frac{.0522 \times .2755}{.144} = .0999$

$h_v = \frac{k}{D}\ .022\ N_{Pr}^{.6}\ N_{Re}^{.8} = \frac{.144}{D} \times .022 \times (.0999)^{.6} \times (2.707\ VD)^{.8}$

$= 1.764 \times 10^{-3}\ \frac{VD^{.8}}{D}$

$VD^2 = \frac{4\ \dot{m} \times 3600}{\rho \pi\ N_T}$; $VD = \frac{4 \times 185 \times 3600}{\pi \times .1413\ N_T \times D} = \frac{6.001 \times 10^6}{D N_T}$

$h_v = \frac{1.764 \times 10^{-3}}{D} \times \left(\frac{6.001 \times 10^6}{D N_T}\right)^{.8} = \frac{466.76}{D^{1.8} N_T^{.8}}$

Subcooled region   T = 1678°R

h_ℓ = 23.13 BTU/hr ft

ρ_ℓ = 42.95 lbm/ft³

μ = .347 lbm/hr ft $N_{Pr} \approx .0019$

$h_s = \frac{23.13}{D}\left(6.3 + .003\left(\frac{VD \times 42.95}{.347}\right)(.0019)\right) = \frac{23.13}{D}(6.3 + 7.055 \times 10^{-4} VD$

$VD = \frac{4\ (185)\ 3600}{42.95 \times \pi\ N_T\ D} = \frac{1.974 \times 10^4}{D N_T}$

$h_s = \frac{23.13}{D}\left(6.3 + \frac{13.93}{D N_T}\right) = \frac{145.7}{D} + \frac{322.2}{D^2 N_T}$

(5)

At 2236°R $h_{fg} = 774.9$ BTU/lb $\quad c_{pl}(2236°R) = .1981$ $\quad c_{pl}(1678°R) = .1836$ $\quad \bar{c}_{pl} = .1908$

Total heat flux required $\dot{Q}_I = \dot{m}(c_{pl}\Delta T + h_{fg})$

$\dot{Q}_I = 185(.1908 \times 558 + 774.9) = 1.631 \times 10^5$ BTU/sec ; $5.870 \times 10^8 \frac{BTU}{hr}$

$\dot{Q}_s = \dot{m} c_p \Delta T = 7.091 \times 10^7$ BTU/hr

$\dot{Q}_B = .6 \, \dot{m} h_{fg} = 3.097 \times 10^8$ BTU/hr

$\dot{Q}_v = .4 \, \dot{m} h_{fg} = 2.064 \times 10^8$ BTU/hr

$\dot{Q}_I = \dot{Q}_A - A_A \sigma T_w^4 \qquad \dot{Q}_A = I_s \times C_{r\,eff} \times A_A$

$\dot{q}_I = \frac{\dot{Q}_I}{A_T} \qquad A_T$, tube Area $= \frac{\pi}{2} A_c$, cavity area

$$\dot{q}_I = \frac{I_s C_{re} A_A - A_A \sigma T_w^4}{\frac{\pi}{2} A_c}$$

$$\dot{q}_I = \frac{I_s C_{re} - \sigma T_w^4}{\pi/2 \; A_c/A_A}$$

$\dot{q}_I = h_s(T_{w_s} - \bar{T}_f) \qquad \dot{q}_I = h_B(T_{w_B} - T_B) \qquad \dot{q}_I = h_v(T_{w_v} - T_v)$

$\bar{T}_f = 1957°R \qquad T_B = T_v = T_{SAT} = 2236°R$

$$A_T = \frac{\dot{Q}_I}{\dot{q}_I} = \frac{5.870 \times 10^8}{\dot{q}_I}$$

$A_s = .1208 \, A_T \qquad A_B = .5276 \, A_T \qquad A_v = .3516 \, A_T$

$$\Delta P = \frac{153.62 \times L_s}{N_T^{1.820} \; D^{4.820}} \qquad L_s = \frac{A_s}{\pi D N_T}$$

$$\Delta P = \frac{1}{\dot{q}_I} \times \frac{3.674 \times 10^9}{N_T^{2.82} \; D^{5.82}} \quad \text{lb/ft}^2$$

$$\Delta P_r = \frac{.7638}{N_T^2 (.3048D)^4}$$

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D (ft)	N_T	h_S	h_{NC}	$T_{W_S} - T_S$	$T_{W_B} - T_B$	$T_{W_N} - T_{N}$
.05	100	4,203	2,576	12.72	4	21
	500	3,172	711	16.85		75
	1,000	3,043	408	17.57		131
	2000	2,979	234	17.94		228
.10	100	1,779	740	30.05		72
	500	1,522	204	35.12		262
	1000	1,489	117	35.90		457
	2000	1,473	67.3	36.29		794 *
.20	100	809	212	66.07		252
	500	745	58.6	71.75		912 *
	1000	737	33.7	72.52		1586 *
	2000	733	19.3	72.92		2769 *
.40	100	384	61.0	139.19		876
	500	368	16.8	145.25		3182
	1000	366	9.7	146.04		5510
	2000	365	5.6	146.44	↓	9545

$A_c/A_n = 6.5$ $\quad C_{fc} = 1441$ $\quad$ Dia apert = 67 in

try $T_W = 2350°R$

$$q_I = \frac{415 \times 1441 - 1.714 \times 10^{-9} (2350)^4}{\frac{\pi}{4} \times 6.5} = 53,450 \text{ BTU/hr ft}^2$$

D	N_T	ΔP	P_n	M_V	M_K
.05	100	40,815	1416	2.534×10^5	731
	500	436	56.6	3,697	↓
	1000	61.8	14.2	1,073	
	2000	8.7	3.5	720	
.10	100	722	88.5	11,480	1461
	500	7.7	3.5	1,501	↓
	1000	1.1	.9		
	2000	.2	.2		
.20	100	12.8	5.5		2923
	500	.1	.2		↓
	1000	—	.1		
	2000	—	—		
.40	100	.2	.3		5840
	500	—	—		↓
	1000	—	—		
	2000	—	—		

Reversed Potassium Boiler . 9/20/77

Boiler DIA : .05' N : 2000 TUBES

(mod) $\dot{m} = 179.6$ lb/sec $\dot{Q}_T = 179.6\,(.1965 \times 551 + 774.9) = 5.697 \times 10^5$ BTU/hr

$\dot{q} = \dfrac{.93\,(415 \times 1441) - 1.714 \times 10^{-9}\,(2285)^4}{\pi/2 \times 6.5} = 49,894$ BTU/hr ft²

$A_T = 5.697 \times 10^5 / 49,894 = 11,418$ ft²

$L_T = \dfrac{A_T}{n_T \pi D_T} = \dfrac{11,418}{2000\,\pi \times .05} = 36.34$ ft

Manifolds $L_M = 2 \times .05 \times 2000 = 200$ ft , 60.96 m

Temps. $T_{w_S} = \dfrac{\dot{q}_T}{h_S} + 1957°R = 1974°R$

$T_{w_B} = 2240°R$ $T_{w_V} = \dfrac{\dot{q}_T}{h_V} + 2236°R = 2447°R$

Pressure drops.

Frictional $\Delta P_f = \dfrac{144.8\,L_S}{N_T^{1.82}\,D^{4.82}}$ $L_S = .1208 \times L_T = 4.39'$

$\Delta P_f = 1.165 \times 10^3$ lb/ft² $= 8.09$ PSIA

Momentum $\Delta P_m = \dfrac{.7199}{N_T^2\,(.3048D)^4} = 3.34$ PSIA

MANIFOLDS

liquid $\dot{m} = 81.5$ kg/sec $D = .145$ m

$N_{Re} = \dfrac{4\dot{m}}{\pi \mu D} = 5.505 \times 10^6$ $f = .009$

$\Delta P = \dfrac{8}{\pi^2}\dfrac{f}{\rho}\dfrac{L\,\dot{m}^2}{D^5} = \dfrac{8 \times .009 \times 60.96 \times 81.5^2}{\pi^2 \times 688 \times (.145)^5} = 6.698 \times 10^4$ nt/m² ; 9.71 PSI.

vapor $L = 200$ ft, 60.96 m $D = .55$ m

$N_{Re} = 8.576 \times 10^6$ $f = .008$

$\Delta P = 2.305 \times 10^4$ nt/m² 3.34 PSIA

Total Press = 75.4 (turbine) + 3.34 (vapor man) + 3.34 + 8.09 (tube) + 9.71 (liq man) = 99.88 PSIA

MASSES

INLET MAN $T = 1218\ °F$ $\bar{R} = 2.02$ in

$\sigma_{cr} = 35{,}000$ $\bar{t} = \frac{99.88 \times 2.02}{.667 \times 35000} = .0086$ in, 2.20×10^{-4} m

→ $m_m = 60.96 \times \pi \times .103 \times 2.2 \times 10^{-4} \times 9{,}010 = 39.1$ kg

→ $m_K = 60.96\ \pi \left(\frac{.103}{2}\right)^2 \times 688 = 349.46$ kg

Total M_{in} = **389 kg**

Outlet man $T = 1776\ °F$ $\bar{D} = .39$ m

$\sigma_{cr} = 14{,}500$ PSI $\bar{t} = \frac{78.7 \times 15.31}{2 \times .667 \times 14{,}500} = .062$ in, 1.58×10^{-3} m

→ $m_m = 60.96 \times \pi \times .39 \times 1.58 \times 10^{-3} \times 9{,}010 = 1{,}063$ kg

→ $m_K = 60.96 \times \pi \times \frac{.39^2}{4} \times 2.263 = 16.48$ kg

total M_{op} = **1079 kg**

Tubes:

subcooled $L_s = 4.39'$ & boiling $L_B = 19.17'$ vapor $L_v = 12.78'$

$P = 90$ PSIA $D = .05$ ft $t = .005''$ min gage, 1.27×10^{-4} m

→ $m_m = 11.08 \text{ m} \times \pi \times .0152 \times 1.27 \times 10^{-4} \times 2000 \times 9010 = 1210$ kg

→ $m_K = 11.08 \times \pi \times \frac{.0152^2}{4} \times 82.57 \times 2000 = 331$ kg

total M_{Tub} = **1541 kg**

Total Boiler Mass (per engine) : 389 (IN MAN) + 1541 (TUBES) + 1079 (OUT MAN) = **3009 kg**

Subs. mass of Boiler K : 697 kg

mass of metal : 2312 kg

Total for one SPS 16 x 36 = 576 engines 1.733×10^6 kg

mass K : $.401 \times 10^6$ kg

mass metal : 1.332×10^6 kg

"FIXED" PACKET MASS: D180-25764-6

FILM 3 μM Kapton, $\rho = 1.42 \times 10^3$ kg/m³

A = 1000 m², mass = 4.26 kg

\+ seams, doublers, etc. ———————— 4.47 kg

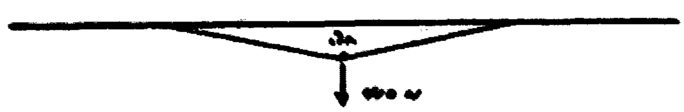
ALUMINIZATION, 1000 Å = 0.1 μM, $\rho = 2.7 \times 10^3$ kg/m³ 0.27 kg

4.74 kg

TENSION TO 1000 PSI ALONG EDGE MEMBER

= 6.9×10^6 N/m² — PER LINEAR M, 20.7N (4.65 lbf)

EDGE MEMBER LENGTH = 19.81 M, F = 410 N (92.1 lbf)



EDGE IS CYLINDER, L = 19.81 M, t = 2×10^{-4} M (8 mil)

D = 0.1 M, ρ = 1750 kg/m³

MASS = 2.17 kg EA, + LOCAL THICKENING, BRIDLE FITTINGS, ETC 2.29 kg EA.

BRIDLES, L = 10 M, T = 205 N × 8 = 64 N, ULTIMATE

KEVLAR TAPE, 100,000 PSI, $a = 1.45 \times 10^{-7}$ M²,

$V = 1.45 \times 10^{-6}$, × 1500 kg/M³ M = 0.002 kg

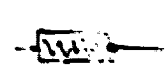
USE 0.01 kg,

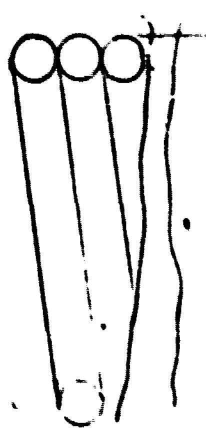
INCLUDES LOWER BRIDLE LINES

SPRING, T = 820 N IN L ≈ 0.1 M

ASSUME WOUND OF STEEL WIRE, D = 0.7 CM, IN COIL 5CM DIA,

L = 10 CM COLLAPSED, 25 CM MAX EXTENSION



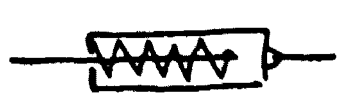


$L = (0.05)(\pi) \times \frac{0.10}{0.007} = 2.24$ M

$A = \frac{(.007)^2 \pi}{4}$

$V = 8.6 \times 10^{-5}$ m³, 8000 = 0.7 kg

in can, 0.8 kg



FACET, 9/14/77

ALUMINIZED FILM, ADHESIVES, ETC.	4.74 kg
EDGE MEMBERS 3 X 2.29	6.87
BRIDLES, HOOKS	0.03
SPRINGS IN CANISTERS 3 X 0.8	2.40
ROCKER ARMS 3 X 0.4	1.20
MOUNT POINTS, 3 X 0.2 (ON STRUTS)	0.60
	15.84

(PRELIM. QUANTITY OF FACETS = 119.32 km², less 5% in gaps x 5% curve
÷ 1020 m² = 112,000 facets

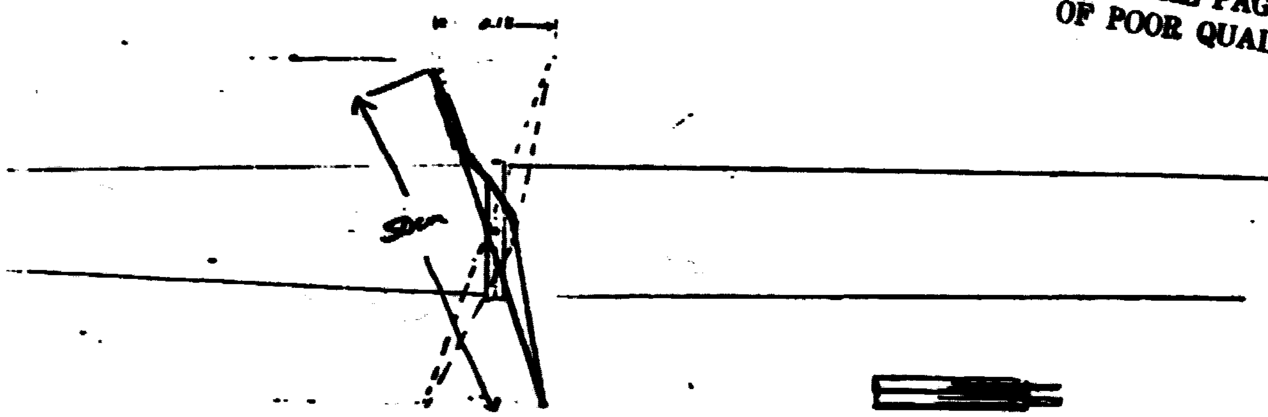
= 1.85 X 10⁶ kg

SUPPORT FRAMEWORK WAS 463 kg/FACET, X 112,000	5.417 X 10⁶ KG
EDGE BEAMS, 1.75 kg/m	0.306 X 10⁶
SUPPORT ARMS, L = 3000 m —	0.562 X 10⁶

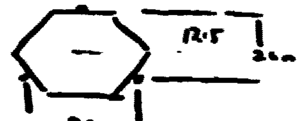
9/14/77

D180-22876-6

ROCKER ARMS, OPERATIONAL ARC = 0.18 m

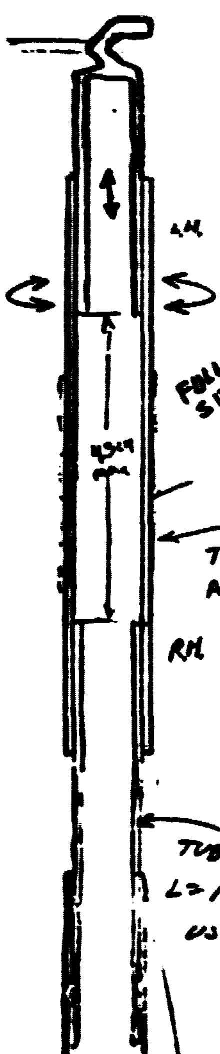


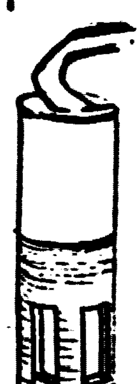
Provide angular adjustment capability of 0.1° — two rockers

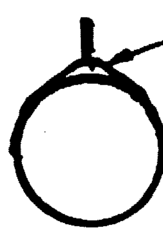


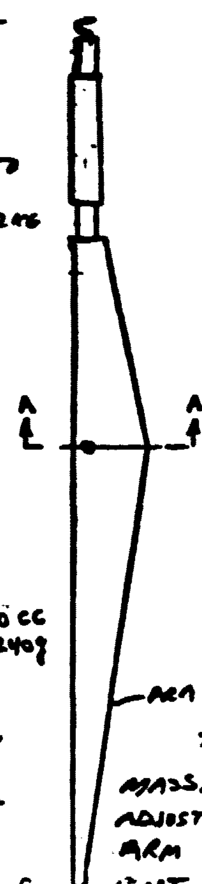
, 4.5 cm travel

368 lbf ← max







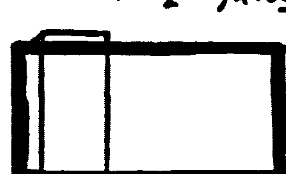


WALL AREA ≈

$2\left(\frac{4+1}{2}+2\right)\times 18 = 162$

$+2\left(\frac{4+2}{2}+2\right)\times 12 = 120$

$282\ cm^2 = 90\ cc$
$-240\ g$



WEIGH AS STEEL TUBE 1.2 cm, t = 2 mm
L = 15 cm = 90 gm = 0.09 kg
use 0.1 kg

368 × 2 × 9 = 6624 lbf
70,000 psi

Compressive load — 520 N
— 0.05 m DIA, 2×10⁻⁴ thick — 3720 psi

MASS, KG

ADJUSTER	0.10
ARM	0.24
PIVOT	0.02
	0.36
MISC	0.04
	0.40 kg

(7 oz)!

Generator Radiators 9/23/77

Shaft Power 18.166 $\times 10^6$ kW
Gen Output 17.857 $\times 10^6$ kW
Dissipation 0.309 $\times 10^6$ kW

Copper temp = 478K
Oil temp ≃ 460K
Radiator surface ≃ 455K , net $\epsilon \cong 0.57$ (tube view factor)
1.38 kW/m² radiated

Rad surface (tube) area = $\frac{0.309 \times 10^6}{1.38}$ = 2.39×10^5 m²

Projected area = 0.712×10^5 m²

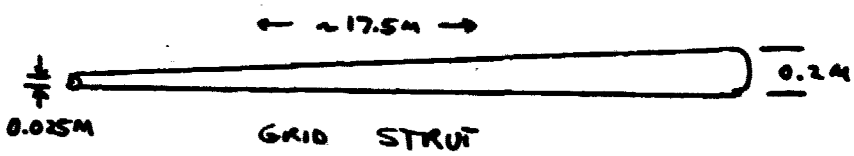
+ 13% for meteoroid oversize = 0.8×10^5 m²

÷ 16 = 5×10^3 m²/cavity —— 71 × 71 m

Area = 0.07 of primary

0.75 $\times 10^6$ kg – panels, manifolds, pumps
0.39 $\times 10^6$ kg – oil
1.14 $\times 10^6$ kg

Support Structure for Facets



Wall $t = 0.2mm$ (.008 IN)

$$\text{Area} = \pi(R+r)\left[H^2 + (R-r)^2\right]^{\frac{1}{2}}$$

$$= \pi(0.1 + 0.0125)\left[175^2 + (0.1-0.0125)^2\right]^{\frac{1}{2}}$$

$$= 6.185\ m^2$$

$\text{Vol} = 1.237 \times 10^{-3}\ m^3$

$\rho = 1750\ kg/m^3$

mass $= 2.165$ kg.

Each facet has 18 of these "GRID STRUTS" or 38.97 kg

"Thickening" and center GRID-TO-GRID JOINTS

9 of 0.25 kg
= 2.25 kg

Ball end fittings, 18 @ 0.20 kg each = 3.60 kg

Sockets (Receive ball end fittings)
2 per facet, 0.75 kg each

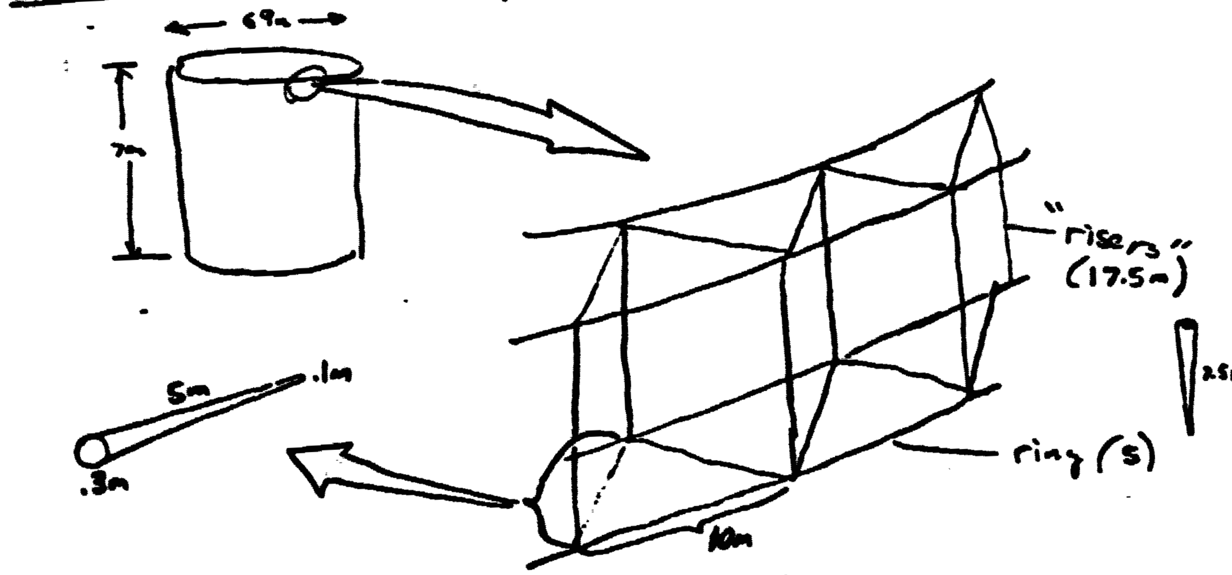
per facet

38.97
2.25
3.60
1.50
46.30 kg

This is the mass of the support dish associated with a single facet

Stress analysis by O. Bullock using $10^{-4}g$ acceleration from thrusters gave factor of safety >2 with above minimum gage.

CAVITY FRAME D180-22876-6



Steel (316) struts, 5m, $t = 1 \times 10^{-4}$ m

6 pcs per 10 m length, or 1.47 kg m^{2}

5 "rings" each 216 m circumference

18 risers = 2340 m — 0.120 $\times 10^6$ kg with fittings

Special engine bearers 10cm dia steel tubes, 180 m long 2mm wall (cylindrical) 0.363 $\times 10^6$ kg

CAVITY INSULATION

Multifoil – Mb with thoria separators

$$\text{Area} = (16) \times (\pi)(69) \times (70) + 16 \frac{(69)^2}{4}\pi = 3.03 \times 10^5 \, m^2$$

5 layers of foil @ 1.65 kg/m^2 = 5.00 $\times 10^5$ kg

CPC skin Geo. Con Ratio. = 3.05

$$\text{Area} = 1.2\pi \left(\frac{69+120}{2}\right)\left[145^2 + (60-35)\right]^{\frac{1}{2}} = 5.17 \times 10^4 m^2$$

$\times 16 = 8.272 \times 10^5 m^2$

Mb foil	25 μm	0.209 $\times 10^6$ kg
Rhodium	1000 Å	0.001
frame, foil supports		0.076
		0.286 $\times 10^6$

use 3×10^6 kg

3.0 COST DATA PACKAGE

3.1 INTRODUCTION

The final Part II cost estimates utilized the Boeing parametric cost model and the mature industry costing methodologies developed during the study. The procedure used was as follows:

The first step was to make cost estimates for DDT&E and first unit costs using the parametric cost model.

The parametric cost model predicts costs for typical aerospace products at typical aerospace production rates on the order of 100 units per year or less. Many of the items in these SPS's must be produced at relatively high production rates to meet any reasonable SPS deployment scenario. Hardware produced at high rates employs different tooling concepts and different production methods, more similar to mass production than typical aerospace techniques. Correlations developed for a wide variety of products indicate a production rate, cost improvement slope of approximately 70%. Adjustments to the PCM results for high production items were made as follows: First, a standard hours estimate of typical aerospace costs was developed utilizing a typical aerospace cost improvement slope for 1,000 units.

(Experience of jetliner production indicates that approximately 1,000 units production are required to reach the standard hours "predictable by tasks/timeline/headcount analyses.) A production rate improvement factor is then calculated based on the ratio of required annual production rate to a typical aerospace product value of 100 units per year. A production rate improvement slope of 70% was used.

In certain instances detailed estimates were available for manufacturing costs. These were used as available.

Total SPS system costs include also costs for space transportation, costs for space construction operations, and costs for ground receiving stations. Details of the launch vehicle cost per flight estimating procedure were reported in Volume V of the Part I Final Report. Launch vehicle cost per flight is dependent on launch rate.

Total transportation costs included transportation of propellants and orbit transfer hardware to low Earth orbit, and in addition the cost of orbit transfer hardware (either chemical orbit transfer vehicles or self-power electric orbit transfer system installations depending on construction location).

Construction costs included the transportation costs for crew rotation and resupply, the crew operations support costs and the amortization of construction base c. .s using typical capital facilities amortization procedures. Construction base habitats and basic structure were amortized over a 25 year period with the construction equipment amortized over an 8 year period. Crew transportation costs presumed for the 1 SPS per year rate, the use of a modified shuttle vehicle at $12 million per flight and for the 4 SPS per year rate, the use of an advanced fully reuseable shuttle at $5 million per flight. Delivery of propellants to low Earth orbit for the crew rotation and resupply orbit transfer vehicles is assumed to occur with the heavy lift launch vehicle at the appropriate cost per flight figure. Costs for orbit transfer installations for the self-power case, were derived using the parametric cost model with production rate adjustments for high production items as previously discussed.

3.2 COST ESTIMATING DETAILS

Table 1 in the cost data package is a capital cost summary for the photovoltaic SPS. It summarizes total costs in accordance with the work breakdown structure generally used and indicates source data and references further backup tables that provide additional detail. Interest during construction is added to the total costs based on an estimated construction period. Growth is added to provide a cost equivalent of the mass growth projections developed and the mass uncertainty analyses.

Table 2 summarizes the mature industry estimate. Table 2 goes to a level of work breakdown structure below that of Table 1. (Note that the "other" category from the first part of Table 2 is included in the multiple-common item in Table 1.) The cost calculations for Table 2 support the SPS (satellite) cost values for GEO construction. The SPS values for solar cells and multiple-common use equipment have been adjusted for the LEO construction case to allow for the increase in SPS size from the reference configuration that was costed. The columns in Table 2 reflect the calculation steps in applying the mature industry approach and some of the columns are not directly related to the final cost estimates. At the left (with the titles), the mass of each costed element is indicated and the number of such elements required carried under the number column. For example, the costed unit for primary structure was estimated to weigh 7250 lb. 1,824 of these units are required to make up an SPS structure. "Slope" indicates the learning slope used to develop the aerospace fully learned unit cost. Cost figures are in thousands. For example, the first unit cost for one 7250 lb element of primary structure as estimated by the PCM method was 2.375 million dollars. The PCM program predicted a first unit cost including the learning for 1824 of these units of 971 million dollars. The fully learned unit (down the 85% curve to 1,000 units) would be $470,000. This figure compares with the column called "PCM unit cost" which is for the first such unit. The next total is simply the product of the fully learned unit times the number of units required. In the case of the primary structure, the mature industry estimates are taken from the detailed manufacturing estimate discussed under enclosure 1, which follows Table 4. The mature industry cost for primary structure was believed to have reached a materials cost plateau such that increasing production rate would not decrease cost. Therefore, the costs for 4 SPS's per year are not less than for one per year. In several of the other elements, however, the cost is production rate sensitive. For example, in processors (under attitude control), 12 of these units are required. Notice that at this low production rate, the estimated mature industry cost is greater than the fully learned aerospace cost since the latter would apply to 1,000 units.

The mature industry estimates were developed from parametric cost model runs that used traditional aerospace estimating methods. The PCM runs are included as Table 3 for the photovoltaic system. Table 4 summarizes the solar cell and blanket estimates that were made. Enclosure 1 describes the detailed manufacturing cost estimate that was made for graphite main structure hardware. Table 5 presents a reference photovoltaic SPS summary weight statement. Table 6 provides the rectenna cost estimate. Tables 7 thru 11 provide construction base cost and mass data. Table 12 provides an estimate for crew support costs (those in addition to crew transportation). The space construction crew represents two crews to account for time off duty (90 days in space and 90 days off), with a 10% margin, and provides a crew support staff of ten people for each crew man working in space. Table 13 summarizes transportation costs estimated. Table 14 provides the mature industry cost estimate for the self-powered orbit transfer system. In this case the system costed included mass growth and the mass growth was deleted and the values carried in Table 13. Table 15 is the parametric cost model run that provides the raw data from which Table 14 was prepared. Table 16 summarizes crew rotation and resupply requirements. Table 17 summarizes the calculations of cost growth equivalent to the mass growth determined from the uncertainty analyses. Table 18 summarizes LEO versus GEO cost differences. Tables 19 thru 27 provide a similar cost package for the thermal engine system.

TABLE 1

CAPITAL COST SUMMARY - PHOTOVOLTAIC SPS (SILICON CR=1)

WBS #	ITEM	SOURCES & REFERENCES	1 SPS/YR		4 SPS/YR	
			LEO CONSTRUCTION	GEO CONSTRUCTION	LEO CONSTRUCTION	GEO CONSTRUCTION
1.01	Solar Power Satellite		(7442)	(7190)	(5587)	(5378)
1.01.00	Multiple/Common	. Mature Industry Estimate, Table 2 . Mature Industry Discussion . Parametric Cost Model Run, Table 3	897	793	760	661
1.01.01	Energy Collection	. Solar Cell Costs, Table 4	0	0	0	0
1.01.02	Energy Conversion	. Solar Cell Cost Discussion, Volume II	3731	3588	2793	2686
1.01.03	Power Distribution	. Structural Mfg Estimate, Encl. 1 . Varian Analysis of Klystron Production	138	133	82	79
1.01.04	Microwave Power Transmission	. MPTS Error Analysis . SPS Mass Estimate, Table 5 & Backup . LEO Figures Reflect 5% Oversize	2676	2676	1952	1952
1.02	Ground Receiving Station	. Rectenna Cost Estimate, Table 6 . Bovay Studies (JSC Contract) . Raytheon Studies (Various Contracts) . Rectenna Optimal Sizing Analysis	(4446)	(4446)	(4000)	(4000)
2.0	Construction/ Space Support		(1109)	(1126)	(1109)	(1126)
2.01	Construction Base (Facility Writedown)	. Writedown Summary, Table 7 . Facility Mass & Cost Estimates, Tables 8 & 9 . Construction Analyses & Base Definitions (See Volume V)	596	620	596	620
2.02	Space Support					
2.02.01	Staging Base	. Staging Base Mass & Cost Estimates, Tables 10 & 11	N/A		N/A	
2.02.02	Crew Support	. Crew Support ROM Estimate, Table 12 . Crew Reqts from Construction Analysis (Parts I & II Documentation)	497	506	597	506
2.02.03	Other OPS Support		16		16	

TABLE 1

CAPITAL COST SUMMARY - PHOTOVOLTAIC SPS (SILICON CR=1) (CONT)

WBS #	ITEM	SOURCES & REFERENCES	1 SPS/YR		4 SPS/YR	
			LEO CON-STRUCTION	GEO CON-STRUCTION	LEO CON-STRUCTION	GEO CON-STRUCTION
3.00	Space Transportation		(6445)	(9780)	(4188)	(6522)
3.01	Earth - LEO	. Numbers of Flights & Costs Summary, Table 13				
3.01.01	Freight	. Cost Per Flight Analyses (Parts I & II Documentation)	3139	2415	2155	1658
3.01.02	Crew	. Cost Per Flight Discussion, Volume II	336	336	140	140
3.02	LEO-GEO	. HLLV Operations Studies, Contract NAS				
3.02.01	Freight	. OTV Performance (Volume V)	2816	6670	1790	4482
		. OTS Performance (Part I)	154	359	103	242
		. OTS Mature Industry Estimate, Table 14				
		. OTS PCM Run, Table 15				
		. FSTSA Reports (Contract NAS9-14323)				
		. Crew Rotation & Resupply Summary, Table 16				
		. Crew Duty Cycle Studies (Part I)				
		. Advanced Earth Orbit Transportation Systems Technology Requirements (Contract NAS1-13944)				
	Interest During Construction	Contruction/Transportation Timelines	(700 days) (1864)	(450 days) (1388)	(566 days) (1154)	(366 days) (851)
	Growth	. Table 17 . Uncertainty Analyses . FSTSA Mass/Cost Growth Correlation	(3450)	(4034)	(938)	(1094)
	Total		24,756	27,964	16,976	18,971

TABLE 2

MATURE INDUSTRY ESTIMATE, PHOTOVOLTAIC SPS AND MPTS

ITEM & MASS (LB)	NUMBER	SLOPE	PCM UNIT COST	PCM TFU	FULLY LEARNED UNIT	TOTAL	MATURE INDUSTRY @1 SPS/YR	MATURE INDUSTRY @4 SPS/YR	DOLLAR/KG
P/V SPS							4,745,750	3,495,900	
OTHER							225,988	166,971	
MULT/COM							637,278	564,266	
PRIM STRUC 7250#	1,824	.85	2,375	971,550	470	857,615	360,000	360,000	50 (From Mfr, Est)
ATT CONT							152,891	79,879	
THRUSTERS 110 Lb.	640	.85	1,328	243,150	262	168,260	66,510	33,255	2,082
PROCESSORS 12,000 Lb.	12	.85	6,248	51,550	1,236	14,843	42,848	21,424	655
STRUCTURE 10,000 Lb.	4	.85	7,505	25,140	1,485	5,943	25,140	14,860	1,637
TANKS 1,130 Lb.	8	.85	1,040	6,178	206	1,647	5,823	2,912	1,420
INSTRUM. 1,000 Lb.	4	.85	3,752	12,570	742	2,971	12,570	7,428	8,188
CENTRAL COMPUTE 500 Lb	3	1.0	7,385	28,157	9,385	28,157	28,157	28,157	
COMMUNIC 2,000 Lb.	3	1.0	24,576	73,729	24,576	73,729	73,729	73,729	
ANT YOKE 13,800 Lb.	2	.85	12,145	22,501			22,501	22,501	

TABLE 2 (Continued)

ITEM & MASS (LB)	NUMBER	SLOPE	PCM UNIT COST	PCM TFU	FULLY LEARNED UNIT	TOTAL	MATURE INDUSTRY 01 SPS/YR	MATURE INDUSTRY 04 SPS/YR	DOLLAR/KG
POWER GENERATOR							3,749,628	2,686,207	
SOLAR BLANKETS		.8	15,056	9,945,165					
ARRAY PANELS 1 Lb.	78,387,000	.8	17		3.365	2,633	3,588,000	2,563,000	$35/M² & $25/M²
JUMPERS 0.01 Lb.	78,387,000	.85	0.123		.024	2,537,800	16,000	16,000	$45/KG
NETWORK	6,124	.85	444		87	538,300	68,786	68,786	$25/KG
CATERNARIES	6,124	.85	496		98	601,341	76,842	38,421	$30/KG
POWER DISTRIBUTION							132,856	78,956	
SWITCHGEAR 1,320 Lb.	208	.85	3,787	292,000	750	156,000	108,000	54,100	868
BUSSES 15,000 Lbs.	32	.85	626	11,276	124	3,966	7,000	7,000	$32
ROTARY JOINT 38,000 Lb.	2	.85	9,639	17,856			17,856	17,856	$560

TABLE 2 (Continued)

ITEM & MASS (LB)	NUMBER	SLOPE	PCM UNIT COST	PCM TFU (1 MPTS)	FULLY LEARNED UNIT	TOTAL	MATURE INDUSTRY 01 SPS/YR (2 MPTS)	MATURE INDUSTRY 04 SPS/YR (2 MPTS)	DOLLAR/KG
MPTS TOTAL (2 Ant)							2,675,642	1,961,823	
CHECKOUT & PKG'G							54,000	54,000	
MULT/COM				318,033			469,976	347,517	
PRIMARY STRUC (965 Lb.)	240	.85	431	21,760	85	20,478	13,218	6,609	125
SEC STRUC (7,137 Lb)	122	.85	2,344	69,857	464	56,613	51,256	25,627	129
ATT CONTROL (1,000 Lb)	24	90	13,278	124,529	4,646	111,515	201,736	111,515	21,000
CENTRAL COMPUTE (500 Lb)	6	1	9,385	28,157	9,385	56,310	56,310	56,310	41,000
COMMUNIC (2,000 Lb)	6	1	24,576	73,729	24,576	147,456	147,456	147,456	27,000
POWER DISTRIBUTION				1,188,068			632,497	446,907	
PWR PROC (12,000 Lb)	456	90	3,497	410,414	1,223	558,000	261,317	261,317	105
SWITCHGEAR (660 Lb)	912	85	2,120	299,137	420	382,767	126,746	63,373	464
THERMAL CONTROL (3,600 Lb.)	456	85	3,476	287,699	688	313,800	146,948	73,474	197

TABLE 2 (Continued)

ITEM & MASS (LB)	NUMBER	SLOPE	PCM UNIT COST	PCM TFU	FULLY LEARNED UNIT	TOTAL	MATURE INDUSTRY @1 SPS/YR	MATURE INDUSTRY @4 SPS/YR	DOLLAR/KG
POWER DISTRIBUTION (7,000 Lbs.)	456	85	2,306	190,818	457	208,175	97,486	48,743	67
SUBARRAYS				6,707,654			1,519,069	1,103,399	
STRUCTURE AND WAVEGUIDES (685 Lb.)	13,864	85	323	368,651	64	886,534	258,439	258,439	60
KLYSTRONS (70 KW_{RF})	194,112	90	53	687,240	18	3,600,136	524,102	339,696	Varian Estimates
THERMAL CONTROL	194,112	85	157	1,762,474	31	6,033,318	274,000	274,000	45
CONTROL CKTS (11 Lb.)	194,112	90	300	3,889,287	105	20,378,131	462,528	231,264	477

Table 3A Parametric Cost Model Output for Photovoltaic SPS

NO	NAME	SUB TO	ELEMENT METHOD	SOUR- CES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
1	TOTAL PROGRAM	0	DDT&E SUBS	0	0.00	0	0	0	0.0			1,900,930
	0		OPCODE= 0									
			UNIT SUBS	0	0.00	0				0	0	13,710,942
			OPCODE= 0									
2	PROG INTEG & MGMT	1	DDT&E FACTOR	3	0.06	0	0	0	0.0			83,654
	0		OPCODE= 2									
			UNIT FACTOR	3	0.06	0				0	0	738,356
			OPCODE= 2									
3	PHOTOV SPS	1	DDT&E SUBS	0	0.00	0	0	0	0.0			1,817,276
	0		OPCODE= 0									
			UNIT SUBS	0	0.00	0				0	0	12,972,589
			OPCODE= 0									
4	FLT SYS D&D	3	DDT&E SUBS	0	0.00	0	0	0	0.0			336,536
	0		OPCODE= 0									
			UNIT SUBS	0	0.00	0				0	0	11,281,891
			OPCODE= 0									
5	SUSTAINING	3	DDT&E FAC UN	4	0.05	0	0	0	0.0			393,262
	0		OPCODE= 3									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
6	SE & I	3	DDT&E CER*	4	0.00	0	0	0	0.0			27,669
	0		OPCODE= 12	32	0.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									

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Table 3A (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
7	FLT SYS DD&T	0	DDT&E FACTOR	4	1.00	0	0	0	0.0			0
0			OPCODE= 2	6	1.00							
				9	1.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
8	SYSTEM TEST	3	DDT&L SUBS	0	0.00	0	0	0	0.0			716,921
0			OPCODE= 0									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
9	SYS TEST LBR	8	DDT&E CER=	4	0.00	0	0	0	0.0			265,645
0			OPCODE= 12	34	0.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
10	GR TEST HDWE	8	DDT&E FAC UN	4	0.02	0	0	0	0.0			225,637
0			OPCODE= 3									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
11	FLT TEST HDWE	8	DDT&E FAC UN	4	0.02	0	0	0	0.0			225,637
0			OPCODE= 3									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
12	SOFTWARE ENGR	3	DDT&E CER=	7	0.00	0	0	0	0.0			130,478
0			OPCODE= 12	37	0.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									

Table 3A (continued)

NO	NAME	SUB TO	ELEMENT	METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
13	GSE	3	DDT&E	FACTOR	4	0.10	0	0	0	0.0			42,208
	0		OPCODE= 2										
			UNIT	FACTOR	4	0.10	0				1	100	844,561
			OPCODE= 2										
14	TOOLING	3	DDT&E	FACTOR	4	0.25	0	0	0	0.0			150,200
	0		OPCODE= 2										
			UNIT	N/A	0	0.00	0				0	0	0
			OPCODE= 8										
15	ASSY & C/O	3	DDT&E	N/A	0	0.00	0	0	0	0.0			0
	0		OPCODE= 8										
			UNIT	FAC UN	4	0.07	0				0	0	846,141
			OPCODE= 3										
16	MULT/COM	4	DDT&E	SUBS	0	0.00	0	0	0	0.0			220,960
	0		OPCODE= 0										
			UNIT	SUBS	0	0.00	0				0	0	1,412,034
			OPCODE= 0										
17	PRIM STRUCT	16	DDT&E	CER	1	1.00	30	0	0	0.0			6,354
	7250 LBS		OPCODE= 1										
			UNIT	CER	46	1.00	45				1824	84	2,375
			OPCODE= 1										
										AGGREGATED VALUES			971,558
18	ATT CONTROL	16	DDT&E	SUBS	0	0.00	0	0	0	0.0			101,453
	0		OPCODE= 0										
			UNIT	SUBS	0	0.00	0				0	0	338,589
			OPCODE= 0										

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Table 3A (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (C00)
19	THRUSTERS	18	DDT&E CER	21	1.00	31	0	0	0.0			8,321
	110 LBS		OPCODE= 1									
			UNIT CER	66	1.00	45				640	84	1,328
			OPCODE= 1									
									AGGREGATED VALUES			243,150
20	PROCESSOPS	18	DDT&E CER	14	1.00	31	0	1	5.0			43,226
	12000 LBS		OPCODE= 1									
			UNIT CER	59	0.20	45				12	84	6,248
			OPCODE= 1									
									AGGREGATED VALUES			51,550
21	STRUCTURE	13	DDT&E CER	2	1.00	30	0	0	5.0			30,939
	10000 LBS		OPCODE= 1									
			UNIT CER	47	1.00	45				4	84	7,505
			OPCODE= 1									
									AGGREGATED VALUES			25,140
22	TANKS	18	DDT&E CER	2	1.00	30	0	0	5.0			4,967
	1130 LBS		OPCODE= 1									
			UNIT CER	47	1.00	45				8	84	1,040
			OPCODE= 1									
									AGGREGATED VALUES			6,178
23	INSTRUM	18	DDT&E CER	15	1.00	31	0	0	0.0			13,999
	1000 LBS		OPCODE= 1									
			UNIT CER	60	1.00	45				4	84	3,752
			OPCODE= 1									
									AGGREGATED VALUES			12,570
24	CENTRAL COMPUTE	16	DDT&E CER	19	1.00	31	0	90	5.0			43,523
	500 LBS		OPCODE= 1									
			UNIT CER	64	1.00	45				3	100	9.385
			OPCODE= 1									
									AGGREGATED VALUES			28,157

Table 3A (continued)

NO	NAME		SUB TO	ELEMENT METHOD	SOUR-CES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
25	COMMUNIC		16	DDT&E CER	16	1.00	31	0	90	5.0			69,629
	2000	LBS		OPCODE= 1									
				UNIT CER	61	1.00	45				3	100	24,576
				OPCODE= 1									
											AGGREGATED VALUES		73,729
26	PWR GEN		4	DDT&E SUBS	0	0.00	0	0	0	0.0			3,953
	0			OPCODE= 0									
				UNIT SUBS	0	0.00	0				0	0	9,326,210
				OPCODE= 0									
27	SOLAR BLANKETS		26	DDT&E SUBS	0	0.00	0	0	0	0.0			376
	0			OPCODE= 0									
				UNIT SUBS	0	0.00	0				6124	79	15,710
				OPCODE= 0									
											AGGREGATED VALUES		8,551,862
28	ARRAY PANELS		27	DDT&E CER	26	1.00	30	0	0	0.0			375
	10.75	SQ FT		OPCODE= 1									
				UNIT CER	71	0.30	45				12800	79	17
				OPCODE= 1									
											AGGREGATED VALUES		15,486
29	JUMPERS		27	DDT&E CER	13	1.00	30	0	0	0.0			0
	0.01	LBS		OPCODE= 1									
				UNIT CER	57	1.00	45				12800	84	0
				OPCODE= 1									
											AGGREGATED VALUES		224
30	NETWORK		26	DDT&E CER	1	1.00	30	0	0	0.0			1,065
	1000	LBS		OPCODE= 1									
				UNIT CER	46	1.00	45				6124	84	444
				OPCODE= 1									
											AGGREGATED VALUES		460,436

Table 3A (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
31	CATERNARIES	26	DDT&E CER	2	1.00	30	0	0	0.0			2,511
	500 LBS		OPCODE= 1									
			UNIT CER	47	1.00	45				6124	84	496
			OPCODE= 1									
									AGGREGATED VALUES			513,915
32	PWR DISTR	4	DDT&E SUBS	0	0.00	0	0	0	0.0			96,840
	0		OPCODE= 0									
			UNIT SUBS	0	0.00	0				0	0	321,148
			OPCODE= 0									
33	SWITCHGEAR	32	DDT&E CER	14	1.00	30	0	50	5.0			4,624
	1320 LBS		OPCODE= 1									
			UNIT CER	59	1.00	45				208	84	3,787
			OPCODE= 1									
									AGGREGATED VALUES			292,014
34	BUSSES	32	DDT&E CER	1	0.10	29	0	0	0.0			1,459
	15000 LBS		OPCODE= 1									
			UNIT CER	46	0.10	45				32	84	626
			OPCODE= 1									
									AGGREGATED VALUES			11,276
35	ROTARY JOINT	32	DDT&E CER	2	1.00	29	0	0	0.0			90,756
	38000 LBS		OPCODE= 1									
			UNIT CER	46	1.00	45				2	84	9,639
			OPCODE= 1									
									AGGREGATED VALUES			17,857
36	ANTENNA YOKE	4	DDT&E CER	4	0.90	29	0	50	5.0			14,781
	13800 LBS		OPCODE= 1	5	0.10							
			UNIT CER	47	0.90	45				2	84	12,145
			OPCODE= 1	50	0.10							
									AGGREGATED VALUES			22,501

Table 3B Parametric Cost Model Output for Transmitter

NO	NAME	SUB TO	ELEMENT METHOD	SOUR-CES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
1	TOTAL PROGRAM 0	0	DDT&E SUBS OPCODE= 0	0	0.00	0	0	0	0.0			1,237,735
			UNIT SUBS OPCODE= 0	0	0.00	0				0	0	9,765,689
2	PROG INTEG & MGMT 0	1	DDT&E FACTOR OPCODE= 2	3	0.06	0	0	0	0.0			63,081
			UNIT FACTOR OPCODE= 2	3	0.06	0				0	0	526,290
3	MICROWAVE PTS 0	2	DDT&E SUBS OPCODE= 0	0	0.00	0	0	0	0.0			1,174,653
			UNIT SUBS OPCODE= 0	0	0.00	0				0	0	9,239,322
4	FLT SYS D&D 0	3	DDT&E SUBS OPCODE= 0	0	0.00	0	0	0	0.0			288,791
			UNIT SUBS OPCODE= 0	0	0.00	0				0	0	8,213,757
5	MULT/COMMON 0	4	DDT&E SUBS OPCODE= 0	0	0.00	0	0	0	0.0			213,815
			UNIT SUBS OPCODE= 0	0	0.00	0				0	0	318,033
6	PRIMARY STRUC 965 LBS	5	DDT&E CER OPCODE= 1	1	1.00	30	0	0	0.0			1,032
			UNIT CER OPCODE= 1	44	1.00	45				120	84	431
									AGGREGATED VALUES			21,760

Table 38 (continued)

NO	NAME	SUB TO	ELEMENT	METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD	MOD CMPLX	NUMBER	LRN %	COST (000)
7	SECONDARY STRUC	5	DDT&E	CER	1	1.00	30	0	0	0.0			6,264
	7137 LBS		OPCODE= 1										
			UNIT	CER	46	1.00	45				61	84	2,344
			OPCODE= 1										
										AGGREGATED VALUES			69,857
8	ATTITUDE CONTROL	5	DDT&E	CER	25	1.00	31	0	0	0.0			17,206
	1000 LBS		OPCODE= 1										
			UNIT	CER	67	1.00	45				12	89	13,278
			OPCODE= 1										
										AGGREGATED VALUES			124,529
9	CENTRAL COMPUTE	5	DDT&E	CER	19	1.00	31	0	1	5.0			72,756
	500 LBS		OPCODE= 1										
			UNIT	CER	64	1.00	45				3	100	9,385
			OPCODE= 1										
										AGGREGATED VALUES			28,157
10	COMMUNIC	5	DDT&E	CER	16	1.00	31	0	0	5.0			116,556
	2000 LBS		OPCODE= 1										
			UNIT	CER	61	1.00	45				3	100	24,576
			OPCODE= 1										
										AGGREGATED VALUES			73,729
11	PWR DISTR	4	DDT&E	SUBS	0	0.00	0	0	0	0.0			56,480
	0		OPCODE= 0										
			UNIT	SUBS	0	0.00	0				0	0	1,188,070
			OPCODE= 0										
12	PWR PROC	11	DDT&E	CER	14	1.00	30	0	0	0.0			35,235
	12000 LBS		OPCODE= 1										
			UNIT	CER	59	0.10	45				228	89	3,497
			OPCODE= 1										
										AGGREGATED VALUES			410,414

Table 3B (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
13	SWITCHGEAR	11	DDT&E CER	14	1.00	29	0	0	0.0			3,235
	650 LBS		OPCODE= 1									
			UNIT CER	59	1.00	45				456	84	2,120
			OPCODE= 1									
									AGGREGATED VALUES			299,137
14	THERMAL CONTROL	11	DDT&E CER	9	1.00	30	0	0	0.0			12,156
	3600 LBS		OPCODE= 1									
			UNIT CER	54	1.00	45				228	84	3,476
			OPCODE= 1									
									AGGREGATED VALUES			287,699
15	PWR DISTR	11	DDT&E CER	1	1.00	29	0	0	0.0			5,852
	7000 LBS		OPCODE= 1									
			UNIT CER	46	1.00	45				228	84	2,306
			OPCODE= 1									
									AGGREGATED VALUES			190,818
16	SUBARRAYS	4	DDT&E SUBS	0	0.00	0	0	0	0.0			10,495
	0		OPCODE= 0									
			UNIT SUBS	0	0.00	0				6932	84	5,895
			OPCODE= 0									
									AGGREGATED VALUES			6,707,654
17	STRUCTURE	16	DDT&E CER	1	1.00	30	0	0	0.0			758
	685 LBS		OPCODE= 1									
			UNIT CER	46	1.00	45				1	100	323
			OPCODE= 1									
18	KLYSTRONS	16	DDT&E CER	21	2.00	30	20	0	0.0			6,860
	70 KWRF		OPCODE= 1									
			UNIT CER	87	2.00	45				15	89	53
			OPCODE= 1									
									AGGREGATED VALUES			603

Table 3B (continued)

NO	NAME	SUB TO	ELEMENT	METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
19	THERM CONT	16	DDT&E	CER	9	1.00	31	0	0	0.0			629
	70 LBS		OPCODE= 1										
			UNIT	CER	54	1.00	45				15	84	157
			OPCODE= 1										
										AGGREGATED VALUES			1,549
20	CONTROL CKTS	16	DDT&E	CER	23	1.00	31	0	0	0.0			2,247
	11 LBS		OPCODE= 1										
			UNIT	CER	68	1.00	45				15	89	300
			OPCODE= 1										
										AGGREGATED VALUES			3,418
21	ASSY & C/O	3	DDT&E	N/A	0	0.00	0	0	0	0.0			0
	0		OPCODE= 8										
			UNIT	FAC UN	4	0.05	0				0	0	410,687
			OPCODE= 3										
22	TOOLING	3	DDT&E	FACTOR	4	0.10	0	0	0	0.0			49,363
	0		OPCODE= 2										
			UNIT	N/A	0	0.00	0				0	0	0
			OPCODE= 8										
23	SYSTEM TEST	3	DDT&E	SUBS	0	0.00	0	0	0	0.0			359,085
	0		OPCODE= 0										
			UNIT	N/A	0	0.00	0				0	0	0
			OPCODE= 8										
24	SYS TEST LABOR	2[illegible]	DDT&E	CER*	4	0.00	0	0	0	0.0			194,811
	0		OPCODE= 12		34	0.00							
			UNIT	N/A	0	0.00	0				0	0	0
			OPCODE= 8										

Table 38 (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
25	GR TEST HDWE	23	DDT&E FAC UN	4	0.01	0	0	0	0.0			82,137
	0		OPCODE= 3									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
26	FLT TEST HDWE	23	DDT&E FAC UN	4	0.01	0	0	0	0.0			82,137
	0		OPCODE= 3									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
27	SE & I	3	DDT&E CER*	4	0.00	0	0	0	0.0			22,420
	0		OPCODE= 12	32	[illegible]							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
28	SUSTAINING	3	DDT&E FAC UN	4	0.05	0	0	0	0.0			286,313
	0		OPCODE= 3									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
29	FLT SYS DD&T	0	DDT&E FACTOR	4	1.00	0	0	0	0.0			0
	0		OPCODE= 2	24	1.00							
				27	1.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
30	SOFTWARE ENGR	3	DDT&E CER*	29	0.00	0	0	0	0.0			120,581
	0		OPCODE= 12	37	0.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									

Table 38 (continued)

ID	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
31 GSE		3	DDT&E CER=	4	0.00	0	0	0	0.0			56,097
0			OPCODE= 12	38	0.00							
			UNIT FACTOR	4	0.10	0				1	100	614,880
			OPCODE= 2									

TABLE 4

SOLAR CELL/BLANKET COSTS

1) J. Gauger's Mature Industry Correlation

8¢ to 17¢/Watt = 13.60 to 28.90/M^2 (Cells Only)

= 22.00 to \$37/M^2 (Array Panels)

2) Manufacturers Estimates

10¢ to 25¢/Watt (Cells Only)

= 17.00 to 42.50/M^2 (Cells Only)

= \$25.00 to \$50/M^2 (Array Panels)

3) Production Rate

Today \$10,000/M^2 for 50 kw

Then $(17e6/50)^{-1/2}$ = .0017 x 10,000 (70% Curve)

= \$17.00/M^2

Energy Cost = \$17/M^2 for \$34/M^2 @ 1 SPS/YR

4) Denman's Estimate - \$40/M^2 (Median)

Average of these values is \$35/M^2 @ 1 SPS/YR;

use \$25/M^2 for 4 SPS/YR

ENCLOSURE I

Manufacturing Analysis–Terrestrial Fabrication of Primary Structure Strut Assemblies

Our reference structure fabrication concept has proposed use of 10M tapered strut segments (20M strut assemblies) as the basic beam construction building block. In this approach, a highly automated terrestrial factory which produce strut segments on a mass production basis and package in high density magazines for transport to the LEO construction base.

During this period we expanded our analysis to include a brief look at factory manufacturing processes and non-recurring facility and tooling needs to sustain a "thruput" of one SPS/year. Specific objectives were to: a) gain a better understanding of rate processing requirements and to review producibility of the proposed tapered strut design; b) identify production rate "short fall" high risk areas; and c) test our mature industry estimate for primary/secondary structure.

Machine Process Center Concept

We subjected the strut design, and a slightly modified derivative, to step by step manufacturing process plan analysis. With a reasonably detailed processing plan in-hand we then established the "process flow limiters" for each operation or process step (i.e., feed and speed achievable for that process using that material) which gave us a reasonable feel for the effective yield of each process step. By applying the annual strut segment rate to produce one SPS per year (1.4×10^6 strut halves) we were then able to size the machine tools, special tooling, material consumption facility needs, etc.

Two mass production manufacturing concepts were evaluated. The first, generally referred to as the "Machine Process Center Concept," assumes design of special purpose machine tools (process centers) that essentially fabricate a completed part from raw materials, i.e., beam builder or automotive block processing type centers. In this case, complete injection molded end fittings and finish machined center fittings are loaded into the processing center and tension winding, curing, NDT inspection, etc., steps are all completed within the center with center operation sequenced by N.C. program. The second process evaluated was a typical "Process Station Flow-thru Concept" whereby each successive process step is accomplished by special purpose in-line (assembly line) machine tools. Each machine tool (station) is connected by appropriate transfer equipment with, buffer storage between stations and multiple stations added at "process flow limiter" (bottleneck) positions. Specific features of each of these concepts are presented in Tables E-1 and E-2. Figure E-1 illustrates the process flow for the assembly line concept.

Table E-1
Primary Structure Production Concept
Opt 1: Machine Process Center

- STRUT END FITTING: (Gr/THERMOPLASTIC) INJECTION MOLDED NET IN MULTI CAVITY MOLDS
- CENTER JOINT: (7075 ALUM) CLOSE TOL DIE FORGING WITH FINAL SIZING ACCOMPLISHED ON SPECIALIZED NC TURNING MACHINE STATIONS
- STRUT TUBE ASSEMBLY
  - LARGE 8 TURRET TURNING CENTER SEQUENCES PARTS IN 4 PROCESS STAGES
    - STAGE 1 COOL DOWN, LOAD FITTINGS, APPLY FILM ADHESIVE & PARTING FILMS
    - STAGE 2 CIRC WINDING
    - STAGE 3 DEBULK & CURE
    - STAGE 4 NDT, PART REMOVAL, TOOL CHANGEOUT/REPAIR
  - 2 MIL TAPE (13MM WIDE BY CONTINUOUS) TENSION WOULD @ ≈ 180 RPM
  - 8 SPOOL (4 PAIRS) TAPE LAYING WITH 4.7M/MIN YIELD/LAYER (STRUT COMP. 3.6 MIN)
  - TAPE WILL BE "B" STAGGED Gr/E TO SHORTEN CURE (MICROWAVE)
  - COCURRING OF END FITTING & STRUT TUBE
- PROCESS CENTER YIELD 30 PARTS/HR (THRUPUT 16 MIN/PART) (NEED 10 CENTERS)
- AUTOMATED NON-DESTRUCTIVE INSPECTION (NDT)--INCLUDES LIMIT LOAD STATIC TESTS
- PLANT AREA NEEDS 80-100K SQ/FT INCLUDING REFRIG STORIES, MAT'L STAGING MACHINE CENTERS, RWK CENTER
- TOOLING--APPROX 600 TOOLS INCL NC MASTERS FOR TURNING MANDREL FABRICATION
- ONE 750-1000 TON PRESS WITH 8-10 CAVITY MOLD--COOL DOWN & SCARF REMOVAL STATIONS IN PROCESS LINE
- STATIONS WILL ACCEPT DIE PRE-FORMS VIA CENTER FEED TRANSFER SYSTEM--CARBINE MULTI-SPINDLE CUTTING STATIONS FOR TURNING, & GANG MILL FINGER CUTS--MACHINE YIELD 16-20/HR--19 STATIONS REQUIRED. PROCESS STATION IN LINE FOR NDT, HEAT TREAT, ANODIZE, ETC.

Table E-2
Primary Structure Production Concept
Opt 2: Process Station Flow-Thru

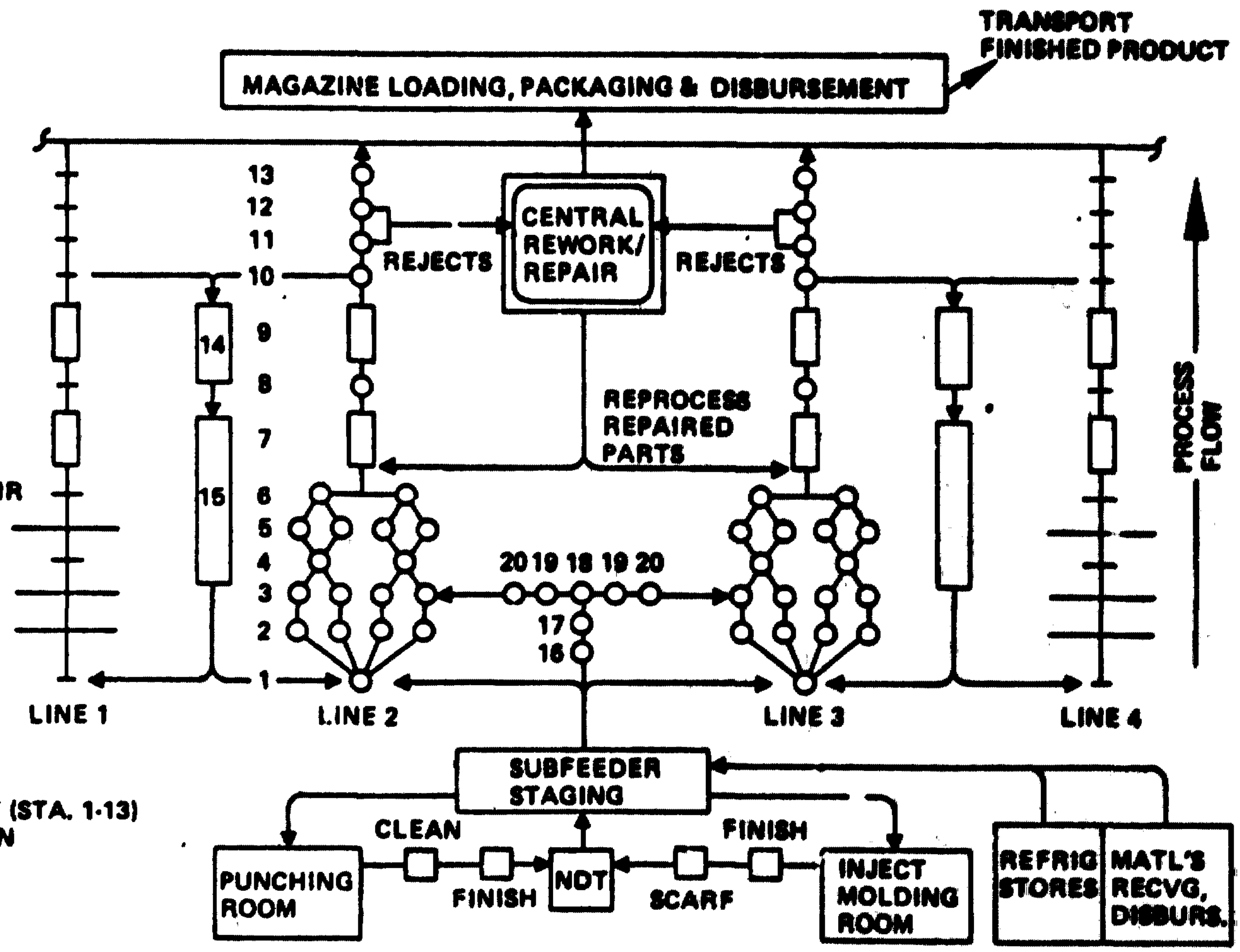
- STRUT END FITTING & CENTER JOINT: (BOTH Gr/THERMOPLASTIC)--INJECTION MOLDED NET IN MULTI CAVITY MOLDS--SAME AS OPT 1
- STRUT TUBE ASSEMBLY
  - SPECIAL PURPOSE MACHINE STATIONS WITH FLOW THRU TRANSFER SYSTEM--BUFFER STORAGE BETWEEN STATIONS & PARTS CROSS TRANSFER AT MULTI POSITION STATIONS
  - 2 MIL TAPE (13MM WIDE BY CONTINUOUS--TENSION WOULD @ ≈ 180 RPM)
  - KEY WINDING STATIONS INCLUDE
    - 4 STATIONS CIRC WINDING POSITIONING FABRIC & INNER KEVLAR
    - 4 STATIONS LAYING 0° Gr/E GORES (PRECUT & FORMED)
    - 4 STATIONS CIRC WINDING 90° KEVLAR OVER-WRAPS
- PRODUCTION LINE YIELD 90-92 PARTS/HR (3 LINES REQUIRED)
- AUTOMATED NON-DESTRUCTIVE TESTING (NDT)--SAME AS OPT 1
- PLANT AREA NEEDS 60-70K SQ/FT TOTAL
- TOOLING: APPROX 400 TOOLS--MORE MANDRELS THAN OPT 1 BY ELIMINATE TURNING TOOLING

Figure E-1
Strut Tube Process Flow-Thru
Facility Concept

SPS-1367

WORK STATION
TASK DESCRIP.

1 LOAD FITTINGS
2 INNER CIRC WIND
3 CENTER GORE LAY
4 VACUUM DEBULK
5 OUTER CIRC WIND
6 VACUUM DEBULK
7 MICROWAVE CURE
8 REM DEBULK TOOL
9 POSTCURE
10 MANDREL REMOVAL
11 NDT–ANALYZER
12 NDT–STATIC LOAD
13 FINAL ASSY
14 TOOL COOLDOWN
15 TOOL CHANGE/REPAIR
16 GORE TAPE PREP
17 GORE LASER TRIM
18 REAPPLY CARRIER
19 INDUCTION HEAT
20 CONTOUR ROLL



SIZING DATA:
92 PARTS/HR/LINE
19 MINUTES TO THRUPUT (STA. 1-13)
2.6 MINUTES MAX STATION

The results of our studies clearly show that production rates of 300 strut segments per hour (3 shift/5 day week basis) are easily believable with modest non-recurring investment using current available aerospace processing technique. No high risk or long lead process development tasks were identified. Table E-3 provides summary costing data on the strut segment alternate design/processing approaches reviewed. Our detail manufacturing plan analysis has confirmed that the mature industry cost estimate of $55/kg (now year dollars) for terrestrial fabrication of primary/secondary structure is credible. We do, in fact, believe further design/process producibility efforts will yield even lower primary structure costs.

Table E-3
Cost Analysis Summary
(77$)

- MACHINE PROCESS CENTER (ORIGINAL STRUT DESIGN)

  NON-RECURRING: ($60 x 10^6 FACILITY, 2.6 x 10^6 TOOLING) $62.6 x 10^6

  RECURRING:

MATL	617.20	(96%)	=	$640/20M STRUT
LABOR	22.90	(4%)		

  AVERAGE COST--OPT 1 PLAN [R + (NR/8 YRS)] = $57.87/kg

- PROCESS STATION FLOW THRU (MODIFIED DESIGN)

  NON-RECURRING: ($55 x 10^6 FACILITY, 2 x 10^6 TOOLING) $57 x 10^6

  RECURRING:

MATL	506.20	(96%)	=	$527/20M STRUT
LABOR	20.10	(4%)		

  AVERAGE COST--OPT 2 PLAN [R + (NR/8 YRS)] = $47.58/kg

- PRIMARY STRUT MATURE INDUSTRY ESTIMATE = $55/kg

TABLE 5
REFERENCE PHOTOVOLTAIC SPS
SUMMARY WEIGHT STATEMENT
(Weight in Kilograms)

1.0	SOLAR ENERGY COLLECTION SYSTEM		51,782,300
	1.1 Primary Structure	5,385,000	
	1.2 Secondary Structure	1	
	1.3 Mechanical Rotary Joint	66,800	
	1.4 Maintenance Station	———	
	1.5 Control	178,100	
	1.6 Instrumentation/Communications	4,000	
	1.7 Solar Cell Blanket	43,750,000	
	1.8 Solar Concentrators	———	
	1.9 Power Distribution	2,398,400	
2.0	MICROWAVE POWER TRANSMISSION SYSTEM		25,212,200
	(TOTAL - LESS GROWTH)		(76,994,500)
3.0	WEIGHT GROWTH ALLOWANCE - 26.6%		20,505,500
	(TOTAL - WITH GROWTH)		(97,500,000)

1 Distributed to other WBS items.

TABLE 6

RECTENNA NOMINAL COST ESTIMATE @ 1 SPS/YR

BEAM DIAMETER 13 KM

RECTENNA INTERCEPT DIAMETER 9.36 KM @ 95% EFFICIENCY

RECTENNA GROUND AREA $= 1.535 \times \pi/4 \times 9.75^2 = 105\ KM^2$

RECTENNA PANEL AREA $= 68.8\ KM^2$

TOTAL CONTROLLED AREA (LAND AQUIS) $= 204 KM^2 = 50{,}400$ ACRES

WBS	ITEM	ESTIMATING FACTOR	NUMBER	COST, MILLIONS
1.02				
1.02.00	Mult/Common			
1.02.00.01	Land	$5,000/Acre Acquis & Prep	50,400 Acres	252
1.02.00.02	Prim Structure	$\$10/M^2$	$68.8\ KM^2$	688
1.02.00.03	Control	$1,000/Subunit	500 Subunits	0.5
1.02.00.04	Commun			50
1.02.01	Energy Coll/Conv			
1.02.01.00	Support Str/Gnd Plane	$\$3/M^2$	$68.8\ KM^2$	206
1.02.01.01	Dipole/Diode/Filter Units	0.08 Ea @ 70 CM^2/Element	0.983×10^{10}	787
1.02.02	Power Distr. Sys.			
1.02.02.01	Busses	Satellite Value		7
1.02.02.02	Processors	$50/KWe	4.65×10^6 KWe	233
				2,223

= 4,446 for 2 Rectennas

TABLE 7

CONSTRUCTION BASE WRITE DOWN SUMMARY
PHOTOVOLTAIC SPS
LEO CONSTRUCTION

Item	Cost (Millions)	Amortized Over	Cost/SPS (Millions)
LEO Base			
Facility	3465	25 years	139
Facility O/H	1629	25 years	65
Constr. Equip.	1310	8 years	164
C.E. O/H	616	8 years	77
GEO Base			
Facility	380	25 years	15
Facility O/H	179	25 years	7
Constr. Equip.	425	8 years	53
C.E. O/H	201	8 years	25
LEO Base Transport	625	15 years	42
GEO Base Transport	137.5	15 years	9
			596

TABLE 7(Cont'd)

ITEM	Cost (Millions)	Amortized Over	Cost/SPS (Millions)
LEO Staging Base			
Facility	650	25 years	26
Facility Wrap	304	25 years	12
Equipment	135	8 years	[illegible]
Equipment Wrap	61	8 years	2
GEO Construction Base			
Facility	3610	25 years	144
Facility Wrap	1690	25 years	68
Equipment	1555	8 years	194
Equipment Wrap	730	8 years	91
LEO S/B Transportation	37.5	15 years	3
GEO C/B Transportation	1125	15 years	75
			620

TABLE 8

P/V CONST BASE COST SUMM
(FIRST SET) $M

LEO Base		(7020)
Facility	3465	
Const Equip	1310	
Overhead	2245	
GEO Base		(1185)
Facility	380	
Const. Equip	425	
Overhead	380	
		$8205 [1]

[1] This has 90% learning within the first set but does not include those units used for testing.

TABLE 8 (Cont'd)

Facility		(3465)
Foundation	250	
Crew Modules	2870	
Cargo Handling	330	
Base Subsys	15	
Maint. Provisions	-	
Const. & Support Equip.		(1310)
Struct Assy.	356	
Energy Collection Conversion	165	
Power Distrib.	75	
Subarray Install.	80	
Cranes/Manip	560	
Indexers	80	
	Basic HRW	4775
Spares		715
Install, Assy, C/O		765
SE&I		335
Proj. Mgt.		95
Sys. Test		145
GSE		190
		$7020 M

TABLE 9

P/V CONST BASE MASS SUMMARY

		$(10^3 kg)$
LEO CONST BASE		(5870)
Facility	5200	
Const & Supp Equip	400	
Consumables	270	
GEO CONST BASE		(770)
Facility	565	
Const & Supp Equip	175	
Consumables	30	
		6640

TABLE 9 (Cont)

LEO CONST. BASE	10^3 kg	
FACILITY	(5200)	
Foundation	2500	
Crew Modules	2000	[1]
Cargo Handling/Distribution	400	
Base Subsystems	200	
Maintenance Provisions	100	
CONST & SUPPLY EQUIPMENT	(400)	
Struct. Assy.	80	
Solar Array Inst.	60	
Power Dist. Inst.	20	
Subarray Inst. (Incl. sec str)	30	
Cranes/Manipulators	180	
Indexers	30	
TOTAL DRY	5600	
CONSUMABLES (90 Days)	270	

[1] Includes 33% growth allow. No other item does.

TABLE 9 (Continued)

GEO FINAL ASSY BASE

	10^3 kg	
Facility		(565)
Foundation	280	
Crew Module	220	
Cargo Handling/Dist	55	
Base Subsystems	10	
Const & Support Equipment		(175)
Solar Array Inst.	50	
Crane/Manipul.	15	
Indexers	6	
Docking Cranes	104	
		740

TABLE 10

COST SUMMARY

P/V GEO CONST CONCEPT

		$\$10^6$M
LEO Staging Depot		($1130)
GEO Const Base		(7585)
Facility	3610	
Const Equip	1555	
Wraparound	2420	
		$87[illegible] M

TABLE 10 (Continued)

LEO STAGING DEPOT		($\$10^6$)
Foundation		1
Crew Modules		645
Base Subsystems		4
Vehicle and Payload Handling		120
Propellant Storage and Distribution		15
Basic Hardware		$785
Spares (15%)		115
Install, Assy, C/O (16)		125
SE&I (7)		55
Proj. Mgt. (2)		15
Sys. Test (3)		25
GSE (4%)		30
	Total	$1150

TABLE 10 (Continued)

GEO CONST BASE

Facility		(3610)
Foundation		250
Crew Modules		3020
Cargo Handling		330
Base Subsystems		10
Maintenance Prov		-
Construction Equip		(1555)
Struct Assy		350
Energy Collection & Conversion		165
Power Dist.		75
Subarray Inst.		80
Cranes/Manip		760
Indexers		125
	Basic Hardware	5165
Spares		775
Install, Assy, C/O		825
SE&I		360
Proj. Mgt.		100
Sys. Test		155
GSE		205
		2420
	Total	7585

TABLE 11

MASS SUMMARY

P/V SAT

GEO CONST CONCEPT

	10^3 kg	
LEO STAGING DEPOT		(750)
Facility & Equip.	730	
Consumables	20	
GEO Const Base		(6535)
Facility	5730	
Const. Equip.	515	
Consumables	270	
		7285

TABLE 11 (Cont.)

		$(10^3$ kg)
GEO Const. Base		
Facility		(5750)
Foundation		2500
Crew Modules		2690
Cargo Handling/Dist		400
Base Subsystems		60
Maint. Provision		100
Construction Equip.		(515)
Struct. Assy.		80
Solar Array Inst.		60
Power Dist. Inst.		20
Subarray Inst.		30
Cranes/Manipulators		255
Indexes		70
	Total Day	6265
Consumables (90 Days)		270
		6535

TABLE 11 (Cont.)

LEO Staging Depot	10^3 kg
Foundation	15
Crew Modules	590
Base Subsystems	30
Vehicle and Payload Handling	40
Propellant Storage and Distribution	55
	730
Consumables (90 days)	20
Total	750

TABLE 12

CREW SUPPORT ROM ESTIMATE

LEO CONSTRUCTION

Crew Size = 541		
Total Staff = 2 (541) + 10%	=	1190
Cost $120K/Man-Year =		$143M
Crew Support 10X Working Crew = 5410 (on ground) @ $50K/Man-Year		$271M
Training, etc. (20%)		$83M
		497M

GEO CONSTRUCTION

Crew Size = 551

By Ratio, Cost is $506M

THERMAL ENGINE LEO CONSTRUCTION

Crew Size = 811

By Ratio, Cost is $745M

There is an estimated additional $4M operations support per SPS for LEO construction to accommodate the more complex operations.

TABLE 13

NUMBERS OF FLIGHTS & COSTS SUMMARY

HLLV Cost/Flt = 67.56 X (Annual Rate) -.2715

	Cost 1 SPS/Yr LEO	Cost 1 SPS/Yr GEO	Cost 4 SPS/Yr LEO	Cost 4 SPS/Yr GEO
1. P/V Hardware • Mass is 77,000 Tons • HLLV Payload is 391 Tons • 10% for Packaging Flights = 217 (GEO) = 228 (LEO - 5% Oversize)	3139	2415	2155	1658
2. Orbit Transfer Sys (LEO) Mass is 12,236 tons (Total SPS) 10% for packaging 35 Flights (LEO)	482	--	330	--
3. OTV's 217 trips to GEO wears out 4.34 vehicles = 4.34 flights (GEO)	-	48	-	33
4. Propellant for OTS OTS = 3620 ton/module x 8 modules & 5% boiloff = 30408 tons - tanks are in OTS above = 78 flights (LEO)	1074	--	737	
5. Propellant for OTV's • Factor = 2.075 (includes boiloff but not tanker) • Mass is 77,000 tons + 10% packaging • Allow 15% for tankers, transfer & boiloff 517 flights (GEO)	--	5754	--	3950

TABLE 13 (Continued)

6. OTV Cargo	(0)	(868)	(0)	(499)
None (LEO)	0		0	
217 Flights (GEO)		868		499
7. Crew Rotation & Resupply	(476)	(695)	(234)	(382)
Shuttle ($12M/Flt, 1 SPS per yr)	336	336		
Advanced Shuttle ($5M/Flt, 4 SPS/Yr)			140	140
28 Flights per SPS				
HLLV - Supplies 5 Flights LEO	69	44	47	31
4 Flights GEO				
HLLV Tanker 5 (LEO)	69	267	47	183
24 (GEO)				
OTV Flights 4 (LEO)	16		9	
12 (GEO)		48		28
OTV @ $4M/Flt 1 SPS/Yr & 2.3M/Flt 4 SPS/Yr				
Total HLLV Flights	351	766	1404	3064
$/Flt	13.77	11.13	9.45	7.64
8. OTS Hardware (From Table 14 with growth deleted)	1260		723	

TABLE 14
SELF-POWER ORBIT TRANSFER SYSTEM MATURE INDUSTRY COST ESTIMATE

ITEM & MASS (LB)	#	SLOPE	PCM UNIT COST	PCM TFU (1 OTS)	FULLY LEARNED UNIT	TOTAL	MATURE INDUSTRY @ 1 SPS/YR (8 OTS)	MATURE INDUSTRY @ 4 SPS/YR	$/KG
OTS System							1,458,160	836,643	
							69,436	39,840	
OTS							1,388,724	796,803	
Thruster Panel (13,532,000)							790,432	440,177	
Panel Struc (1540 LB)	192	.85	641		127	24,364	17,583	8,792	$131
Thrusters (110 LBS)	26,880	.85	409		81	2,176,490	132,752	66,376	$ 98
Processors (18,230 LBS)	384	.85	6,151		1,217	467,607	238,624	119,312	$ 75
Switchgear (660 LBS)	1920	.85	2,120		420	805,826	183,903	91,952	$320
Interrupter (50 LBS)	26,880	85	244		48	1,298,444	79,197	79,197	$130
Interrupter (2 LBS)	26,880	.85	16		3.17	85,143	5,193	2,596	$212
Cabling (1500 LBS)	192	.85	3,496		692	132,835	95,901	47,950	$734
Instrum (200 LBS)	192	.85	968		192	36,794	26,554	13,277	1524
Prop Sys (1500 LBS)	192	.85	391		77	14,862	10,725	10,725	82

C-3

TABLE 14 (Continued)

ITEM & MASS (LB)	#	SLOPE	PCM UNIT COST	PCM TFU (1 OTS)	FULLY LEARNED UNIT	TOTAL	MATURE INDUSTRY @ 1 SPS/YR (8 OTS)	MATURE INDUSTRY @ 4 SPS/YR	$/KG
Thrust. Frame (6160 LBS)	32	.85	2,069		410	13,104	23,170	11,585	$260
Gimbal Assy (6160 LBS)	32	.85	11,876		2,351	75,235	133,000	66,500	$1487
Computer (100 LBS)	32	.85	2,448		484	15,508	27,415	13,707	18,000
Communic (100 LBS)	32	.85	1,718		340	10,883	19,240	9,620	13,000
Standoff Str (10,000 LBS)	32	.85	3,117		617	19,746	34,907	17,454	240
Argon Tks (40,000 LBS)	32	.85	6,801		1,346	43,085	76,164	38,082	131
LO_2 Tks (16,000 LBS)	32	.85	3,106		615	19,677	34,784	17,392	149
LH_2 Tks (10,000 LBS)	32	.85	2,078		411	13,164	23,271	41,636	160
Tank Insul.	16	.90	1,083		378	6,063	15,159	7,580	2
Prop. Sys. (10,000 LBS)	32	.85	1,443		285	9,141	16,160	16,160	111
Chem. Thr. (1000 LBS)	96	.85	74		14	1,406	1,435	1,435	
TCS/RAD (8680 LBS)	384	.85	4,027		797	306,138	156,225	78,113	103
Pwr. Distr. (41,830 LBS)	160	.85	1,492		295	47,260	37,362	37,362	12

Table 15 Parametric Cost Model Output for Orbit Transfer System

NO	NAME	SUB TO	ELEMENT	METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
1	TOTAL PROGRAM	0	DDT&E	SUBS	0	0.00	0	0	0	0.0			1,430,785
	0		OPCODE= 0										
			UNIT	SUBS	0	0.00	0				0	0	1,479,087
			OPCODE= 0										
2	PROG INTEG & MGMT	1	DDT&E	FACTOR	3	0.06	0	0	0	0.0			40,535
	0		OPCODE= 2										
			UNIT	FACTOR	3	0.06	0				0	0	79,610
			OPCODE= 2										
3	OTS INSTL	1	DDT&E	SUBS	0	0.00	0	0	0	0.0			1,390,249
	0		OPCODE= 0										
			UNIT	SUBS	0	0.00	0				0	0	1,399,476
			OPCODE= 0										
4	FLT SYS D&D	3	DDT&E	SUBS	0	0.00	0	0	0	0.0			211,482
	0		OPCODE= 0										
			UNIT	SUBS	0	0.00	0				0	0	1,217,131
			OPCODE= 0										
5	SUSTAINING	3	DDT&E	FAC UN	4	0.05	0	0	0	0.0			42,401
	0		OPCODE= 3										
			UNIT	N/A	0	0.00	0				0	0	0
			OPCODE= 8										
6	SE & I	3	DDT&E	CER*	4	0.00	0	0	0	0.0			19,141
	0		OPCODE= 12		32	0.00							
			UNIT	N/A	0	0.00	0				0	0	0
			OPCODE= 8										

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Table 15 (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOUR-CES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
7	FLT S/S DD&T	0	DDT&E FACTOR	4	1.00	0	0	0	0.0			0
	0		OPCODE= 2	6	1.00							
				9	1.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
8	SYSTEM TEST	3	DDT&E SUBS	0	0.00	0	0	0	0.0			905,635
	0		OPCODE= 0									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
9	SYS TEST LBR	8	DDT&E CER*	4	0.00	0	0	0	0.0			154,303
	0		OPCODE= 12	34	0.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
10	GR TEST HDWE	8	DDT&E FAC UN	4	0.30	0	0	0	0.0			365,139
	0		OPCODE= 3									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
11	FLT TEST HDWE	8	DDT&E FAC UN	4	0.30	0	0	0	0.0			365,139
	0		OPCODE= 3									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
12	SOFTWARE ENGR	3	DDT&E CER*	7	0.00	0	0	0	0.0			94,321
	0		OPCODE= 12	37	0.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									

Table 15 (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS X	MOD X	MOD CMPLX	NUMBER	LRN X	COST (000)
13	GSE	3	DDT&E FACTOR	4	0.10	0	0	0	0.0			25,724
	0		OPCODE= 2									
			UNIT FACTOR	4	0.10	0				1	100	91,061
			OPCODE= 2									
14	TOOLING	3	DDT&E FACTOR	4	0.25	0	0	0	0.0			91,542
	0		OPCODE= 2									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
15	ASSY & C/O	3	DDT&E N/A	0	0.00	0	0	0	0.0			0
	0		OPCODE= 8									
			UNIT FAC UN	4	0.07	C				0	0	91,284
			OPCODE= 3									
16	THRUSTER PANEL	4	DDT&E SUBS	0	0.00	0	0	0	0.0			73,114
	0		OPCODE= 0									
			UNIT SUBS	0	0.00	0				24	84	70,031
			OPCODE= 0									
									AGGREGATED VALUES			1,003,973
17	PANEL STRUCT	16	DDT&E CER	1	1.00	30	0	0	0.0			1,572
	1540 LBS		OPCODE= 1									
			UNIT CER	46	1.00	45				1	100	641
			OPCODE= 1									
18	THRUSTERS	16	DDT&E CER	21	1.00	31	0	0	0.0			8,321
	110 LBS		OPCODE= 1									
			UNIT CER	46	0.25	45				140	84	409
			OPCODE= 1									
									AGGREGATED VALUES			23,226

Table 15 (continued)

NO	NAME	SUB TO	ELEMENT	METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
19	PROCESSORS	16	DDT&E	CER	7	1.00	29	0	0	0.0			48,492
	18230 LBS		OPCODE= 1										
			UNIT	CER	52	0.50	45				2	84	6,151
			OPCODE= 1										
										AGGREGATED VALUES			11,395
20	SWITCHGEAR	16	DDT&E	CER	14	1.00	30	0	50	5.0			2,648
	660 LBS		OPCODE= 1										
			UNIT	CER	59	1.00	45				10	84	2,120
			OPCODE= 1										
										AGGREGATED VALUES			15,097
21	INTERRUPTER	16	DDT&E	CER	14	1.00	30	0	0	0.0			428
	50 LBS		OPCODE= 1										
			UNIT	CER	59	1.00	45				140	84	244
			OPCODE= 1										
										AGGREGATED VALUES			13,877
22	INTERRUPTER	16	DDT&E	CER	14	1.00	30	0	0	0.0			32
	2 LBS		OPCODE= 1										
			UNIT	CER	59	1.00	45				140	84	16
			OPCODE= 1										
										AGGREGATED VALUES			937
23	CABLING	16	DDT&E	CER	13	1.00	29	0	0	0.0			3,804
	1500 LBS		OPCODE= 1										
			UNIT	CER	58	1.00	45				1	100	3,496
			OPCODE= 1										
24	INSTRUM	16	DDT&E	CER	15	1.00	30	0	0	0.0			3,218
	200 LBS		OPCODE= 1										
			UNIT	CER	60	1.00	45				1	100	968
			OPCODE= 1										

Table 15 (continued)

NO	NAME	SUB TO	ELEMENT	METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
25	PROP SYS	16	DDT&E	CER	40	1.00	30	0	0	0.0			4,596
	1500 LBS		OPCODE= 1										
			UNIT	CER	76	1.00	45				1	100	391
			OPCODE= 1										
26	THRUSTER FRAME	4	DDT&E	CER	1	1.00	29	0	0	0.0			5,214
	6160 LBS		OPCODE= 1										
			UNIT	CER	46	1.00	45				4	84	2,069
			OPCODE= 1										
										AGGREGATED VALUES			6,932
27	GIMBAL ASSY	4	DDT&E	CER	2	0.75	30	0	0	0.0			46,039
	6160 LBS		OPCODE= 1		6	0.25							
			UNIT	CER	47	0.75	45				4	84	11,876
			OPCODE= 1		51	0.25							
										AGGREGATED VALUES			39,782
28	COMPUTER	4	DDT&E	CER	19	1.00	30	0	50	5.0			12,614
	100 LBS		OPCODE= 1										
			UNIT	CER	64	1.00	45				4	84	2,448
			OPCODE= 1										
										AGGREGATED VALUES			8,200
29	COMMUNIC	4	DDT&E	CER	16	1.00	30	0	50	5.0			7,328
	100 LBS		OPCODE= 1										
			UNIT	CER	61	1.00	45				4	84	1,718
			OPCODE= 1										
										AGGREGATED VALUES			5,754
30	STANDOFF STR	4	DDT&E	CER	1	1.00	29	0	50	5.0			6,279
	10000 LBS		OPCODE= 1										
			UNIT	CER	46	1.00	45				4	84	3,117
			OPCODE= 1										
										AGGREGATED VALUES			10,443

Table 15 (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
31	ARGON TANKS	8	DDT&E CER	81	1.00	29	0	0	0.0			21,053
	40000 LBS		OPCODE= 1									
			UNIT CER	82	1.00	45				4	84	6,801
			OPCODE= 1									
									AGGREGATED VALUES			22,783
32	LO2 TANKS	4	DDT&E CER	81	1.00	29	0	0	0.0			9,184
	16000 LBS		OPCODE= 1									
			UNIT CER	82	1.00	45				4	84	3,106
			OPCODE= 1									
									AGGREGATED VALUES			10,406
33	LH2 TANKS	4	DDT&E CER	81	1.00	29	0	0	0.0			6,004
	10000 LBS		OPCODE= 1									
			UNIT CER	82	1.00	45				4	84	2,078
			OPCODE= 1									
									AGGREGATED VALUES			6,962
34	TANK INSUL	4	DDT&E CER	8	1.00	30	0	0	0.0			5,655
	2200 SQ FT		OPCODE= 1									
			UNIT CER	53	1.00	45				16	84	104
			OPCODE= 1									
									AGGREGATED VALUES			1,083
35	PROPELLANT SYS	4	DDT&E CER	40	1.00	30	0	0	0.0			12,521
	10000 LBS		OPCODE= 1									
			UNIT CER	76	1.00	45				4	84	1,443
			OPCODE= 1									
									AGGREGATED VALUES			4,834
36	CHEM THRUST	4	DDT&E CER	42	0.50	31	0	0	0.0			11,444
	1000 LBF		OPCODE= 1									
			UNIT CER	78	0.50	45				12	89	74

Table 15 (continued)

NO	NAME	SUB TO	ELEMENT	METHOD	SOURCES	BLEND FACTORS	SUPT FROM	DTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
37	TCS/RADIATORS	4	DDT&E	CER	9	1.00	29	0	75	3.0			12,403
	8680 LBS		OPCODE= 1										
			UNIT	CER	54	0.50	45				48	84	4,027
			OPCODE= 1										
										AGGREGATED VALUES			99,542
38	POWER DISTR	4	DDT&E	CER	1	0.10	29	0	0	0.0			3,677
	41830 LBS		OPCODE= 1										
			UNIT	CER	46	0.10	45				20	84	1,492
			OPCODE= 1										
										AGGREGATED VALUES			18,513

TABLE 16

CREW ROTATION/RESUPPLY

Launches Per Year

	LEO Const.		GEO Const	
	P/V	T/E	P/V	T/E
Shuttle Growth (Crew to LEO)	28	44	28	
HLLV-Supplies	4	6	4	
HLLV-Tanker	5	5	24	
OTV	4	4	12	

TABLE 17

GROWTH CALCULATIONS

Growth is Applied to:

- SPS
- Construction/Space Support
- Space Transportation
- Pro Rata Share of Interest During Construction

	1 SPS/Yr		4 SPS/Yr	
	LEO	GEO	LEO	GEO
SPS	7442	7190	5587	5378
Constr/Space Sup	1109	1126	1109	1126
Space Trans	6445	9780	4188	6522
Pro Rata IDC	1437	1114	842	651
Subtotal	16433	19210	11726	13677
Mass Growth	26.6%	26.6%	10%	10%
Cost Growth Equiv.	21%	21%	8%	8%
Cost Growth Amount	3450	4034	938	1094

TABLE 18 LEO/GEO DIFFERENCES

RFP REF	ITEM	RATIONALE	DELTA COST IN MILLIONS PER SPS (GEO - LEO) RECURRING (4 SPS/YR)	INITIAL NON-RECURRING
a)	Transportation Requirements (Includes Crew)	o HLLV Launch Rate, 1400/Yr VS 3064/Yr @ 4 Yr 350/Yr VS 766/Yr @ 1/Yr	Net = 2,343	-1,431 (OTS) 2,223 (Fleet Invoice)
		o See Also Table 1		
b)	Construction Requirements	o See Tables 1,7,8,9,10,11 for Facility Delta Costs	24	530
		o Stationkeeping Propellant 800 Kg/day - 292 Tons/Yr	-9	
		o Crew Support	9	
c)	SPS Design Requirements	o Oversizing for Radiation Degradation	-139	-350
		o Delta Structural Mass - 854 Tons for GEO (See Table 4, Sheet 2)	-70	-175
		o Satellite Mods. for OTS Included in OTS Costs		
d)	Degradation Potential	o Included in SPS Design Requirements (Oversizing Compensates for Output and Mismatch loss)		
e)	Launch Site Differential Effects	o Higher Launch Rate for GEO (See (a)		1,715 Lanch Facility Costs
f)	Startup	o Orbit Transfer Hardware Elements Included in OTS Cost		
		o Delta Interest During Construction	-303	
g)	Operations Considerations	o Can't Reuse Packaging Materials and Pallets for GEO (Not Quantified)		
		o No Difference In Numbers of Vehicles in Flight. More Complex Monitoring for OTS.	-10	
		o Docking Equipment Included in GEO Facility for LEO Construction		
h)	Collision	o Estimated Collision Avoidance Propellant 32 Tons/Yr	-1	
		o Object Monitoring Cost	-5	
i)	Cost Differentials	o Other Factors Itemized in This Table		
		o Delta Growth (Factor on Delta Cost)	156	
j)	Orbit Transfer Complexity	o Hardware/Software Costs Reflected as OTS Costs	-	
		o Software Preliminary Design Incorporated In Existing Simulations		
TOTAL COST DIFFERENTIALS			1,995	2,512

3.3 REFERENCE THERMAL ENGINE

Cost Data Package

Table 19 provides a cost summary and references the backup substantiation material. Tables 20 through 27.

TABLE 19 CAPITAL COST SUMMARY-THERMAL ENGINE SPS (RANKINE)

DOLLARS IN MILLIONS

WBS NUMBER	ITEM NUMBER	SOURCES AND REFERENCES	1 SPS/YR LEO CONSTRUCTION	1 SPS/YR GEO CONSTRUCTION	4 SPS/YR LEO CONSTRUCTION	4 SPS/YR GEO CONSTRUCTION
1.01	Solar Power Satellite	o Mature Industry Estimate, Table 20	(7,987)	(7,987)	(5,284)	(5,284)
1.01.00	Multiple/Common and Pkg'g	o PCM Run, Table 21	1,196	1,196	846	846
	Energy Collection	o General Electric Turbine, Generator, & Pump Cost Estimates	374	374	374	374
	Energy Conversion	o Structural Mfr. Estimate, 9th MPR	3,365	3,365	1,890	1,890
	Power Distribution	o Varian Analysis of Klystron Production	376	376	222	222
	Microwave Power Transmission	o MPTS Error Analysis	2,676	2,676	1,952	1,952
		o SPS Mass Estimate, Table 22				
1.02	Ground Receiving Station	(Same as Photovoltaic)	(4,446)	(4,446)	(4,000)	(4,000)
2.00	Construction & Space Support		(1,716)	(1,768)	(1,716)	(1,768)
2.01	Construction Base (Facility Writedown)	Writedown Summary, Table 23 Facility Mass & Cost Estimates Tables 24 and 25	971	1,010	971	1,010
2.02	Space Support					
2.02.01	Staging Base	(Same as P/V)	N/A		N/A	
2.02.02	Crew Support	o Crew Support ROM Estimates, Table 12 o Crew Requirements from Construction Analyses (Part I Vol. III and Part II Vol. IV)	745	758	745	758
2.02.03	Other OPS Support		16		16	
3.00	Space Transportation	o Numbers of Flights and Costs Summary, Table 26	(7,425)	(11,182)	(4,678)	(7,275)
3.01	Earth - Leo					
3.01.01	Freight	o Other References Same as Photovoltaic	3,900	3,270	2,527	2,095
3.01.02	Crew		528	528	220	220
3.02	LEO - GEO		181	533	141	357
3.02.01	Freight		2,816	6,851	1,790	4,603
3.02.02	Crew					
	Interest During Construction		(700 Days) (2,068)	(450 Days) (1,563)	(566 Days) (1,215)	(366 Days) (916)
	Growth	Table 27	(2,946)	(3,489)	(755)	(903)
		TOTALS	26,588	30,435	17,648	20,146

TABLE 20

MATURE INDUSTRY ESTIMATE, THERMAL ENGINE SPS

ITEM & MASS (LB)	#	SLOPE	PCM UNIT COST	PCM TFU	FULLY LEARNED UNIT	TOTAL	MATURE INDUSTRY @ 1 SPS/yr	MATURE INDUSTRY @ 4 SPS/YR	$/KG
T/E SPS							5,311,168	3,341,927	
Other							252,913	159,139	
Mult/Com							942,079	686,546	
Prim. Struc (8537 LBS)	200	.85	2,727	203,993	540	107,974	76,340	46,744	98
Att. Control							451,852	229,925	
Thrusters (110 LBS)	5120	.85	1,328	1,198,036	263	1,346,084	188,121	94,060	$736
Processors (12,000 LBS)	96	.85	6,248	264,920	1237	118,745	121,194	60,597	231
Structure (10,000 LB)	32	.85	7,505	135,001	1485	47,545	84,048	42,024	579
Tanks (1130 LB)	64	.85	1,040	32,174	205	13,177	16,471	8,235	502
Instrum (1000 LBS)	32	.85	3,752	67,500	743	23,769	42,018	21,009	2,895
Central Compute (700 LBS)	3	1.0	12,430	37,291	--	--	37,291	37,291	
Communic (2000 LBS)	3	1.0	24,576	73,729			73,729	73,729	
Ant. Yoke (258,000 LBS)	2	.85	163,474	302,857			302,857	302,857	1,294

TABLE 20 (Continued)

ITEM & MASS (LB)	#	SLOPE	PCM UNIT COST	PCM TFU (1 MPTS)	FULLY LEARNED UNIT	TOTAL	MATURE INDUSTRY @ 1 SPS/YR (2 MPTS)	MATURE INDUSTRY @ 4 SPS/YR	$/KG
Energy Coll							374,456	374,456	
Concent							374,456	374,456	
Structure (8537 LBS)	1600	.85	2727	119,349	540	863,792	310,000	310,000	50
Facets (35 lbs)	116,000	.85	44		8.7	1,010,450	64,456	64,456	35
Energy Conversion							3,365,444	1,899,974	
Cavity (137,779 lbs)	16			297,547			297,547	297,547	298
Boiler (12,615 Lb)	576	.85	25,079		4964	2,859,808	1,191,587	595,793	361
CPC/Door (20,250 lbs)	16	.85	26,669	277,050	5279	84,475	211,188	105,594	1436
Turbines (52,646 lb)	576	.85	23,199		4592	2,645,428	1,102,262	551,130	80.1
Generators (9600 lbs)	576	.85	6,397		1266	729,463	303,942	151,971	121
Pumps (3766 lb)	576	.85	3,150		624	359,200	149,667	74,833	152
Radiator Manifold (8587 Lb)	32	.85	2,094		415	13,265	109,251 23,450	97,526 11,725	188

TABLE 20 (Continued)

ITEM & MASS (LB)	#	SLOPE	PCM UNIT COST	PCM TFU (1 MPTS)	FULLY LEARNED UNIT	TOTAL	MATURE INDUSTRY @ 1 SPS/YR (2 MPTS)	MATURE INDUSTRY @ 4 SPS/YR	$/KG
H. P. Panels (98 LB)	192960	.85	59		11.7	2,253,842	85,801	85,801	10
Potassium (13.36E6LB)							25,880	25,880	4
Power Distr.							376,276	221,812	
Switchgear (1320 LB)	364	.85	3787	449,414	749	272,898	143,038	71,519	656
Busses (150,000 LB)	364	.85	4392	521,153	869	316,495	165,889	82,944	67
Rotary Joint (57,000 LB)	2	.85	36,353	67,349			67,349	67,349	1302

Table 21 Parametric Cost Model Output for Thermal Engine SPS

NO	NAME	SUB TO	ELEMENT	METHOD	SOUR-CES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
1	TOTAL PROGRAM	0	DDT&E	SUBS	0	0.00	0	0	0	0.0			5,277,159
	0		OPCODE= 0										
			UNIT	SUBS	0	0.00	0				0	0	24,804,144
			OPCODE= 0										
2	PROG INTEG & MGMT	1	DDT&E	FACTOR	3	0.06	0	0	0	0.0			284,913
	0		OPCODE= 2										
			UNIT	FACTOR	3	0.06	0				0	0	1,292,617
			OPCODE= 2										
3	TE SPS	1	DDT&E	SUBS	0	0.00	0	0	0	0.0			4,992,249
	0		OPCODE= 0										
			UNIT	SUBS	0	0.00	0				0	0	22,711,536
			OPCODE= 0										
4	FLT SYS D&D	3	DDT&E	SUBS	0	0.00	0	0	0	0.0			1,159,597
	0		OPCODE= 0										
			UNIT	SUBS	0	0.00	0				0	0	19,751,440
			OPCODE= 0										
5	SUSTAINING	3	DDT&E	FAC UN	4	0.05	0	0	0	0.0			688,434
	0		OPCODE= 3										
			UNIT	N/A	0	0.00	0				0	0	0
			OPCODE= 8										
6	SE & I	3	DDT&E	CER	4	0.00	0	0	0	0.0			86,255
	0		OPCODE= 12		32	0.00							
			UNIT	N/A	0	0.00	0				0	0	0
			OPCODE= 8										

TABLE 21 (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
7	FLT SYS DD&T	0	DDT&E FACTOR	4	1.00	0	0	0	0.0			0
	0		OPCODE= 2	6	1.00							
				9	1.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
8	SYSTEM TEST	3	DDT&E SUBS	0	0.00	0	0	0	0.0			1,815,267
	0		OPCODE= 0									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
9	SYS TEST LBR	8	DDT&E CER*	4	0.00	0	0	0	0.0			1,420,239
	0		OPCODE= 12	34	0.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
10	GR TEST HDWE	8	DDT&E FAC UN	4	0.01	0	0	0	0.0			197,514
	0		OPCODE= 3									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
11	FLT TEST HDWE	8	DDT&E FAC UN	4	0.01	0	0	0	0.0			197,514
	0		OPCODE= 3									
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									
12	SOFTWARE ENGR	3	DDT&E CER*	7	0.00	0	0	0	0.0			566,471
	0		OPCODE= 12	37	0.00							
			UNIT N/A	0	0.00	0				0	0	0
			OPCODE= 8									

TABLE 21 (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
13	GSE 0	3	DDT&E FACTOR OPCODE= 2	4	0.10	0	0	0	0.0			140,343
			UNIT FACTOR OPCODE= 2	4	0.10	0				1	100	1,478,735
14	TOOLING 0	3	DDT&E FACTOR OPCODE= 2	4	0.25	0	0	0	0.0			527,800
			UNIT N/A OPCODE= 8	0	0.00	0				0	0	0
15	ASSY & C/O 0	3	DDT&E N/A OPCODE= 8	0	0.00	0	0	0	0.0			0
			UNIT FAC UM OPCODE= 3	4	0.07	0				0	0	1,481,350
16	MULT/COMMON 0	4	DDT&E SUBS OPCODE= 0	0	0.00	0	0	0	0.0			311,613
			UNIT SUBS OPCODE= 0	0	0.00	0				0	0	2,012,645
17	PRIM STRUC 8537 LBS	16	DDT&E CER OPCODE= 1	1	1.00	30	0	0	0.0			7,363
			UNIT CER OPCODE= 1	46	1.00	45				200	84	2,727
									AGGREGATED VALUES			283,993
18	ATT CONTROL 0	16	DDT&E SUBS OPCODE= 0	0	0.00	0	0	0	0.0			91,887
			UNIT SUBS OPCODE= 0	0	0.00	0				0	0	1,697,632

TABLE 21 (continued)

NO	NAME		SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
19	THRUSTERS		18	DDT&E CER	21	1.00	31	0	0	0.0			8,321
	110	LBS		OPCODE= 1									
				UNIT CER	66	1.00	45				5120	84	1,328
				OPCODE= 1									
										AGGREGATED VALUES			1,198,036
20	PROCESSORS		18	DDT&E CER	14	1.00	31	0	50	5.0			33,627
	12000	LBS		OPCODE= 1									
				UNIT CER	59	0.20	45				96	84	6,248
				OPCODE= 1									
										AGGREGATED VALUES			264,920
21	STRUCTURE		18	DDT&E CER	2	1.00	30	0	0	0.0			30,967
	10000	LBS		OPCODE= 1									
				UNIT CER	47	1.00	45				32	84	7,505
				OPCODE= 1									
										AGGREGATED VALUES			135,001
22	TANKS		18	DDT&E CER	2	1.00	30	0	0	0.0			4,971
	1130	LBS		OPCODE= 1									
				UNIT CER	47	1.00	45				64	84	1,040
				OPCODE= 1									
										AGGREGATED VALUES			32,174
23	INSTRUM		18	DDT&E CER	15	1.00	31	0	0	0.0			13,999
	1000	LBS		OPCODE= 1									
				UNIT CER	60	1.00	45				32	84	3,752
				OPCODE= 1									
										AGGREGATED VALUES			67,500
24	CENTRAL COMPUTE		16	DDT&E CER	19	1.00	31	0	0	0.0			95,701
	700	LBS		OPCODE= 1									
				UNIT CER	64	1.00	45				3	100	12,430
				OPCODE= 1									

TABLE 21 (continued)

NO	NAME		SUB TO	ELEMENT	METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
25	COMMUNIC		16	DDT&E	CER	16	1.00	31	0	0	0.0			116,660
	2000	LBS		OPCODE= 1										
				UNIT	CER	61	1.00	45				3	100	24,576
				OPCODE= 1										
											AGGREGATED VALUES			73,729
26	POW GEN MOD		4	DDT&E	SUBS	0	0.00	0	0	0	0.0			462,406
	0			OPCODE= 0										
				UNIT	SUBS	0	0.00	0				16	84	1,575,991
				OPCODE= 0										
											AGGREGATED VALUES			16,372,154
27	CONCENTRATOR		26	DDT&E	SUBS	0	0.00	0	0	0	0.0			5,091
	0			OPCODE= 0										
				UNIT	SUBS	0	0.00	0				0	0	171,851
				OPCODE= 0										
28	STRUCTURE		27	DDT&E	CER	1	1.00	29	0	50	3.0			4,819
	8537	LBS		OPCODE= 1										
				UNIT	CER	46	1.00	45				100	84	2,727
				OPCODE= 1										
											AGGREGATED VALUES			119,349
29	FACETS		27	DDT&E	CER	2	1.00	30	0	0	0.0			272
	35	LBS		OPCODE= 1										
				UNIT	CER	47	1.00	45				7250	84	44
				OPCODE= 1										
											AGGREGATED VALUES			52,501
30	CAVITY		26	DDT&E	CER	1	1.00	30	0	0	0.0			91,029
	137779	LBS		OPCODE= 1										
				UNIT	CER	46	1.00	45				1	100	28,642
				OPCODE= 1										

TABLE 21 (continued)

NO	NAME		SUB TO	ELEMENT	METHOD	SOUR-CES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
31	BOILER		26	DDT&E	CER	2	3.00	30	0	0	0.0			94,775
	12615	LBS		OPCODE=	1									
				UNIT	CER	47	3.00	45				36	84	29,079
				OPCODE=	1									
											AGGREGATED VALUES			494,844
32	CPC/DOOR		26	DDT&E	CER	2	2.00	30	0	0	0.0			100,336
	20250	LBS		OPCODE=	1									
				UNIT	CER	47	2.00	45				1	100	26,669
				OPCODE=	1									
33	TURBINES		26	DDT&E	CER	7	1.00	29	0	0	0.0			110,526
	52646	LBS		OPCODE=	1									
				UNIT	CER	52	1.00	45				36	84	23,199
				OPCODE=	1									
											AGGREGATED VALUES			457,744
34	GENERATORS		26	DDT&E	CER	7	1.00	29	0	0	0.0			29,480
	9600	LBS		OPCODE=	1									
				UNIT	CER	52	1.00	45				36	84	6,397
				OPCODE=	1									
											AGGREGATED VALUES			126,228
35	PUMPS		26	DDT&E	CER	7	1.00	29	0	0	0.0			14,272
	3766	LBS		OPCODE=	1									
				UNIT	CER	52	1.00	45				36	84	3,150
				OPCODE=	1									
											AGGREGATED VALUES			62,163
36	RADIATOR		26	DDT&E	SUBS	0	0.00	0	0	0	0.0			16,894
	0			OPCODE=	0									
				UNIT	SUBS	0	0.00	0				36	84	10,534
				OPCODE=	0									
											AGGREGATED VALUES			207,047

TABLE 21 (continued)

NO	NAME	SUB TO	ELEMENT METHOD	SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
37	MANIFOLDS	36	DDT&E CER	40	2.00	29	0	0	0.0			15,857
	8587 LBS		OPCODE= 1									
			UNIT CER	76	2.00	45				2	84	2,094
			OPCODE= 1									
									AGGREGATED VALUES			3,880
38	H. P. PANELS	36	DDT&E CER	40	1.00	29	0	0	0.0			1,037
	98 LBS		OPCODE= 1									
			UNIT CER	76	1.00	45				335	84	59
			OPCODE= 1									
									AGGREGATED VALUES			6,654
39	POWER DISTR	4	DDT&E SUBS	0	0.00	0	0	0	0.0			145,334
	0		OPCODE= 0									
			UNIT SUBS	0	0.00	0				0	0	1,037,916
			OPCODE= 0									
40	SWITCHGEAR	39	DDT&E CER	14	1.00	30	0	0	0.0			5,947
	1320 LBS		OPCODE= 1									
			UNIT CER	59	1.00	45				364	84	3,787
			OPCODE= 1									
									AGGREGATED VALUES			449,414
41	BUSSES	39	DDT&E CER	1	0.10	29	0	0	0.0			11,651
	150000 LBS		OPCODE= 1									
			UNIT CER	46	0.10	45				364	84	4,392
			OPCODE= 1									
									AGGREGATED VALUES			521,153
42	ROTARY JOINT	39	DDT&E CER	2	1.00	29	0	0	0.0			127,735
	57000 LBS		OPCODE= 1									
			UNIT CER	47	1.00	45				2	84	36,353
			OPCODE= 1									

TABLE 21 (continued)

NO	NAME		SUB TO	ELEMENT	METHOD		SOURCES	BLEND FACTORS	SUPT FROM	OTS %	MOD %	MOD CMPLX	NUMBER	LRN %	COST (000)
43	ANT YOKE		4	DDT&E	CER		1	0.90	29	0	0	0.0			240,243
	258000	LBS			OPCODE=	1	5	0.10							
				UNIT	CER		47	0.90	45				2	84	163,474
					OPCODE=	1	50	0.10							
												AGGREGATED VALUES			302,857
44	POTASSIUM		4	DDT&E	N/A		0	0.00	0	0	0	0.0			0
	13355500	LBS			OPCODE=	8									
				UNIT	CER		46	0.01	0				1	100	25,880
					OPCODE=	1									

TABLE 22

THERMAL ENGINE MASS STATEMENT

		Values are Thousands of Metric Tons
1.0.	SPS	80,170
1.01.00	Mult/Common Use Equipment	2,662
1.01.00.00	Primary Structure	774
1.01.00.01	Satellite Control	1,450
1.01.00.02	Com and Data	4
1.01.00.03	Mech Sys. and Other	200
1.01.00.04	Antenna Yoke	234
1.01.01	Energy Collection	8,091
1.01.01.00	Support Structure	6,254
1.01.01.01	Facets	1,837
1.01.02	Energy Conversion:	40,084
1.01.02.00	Support Str	0 (included in primary structure)
1.01.02.01	CPC and Light Doors	324
1.01.02.02	Cavity Absorber	1,000
1.01.02.03	Thermal Engines	21,933
	Boilers	3,296
	Turbines	13,755
	Generators and Coolers	3,648
	Pumps	1,234
1.01.02.04	Radiators	10,769
1.01.02.05	Fluids	6,058
1.01.03	Power Distr.	4,978
1.01.04	MPTS	24,355

TABLE 23
CONSTRUCTION BASE WRITEDOWN SUMMARY
THERMAL ENGINE SPS

LEO CONSTRUCTION

ITEM	COST (MILLIONS)	AMORTIZED OVER	COST/SPS (MILLIONS)
LEO BASE			
Facility	4,670	25 Years	187
Facility Wrap	2,185	25 Years	87
Equipment	2,930	8 Years	366
Equipment Wrap	1,370	8 Years	171
GEO BASE			
Facility	600	25 Years	24
Facility Wrap	280	25 Years	11
Equipment	250	8 Years	31
Equipment Wrap	115	8 Years	14
LEO BASE TRANSPORT	995	15 Years	66
GEO BASE TRANSPORT	207	15 Years	14
			971

TABLE 24

T/E CONSTRUCTION BASE COST SUMMARY
FIRST SET
(Dollars in Millions)

LEO BASE		(11,155)
FACILITY	4,670	
CONSTRUCTION & SUPPORT EQUIPMENT	2,930	
WRAP-AROUND	3,555	
GEO BASE		(1,245)
FACILITY	600	
CONSTRUCTION & SUPPORT EQUIPMENT	250	
WRAP-AROUND	395	
		($12,400M)

TABLE 24 (continued)

TFU COST SUMMARY

T/E LEO CONSTRUCTION BASE		$\$10^6$
FACILITY		(4,670)
FOUNDATION	400	
CREW MODULES	3,600	
CARGO HANDLING/DISTRIBUTION	470	
BASE SUBSYSTEMS	200	
MAINTENANCE PROVISIONS	-	
CONSTRUCTION AND SUPPORT EQUIPMENT		(2,920)
STRUCTURE ASSEMBLY	1,420	
ENERGY COLLECTION	280	
ENERGY CONVERSION	250	
POWER DISTRIBUTION	190	
SUBARRAY INSTALLATION	90	
CRANES/MANIPULATORS	600	
INDEXERS	90	
BASIC HARDWARE		7,590
SPARES (15%)		1,135
INSTALLATION, ASSEMBLY C/O (16%)		1,210
SE&I (7%)		530
PROJECT MANAGEMENT (2%)		150
SYSTEMS TEST (3%)		225
GSE (4%)		305
TOTAL		$11,145 M

TABLE 25

T/E CONSTRUCTION BASE MASS SUMMARY

	$(10^3 Kg)$	
LEO CONSTRUCTION BASE		(8,960)
FACILITY	7,615	
CONSTRUCTION AND SUPPORT EQUIPMENT	945	
CONSUMABLES [1]	400	
GEO FINAL ASSEMBLY BASE		(850)
FACILITY	690	
CONSTRUCTION AND SUPPORT EQUIPMENT	130	
CONSUMABLES [1]	30	
TOTAL		9,810

[1] 90 Days

Table 25 (continued)

T/E MASS SUMMARY

LEO CONSTRUCTION BASE

		10^3 Kg
FACILITY		(7,615)
FOUNDATION	4,000	
CREW MODULES	2,600	
CARGO HANDLING/DIOTRCK	515	
BASE SUBSYSTEMS	400	
MAINTENANCE PROVISION	100	
CONSTRUCTION AND SUPPORT EQUIPMENT		(945)
STRUCTURE ASSEMBLY	500	
ENERGY COLLECTION INSTALLATION	75	
POWER DISTRIBUTION INSTALLATION	70	
SUBARRAY INSTALLATION	30	
CRANES/MANIPULATORS	240	
INDEXERS	30	
TOTAL DRY		8,560
CONSUMABLES (90 Days)		400
		8,960

Table 25 (continued)
T/E MASS SUMMARY

GEO FINAL ASSEMBLY BASE		10^3Kg
FACILITY		(690)
FOUNDATION	390	
CREW MODULES	220	
CARGO HANDLING/DISTRIBUTATION	60	
BASE SUBSYSTEMS	20	
MAINTENANCE PROVISIONS	-	
CONSTRUCTION & SUPPORT EQUIPMENT		(130)
CRANES/MANIPULATORS	35	
DOCKING CRANES	60	
INDEXERS	35	
HARDWARE TOTAL		820

TABLE 26

NUMBERS OF FLIGHTS AND COSTS SUMMARY

HLLV COST/FLT = 67.56 X (ANNUAL RATE) -.2715

	COST			
	1 SPS/YR		4 SPS/Yr	
	LEO	GEO	LEO	GEO
1. T/E HARDWARE				
o Mass is 80,170 Tons				
o HLLV Payload is 391 Tons				
o 10% for Packaging				
225 Flights LEO & GEO	3,098	2,468	2,126	1,694
Expendable Shrouds	802	802	401	401
2. ORBIT TRANSFER SYSTEM				
Same as P/V 35 Flights (LEO)	482		330	
3. OTV'S 225 Flights				
Wears Out 4.5 Vehicles 4.5 Flights (GEO)		49		34
4. PROPELLANT FOR OTS				
Same as P/V				
78 Flights LEO	1,074		737	
5. PROPELLANT FOR OTV'S				
Same Rationale as P/V				
538 Flights (GEO)		5,902		4,051
6. OTV CARGO	(0)	(900)	(0)	(518)
(OTV Cost/Flight)				
225 Flights (GEO)	0	900	0	518
7. CREW ROTATION AND RESUPPLY				
Shuttle ($12M/Flt, 1 SPS/Yr	528	528		
Advanced Shuttle ($5M/ Flight, 4 SPS/Yr)			220	220
44 Flights/SPS				

Table 26 (continued)

	COST			
	1 SPS/YR		4 SPS/Yr	
	LEO	GEO	LEO	GEO
7. (Continued)				
HLLV - Supplies				
7 Flights LEO	96	66	66	45
6 Flights GEO				
HLLV - Tanker				
5 (LEO)	69		47	
36 (GEO)		395		271
OTV - 18 Flights GEO		72		41
4 Flights LEO	16		28	
OTS Hardware	(1,260)		(723)	
(Refer to P/V)				
TOTAL HLLV FLIGHTS	350	809	1,400	3,236
DOLLAR/FLIGHT	13.77	10.97	9.45	7.53

TABLE 27
GROWTH CALCULATIONS

Growth is Applied to:

- SPS
- Construction/Space Support
- Space Transportation
- Pro Rata Share of Interest During Construction

	1 SPS/YR		4 SPS/YR	
	LEO	GEO	LEO	GEO
SPS	7,987	7,987	5,284	5,284
Construction/Space Support	1,716	1,768	1,716	1,768
Space Transportation	7,425	11,182	4,678	7,275
Pro Rata IDC	1,642	1,289	905	716
SUBTOTAL	18,770	22,226	12,583	15,043
Mass Growth	20%	20%	7.5%	7.5%
Cost Growth Equiv.	15.7%	15.7%	6%	5%
Cost Growth Amount	2,946	3,489	755	903

3.4 NONRECURRING COST

An estimate was made of the nonrecurring costs required to construct the first SPS. In order to accomplish this estimate, it was necessary to invoke certain programmatic assumptions. These do not represent conclusions or recommendations as to how an SPS program should be conducted. There are of course many possible program options; no systematic analysis and comparison has been conducted. The assumptions for nonrecurring cost were:

- o After a technology verification program, involving ground and flight programs but no new space vehicles, development of the 10,000 megawatt SPS, and its associated systems begins.

- o The production capacity initially developed is sized for a production rate of one SPS per year.

Table 3.4-1 presents the principal elements of the nonrecurring estimate, and the sources of data.

Table 3.4-1
Total Costs Through #1 SPS
(Photovoltaic System)

Item	Cost (Billions)	Source/Rationale
Technical Verification	3.0	Ground + Flight Verification Program summarized in Volume II Draft
Energy Conversion DDT&E	1.9	p. 121, this volume PCM DDT&E total
Power Transmission DDT&E	1.24	p. 127, this volume PCM DDT&E total
Power Receiver DDT&E	0.25	ROM estimate for diode/dipole/filter assemblies and field tests
SPS Freighter & Tanker Devel.	8.0	Part I Vol. 5, pp. 31, 47, 50. Sum of DDT&E totals
Crew OTV	1.0	Part I, Vol. 5 with allowance for crew cab
SPS Orbit Transfer System	1.43	Vol. 6 Draft, p. 161, PCM DDT&E total
Construction Base	6.9	Based on JSC estimate
SPS Hardware Production Facilities	10.2	Solar Blankets 5.0 Klystrons 1.5 Structures 1.2 All Other 2.5
SPS Freighter Production	0.70	3x Boeing 747 Plant at Everett, Wash.
Launch Facilities at KSC	4.0	Extrapolation of Part I, Vol. 5, p. 149 to 500 flts/yr
#1 Construction Base	8.8	Vol. 6 Draft p. 145, plus transport cost

Table 3.4-1 (Continued)

Item	Cost (Billions)	Source/Rationale	
Initial Fleet	7.4	10 boosters and 11 upper stages to support 500 flts/yr	
#1 SPS	28.8	As follows:	
Sum	83.62	(1) 1 SPS/yr without growth and interest	19.442
		(2) Deduct following amortizations:	
		Solar blanket plant	.60
		Structures plant	.02
		Klystron plant	.12
		Rectenna factory	.25
		Constr. base	.596
		Transp. fleet	1.500
		(3) Results	16.306
		(4) Add growth	2.894
		(5) Result	19.200
		(6) Add 50% for prototype factor:	28.800

4.0 UNCERTAINTY ANALYSIS DATA PACKAGE

4.1 APPROACH AND SUMMARY

An important objective of the SPS systems study was to make the best possible estimates of uncertainty in size, mass and costs, for the SPS systems characterized. The methodology employed was newly developed for the study and included the principal steps indicated in Figure 4-1. The basis for the uncertainty analyses was itemized estimates in the uncertainties of component performance, masses, and cost. A typical example would be the uncertainty in solar cell efficiency and degradation. This is an example of the case where correlation exists between the two factors; i.e., more efficient cells tend to experience somewhat greater degradation because the greater efficiency tends to be associated with greater thickness and experimental data indicate thicker cells degrade more. In developing the statistics in size, mass and cost, these kinds of correlations were taken into account through use of a bivariate normal distribution probability model.

Also providing input data to the uncertainty analyses was a conventional mass property analyses for the systems with estimated uncertainties in such factors as structural crippling criteria, solar cell thickness, and turbomachinery unit masses. Additional uncertainties were developed in system costs, such as uncertainty in solar cell cost per unit area and uncertainties in machinery costs. These uncertainties were coupled with the cost analyses discussed later to prepare the cost statistics. Size statistics and mass statistics were combined to develop a joint mass/size uncertainty estimate and mass statistics and cost statistics were combined to generate combined cost/mass uncertainties. The bivariate normal distribution model was used to statistically combine the uncertainties, with recognition of correlations between component uncertainties where significant correlations were determined to exist.

The uncertainty analysis, in addition to estimating uncertainties, produced the unexpected result of predicting mass growth equivalent to that predicted by historical correlations. It had been believed that mass growth was the result of unpredictable variables, e.g., changes in program requirements. The outcome of this uncertainty analysis suggests that growth is more predictable than formerly believed and in fact results largely from the natural tendency to set point design parameters on the optimistic side of the actual uncertainty range.

Figure 4-2 compares the statistically-derived result for the photovoltaic SPS with the worst-on-worst and best-on-best results defined by combining all the most optimistic component uncertainties and all the most pessimistic component performances. As increased detail is developed in this kind of analysis, the worst-on-worst and best-on-best extremes will continue to become further apart, while the statistical uncertainties will tend to change little and will approach a representation of true uncertainties. Significantly, the reference point design was outside the projected 3 sigma range for mass and size. This resulted primarily because the efficiency chain assigned to the reference design was more optimistic than the most probable efficiency chain defined by the statistical analyses.

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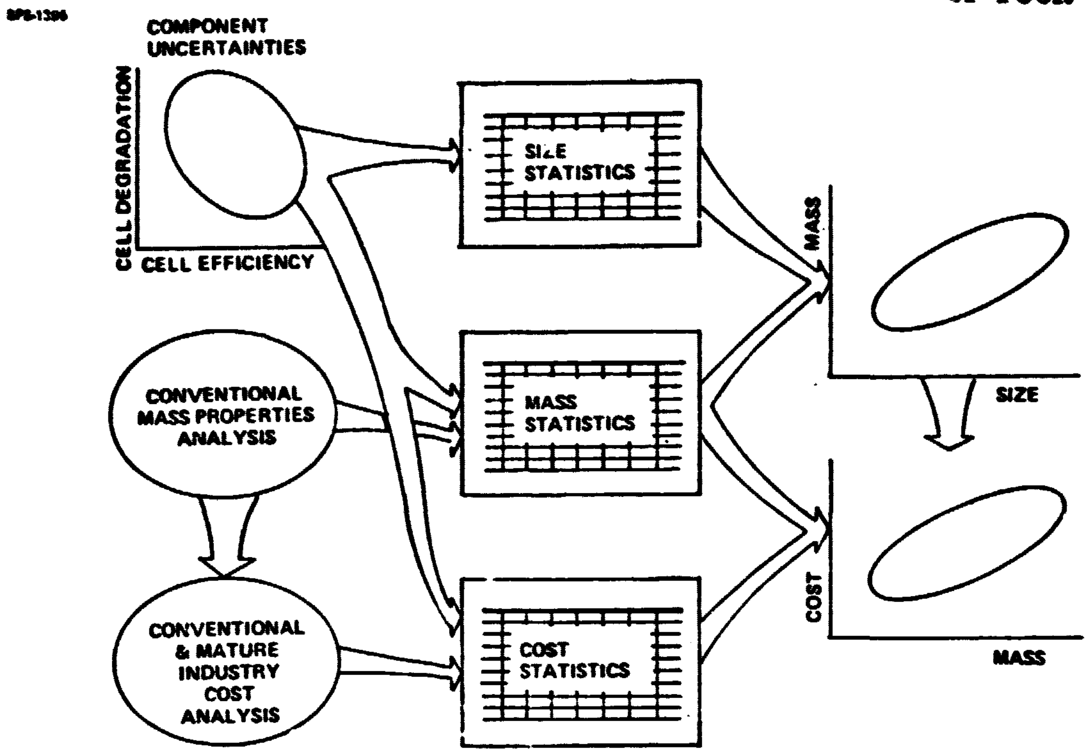

FIGURE 4-1 UNCERTAINTY ANALYSIS METHODOLOGY

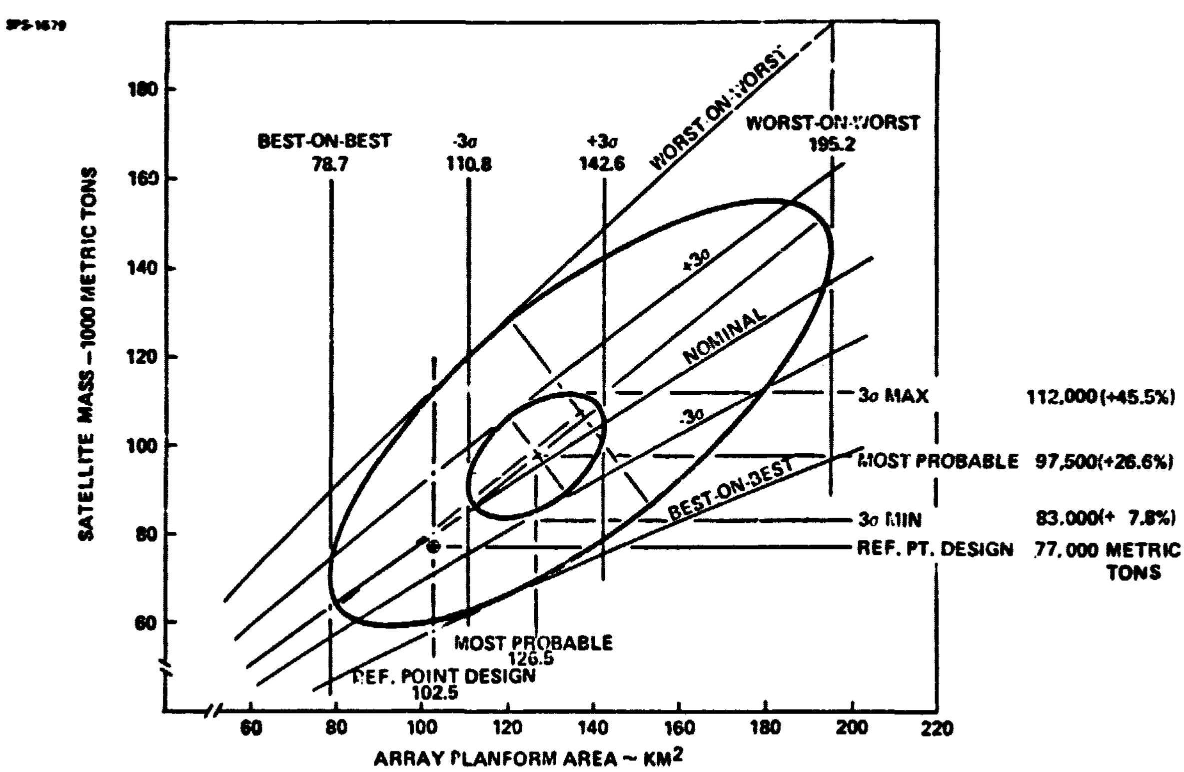

FIGURE 4-2 PHOTOVOLTAIC SPS MASS/SIZE UNCERTAINTY ANALYSIS RESULTS

Presented in Figure 4-3 is an uncertainty estimate for the thermal engine comparable to the previous one for the photovoltaic system. Because the technology of the thermal engine system is somewhat more mature, it would be expected to estimate somewhat less mass growth and that turned out to be the case. An additional factor in the reduced mass growth projection is that a significant part of the size escalation is associated with the size of the concentrator which is a low-mass component of the thermal engine system.

With costs included in the uncertainty analyses, it is necessary to discriminate between the 1 SPS per year case and the 4 SPS per year case. As discussed under cost analyses, for the 4 SPS per year case, an estimate was made that about 60% of the predicted mass growth could be removed by product improvement. Similarly to the size and mass estimates, the reference design trended towards the optimistic side of the median of the cost uncertainties as shown in Figure 4-4. Consequently, one sees first a cost escalation at the reference design point and then a further cost growth associated with the mass growth projection. Note the very high correlation between cost and mass uncertainties. This corresponds to the historical indications that cost growth is frequently associated with mass growth, and especially with the compensation for (or removal of) mass growth in a system when performance requirements dictate that mass growth be limited to predetermined values.

The bottom line for an SPS system is its capability to produce power at an acceptable cost. The result shown in Figure 4-5 represents the final result of the costing and uncertainty analyses. Uncertainties for busbar power costs include the uncertainties in unit costs as well as uncertainties in the appropriate capital charge factor to be applied and the plant factor at which the SPS can operate. Capital charge factors from 12-18 percent were considered and the plant factor uncertainty was taken as 70%-90% at one SPS per year and 85%-95% for four SPS's per year. These uncertainties were statistically combined with the cost uncertainties derived by the cost uncertainty analyses.

4.2 COMPONENT AND ELEMENT UNCERTAINTIES

Component and element uncertainties that went into the uncertainty analysis are tabulated in Tables 4-1, 4-2 and 4-3. Cost uncertainties at this level were not completed as it was found that uncertainties in solar cell costs, ground receiver costs, and transportation costs entirely dominated the overall cost uncertainties. Of greatest significance are the size/mass uncertainty effects on costs; these are included in the overall cost uncertainty data discussed in Section 4.4.

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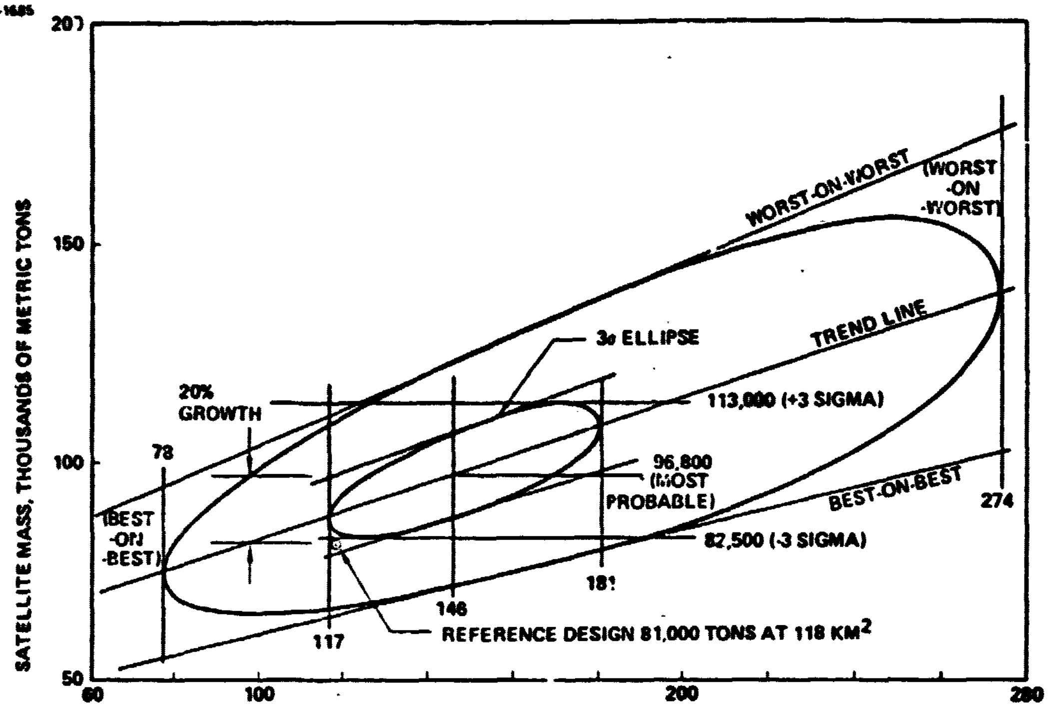

FIGURE 4-3 RANKINE THERMAL ENGINE SIZE /MASS UNCERTAINTY ANALYSIS RESULTS

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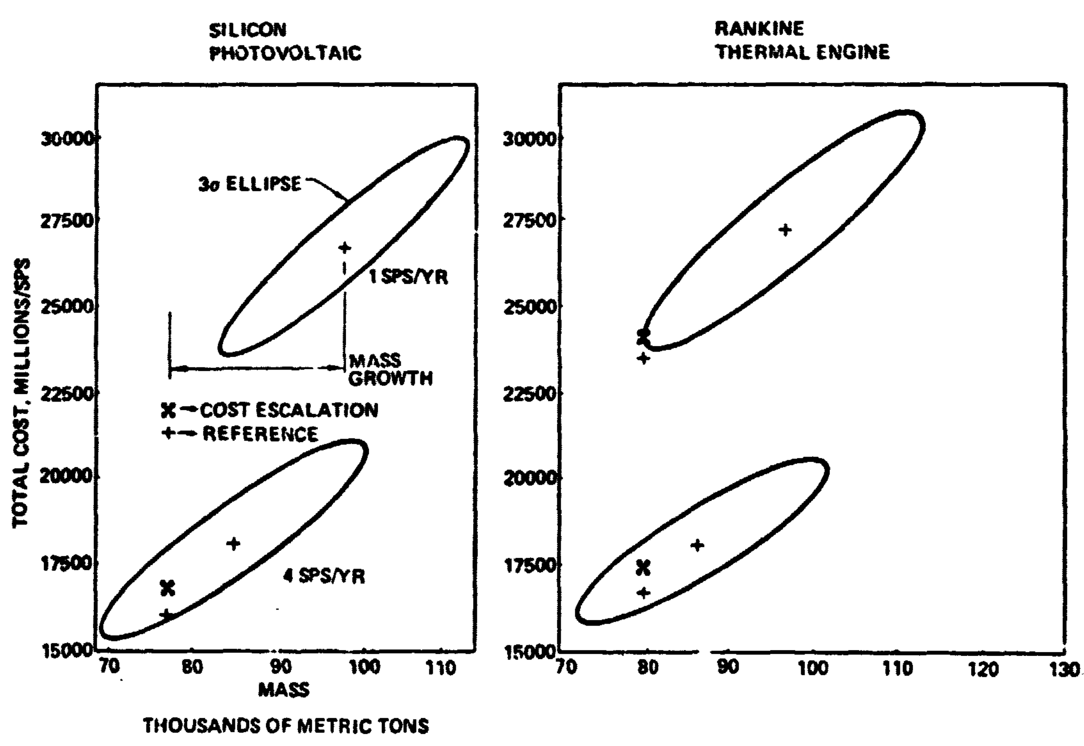

FIGURE 4-4 MASS/COST UNCERTAINTY ANALYSIS RESULTS

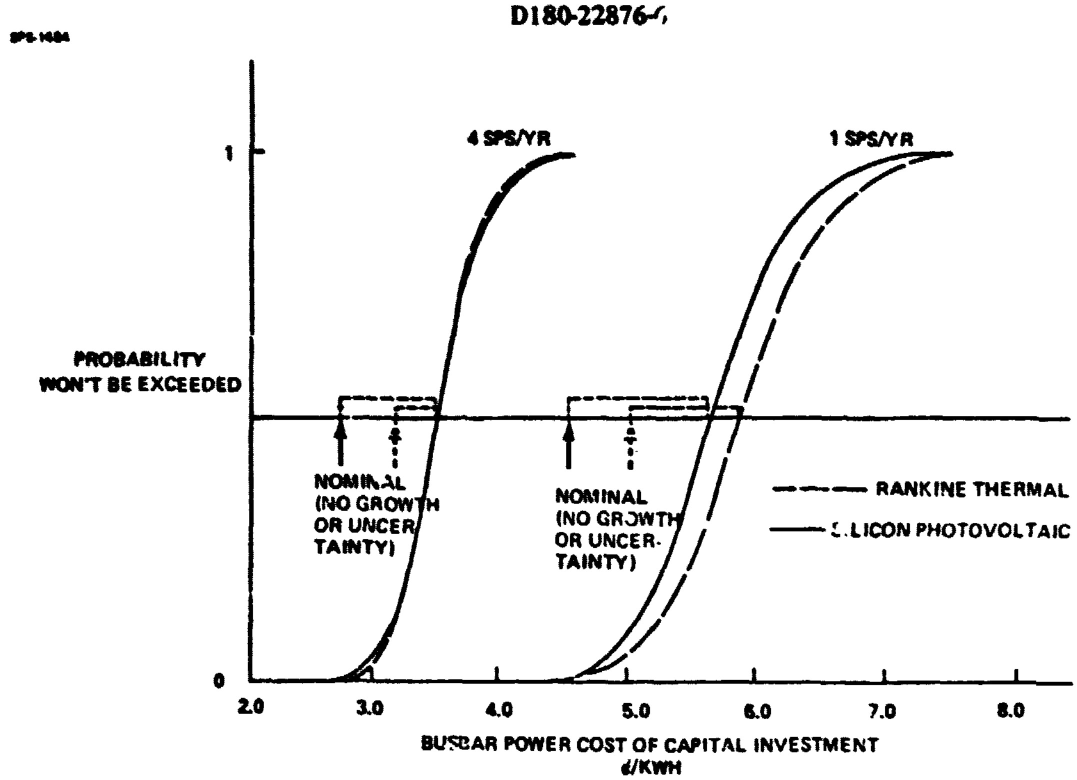

FIGURE 4-5 PREDICTED BUSSBAR POWER COST & UNCERTAINTIES

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Table 4-1 Photovoltaic Traceability/Uncertainty Worksheet

ITEM #	ITEM	VALUE FROM JSC-11568 GREEN BOOK	CURRENT VALUE	REASON FOR CHANGE	WORST CASE	RATIONALE	BEST CASE	RATIONALE	SPS SENSITIVITY (% PER %) MASS	SPS SENSITIVITY (% PER %) COST	CORRELATED VARIABLES
1	Solar cell thickness	100 um	50 um	1. Lower rad. degradation 2. Lower mass 3. Lower efficiency a. Add "Saw-tooth" cover 4. Currently manufacturable	100 um	1. Handling 2. Lower manuf. cost 3. Slightly more efficient	40 um	1. Rapid decrease in efficiency below 40 um. 2. Recognized lower limit for silicon cells. 3. Lower mass	*		Radiation degradation mass Efficiency(?)
2.	Solar cell Unit mass (g/m²)	265	115.8	1. For 50 um cell	231.6	1. For 100 um cell	92.6	1. For 40 um cell			Cell thickness
3.	Solar Cell Efficiency (AMO-25°C)	16%	17.3%	1. For 15.8% cell with 10% increase for "saw-tooth" cover. 2. Presently 16.5% cells available in lab tests	14.8%	1. For 13.5% cell with "saw tooth" cover. 2. 13.5% - 50 um cells now available	18%	1. Recognized target for silicon solar cells with or without covers.			Manuf. processes cell thickness(?) mass
4.	Radiation degradation factor (for 30 years)	-	0.97	1. Based on 70% annealing recovery & 50 um solar cell degradation with a 75 um cover.	0.90	1. Based on no annealing recovery & a 50 um solar cell and 75 um cover.	1.00	1. Based on 100% annealing recovery on 50 um solar cell with 75 um cover			Solar cell thickness Cover thickness Substrate thickness Annealing efficiency Mass. End efficiency
5.	Annealing Recovery	-	95%	1. 95% recovery demonstrated by NRL tests	95% per anneal	1. No repeated annealing has been documented.	100%	1. Theoretically possible			Type of blanket End efficiency, Mass
6.	Solar cell unit cost	72 $/m²	40 $/m²	1. Mature industry projection	67 $/m²	1. ERDA projected 30$/watt max. 2. Space cell may cost more.	22$/m²	1. ERDA projected 10¢/watt min. 2. Approx. 20 billion solar cells/SPS will justify sophisticated tooling.			Type of cell Efficiency Thickness, Process
7.	Solar cell cover Unit mass	55	167.6	1. Three mil-borosilicate glass a. Plastic films not compatible b. Radiation degradation c. Annealing compatibility d. Incorporation of "saw-tooth" e. Electrostatic Bonding	167.6	1. Three mill borosilicate W/O "saw-tooth" a. Manufacturability b. Radiation protection	111.7	1. Two mil borosilicate a. Low pt. in efficiency & mass bucket trade. 2. "Saw-tooth" may not be necessary for 18% solar cell.			Radiation degradation Efficiency Mass
8.	Cover UV degradation factor for 30 years	-	0.956	1. Design point	0.956	1. Possible conservative estimate	1.00	1. If no u-v degradation on borosilicate glass (possible)			End efficiency Mass
9.	Solar cell substrate unit mass (g/m²)	91	111.9	1. Two mil borosilicate glass a. Radiation protection b. Annealing compatibility c. Electrostatic bonding	167.6	1. Three mil borosilicate glass a. More radiation protection b. Manufacturability	62.7	1. One mil kapton/one mil adhesive a. Possibly enough rad. prot. b. If no annealing or if annealing compatible			Radiation degradation Annealing End efficiency Mass

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Table 4-1 Photovoltaic Traceability/Uncertainty Worksheet (continued)

ITEM #	ITEM	VALUE FROM JSC-11568 GREEN BOOK	CURRENT VALUE	REASON FOR CHANGE	WORST CASE	RATIONALE	BEST CASE	RATIONALE	SPS SENSITIVITY (% PER %)		CORRELATED VARIABLES
									MASS	COST	
10.	Solar cell mismatch loss factor	-	0.99	1. Acceptable manufacturing tolerance for performance	0.99	1. Should not be any larger than this.	0.99	1. Acceptable penalty			End Efficiency, Mass
11.	Solar panel lost area factor	-	0.961	1. Cell area/panel area ratio	0.961	1. Conservative design	0.961	1. Acceptable penalty			End Effic'cy Blanket Mass
12.	Solar cell interconnect unit mass (g/m^2)	10	11.4	1. Half milcopper a. Very low I^2R loss b. Back-connected cells need only short interconnectors.	11.4	1. Conservative value	3.4	1. Half Mil Aluminum a. Still low I^2R Loss (1) Slightly more b. Lower mass			End Effic'cy Mass Mfg'ability Handling
13.	Solar cell string I^2R losses	0.998		1. Calculated for ref. blanket	0.995	1. Aluminum Interconnects 2. Longer strings	0.999	1. Thicker interconnect 2. Shorter blanket			End Effic'cy Mass Aspect Ratio Bus I^2R Loss
14.	Solar Blanket Unit Mass (g/m^2)	412	426.9	1. Combination of component masses							
15.	Support & attachment unit mass (g/m^2)	-	5.0	1. Design point including installation joints, tapes, & catenary sys.	7.5	1. More support (50%) 2. Higher loading	2.5	1. Use uniaxial tapes 2. Lower loading			
	POWER DISTRIBUTION										
16.	Bus Mass (K_S/Kwe)	0.1905	0.1215	1. No lateral busbars 2. Emissivity (E_W) = 0.90	0.1640	1. Lateral & longitudinal bus bars	0.0699	1. Optimized for low aspect ratio.			Bus Effic'cy (I^2R) Aspect ratio Cur'nt Den'ty
17.	Current Density (A/cm^2)	558	633	1. Optmized for minimum satellite mass.	569.7	1. To lower I^2R loss if E_H 0.90	696	1. Reflects Lower I^2R Loss if E_W 0.90			Emissivity Bus Mass Bus Effic'cy
18.	Bus I^2R Loss	8.5%	6.6%	1. Reflects no lateral Bus bars.	9.0%	1. Lateral and longitudinal bus bars.	3.9%	1. Optimized for low aspect ratio			Efficiency Mass Aspect Ratio Bus Config.
19.	Bus Unit Cost ($/kg)	2.2	22	1. Reflects material and manufacturing cost.							
20.	Switchgear Mass (g/Kwe)	3.87	4.55	1. Based on Hughes best plasma switch gear data.							System Mass
21.	Switch gear cost ($/$K_s$)	98	414	1. Small amount necessary would not support nature industry projections.							

Table 4-1 Photovoltaic Traceability/Uncertainty Worksheet (continued)

ITEM #	ITEM	VALUE FROM JSC-11568 GREEN BOOK	CURRENT VALUE	REASON FOR CHANGE	WORST CASE	RATIONALE	BEST CASE	RATIONALE	SPS SENSITIVITY ($ PER $) MASS	COST	CORRELATED VARIABLES
	STRUCTURE										
22.	Crippling Criteria										
	Minimum Guage										
	Unit Mass ($Kg/_m$)										
23.	Unit Cost ($/Kg)	-	55	1. Mature Industry Projection	60	1. Metal instead of non-metal-joints from detailed manufacturing & fabrication analysis.	40	1. Detailed mfg. & fabrication analysis (terrestrial) yielded 48 $/kg presently at one SPS/year.			
	CONTROL SYSTEMS										
24.	Flight Control System Mass (Metric Tons)	340	190	1. First detailed analysis a. Optimized I_{sp} b. Perfect control laws							Mass Configuration Aspect Ratio Orbit
25.	Flight Control System Cost ($/Kg)	-	440	1. Conservative a. Small overall effect							

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Table 4-2 Thermal Engine Traceability/Uncertainty Worksheet

ITEM #	ITEM	VALUE FROM MSFC SPS STUDY	CURRENT VALUE	REASON FOR CHANGE	WORST CASE	RATIONALE	BEST CASE	RATIONALE	SPS SENSITIVITY ($ PER $) MASS	SPS SENSITIVITY ($ PER $) COST	CORRELATED VARIABLES
1	Plastic Film Reflectivity, Initial	0.87	0.90	Tests by Boeing Engineering & Construction	0.87	Measured Kapton Value	0.96	With Ag overcoat	-0.110		
2	Reflectivity degradation (1 = none)	1.0	1.0		0.70	Project ABLE data	1.0	Solar sail test. indicate no degradation until rad. dose ≈ 50 times SPS	-0.110		
3	Plastic Film Thickness	8 μM	3 μM	Solar Sail Work, Dupont Projections	8 μM	Heavier gauge required for "handling"	1.5 μM	Solar sail work, Dupont projections	+0.022		
4	Cavity Reflectance Loss	5%	5%		5%	Bench Model Cavity Tests	≈ 2%	High temperature anti-reflective coating	+0.008		
5	CPC Reflectivity	N/A	0.865	N/A	0.800	Extreme distortion in reflector surface	0.865	Calculated performance from ray trace program; rhenium reflector, C.R. = 3	-0.120		
6	Cavity Emissivity based on aperture area	0.8	1.00	Conservatism	1.00	Black body limit	0.8	With low emissivity high temperature interior coatings	+0.009		
7	Boiler material allowables	100%	100%		80%	No 30 year test data on niobium	120%	No 30 year test data	-0.041		
8	Boiler Droplet Removal	N/A	No Removal System	N/A	Vortex Removal System	Once - through boilers may omit droplets	No Removal System	Temperature ratio selected tends to total vaporization	0.855 increase if required		
9	Turbine Efficiency	N/A	80%	N/A	80%	Obtained in LeRC tests	85%	Aerodynamic improvements	-0.83		
10	Turbine Mass	N/A	1.00	N/A	1.20	G.E. Estimate	0.60	G.E. Estimate	+0.17		
11	Generator Efficiency	0.984	0.984		0.984	Currently obtained	0.986	Improvements	-0.70		

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Table 4-2 Thermal Engine Traceability/Uncertainty Worksheet (continued)

ITEM #	ITEM	VALUE FROM MSFC SPS STUDY	CURRENT VALUE	REASON FOR CHANGE	WORST CASE	RATIONALE	BEST CASE	RATIONALE	SPS SENSITIVITY ($ PER $)		CORRELATED VARIABLES
									MASS	COST	
12	Generator Temperature	400K	400K		400K	Current capability	480K	Advanced insulation	-0.055		
13	Generator specific mass	0.22	0.14 ky/kWe	Aerospace rather than terrestrial practice	0.22 ky/kWe	Current long life airborne gen.	0.08	Advanced airborne generators (short life)	+0.031		
14	Meteoroid Environment	"100%"	"100%"		"100%"	Current model is considered pessimistic	"60%"	Current model is considered pessimistic	+0.09		
15	Heat Pipe Meteoroid Resistance	"100%"	"100%"		"200%"	Elevated temperature steel may offer poor resistance	"80%"	Gas gun test data may be pessimistic	+0.09		

Table 4-3 MPTS Traceability/Uncertainty Worksheet

ITEM #	ITEM	VALUE FROM JSC-11568 GREEN BOOK	CURRENT VALUE	REASON FOR CHANGE	WORST CASE	RATIONALE	BEST CASE	RATIONALE	SPS SENSITIVITY ($ PER %)		CORRELATED VARIABLES
									MASS	COST	
1.	% of electric power that must be processed	N/A	15%	Multiple voltage requirements of high-efficiency klystron	30%	Voltage/current requirements of depressed collector are rough estimates	10%	Could go to more busses and tailored array voltages.			
2.	Power Processing & Distr. Efficiency	98%	97%	Detailed Analysis including I^2R	96%	Uncertainty in thermal environment and % power processed	98%	Same			
3.	Power Processing Mass Kg/kwe	0.02	1.0	Design Pt. W/High H_z Conv	2.7	Low Hz Conv.	1.0	High Hz Conv.			
4.	PPU Thermal Control, kg/kw_z		14.9	Rad. E_u = 0.90	15.8	Rad E_u = 0.85	14.1	Rad. E_u = 0.95			
5.	PPU Cost, $/$KW_e$ of PPU		414								
6.	PPU Thermal Control Cost, $/kg	.									
7.	Klystron Efficiency	87%	85%	Varian Estimate	80%	Effectiveness of Depressed Collectors with high-efficiency RF circuits remains to be demonstrated	86%	Varian Estimate (max)			
8.	Klystron Mass, kg/kw_e	1.14 incl. thermal control	0.85	Detailed Mass Statement							
9.	Klystron Cost $/kwe	46	50	Varian Manufacturing Estimate	100	Assumes more burn-in required	40	Varian facilitization cost was high			
10.	Klystron Heat Removal $(\frac{Kg}{Kwt})$ Mass	Incl. in Klystron	1.63	Heat removal system accounted separately	1.96	20% increase	1.3	20% less			
11.	Klystron Heat Removal Cost	Incl. in Klystron		Heat removal system accounted separately.							
12.	Waveguide I^2R Loss	.98	.985	Calculated Average	.985	Variance analysis not made	.985	Variance Analysis not made.			
13.	Subarray structure Mass Kg/m^2	1.15	.55	Design Pt. Avg. for I-Beam "Egg-Crate"	.66	20% increase	.46	20% less			
14.	Waveguide mass kg/m^2	5.1	1.88	Design Pt. (Gr-Ep) Rect. Section w/cond. coating							

NOTE: Estimates on this page incomplete.

Table 4-3 MPTS Traceability/Uncertainty Worksheet (continued)

ITEM #	ITEM	VALUE FROM JSC-11568 GREEN BOOK	CURRENT VALUE	REASON FOR CHANGE	WORST CASE	RATIONALE	BEST CASE	RATIONALE	SPS SENSITIVITY (% PER %)		CORRELATED VARIABLES
									MASS	COST	
15.	Waveguide & Structure Cost, $/kg	70	$64	Updated Estimate							
16.	RF Control Circuitry Mass kg/kwe	.05	0.059	$\frac{485.2\times10^3}{8.22\times10^6 kw}$	.05		.06				
17.	RF Control Circuitry Cost $/kwe	$56/unit	2.1 $/kw$_e$	Using 341.5 $/kg							
18.	Ideal Beam Efficiency	*	.965	Computer Analysis	.965	Corresponds to 10 db taper	.99	Corresponds to 17 db taper			
19.	Inter-Subarray Losses	*	.956	Computer analysis of phase & amplitude contribution (10^o_E, 1db)	.88	20^0 Phase Error	.97	5^0 Phase Error			
20.	Intra-Subarray Losses	.98	.981	Detailed Error Analysis	.97	Inability to Hold Mechanical Tolerances	.99	Eliminate tilt errors and improve Flatness.			
21.	Atmosphere Absorption	.98	.98	No additional analysis	.98		.98				
22.	Rectenna Intercept Efficiency	* .88	.95	Optimal for Nominal Rectenna	.90	Optimal for high-cost rectenna	.98	Optimal for low-cost rectenna			
23.	RF-DC Conversion	.90	.848	Based on numerical integration for nominal JPL Efficiency vs. Intensity	.79	Assumes low range of JPL estimates.	.90	Raytheon projection for improved diodes			
24.	Grid Interfacing Efficiency	.99	.97	Includes DC-AC processing	.96	ROM Estimate	.98	ROM Estimate			
25.	Land Cost $/Acre	2450	5000	Nominal Median	10000	Assumes some improved property acquisition	2000	Low-cost land; value is mainly site prep.			
25.	Dipole Spacing	0.5	0.5	Test results	0.5	Test results	0.8	Theory shows greater spacing possible			

*These three items combined into "Energy Collection".

NOTE: Estimates on this page incomplete.

Table 4-3 MPTS Traceability/Uncertainty Worksheet (continued)

ITEM #	ITEM	VALUE FROM JSC-11568 GREEN BOOK	CURRENT VALUE	REASON FOR CHANGE	WORST CASE	RATIONALE	BEST CASE	RATIONALE	SPS SENSITIVITY ($ PER $) MASS	SPS SENSITIVITY ($ PER $) COST	CORRELATED VARIABLES
27.	Dipole Cost		4¢	Estimated 2x Material Cost	4¢	Same	0.5¢	Raytheon Estimate (for caps. Dipole integral with structure).			
28.	Average Diodes/Dipole	$8/m²	1	Standard RF Circuit Design	1	Same	3	Advanced RF Circuit			
29.	Diode/Filter Cost		6¢	Boeing Nominal Estimate	20¢	JSC "Worst Case"	1.4¢	Raytheon Estimate			
30.	Support Hdwe Cost, $/m²	$10/m²					3.50	Raytheon Estimate			
31.	Construction Cost, $/m²	Included in support hdwe	12.90		21.50	Bevoy Results	2.30	Raytheon Estimate			
32.	PPU Cost, $/kw$_e$		$40		$100		$25				
33.	Rectenna Area	10 km dia	10 km dia	(0.8 beam diameter + 95% cell effy)	14 km dia.	Full beam for sidelobe suppression	8 km	90% collection efficiency			

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4.3 SIZE/MASS UNCERTAINTY ANALYSIS

The size/mass uncertainty analysis was the first step. It began with analysis of uncertainties in the efficiency chain to determine size uncertainty.

4.3.1 Photovoltaic Size/Mass Uncertainty

Table 1 presents the photovoltaic system efficiency uncertainty worksheet, including the microwave power transmission system. The aggregate values for the MPTS were carried over to the thermal engine size/mass uncertainty analysis.

Table 1

Photovoltaic End-To-End Efficiency Worksheet

SPS

BOEING

SPS-1389

ITEM	NOMINAL	MINIMUM	MAXIMUM	LOG MIN	LOG MAX	LOG MEAN	σ	Correlations
Summer Solstice Factor	.9675	.9675	.9675	-.0330	-.0330	-.0330	0	
Cosine Loss (POP)	.919	.919	.919	-.0845	-.0845	-.0845	0	
Solar Cell Efficiency	.173	.148	.18	-1.9105	-1.7147	-1.8126	.0326	-0.6
Radiation Degradation	.97	.90	1.0	-.1393	0	-.06963	.0232	(-.0009076)
Temperature Degradation	.954	.954	.954	-.0471	-.0471	0.0471	0	
Cover UV Degradation	.956	.956	1.0	-.0450	0	-.0225	.00750	
Cell-to-Cell Mismatch	.99	.99	.99	-.01005	-.01005	-.01005	0	
Panel Lost Area	.961	.961	.961	-.0398	-.0398	-.0398	0	
String I^2R	.998	.995	.999	-.00501	-.001	-.00301	.00067	
Bus I^2R	.934	.91	.961	-.0943	-.0398	-.0670	.0091	
Rotary Joint	1.0	1.0	1.0	0	0	0	0	
Antenna Power Distr	.97	.95	.98	-.0513	-.0202	-.0357	.0052	
DC-RF Conversion	.85	.80	.86	-.223	-.1508	-.1870	.0121	
Waveguide I^2	.985	.985	.985	-.0151	-.0151	-.0151	0	
Ideal Beam	.965	.965	.99	-.0356	-.0100	-.0228	.0043	
Inter-Subarray Errors	.956	.88	.97	-.1278	-.0305	-.0791	.0162	-0.3
Intra-Subarray Errors	.981	.97	.99	-.0304	-.010	-.0203	.0034	(-.0000366)
Atmosphere Absorp.	.98	.93	.98	-.0202	-.0202	-.0202	0	
Intercept Efficiency	.95	.90	.98	-.1054	-.0202	-.0628	.0142	-0.5
Rectenna RF-DC	.848	.79	.92	-.2357	-.0834	-.1596	.0254	
Grid Interfacing	.97	.96	.98	-.0408	-.0202	-.0305	.0034	(-.0000361)
Products/Sums Sizes (Km^2)	.0679 108.8	.0383 193	.095 77.8			-2.822	Sums Q = .00306	

3σ Max = exp (-2.822+ 3x.042) = .0675 size = 109.5
3σ Min = exp (-2.822 - 3x.042) = .0524 size = 141.0

η = .0595 size = 124.0
Correlation prod sum = -.00131
Net σ = $\sqrt{.00306-.00131}$ = .042

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Variation of Satellite Weight with Array Planform Area

The results of a study to determine the variation of satellite weight with array planform area are presented in Figure 4-1. Weight statements, scaling parameters, and scale factors are presented in Table 4-1 for the total satellite, with the detail data for the MPTS being presented in Table 4-2.

As indicated in Table 4-1, the satellite primary structure weight has been scaled directly proportional to structural planform area. The validity of using this scale factor has been verified by analysis. Pertinent data is included in Appendices F, G, and H.

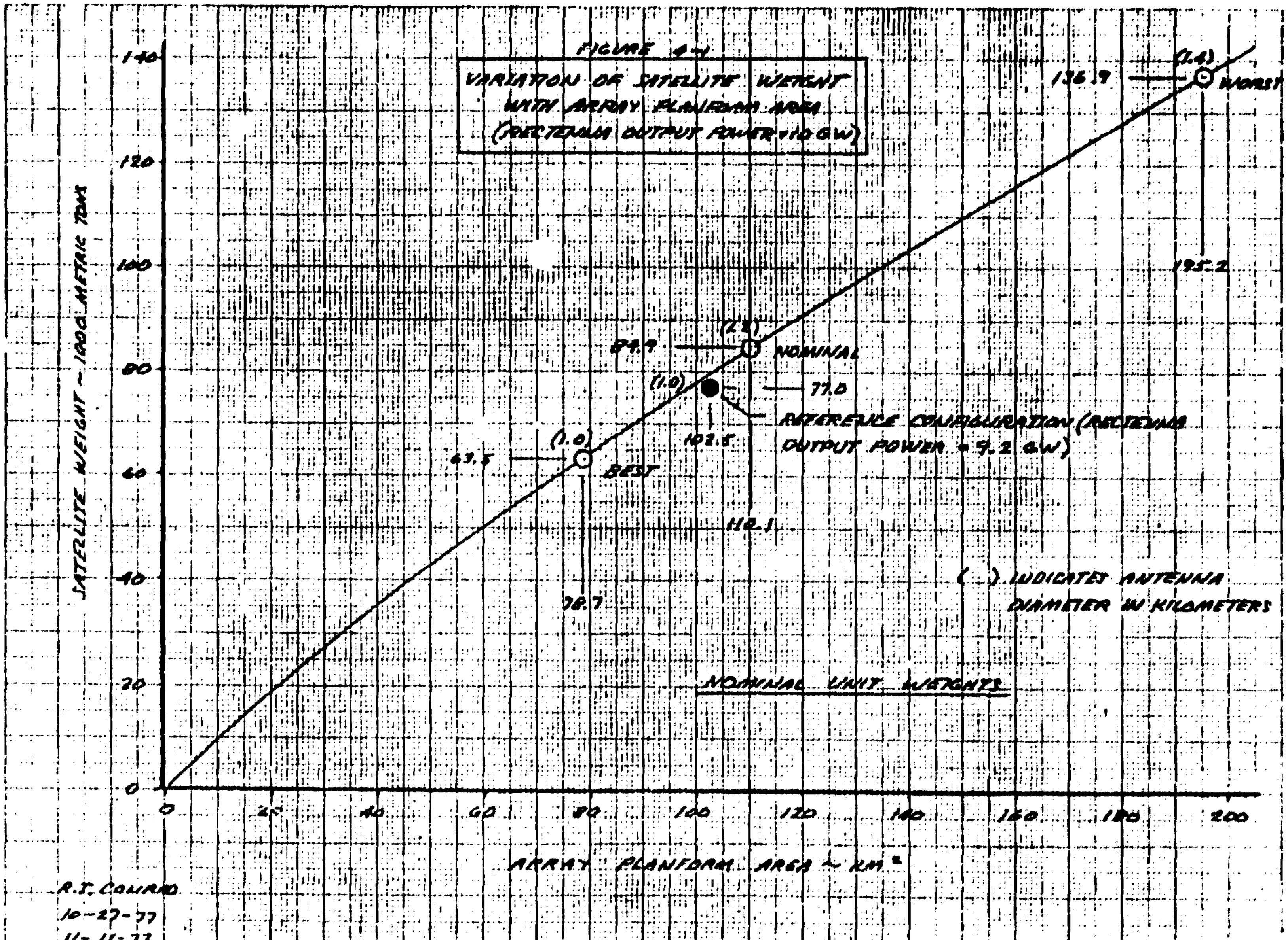

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TABLE 4-1
SATELLITE WEIGHT SUMMARY
(NOMINAL UNIT WEIGHTS)

ITEM	WEIGHT IN METRIC TONS				SCALE FACTOR
	REF.	BEST	NOM.	WORST	
1.0 SOLAR ENERGY COLLECTION SYSTEM	(51,782)	(39,960)	(55,699)	(99,468)	
1.1 PRIMARY STRUCTURE	5385	4278	5747	10,605	S ▷
1.2 SECONDARY STRUCTURE	▷	▷	▷	▷	—
1.3 MECHANICAL ROTARY JOINT	67	67	80	94	D
1.4 MAINTENANCE STATION	—	—	—	—	—
1.5 CONTROL	178	115	207	617	$S \times W_o$
1.6 INSTRUMENTATION/COMMUNICATIONS	4	4	4	4	—
1.7 SOLAR CELL BLANKETS	43,750	33,591	46,994	83,317	A
1.8 SOLAR CONCENTRATORS	—	—	—	—	—
1.9 POWER DISTRIBUTION					
POWER BUSES	2030	1587	2265	4208	$L \times P$
CELL STRING FEEDERS	39	35	42	74	$B \times P$
DISCONNECTS, SWITCH GEAR, CONVERTERS	156	139	169	231	P
ENERGY STORAGE	20	18	22	30	P
ELECTRICAL ROTARY JOINTS	39	35	42	58	P
SUPPORT STRUCTURE ~5%	114	91	127	230	—
2.0 MICROWAVE POWER TRANSMISSION SYSTEM	(25,212)	(23,508)	(29,178)	(37,458)	▷
TOTAL WEIGHT – LESS GROWTH (W_o)	76,994	63,468	84,877	136,926	

	REF.	BEST	NOM.	WORST
STRUCTURAL PLANFORM AREA (S) ~ km^2	112.3	88.8	119.1	220.4
ANTENNA DIAMETER (D) ~ km	1.0	1.0	1.2	1.4
ARRAY PLANFORM AREA (A) ~ km^2	102.5	78.7	110.1	195.2
SATELLITE STRUCTURAL LENGTH (L) ~ km	21.3	18.7	21.9	29.8
POWER TO SLIPRINGS (P) ~ GW MIN.	16.4	14.6	17.8	24.3
NO. OF INTERMEDIATE LONGITUDINAL BEAMS (B)	7	7	7	9

▷ DISTRIBUTED TO OTHER WBS ITEMS

▷ VERIFIED BY ANALYSIS (SEE APPENDICIES F, G, AND H)

▷ DETAILS ON FOLLOWING PAGE

TABLE 4-2
MPTS WEIGHT SUMMARY
(NOMINAL UNIT WEIGHTS)

ITEM	WEIGHT IN METRIC TONS				SCALE FACTOR
	REF.	BEST	NOM.	WORST	
PRIMARY STRUCTURE	52	52	75	102	D^2
SECONDARY STRUCTURE	197	197	284	386	D^2
ANTENNA CONTROL SYSTEMS	(TBD)	(TBD)	(TBD)	(TBD)	—
POWER DISTRIBUTION SYSTEM - EXCL. SUBARRAYS					
• BUSES - ROTARY JOINT TO SECTOR CONTROL	271	271	325	379	D
BUSES - SECTOR CONTROL TO SUBARRAYS	110	110	158	216	D^2
SWITCH GEAR/DISCONNECTS	137	125	148	187	K
DC-DC CONVERTERS	1241	1133	1345	1695	K
THERMAL CONTROL (ACTIVE)	736	672	797	1006	K
ENERGY STORAGE	299	273	324	408	K
SUPPORT STRUCTURE ~ 5%	140	129	155	195	—
ANTENNA COMMUNICATIONS/DATA SYSTEM	(TBD)	(TBD)	(TBD)	(TBD)	—
ANTENNA SUBARRAYS					
KLYSTRONS	4658	4253	5047	6364	K
THERMAL CONTROL	2087	1906	2261	2851	K
DISTRIBUTION WAVEGUIDES	239	239	344	468	D^2
RADIATING WAVEGUIDES	1485	1485	2138	2911	D^2
POWER CONTROL	485	443	525	663	K
POWER DISTRIBUTION	36	33	39	49	K
STRUCTURE	433	433	624	847	D^2
TOTAL WEIGHT - PER ANTENNA	12,606	11,754	14,589	18,739	

ANTENNA DIA. (D) ~ KM	1.0	1.0	1.2	1.4
NO. OF KLYSTRONS (K)	97,036	88,606	105,136	132,570

Effect of Tolerances on Weight of Reference Configuration

The results of a study to determine the effect of tolerances on the weight of the reference configuration are presented in Figure 5-1. A weight tolerances worksheet for the reference configuration is presented in Table 5-1. Note that the tolerances which are the major drivers are those associated with the solar cell blankets, the MPTS, and the primary structure.

A weight tolerances worksheet for the solar cell blankets is presented in Table 5-2.

A weight tolerances worksheet for the MPTS is presented in Table 5-3. Details of the tolerances for the combination of DC-DC converters and thermal control are given in Table 5-4.

A weight tolerances worksheet for the primary structure is presented in Table 5-5. Supporting data include the following: Figure 5-2, which gives the variation of structure weight with array unit weight; Figure 5-3, which gives the variation of structure weight with antenna weight; Figure 5-4, which presents the effect of uncertainty in crippling coefficient on the sizing of a 20 meter long tapered tube of graphite/epoxy; and Table 5-6, which presents a weight distribution for the primary structure with particular emphasis on the amount of graphite/epoxy (tubing) and hardware (tube center joints, tube end fittings, and strut interconnect fittings) comprising beam weight.

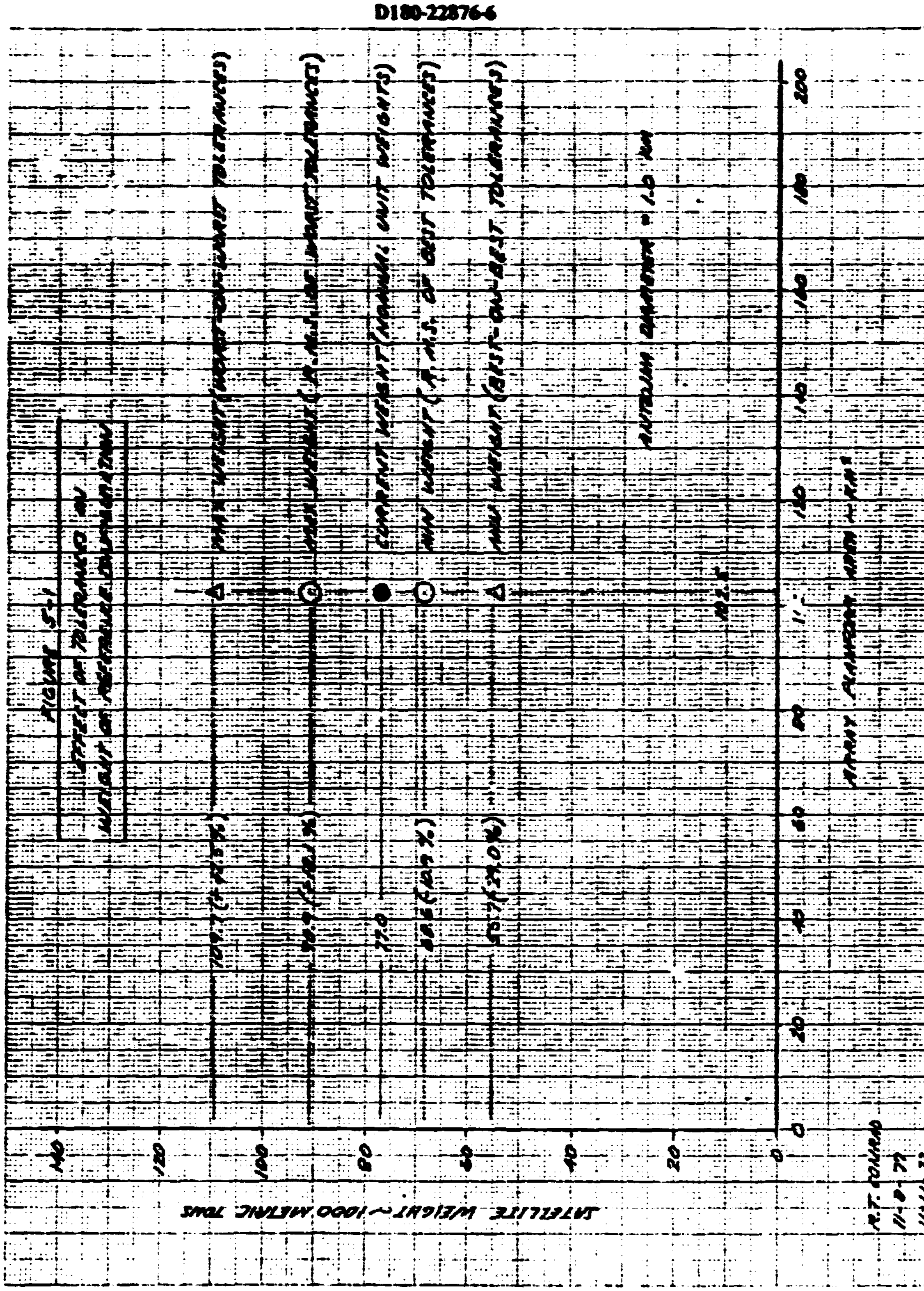


FIGURE 5-1
EFFECT OF TOLERANCES ON WEIGHT OF REFERENCE CONFIGURATION
109.7
MAX WEIGHT (WORST-ON-WORST TOLERANCES)
R.M.S. OF WORST TOLERANCES)
77.0
CURRENT WEIGHT (NOMINAL UNIT WEIGHTS)
MIN WEIGHT (R.M.S. OF BEST TOLERANCES)
55.7 (29.0%)
MIN WEIGHT (BEST-ON-BEST TOLERANCES)
ANTENNA DIAMETER = 1.0 KM
SATELLITE WEIGHT ~ 1000 METRIC TONS
ARRAY PLANFORM AREA ~ KM²
0
20
40
60
80
100
120
140
160
180
200
R.T. CONRAD
11-8-77

TABLE 5-1
WEIGHT TOLERANCES WORKSHEET
REFERENCE CONFIGURATION

ITEM	CURRENT WEIGHT~kg	WORST TOLERANCE		BEST TOLERANCE	
		ΔW ~ kg	%	ΔW ~ kg	%
1.0 SOLAR ENERGY COLLECTION SYSTEM	(51,782,300)	+22,421,000 (ADD.) +13,164,000 (RMS)	+43.3 (ADD.) +25.4 (RMS)	-16,983,000 (ADD.) -8,036,000 (RMS)	-32.8 (ADD.) -15.5 (RMS)
1.1 PRIMARY STRUCTURE	5,385,000	+3,182,000 (ADD.) +1,953,000 (RMS)	+59.1 (ADD.) +36.3 (RMS)	-1,534,000 (ADD.) -802,000 (RMS)	-28.5 (ADD.) -14.9 (RMS)
1.3 ROTARY JOINT	66,800	+67,000	+100.0	-17,000	-25.0
1.5 CONTROL	178,100	+89,000	+50.0	-45,000	-25.0
1.6 INSTRUMENTATION/COMMUN.	4,000	+4,000	+100.0	-1,000	-25.0
1.7 SOLAR CELL BLANKETS	43,750,000	+18,479,000 (ADD.) +13,004,000 (RMS)	+42.2 (ADD.) +29.7 (RMS)	-14,786,000 (ADD.) -7,973,000 (RMS)	-33.8 (ADD.) -18.2 (RMS)
1.9 POWER DISTRIBUTION	2,398,400	+600,000	+25.0	-600,000	-25.0
2.0 MICROWAVE POWER TRANS. SYSTEM	(25,212,200)	+10,294,000 (ADD.) +4,531,000 (RMS)	+40.8 (ADD.) +19.0 (RMS)	-5,342,000 (ADD.) -2,512,000 (RMS)	-21.2 (ADD.) -10.0 (RMS)
TOTAL	76,994,500	+32,715,000 (ADD.) +13,922,000 (RMS)	+42.5 (ADD.) +18.1 (RMS)	-22,325,000 (ADD.) -8,419,000 (RMS)	-29.0 (ADD.) -10.9 (RMS)

TABLE 5-2
WEIGHT TOLERANCES WORKSHEET
REFERENCE CONFIGURATION
(1.7 SOLAR CELL BLANKETS)

ITEM	CURRENT	WORST	BEST
SOLAR CELLS:			
MATERIAL	SILICON →	→	→
THICKNESS ~ MILS	2.0	4.0	1.6
WEIGHT ~ kg	11,670,850	23,341,700	9,336,680
ΔWEIGHT ~ kg	0	+11,670,850	-2,334,170
SOLAR CELL COVERS:			
MATERIAL	FUSED SILICA →	→	→
THICKNESS ~ MILS	3.0	3.0	2.0
WEIGHT ~ kg	16,987,940	16,987,940	11,325,290
ΔWEIGHT ~ kg	0	0	-5,662,650
SOLAR CELL SUBSTRATE:			
MATERIAL	FUSED SILICA →	→	KAPTON/ADHESIVE
THICKNESS ~ MILS	2.0	3.0	1.0/1.0
WEIGHT ~ kg	11,325,290	16,987,940	6,345,800
ΔWEIGHT ~ kg	0	+5,662,650	-4,979,490
SOLAR CELL INTERCONNECTS:			
MATERIAL	COPPER →	→	ALUMINUM
THICKNESS ~ MILS	0.5	0.5	0.5
WEIGHT ~ kg	1,150,160	1,150,160	343,030
ΔWEIGHT ~ kg	0	0	-807,130
MANUFACTURING TOLERANCES ALLOWANCE			
% OF FOREGOING WEIGHTS	5	5	5
WEIGHT ~ kg	2,057,110	2,923,390	1,333,380
ΔWEIGHT ~ kg	0	+866,280	-723,730
SUPPORT & ATTACHMENT:			
DESIGN MATURITY WEIGHT RATIO	1.0	1.5	0.5
WEIGHT ~ kg	558,650	837,975	279,325
ΔWEIGHT ~ kg	0	+279,325	-279,325
TOTAL WEIGHT ~ kg	43,750,000	—	—
WEIGHT TOLERANCE (ADDITIVE) ~ kg	—	+18,479,105	-14,786,495
WEIGHT TOLERANCE (R.M.S.) ~ kg	—	+13,003,955	-7,972,610
WEIGHT TOLERANCE (ADDITIVE) ~ %	—	+42.2	-33.8
WEIGHT TOLERANCE (R.M.S.) ~ %	—	+29.7	-18.2

TABLE 5-3
WEIGHT TOLERANCES WORKSHEET
REFERENCE CONFIGURATION
(2.0 MPTS)

ITEM	CURRENT WEIGHT~kg	WORST TOLERANCE		BEST TOLERANCE	
		%	ΔWT~kg	%	ΔWT~kg
PRIMARY STRUCTURE	105,000	+100	+105,000	-10	0
SECONDARY STRUCTURE	395,000	+50	+198,000	-25	-99,000
ANTENNA CONTROL SYSTEMS	(TBD)	—	—	—	—
POWER DISTRIBUTION SYSTEM-EXCL. SUBARRAYS					
BUSES - ROTARY JOINT TO SECTOR CONTROL	541,200	+15	+81,000	-10	-54,000
BUSES - SECTOR CONTROL TO SUBARRAYS	219,400	+25	+55,000	-10	-22,000
SWITCH GEAR/DISCONNECTS	273,600	+15	+41,000	-50	-137,000
DC-DC CONVERTERS	{2,482,000	{+74}*	{+2,930,000}	{-51}*	{-2,019,000}
THERMAL CONTROL (ACTIVE)	1,472,000}				
ENERGY STORAGE	578,600	+15	+90,000	-50	-279,000
SUPPORT STRUCTURES	279,400	+50	+140,000	-25	-70,000
ANTENNA COMMUNICATIONS/DATA SYSTEM	(TBD)	—	—	—	—
ANTENNA SUBARRAYS					
KLYSTRONS	9,316,000	+25	+2,329,000	-10	-932,000
DISTRIBUTION WAVEGUIDES	478,000	+50	+357,000	-10	-48,000
RADIATING WAVEGUIDES	2,974,000	+50	+2,778,000	-10	-297,000
SOLID STATE CONTROL	970,000	+25	+243,000	-10	-97,000
POWER DISTRIBUTION CABLING	72,000	+25	+18,000	-10	-7,000
THERMAL CONTROL	4,174,000	+25	+1,044,000	-25	-1,044,000
STRUCTURE	866,000	+50	+433,000	-25	-217,000
TOTAL WEIGHT	25,212,200	—	—	—	—
WEIGHT TOLERANCE (ADDITIVE)	—	+40.8	+10,294,000	-21.2	-5,342,000
WEIGHT TOLERANCE (R.M.S.)	—	+18.0	+4,531,000	-10.0	-2,572,000

* DETAILS ON FOLLOWING PAGE

TABLE 5-4
WEIGHT TOLERANCES WORKSHEET
REFERENCE CONFIGURATION
MPTS
DC-DC CONVERTERS + THERMAL CONTROL

THE WEIGHT OF THE DC-DC CONVERTERS (PROCESSORS) PLUS ASSOCIATED THERMAL CONTROL CAN BE EXPRESSED AS

$$W = f_p \left[w_p + (1-\eta_p) w_T \right] P \qquad \sim kg$$

WHERE

f_p = FRACTION OF POWER PROCESSED
w_p = SPECIFIC WEIGHT OF PROCESSORS, kg/kW_e
η_p = PROCESSOR EFFICIENCY FRACTION
w_T = SPECIFIC WEIGHT OF THERMAL CONTROL, kg/kW_T
P = POWER PROCESSED (~POWER OUT OF ROTARY JOINT), kW_e

THE CURRENT, WORST, AND BEST VALUES ARE GIVEN BELOW

	CURRENT	WORST	BEST
f_p	0.15	0.20	0.10
w_p	1.0	1.3	0.9
η_p	0.96	0.95	0.98
w_T	14.9	15.9	13.9
$f_p[w_p+(1-\eta_p)w_T]$	0.2394	0.4190	0.1178
P	16,430,000	→	→
$W \sim kg$	3,954,000	6,884,000	1,935,000
$\Delta W \sim kg$	—	+2,930,000 (+74%)	−2,019,000 (−51%)

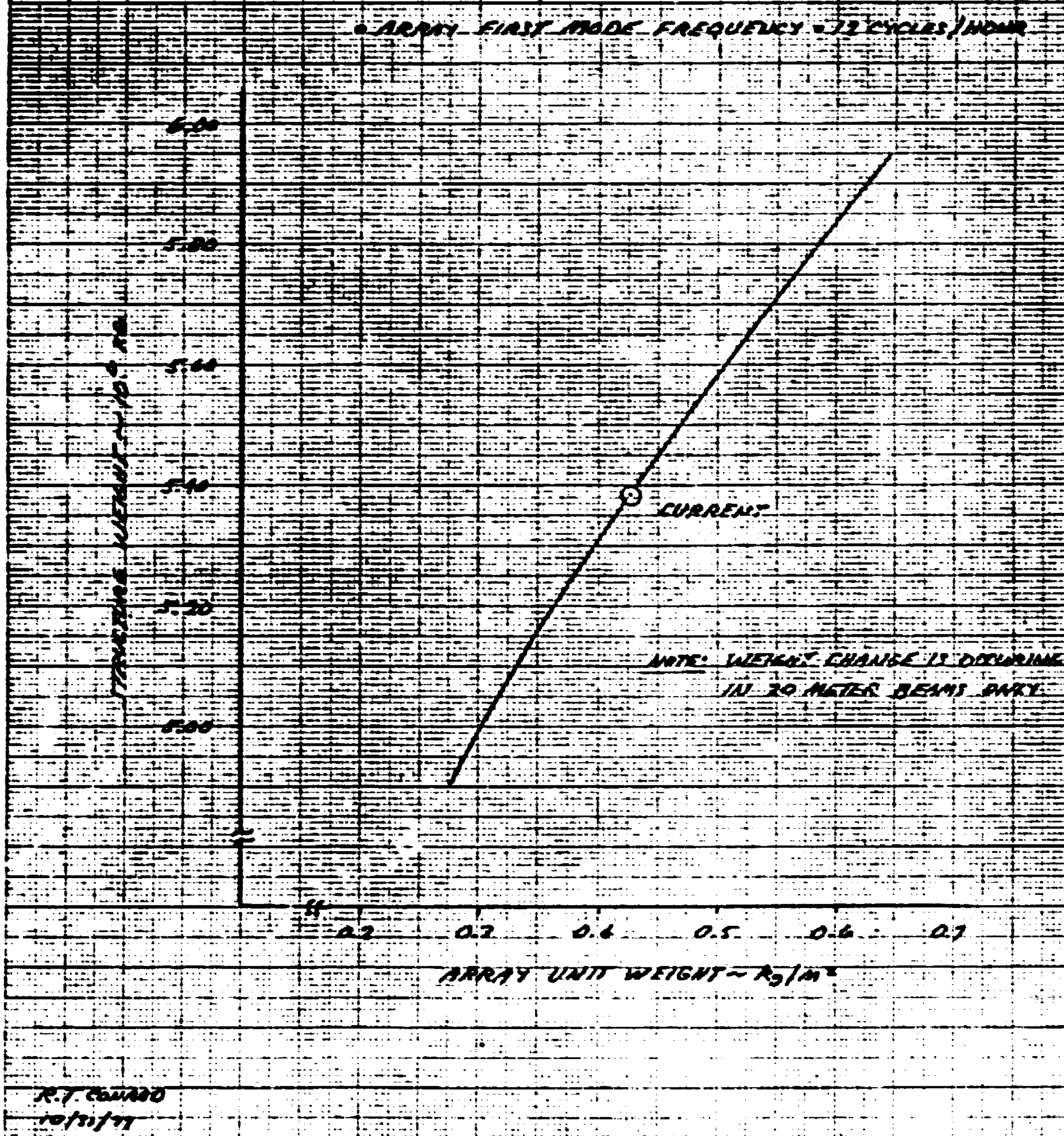
TABLE 5-5
WEIGHT TOLERANCES WORKSHEET
REFERENCE CONFIGURATION
(1.0 PRIMARY STRUCTURE)

ITEM	CURRENT	WORST	BEST
TUBING MATERIAL	GRAPHITE/EPOXY →	→	→
ARRAY UNIT WEIGHT ~ kg/m^2 ▷	0.427	{0.607 (ADDITIVE) 0.554 (R.M.S.)	{0.283 (ADDITIVE) 0.349 (R.M.S.)
ANTENNA WEIGHT ~ 10^6 kg	25.1	{35.5 (ADDITIVE) 29.7 (R.M.S.)	{19.9 (ADDITIVE) 22.7 (R.M.S.)
TUBE CRIPPLING COEFFICIENT	$0.8/\sqrt{R/t}$	$0.4/\sqrt{R/t}$	$1.3/\sqrt{R/t}$
TUBE MINIMUM WALL THICKNESS ~ MILS	10	15	8
LOCATION OF VERTICAL 20 METER BEAMS	MODULE PERIPHERAL NODE POINTS ONLY	ALL NODE POINTS	MODULE PERIPHERAL NODE POINTS ONLY
DESIGN MATURITY WEIGHT RATIO FOR NON-TUBING ITEMS	1.0	1.5	0.75
• IMPACT OF ARRAY WEIGHT ON WEIGHT OF 20M BEAMS ~ kg	0	{+470,000 (ADDITIVE) +340,000 (R.M.S.)	{-160,000 (ADDITIVE) -270,000 (R.M.S.)
• IMPACT OF ANTENNA WT. ON WEIGHT OF 20M BEAMS ~ kg	0	{+42,000 (ADDITIVE) +19,000 (R.M.S.)	{-22,000 (ADDITIVE) -10,000 (R.M.S.)
• IMPACT OF CRIPPLING COEFFICIENT ON WEIGHT OF TUBING IN UPPER SURFACE 20M BEAM CHORDS ~ kg	0	+137,000	-80,000
• IMPACT OF MINIMUM WALL THICKNESS ON WEIGHT OF TUBING EXCLUSIVE OF UPPER SURFACE 20M BEAM CHORDS ~ kg	0	+1,845,000	-724,000
• IMPACT OF LOCATION OF VERTICAL 20M BEAMS ON WEIGHT OF 20M BEAMS ~ kg	0	+203,000	0
• IMPACT OF DESIGN MATURITY WEIGHT RATIO ON WEIGHT OF NON-TUBING ITEMS ~ kg	0	+485,000	-242,000
TOTAL WEIGHT ~ kg	5,385,000	—	—
WEIGHT TOLERANCE (ADDITIVE) ~ kg	—	+3,182,000	-1,534,000
WEIGHT TOLERANCE (R.M.S.) ~ kg	—	+1,953,000	-802,000
WEIGHT TOLERANCE (ADDITIVE) ~ %	—	+59.1	-28.5
WEIGHT TOLERANCE (R.M.S.) ~ %	—	+36.3	-14.9

▷ MAJOR DRIVER WITH RESPECT TO LOADS.

FIGURE 5-2

VARIATION OF STRUCTURE WEIGHT WITH ARRAY UNIT WEIGHT (REFERENCE CONFIGURATION)



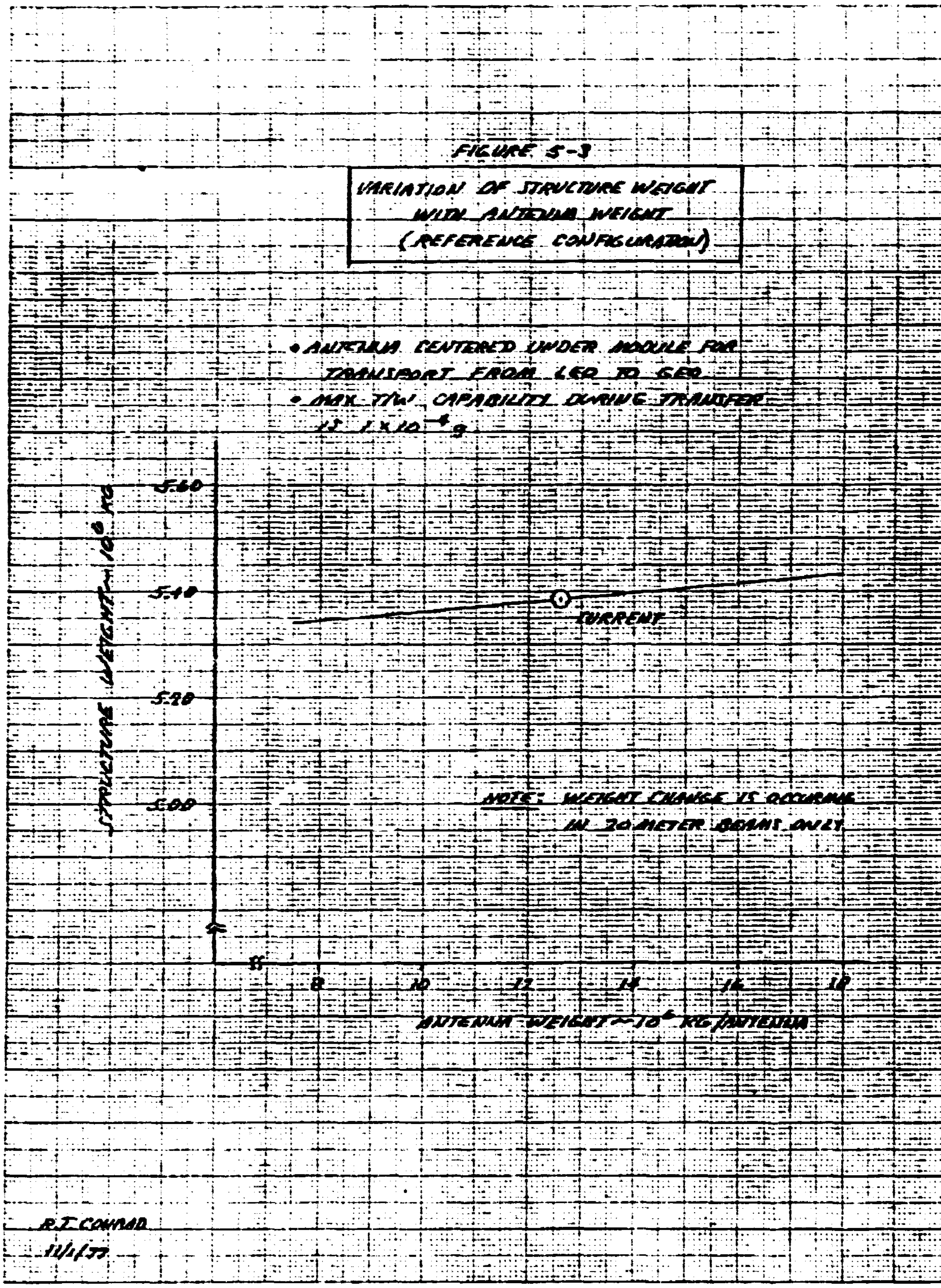


FIGURE 5-3
VARIATION OF STRUCTURE WEIGHT
WITH ANTENNA WEIGHT
(REFERENCE CONFIGURATION)
• ANTENNA CENTERED UNDER MODULE FOR TRANSPORT FROM LEO TO GEO
• MAX T/W CAPABILITY DURING TRANSFER IS 1 x 10⁻⁴ g
5.60
5.40
5.20
5.00
STRUCTURE WEIGHT ~10⁶ KG
CURRENT
NOTE: WEIGHT CHANGE IS OCCURING IN 20 METER BEAMS ONLY
8
10
12
14
16
18
ANTENNA WEIGHT ~10⁶ KG/ANTENNA
R.J. CONRAD
11/1/77

FIGURE 5-4

EFFECT OF UNCERTAINTY IN CRIPPLING COEFFICIENT ON SIZING OF 20M LONG TAPERED TUBE OF GRAPHITE/EPOXY

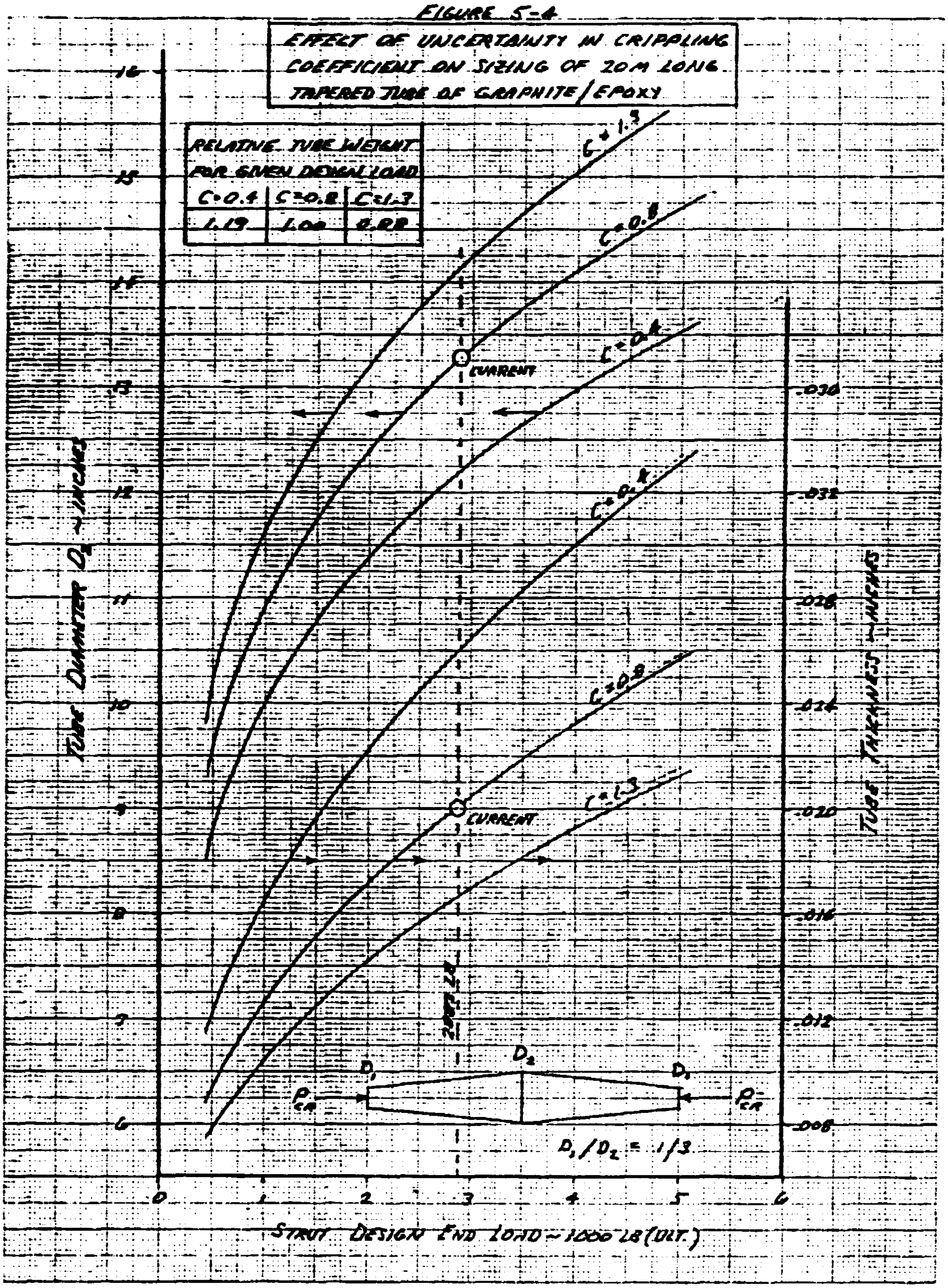


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TABLE 5-6
PRIMARY STRUCTURE WEIGHT DISTRIBUTION
(WEIGHT IN KILOGRAMS)

UPPER SURFACE 20 M BEAMS		1,710,920
G/E TUBING – CHORDS (D_2 = 13.3", t = .020")	720,280	
G/E TUBING – DIAG./BATTENS (D_2 = 13.3", t = .010")	829,200	
HARDWARE	161,440	
LOWER SURFACE 20 M BEAMS		1,347,760
G/E TUBING (D_2 = 13.3", t = .010")	1,186,320	
HARDWARE	161,440	
INTRA SURFACE DIAGONAL 20 M BEAMS		1,547,640
G/E TUBING (D_2 = 13.3", t = .010")	1,362,280	
HARDWARE	185,360	
INTRA SURFACE VERTICAL 20 M BEAMS		231,520
G/E TUBING (D_2 = 13.3", t = .010")	203,840	
HARDWARE	27,680	
ANTENNA SUPPORT FRAME 20 M BEAMS		81,800
G/E TUBING – CHORDS (D_2 = 13.3", t = .020")	34,440	
G/E TUBING – DIAG./BATTENS (D_2 = 13.3", t = .010")	39,640	
HARDWARE	7,720	
ANTENNA YOKE 5 M BEAMS		69,000
G/E TUBING (D_2 = 5.0", t = .008")	39,420	
HARDWARE	29,580	
OTHER STRUCTURES		396,360
TENSION CABLES	13,440	
MODULE-TO-MODULE DOCKING PROVISIONS	63,000	
ADDITIONS TO TRUSS – ANTENNA SUPPORT FRAME BACKUP	20,000	
ANTENNA ROTATION JOINTS/PITCH CONTROLS – ON YOKE	10,000	
ANTENNA SUPPORT STRUCTURE – LEO TO GEO	40,000	
ASSEMBLY HARDWARE – MODULE FRAMES	242,320	
ASSEMBLY HARDWARE – ANTENNA SUPPORT FRAMES	4 200	
ASSEMBLY HARDWARE – YOKE FRAMES	3400	
TOTAL WEIGHT		5,385,000 kg

D_2 = TUBE DIA. AT MIDSPAN
D_1 = TUBE DIA AT END = $\frac{1}{3} D_2$

APPENDIX G

STRUCTURAL PLANFORM SIZING, REFERENCE LENGTHS OF 20 METER BEAMS, AND DESIGN LOADS, STRUT SIZING, AND 20 METER BEAM UNIT WEIGHTS FOR NOMINAL, BEST AND WORST CONFIGURATIONS

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STRUCTURAL PLANFORM SIZING, REFERENCE LENGTHS FOR 20 METER BEAMS, AND DESIGN LOADS, STRUT SIZING, AND 20 METER BEAM UNIT WEIGHTS FOR NOMINAL, BEST, AND WORST CONFIGURATIONS

STRUCTURAL PLANFORM SIZING

THE REQUIRED TOTAL SOLAR PANEL AREAS FOR THE SUBJECT CONFIGURATIONS ARE: NOMINAL CONFIG, 108.8 KM²; BEST CONFIG, 77.8 KM²; WORST CONFIG, 193.0 KM². THESE ARE SOLAR PANEL AREAS EXCLUSIVE OF INSTALLATION EDGE MARGINS (SEE FIGURE 1.7-6). THE RELATIONSHIP BETWEEN THE REQUIRED TOTAL STRUCTURAL BAY AREA AND THE REQUIRED TOTAL SOLAR PANEL AREA CAN BE EXPRESSED AS

$$\left(\frac{\text{REQ'D TOTAL BAY AREA}}{\text{REQ'D TOTAL PANEL AREA}}\right) = \frac{1}{\text{PANEL AREA FACTOR} \times \text{SEGMENT AREA FACTOR} \times \text{ARRAY AREA FACTOR}}$$

FOR THE REFERENCE CONFIGURATION, IT FOLLOWS THAT (SEE PAGE 1.7-7)

PANEL AREA FACTOR = 0.9913 (DESIGN)

AND

SEGMENT AREA FACTOR = 0.9972 (TYPICAL)

THE ARRAY AREA FACTOR IS DEPENDENT ON BAY SIZE, BEAM WIDTH, AND EDGE MARGIN FOR THE CATENARY SUPPORT SYSTEM. FOR THE CASE OF A 20 METER BEAM AND A 1.5 METER EDGE MARGIN FOR INSTALLATION OF THE CATENARY SUPPORT SYSTEM, IT FOLLOWS THAT

$$\text{ARRAY EDGE MARGIN} = \left(\frac{\text{BAY SIZE} - 23}{\text{BAY SIZE}}\right)^2 \quad (\text{MAX})$$

A TABULATION OF CALCULATIONS LEADING TO PLANFORM SIZING DETERMINATION (BAY SIZE, NO. OF BAYS, AND BAY ARRANGEMENT) IS PRESENTED IN FIGURE G-1. THE PLANFORM CONFIGURATIONS ARE SHOWN IN FIGURES G-2, G-3, AND G-4, FOR THE NOMINAL, BEST, AND WORST CONFIGURATIONS, RESPECTIVELY. ALL CONFIGURATIONS HAVE AN ASPECT RATIO OF 4, THIS BEING THE ASPECT RATIO OF THE REFERENCE CONFIGURATION AS DETERMINED BY ELECTRICAL REQUIREMENTS.

REFERENCE LENGTHS FOR 20 METER BEAMS

THE REFERENCE LENGTHS FOR THE 20 METER BEAMS OF THE NOMINAL, BEST, AND WORST CONFIGURATIONS ARE PRESENTED IN FIGURES G-5, G-6, AND G-7, RESPECTIVELY. ALL CONFIGURATIONS HAVE A LONGITUDINAL BENDING DEPTH EQUAL TO APPROXIMATELY 2.1% OF SATELLITE LENGTH, THIS BEING THE THICKNESS RATIO OF THE REFERENCE CONFIGURATION AS DETERMINED BY A 30° TRUSS ANGLE. THE TRUSS ANGLE OF 30° IS MAINTAINED IN THE NOMINAL AND BEST CONFIGURATIONS. HOWEVER, [illegible] WORST CONFIGURATION HAS A LARGER TRUSS ANGLE ([illegible] FOR OPTION 1, 41.5° FOR OPTION 2) DUE TO AVOI[illegible]NCE OF AN EXCESSIVELY LARGE BAY SIZE.

DESIGN LOADS, STRUT SIZING, AND 20 METER BEAM UNIT WEIGHTS

THE SUBJECT DATA IS PRESENTED IN FIGURE G-8. DESIGN LOADS DETERMINATION IS BASED ON THE SCALING RATIONAL OF APPENDIX F. STRUT SIZING IS PER FIGURE A-2, AND 20 METER BEAM UNIT WEIGHTS ARE PER FIGURE D-3.

FIGURE G-1 STRUCTURAL PLANFORM SIZING

CONFIG.	REQ'D TOTAL PANEL AREA M^2	BAY SIZE M	PANEL AREA FACTOR (DESIGN)	SEGMENT AREA FACTOR (TYPICAL)	ARRAY AREA FACTOR (MAX)	(REQ'D TOTAL BAY AREA / REQ'D TOTAL PANEL AREA) ▷	REQ'D TOTAL BAY AREA M^2	REQ'D NO. OF BAYS	BAY ARRANGEMENT FOR AR = 4
REFERENCE ▷	101,330,000	640	.9913	.9972	.9294	1.08845	110,292,000	269.3	
		660	"	"	.9315	1.08599	110,044,000	252.6	
		660	"	"	(< MAX)		111,514,000	256.0	8 × 32
NOMINAL	108,800,000	660	.9913	.9972	.9315	1.08599	118,156,000	271.2	
		680	"	"	.9335	1.08367	117,903,000	255.0	
		680	"	"	(< MAX)		118,374,000	256.0	8 × 32
BEST	77,800,000	560	.9913	.9972	.9195	1.10017	85,593,000	272.9	
		580	"	"	.9223	1.09683	85,333,000	253.7	
		580	"	"	(< MAX)		86,110,000	256.0	8 × 32
WORST	193,000,000	720	.9913	.9972	.9371	1.07750	208,344,000	401.9	
		740	"	"	.9388	1.07755	207,967,000	379.8	
		740	"	"	(< MAX)		219,040,000	400.0	10 × 40 ▷
		600	.9913	.9972	.9248	1.09386	211,115,000	586.4	
		620	"	"	.9272	1.09103	210,569,000	547.8	
		620	"	"	(< MAX)		221,416,000	576.0	12 × 48 ▷

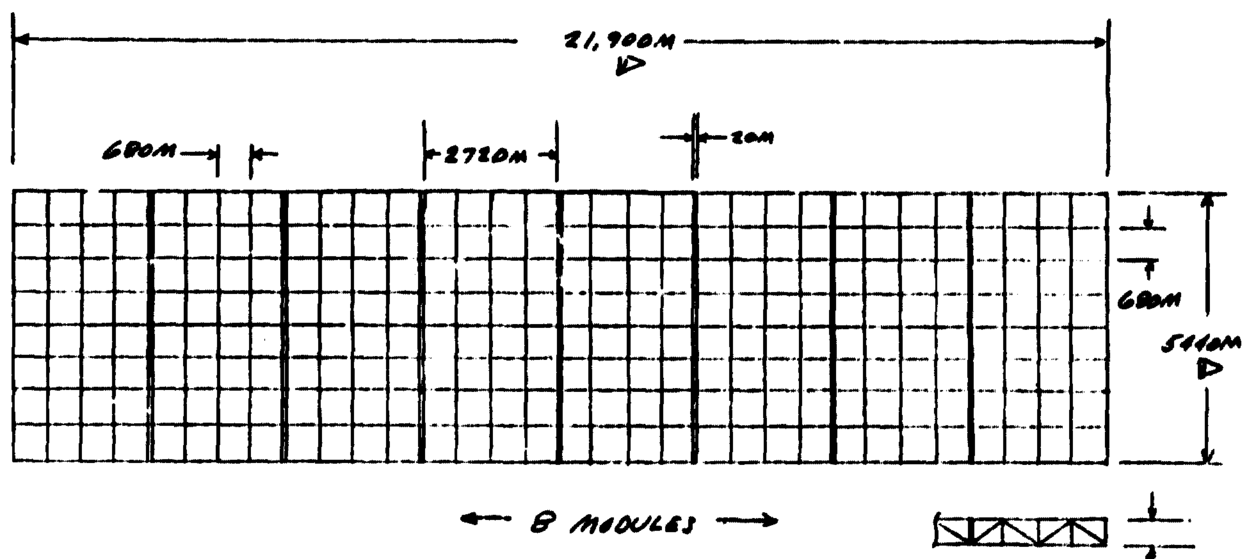
▷ $\left(\frac{\text{REQ'D TOTAL BAY AREA}}{\text{REQ'D TOTAL PANEL AREA}}\right) = \frac{1}{\text{PANEL AREA FACTOR} \times \text{SEGMENT AREA FACTOR} \times \text{ARRAY AREA FACTOR}}$

▷ SHOWN FOR METHOD CHECKOUT PURPOSES.

▷ OPTION 1

▷ OPTION 2

FIGURE G-2
NOMINAL CONFIGURATION
(ALL DIMENSIONS ARE BEAM ℄ TO BEAM ℄)

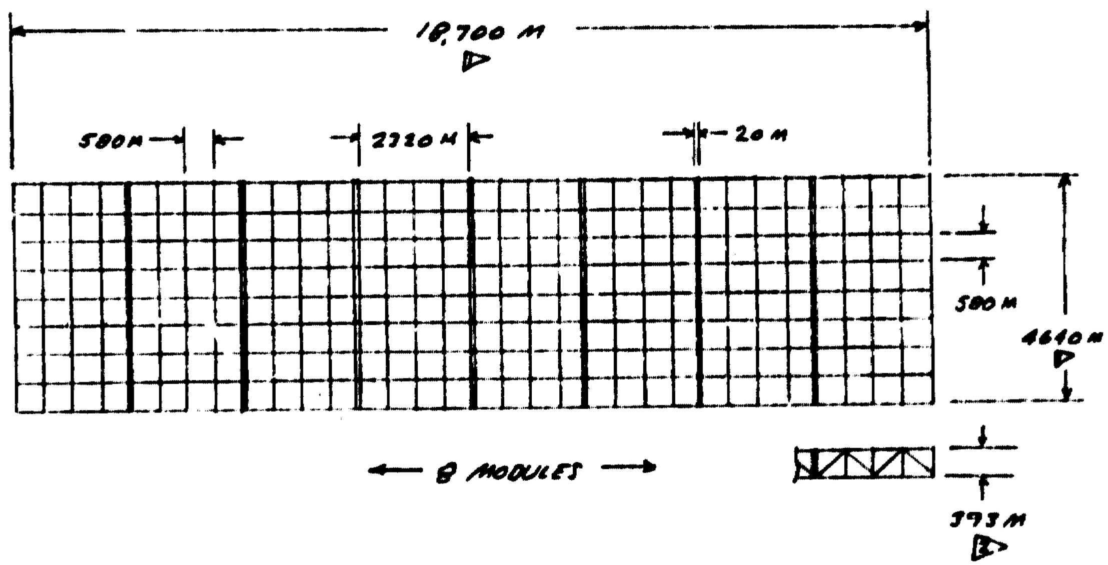


▷ ADD 20M TO OBTAIN TOTAL OVERALL DIMENSION

▷ ADD 23M TO OBTAIN TOTAL OVERALL DIMENSION

STRUCTURAL PLANFORM AREA = 119.14 KM²

FIGURE G-3
BEST CONFIGURATION
(ALL DIMENSIONS ARE BEAM ℄ TO BEAM ℄)



▷ ADD 20M TO OBTAIN TOTAL OVERALL DIMENSION

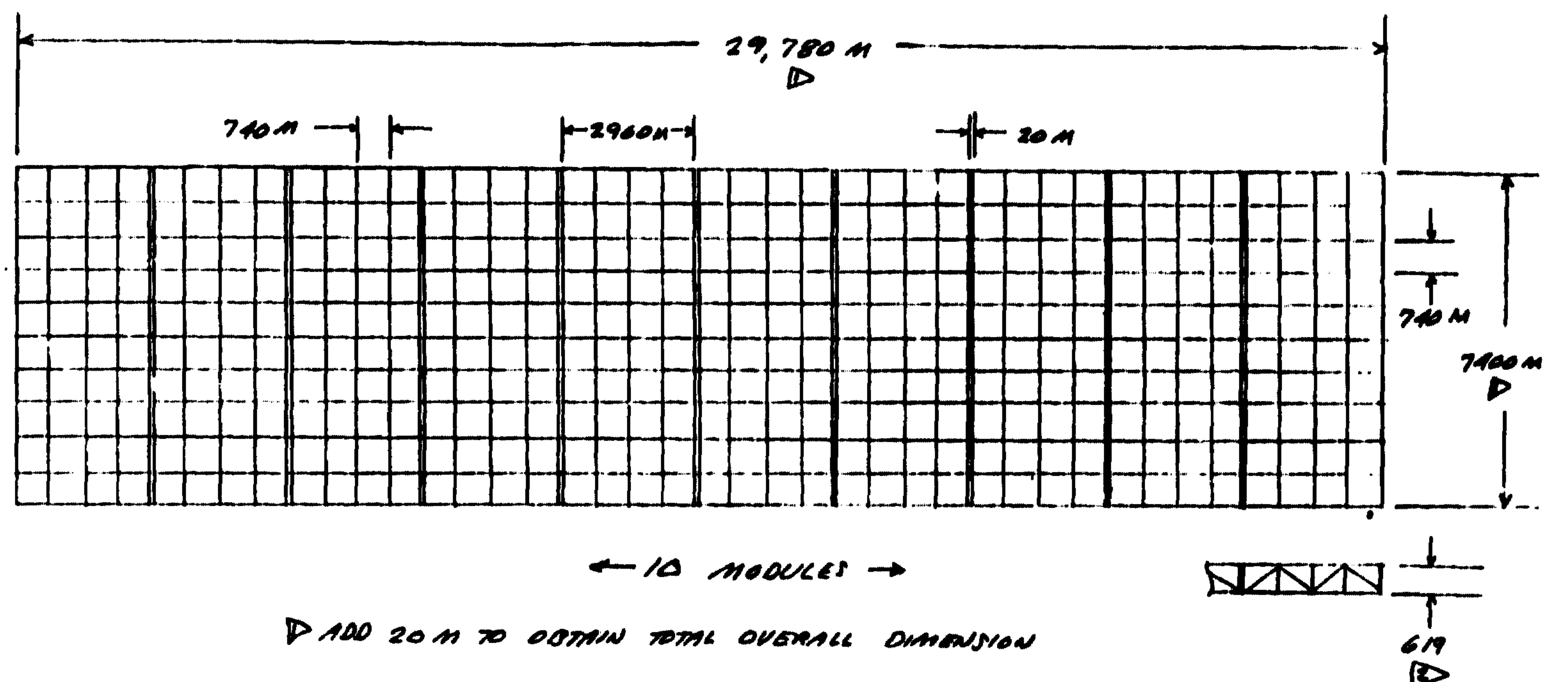
▷ ADD 27M TO OBTAIN TOTAL OVERALL DIMENSION

STRUCTURAL PLANFORM AREA = 86.77 KM^2

FIGURE 6-4A

WORT CONFIGURATION – OPTION 1

(ALL DIMENSIONS ARE BEAM ℄ TO BEAM ℄)

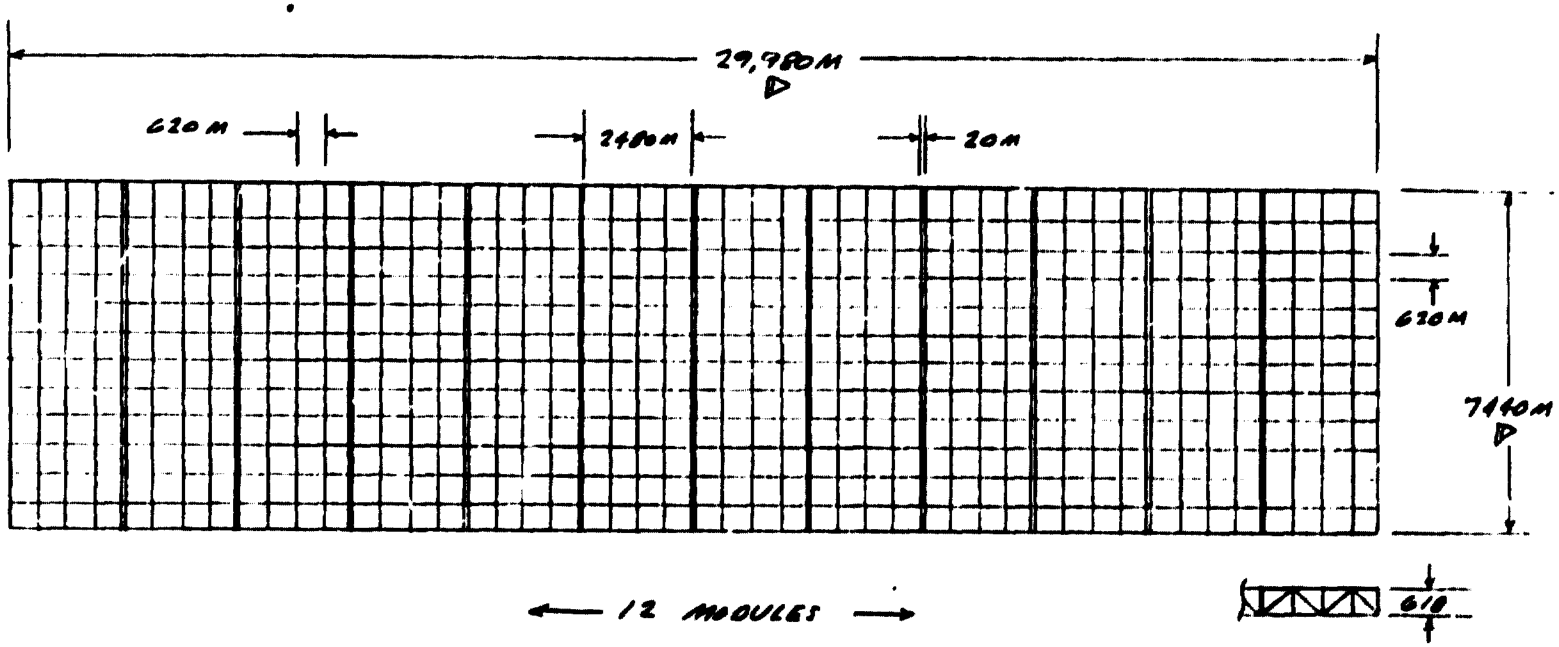


▷ ADD 20 M TO OBTAIN TOTAL OVERALL DIMENSION

▷ ADD 23 M TO OBTAIN TOTAL OVERALL DIMENSION

STRUCTURAL PLATFORM AREA = 220.37 km²

FIGURE G-4B
WORST CONFIGURATION - OPTION 2
(ALL DIMENSIONS ARE BEAM ℄ TO BEAM ℄)

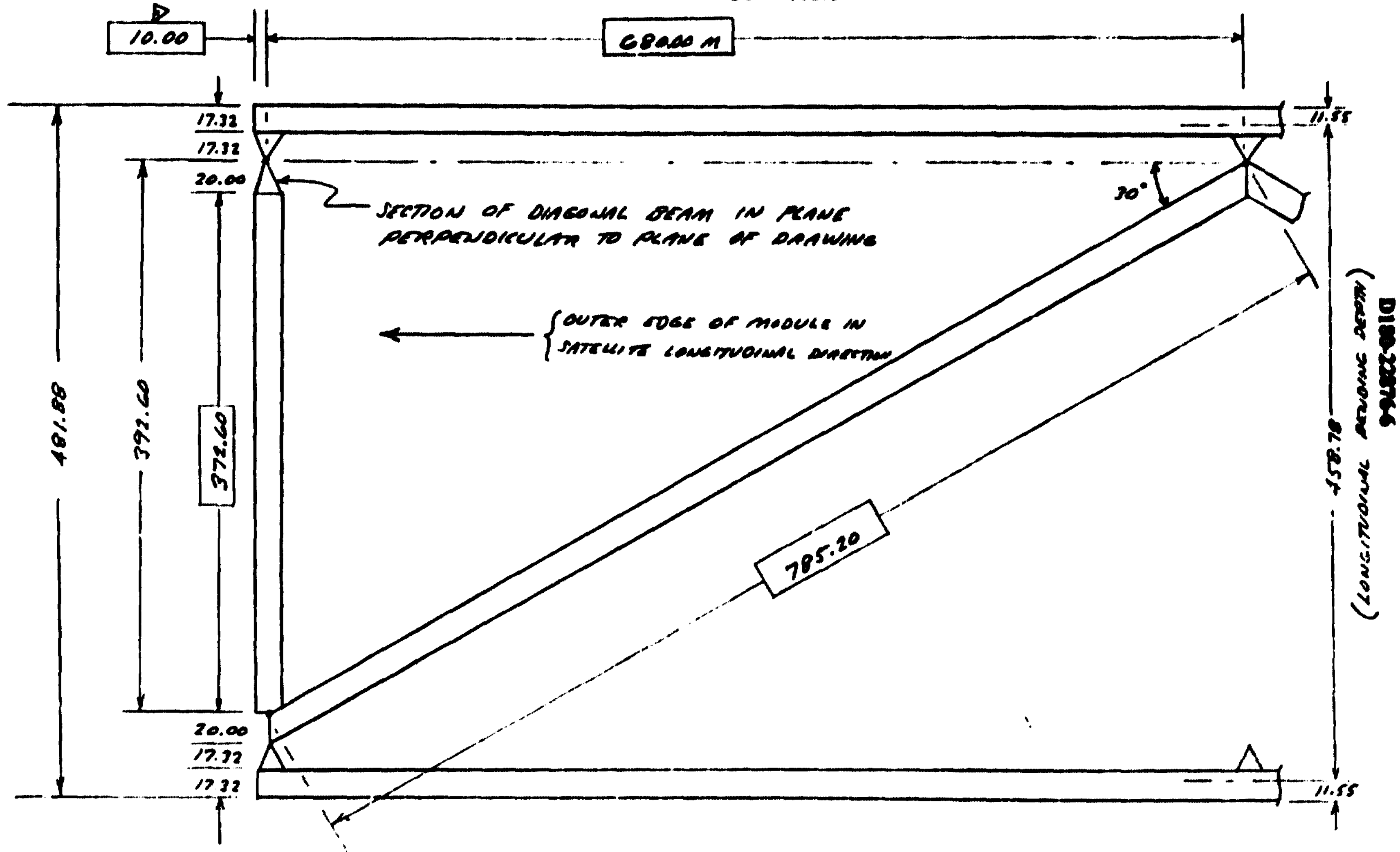


▷ ADD 20M TO OBTAIN TOTAL OVERALL DIMENSION

▷ ADD 23 M TO OBTAIN TOTAL OVERALL DIMENSION

STRUCTURAL PLANFORM AREA = 223.05 KM²

FIGURE G-5
REFERENCE LENGTHS FOR 20 METER BEAMS
NOMINAL CONFIGURATION



▷ DELTA LENGTH AT EDGE. (28 PLACES / SURFACE / MODULE, INCLUDING 2 PLACES / CORNER / SURFACE)

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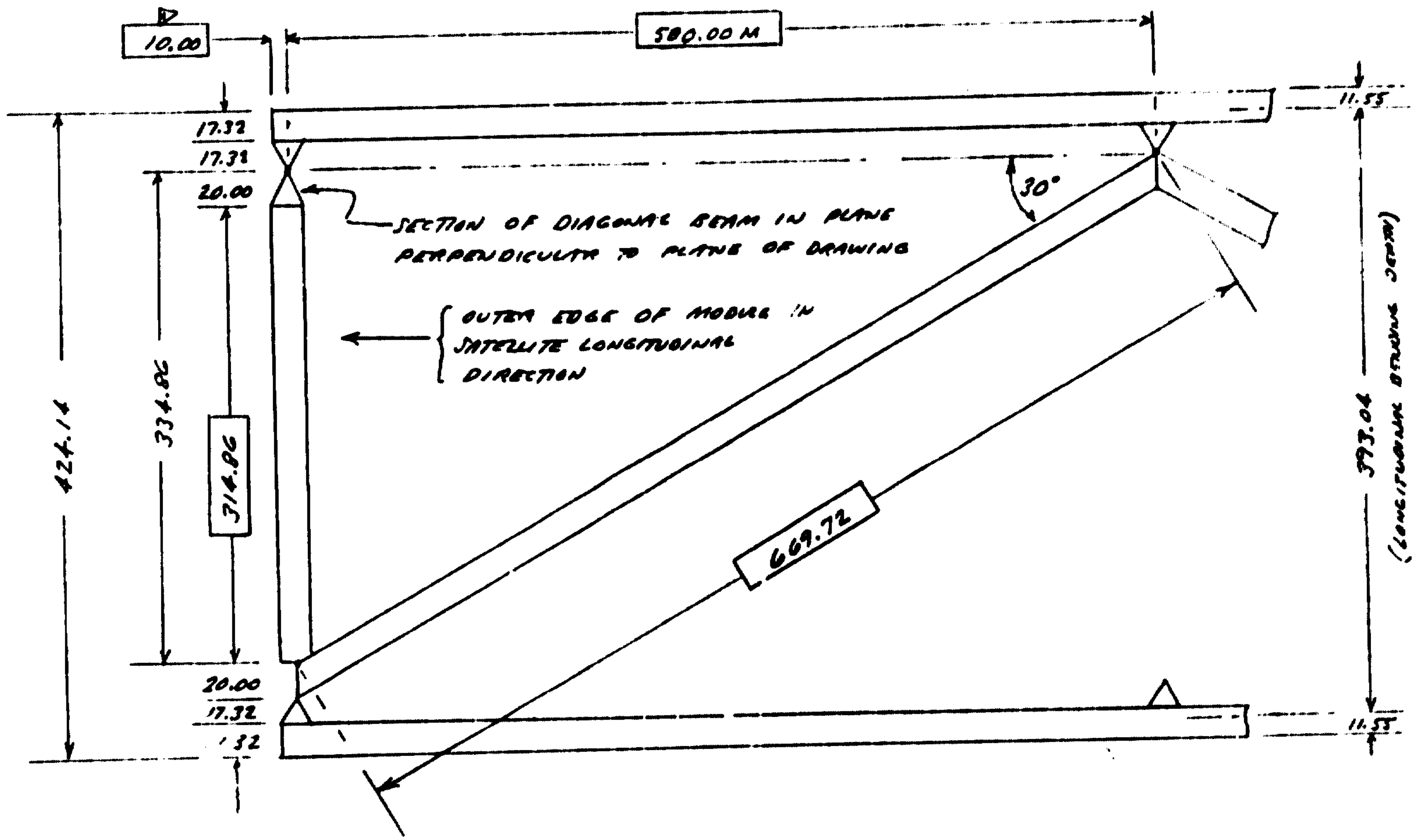
FIGURE G-6
REFERENCE LENGTHS FOR 20 METER BEAMS
BEST CONFIGURATION



▷ DELTA LENGTH AT EDGE. (28 PLACES/SURFACE/MODULE, INCLUDING 2 PLACES/CORNER/SURFACE)

FIGURE G-7A
REFERENCE LENGTHS FOR 20 METER BEAMS
WORST CONFIGURATION (OPTION 1)

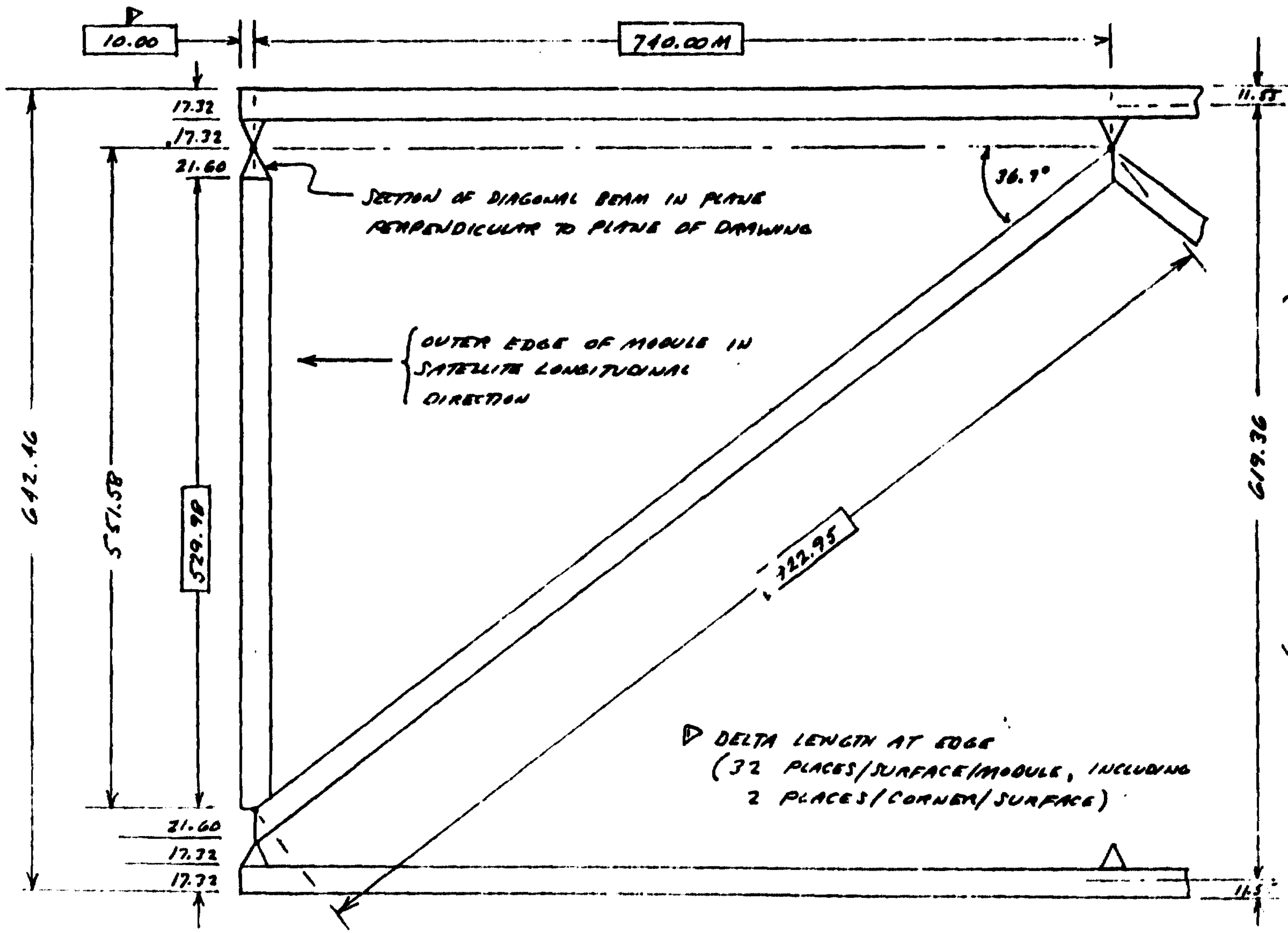


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FIGURE G-78
REFERENCE LENGTHS FOR 20 METER BEAMS
WORST CONFIGURATION (OPTION 2)

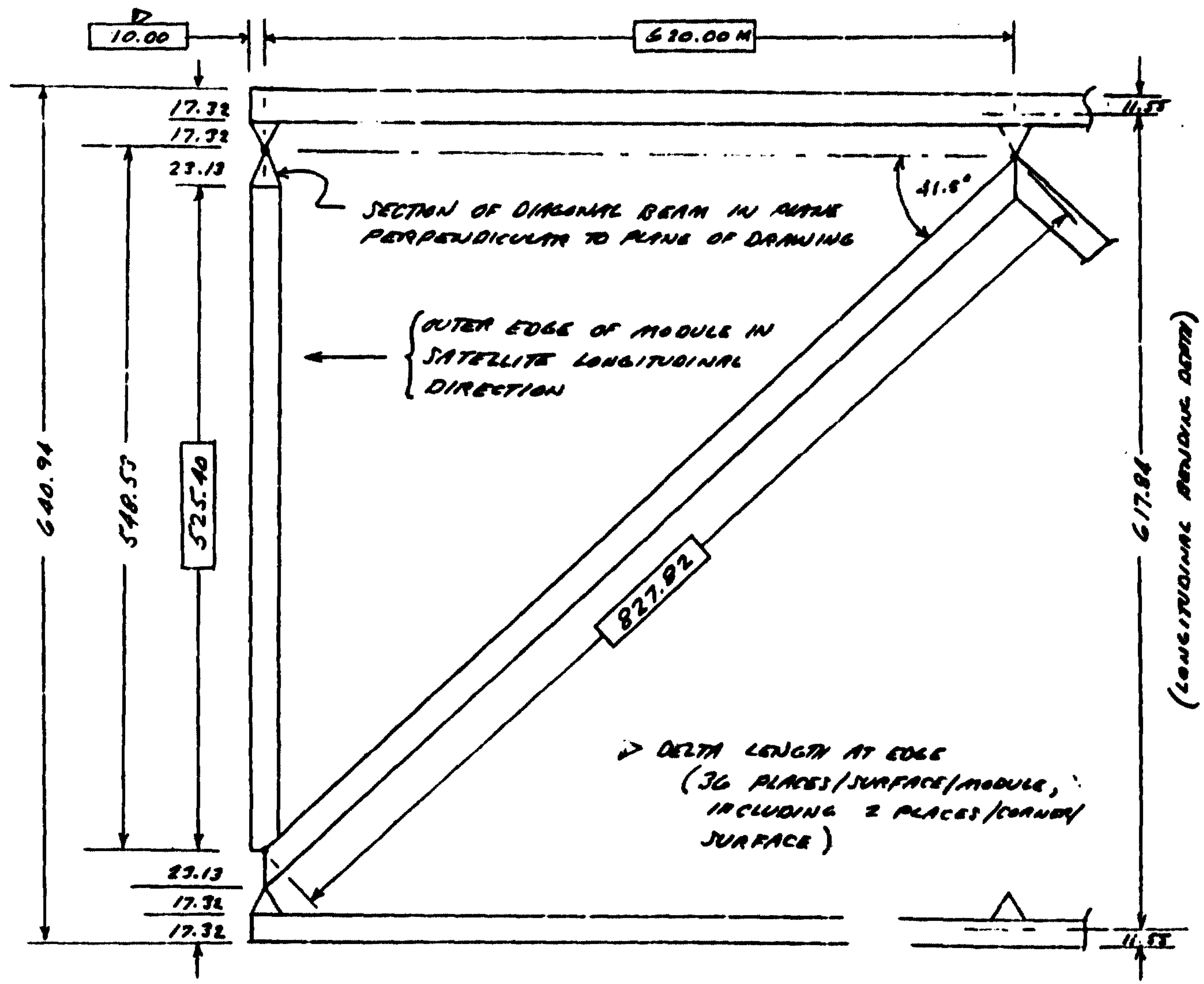

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FIGURE G-8

DESIGN LOADS, STRUT SIZING, AND 20 METER BEAM UNIT WEIGHTS

ITEM	CONFIGURATION				
	REF.	NOM.	BEST	WORST	
				OPTION 1	OPTION 2
PARAMETERS: ▷					
L_{BEAM} ~ m (in.)	660(25,984)	680(26,772)	580(22,835)	740(29,134)	620(24,409)
W_{BEAM} ~ m (in.)	20 (787) →	→	→	→	→
H_{BEAM} ~ m (in.)	17.3 (682) →	→	→	→	→
W_{ARRAY} ~ kg/m²	0.427 →	→	→	→	→
L_{MODULE} ~ m	2640	2720	2320	2960	2480
W_{MODULE} ~ m	5280	5440	4640	7400	7440
H_{MODULE} ~ m	447	456	393	619	618
W_{MODULE} ~ kg/m² (APPROX.)	0.466 →	→	→	→	→
$W_{ANTENNA}$ ~ kg	12,192,000	14,138,000	11,375,000	18,161,000	18,161,000
SCALING TERMS:					
$(L_B - W_B)^2 (W_{ARRAY})$	175,000	186,000	134,000	221,000	154,000
$(L_B \quad _3)(W_{ARRAY})$	273	282	239	307	256
$(L_B - W_{\ })^2 (W_{ARRAY})(L_B)$	1.15×10^8	1.26×10^8	0.78×10^8	1.64×10^8	0.95×10^8
$(W_{MODULE})(L_m)(W_m)/(H_m)$	14,570	15,120	12,760	16,490	13,910
$(W_{ANTENNA})(L_m)/(H_m)$	72×10^6	24×10^6	67×10^6	87×10^6	73×10^6
APPLIED LOADS ON BEAM:					
W_x ~ LB/IN	0.0223	0.0237	0.0171	0.0282	0.0196
W_z ~ LB/IN	0.00040	0.00041	0.00035	0.00045	0.00038
P ~ LB	289	317	196	412	239
ΔP_1 ~ LB	189	197	166	214	181
ΔP_2 ~ LB	456	532	424	551	462
STRUT COLUMN LOAD INCREMENTS:					
$W_x L_B^2 / 12 W_B$ ~ LB	1594	1799	944	2535	1237
$W_z L_B^2 / 24 H_B$ ~ LB	17	18	11	23	14
$P/3$ ~ LB	96	106	65	137	80
$\Delta P_1 / 3$ ~ LB	63	66	55	71	60
$\Delta P_2 / 3$ ~ LB	152	177	141	184	154
(Σ INCREMENTS-APPLIED)	(1922)	(2166)	(1216)	(2950)	(1545)
U.F.S.	1.5				
(Σ INCREMENTS-DESIGN)	(2883)	(3249)	(1824)	(4425)	(2316)
STRUT SIZING: ③▷					
D_{MAX} ~ IN.	13.3	13.6	12.2	14.4	12.8
D_{MIN} ~ IN.	4.4	4.5	4.1	4.8	4.3
t ~ IN.	0.020	0.021	0.017	0.024	0.018
BEAM UNIT WEIGHTS: ②▷					
UPR. SURF. BEAMS ~ kg/m	4.24	4.47	3.60	4.99	3.92
LWR. SURF. BEAMS ~ kg/m	3.34	3.42	3.08	3.61	3.20
INTRA SURF BEAMS ~ kg/m	3.34	3.42	3.08	3.61	3.20

▷ METHODOLOGY PER APPENDIX F.

②▷ FROM APPENDIX A, FIGURE A-2.

③▷ FROM APPENDIX D, FIGURE D-3.

APPENDIX H

VARIATION OF STRUCTURE WEIGHT WITH STRUCTURAL PLANFORM AREA

VARIATION OF STRUCTURE WEIGHT
WITH STRUCTURAL PLANFORM AREA

THE RESULTS OF A STUDY TO DETERMINE THE VARIATION OF STRUCTURE WEIGHT WITH STRUCTURAL PLANFORM AREA ARE PRESENTED IN FIGURE H-1. AS SHOWN, STRUCTURE WEIGHT (FOR ALL PRACTICAL PURPOSES) IS DIRECTLY PROPORTIONAL TO STRUCTURAL PLANFORM AREA.

STRUCTURE WEIGHT SUMMARIES PLUS ASSOCIATED 20 METER BEAM WEIGHT SUMMARIES ARE PRESENTED ON THE FOLLOWING PAGES FOR THE NOMINAL, BEST, AND WORST CONFIGURATIONS. THE STRUCTURAL ARRANGEMENT AND 20 METER BEAM UNIT WEIGHT DATA FOR THESE CONFIGURATIONS IS DEFINED IN APPENDIX G.

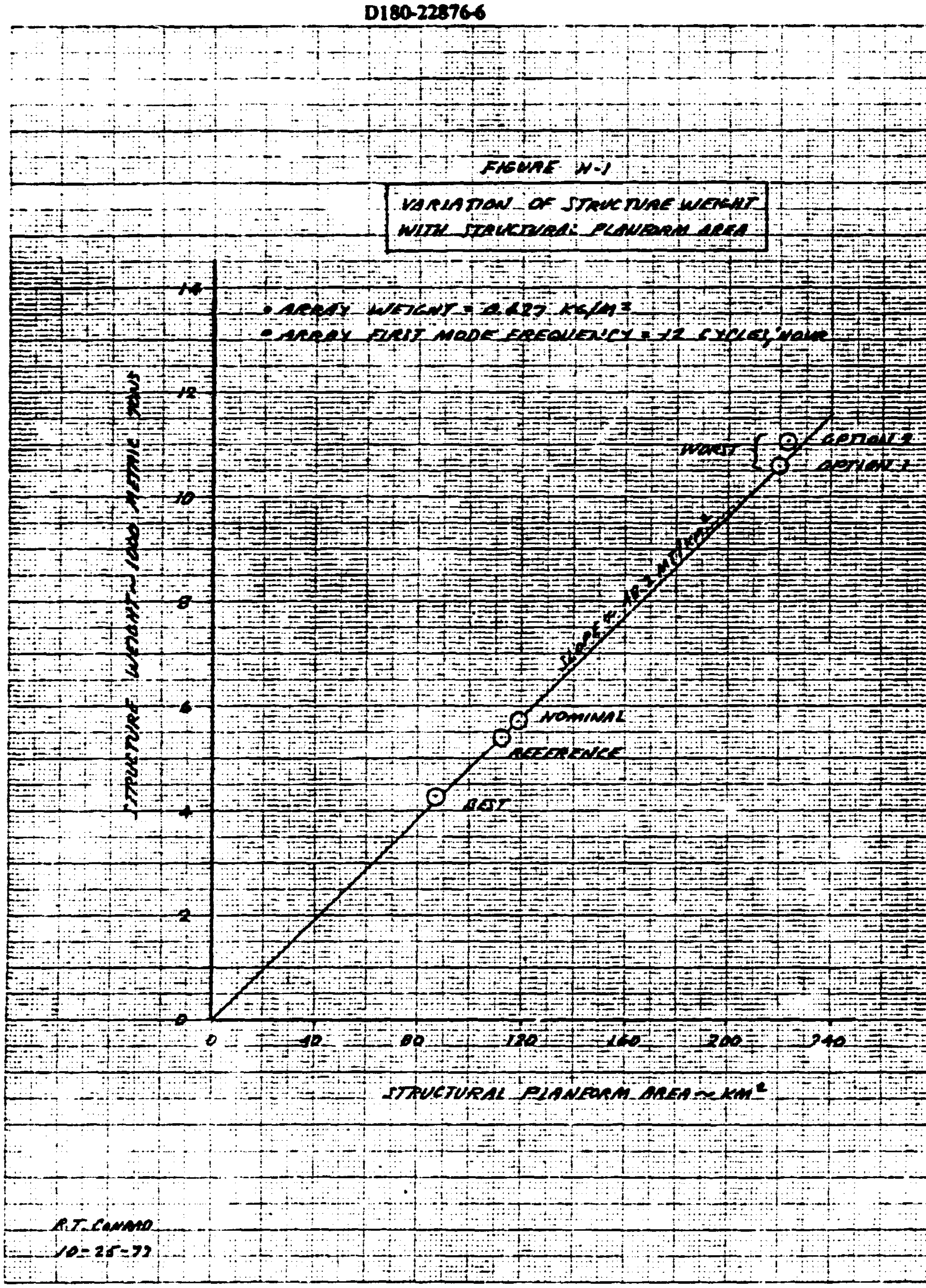
FIGURE H-1
VARIATION OF STRUCTURE WEIGHT
WITH STRUCTURAL PLANFORM AREA
• ARRAY WEIGHT = 0.627 KG/M²
• ARRAY FIRST MODE FREQUENCY = 12 CYCLES/HOUR
WORST
OPTION 2
OPTION 1
NOMINAL
REFERENCE
BEST
STRUCTURE WEIGHT ~ 1000 METRIC TONS
STRUCTURAL PLANFORM AREA ~ KM²
0
2
4
6
8
10
12
14
40
80
120
160
200
240
R.T. CONRAD
10-25-77

STRUCTURE WEIGHT S[illegible]MARY
FOR "NOMINAL" CONFIGURATION

1.1 PRIMARY STRUCTURE

1.1 PRIMARY STRUCTURE				5,746,600 kg
MODULE NO. 1				810,200
BASIC FRAME			678,700	
20M BEAMS		644,640		
TENSION CABLES		1760		
CONTINGENCY ~5%		32,300		
DOCKING PROVISIONS (18 PLACES)			4500	
ANTENNA SUPPORT STRUCTURE			57,000	
EXTERNAL FRAME		46,700		
20M BEAMS	44,440			
CONTINGENCY ~5%	2260			
ADDITIONS TO MODULE FRAME		10,300		
ROTARY JOINT			▷	
ANTENNA YOKE STRUCTURE			50,000	
FRAME		43,500		
5M BEAMS	41,400			
CONTINGENCY ~5%	2100			
ROTATION JOINTS/PITCH CONTROLS		6500		
ANTENNA SUPPORT STRUCTURE (LEO-TO-GEO)			20,000	
MODULE NO. 2				687,700
BASIC FRAME			678,700	
20M BEAMS		644,640		
TENSION CABLES		[illegible]60		
CONTINGENCY ~5%		32,300		
DOCKING PROVISIONS (36 PLACES)			9000	
MODULE NO. 3				687,700
MODULE NO. 4				687,700
MODULE NO. 5				687,700
MODULE NO. 6				687,700
MODULE NO. 7				687,700
MODULE NO. 8				810,200

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▷ INCLUDED ELSEWHERE IN WEIGHT STATEMENT UNDER "MECHANICAL ROTARY JOINT" AND "ELECT[illegible]L ROTARY JOINT."

20 METER BEAM WEIGHT SUMMARY FOR "NOMINAL" CONFIGURATION

20 m BEAMS (PER MODULE) — 644,640 kg

LOCATION/BEAMS	LENGTH OF BEAM PER MODULE (m) ▷1	UNIT WT OF BEAM (kg/m) ▷2	WT. OF BEAM PER MODULE (kg)
UPR SURFACE/LONGITUDINALS	(9×4) × 680 = 24,480	4.47	109,426
" " /LATERALS	(5×8) × 680 = 27,200	"	121,584
" " /EDGE DELTAS	(28) × 10 = 280	"	1252
	(57,960)		(232,262)
LWR SURFACE/LONGITUDINALS	(9×4) × 680 = 24,480	3.42	83,722
" " /LATERALS	(5×8) × 680 = 27,200	"	93,024
" " /EDGE DELTAS	(28) × 10 = 280	"	958
INTRA SURF./LONG. DIAGONALS	(9×4) × 785.2 = 28,267	"	96,674
" " /LATERAL DIAGONALS	(5×8) × 785.2 = 31,408	"	107,415
" " /VERTICALS ▷3	(24) × 372.6 = 8942	"	30,585
	(120,577)		(412,378)
TOTAL - PER MODULE	172,537	—	644,640

▷1 SEE SKETCH FIGURE G-5 FOR REFERENCE BEAM LENGTHS.

▷2 FROM FIGURE G-8

▷3 LOCATED AROUND PERIPHERY OF MODULE ONLY.

STRUCTURE WEIGHT SUMMARY
FOR "BEST" CONFIGURATION

1.1 PRIMARY STRUCTURE — 4,278,400 lb

MODULE NO. 1				606,800
BASIC FRAME			501,800	
20M BEAMS		476,370		
TENSION CABLES		1520		
CONTINGENCY ~5%		23,910		
DOCKING PROVISIONS (18 PLACES)			4500	
ANTENNA SUPPORT STRUCTURE			40,900	
EXTERNAL FRAME		32,100		
20M BEAMS	30,530			
CONTINGENCY ~5%	1570			
ADDITIONS TO MODULE FRAME		8800		
ROTARY JOINT			▷	
ANTENNA YOKE STRUCTURE			41,000	
FRAME		36,200		
5M BEAMS	34,500			
CONTINGENCY ~5%	1,700			
ROTATION JOINTS/PITCH CONTROLS		4800		
ANTENNA SUPPORT STRUCTURE (LEO-TO-GEO)			18,600	
MODULE NO. 2				510,800
BASIC FRAME			501,800	
20M BEAMS		476,370		
TENSION CABLES		1520		
CONTINGENCY ~5%		23,910		
DOCKING PROVISIONS (36 PLACES)			9000	
MODULE NO. 3				510,800
MODULE NO. 4				510,800
MODULE NO. 5				510,800
MODULE NO. 6				510,800
MODULE NO. 7				510,800
MODULE NO. 8				606,800

▷ INCLUDED ELSEWHERE IN WEIGHT STATEMENT UNDER "MECHANICAL ROTARY JOINT" AND "ELECTRICAL ROTARY JOINT."

20 METER BEAM WEIGHT SUMMARY FOR "BEST" CONFIGURATION

20 M BEAMS (PER MODULE) — 476,370 kg

LOCATION/BEAMS	LENGTH OF BEAM PER MODULE (m) ▷1	UNIT WT OF BEAM (kg/m) ▷2	WT. OF BEAM PER MODULE (kg)
UPR SURFACE/LONGITUDINALS	(9×4)×580 = 20,880	3.60	75,168
" " /LATERALS	(5×8)×580 = 23,200	"	83,520
" " /EDGE DELTAS	(28)×10 = 280	"	1008
	(44,360)		(159,696)
LWR SURFACE/LONGITUDINALS	(9×4)×580 = 20,880	3.08	64,310
" " /LATERALS	(5×8)×580 = 23,200	"	71,456
" " /EDGE DELTAS	(28)×10 = 280	"	862
INTRA SURF./LONG. DIAGONALS	(9×4)×669.7 = 24,109	"	74,256
" " /LATERAL DIAGONALS	(5×8)×669.7 = 26,788	"	82,507
" " /VERTICALS ▷3	(24)×314.9 = 7558	"	23,283
	(102,815)		(316,674)
TOTAL-PER MODULE	147,175	—	476,370

▷1 SEE SKETCH FIGURE G-6 FOR REFERENCE BEAM LENGTHS.

▷2 FROM FIGURE G-8

▷3 LOCATED AROUND PERIPHERY OF MODULE ONLY.

STRUCTURE WEIGHT SUMMARY FOR "WORST" CONFIGURATION (OPTION 1)

1.1 PRIMARY STRUCTURE — 10,605,200 kg

MODULE NO. 1				1,184,600
BASIC FRAME			1,018,500	
20M BEAMS		967,750		
TENSION CABLES		2260		
CONTINGENCY ~5%		48,490		
DOCKING PROVISIONS (22 PLACES)			5,500	
ANTENNA SUPPORT STRUCTURE			71,400	
EXTERNAL FRAME		60,200		
20M BEAMS	57,350			
CONTINGENCY ~5%	2850			
ADDITIONS TO MODULE FRAME		11,200		
ROTARY JOINT			▷	
ANTENNA YOKE STRUCTURE			59,200	
FRAME		50,700		
5M BEAMS	48,300			
CONTINGENCY ~5%	2400			
ROTATION JOINTS/PITCH CONTROLS		8,500		
ANTENNA SUPPORT STRUCTURE (LEO-TO-GEO)			30,000	
MODULE NO. 2				1,029,500
BASIC FRAME			1,018,500	
20M BEAMS		967,750		
TENSION CABLES		2260		
CONTINGENCY ~5%		48,490		
DOCKING PROVISIONS (44 PLACES)			11,000	
MODULE NO. 3				1,029,500
MODULE NO. 4				1,029,500
MODULE NO. 5				1,029,500
MODULE NO. 6				1,029,500
MODULE NO. 7				1,029,500
MODULE NO. 8				1,029,500
MODULE NO. 9				1,029,500
MODULE NO 10				1,184,600

▷ INCLUDED ELSEWHERE IN WEIGHT STATEMENT UNDER "MECHANICAL ROTARY JOINT" AND "ELECTRICAL ROTARY JOINT."

20 METER BEAM WEIGHT SUMMARY
FOR "WORST" CONFIGURATION (OPTION 1)

20 m BEAMS (PER MODULE) 967,750 kg

LOCATION/BEAMS	LENGTH OF BEAM PER MODULE (m) [1]	UNIT WT OF BEAM (kg/m) [2]	WT. OF BEAM PER MODULE (kg)
UPR SURFACE/LONGITUDINALS	(11×4)× 740 = 32,560	4.99	162,474
" " /LATERALS	(5×10)× 740 = 37,000	"	184,630
" " /EDGE DELTAS	(32)×10 = 320	"	1596
	(69,880)		(348,700)
LWR SURFACE/LONGITUDINALS	(11×4)× 740 = 32,560	3.61	117542
" " /LATERALS	(5×10)× 740 = 37,000	"	133,570
" " /EDGE DELTAS	(32) × 10 = 320	"	1155
INTRA SURF./LONG.-DIAGONALS	(11×4) × 923.0 = 40,612	"	146,609
" " /LATERAL DIAGONALS	(5×)× 923.0 = 46,150	"	166,602
" " /VERTICALS [3]	(28) × 530.0 = 14,840	"	53,572
	(171,482)		619,050
TOTAL-PER MODULE	241,362	—	967,750

[1] SEE SKETCH FIGURE 6-7A FOR REFERENCE BEAM LENGTHS.

[2] FROM FIGURE 6-8

[3] LOCATED AROUND PERIPHERY OF MODULE ONLY.

STRUCTURE WEIGHT SUMMARY FOR
"WORST" CONFIGURATION (OPTION 2)

1.1 PRIMARY STRUCTURE — 11,077,600 lb

MODULE NO. 1				1,045,300
BASIC FRAME			892,200	
20M BEAMS		847,460		
TENSION CABLES		2240		
CONTINGENCY ~5%		42,500		
DOCKING PROVISIONS (2 PLACES)			6,500	
ANTENNA SUPPORT STRUCTURE			57,400	
EXTERNAL FRAME		48,000		
20M BEAMS	45,690			
CONTINGENCY ~5%	2310			
ADDITIONS TO MODULE FRAME		9,400		
ROTARY JOINT			▷	
ANTENNA YOKE STRUCTURE			59,200	
FRAME		50,700		
5M BEAMS	48,300			
CONTINGENCY ~5%	2,400			
ROTATION JOINTS/PITCH CONTROLS		8,500		
ANTENNA SUPPORT STRUCTURE (LEO-TO-GEO)			30,000	
MODULE NO. 2				898,700
BASIC FRAME			892,200	
20M BEAMS		847,460		
TENSION CABLES		2240		
CONTINGENCY ~5%		42,500		
DOCKING PROVISIONS (5 PLACES)			12,000	
MODULE NO. 3				898,700
MODULE NO. 4				898,700
MODULE NO. 5				898,700
MODULE NO. 6				898,700
MODULE NO. 7				898,700
MODULE NO. 8				898,700
MODULE NO. 9				898,700
MODULE NO. 10				898,700
MODULE NO. 11				898,700
MODULE NO. 12				1,045,300

▷ INCLUDED ELSEWHERE IN WEIGHT STATEMENT UNDER "MECHANICAL ROTARY JOINT" AND "ELECTRICAL ROTARY JOINT."

20 METER BEAM WEIGHT SUMMARY FOR "WORST" CONFIGURATION (OPTION 2)

20 M BEAMS (PER MODULE) — 847,460 kg

LOCATION/BEAMS	LENGTH OF BEAM PER MODULE (m) ▷1	UNIT WT OF BEAM (kg/m) ▷2	WT. OF BEAM PER MODULE (kg)
UPR SURFACE/LONGITUDINALS	(13×4) × 620 = 32,240	3.92	126,381
" " /LATERALS	(5×12) × 620 = 37,200	"	145,824
" " /EDGE DELTAS	(36) × 10 = 360	"	1411
	(69,800)		(273,616)
LWR SURFACE/LONGITUDINALS	(13×4) × 620 = 32,240	3.20	103,168
" " /LATERALS	(5×12) × 620 = 37,200	"	119,040
" " /EDGE DELTAS	(36) × 10 = 360	"	1152
INTRA SURF./LONG. DIAGONALS	(13×4) × 827.8 = 43,046	"	137,747
" " /LATERAL DIAGONALS	(5×12) × 827.8 = 49,668	"	158,935
" " /VERTICALS ▷3	(32) × 525.4 = 16,813	"	53,802
	(179,327)		(573,844)
TOTAL - PER MODULE	249,127	—	847,460

▷1 SEE SKETCH FIGURE G-7B FOR REFERENCE BEAM LENGTHS.

▷2 FROM FIGURE G-8

▷3 LOCATED AROUND PERIPHERY OF MODULE ONLY.

APPENDIX I

CRIPPLING COEFFICIENT UNCERTAINTY FOR SPS GRAPHITE/EPOXY TUBES

CRIPPLING COEFFICIENT UNCERTAINTY FOR SPS GRAPHITE/EPOXY TUBES

Figure I-1 presents a crippling coefficient comparison between the SPS composite tube and metal tubes. Curve is an empirical curve for metal tubes, per NACA TN 3783. Curves and are recommended design curves from a Boeing design manual for the Minuteman program. The positions of curves and relative to curve reflect the degradation of allowable stresses associated with high probabilities (at high confidence levels) of no structural failure. As such, the degradation is a measure of the impact of slight structural imperfections on crippling of thin walled tubes. Curve is the empirical curve for the SPS composite tube, and is reflected in the tube sizing data of Appendix A. This curve was developed using the Boeing design manual equations shown. Curve is the result of applying these equations to some typical metals. (7075 aluminum, 18-8 stainless steel, and inconel were considered. The scatter in crippling coefficient with metal type was negligible.) The close correlation between curve and curve suggests that, when sufficient test data is available, some degradation will occur in the crippling coefficient to be used for design of actual hardware.

Figure I-2 presents crippling coefficient curves for the SPS composite tube. Curve is the nominal curve (designated as curve in Figure I-1). Curve reflects the possibility (Convair position) that the shear modulus G_{xy} has an effective value twice as large as the current predicted value of 0.6×10^6 psi. Curve reflects the assumption that 'A' allowables for point design of composite tubes will have the same position relative to nominal values as do 'B' allowables for general design of metal tubes. Curve is an approximation to the nominal curve for R/t values between 150 and 1500. Curve is the recommended upper uncertainty curve. It reflects the use of a twice larger shear modulus and, in addition, allows for a more optimum tube definition. Curve is the recommended lower uncertainty curve. It allows for some margin of error in the location of the curve corresponding to 'A' allowables.

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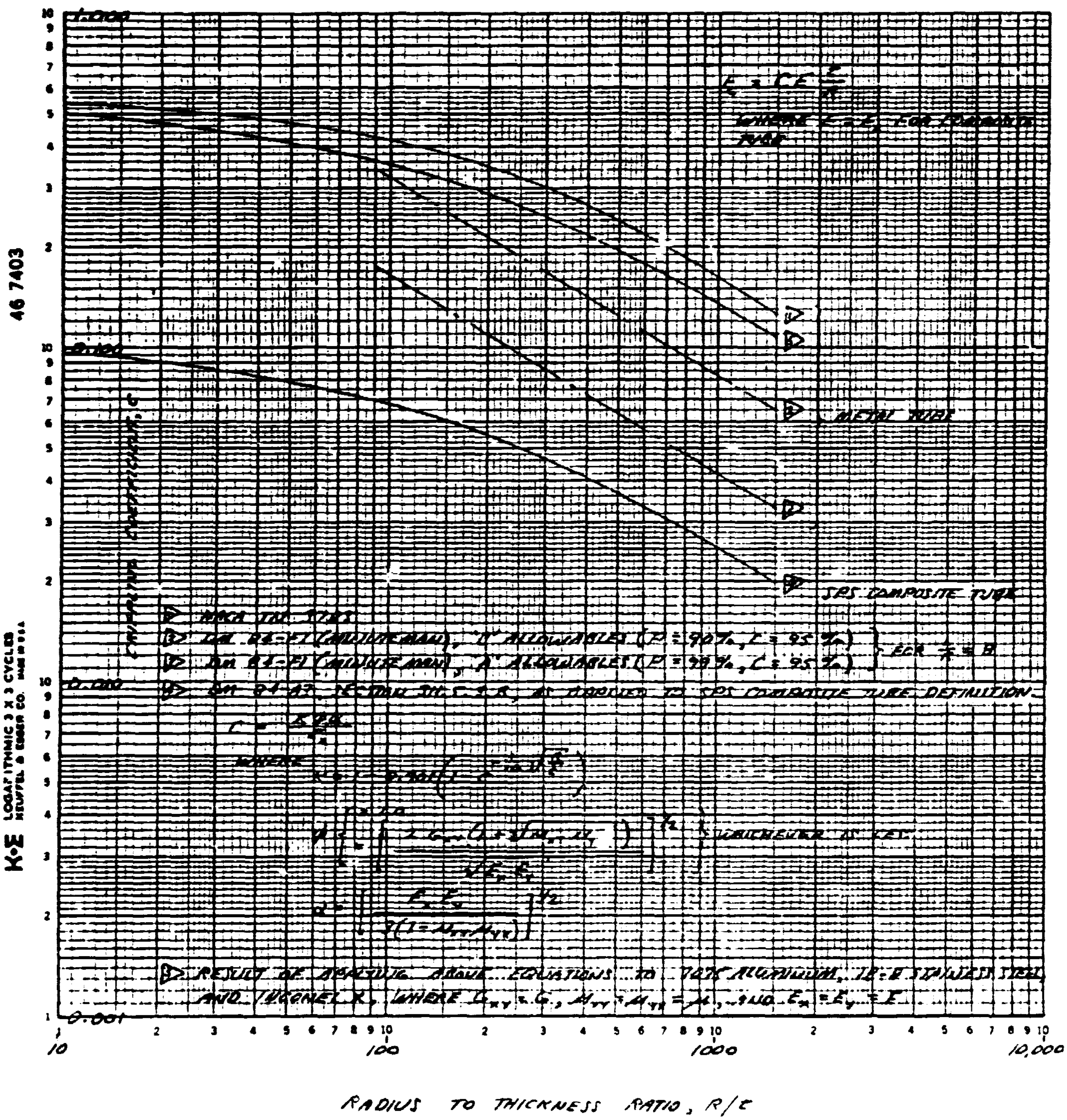
FIGURE I-1

CRIPPLING COEFFICIENT COMPARISON

– SPS COMPOSITE TUBE VS. METAL TUBE –

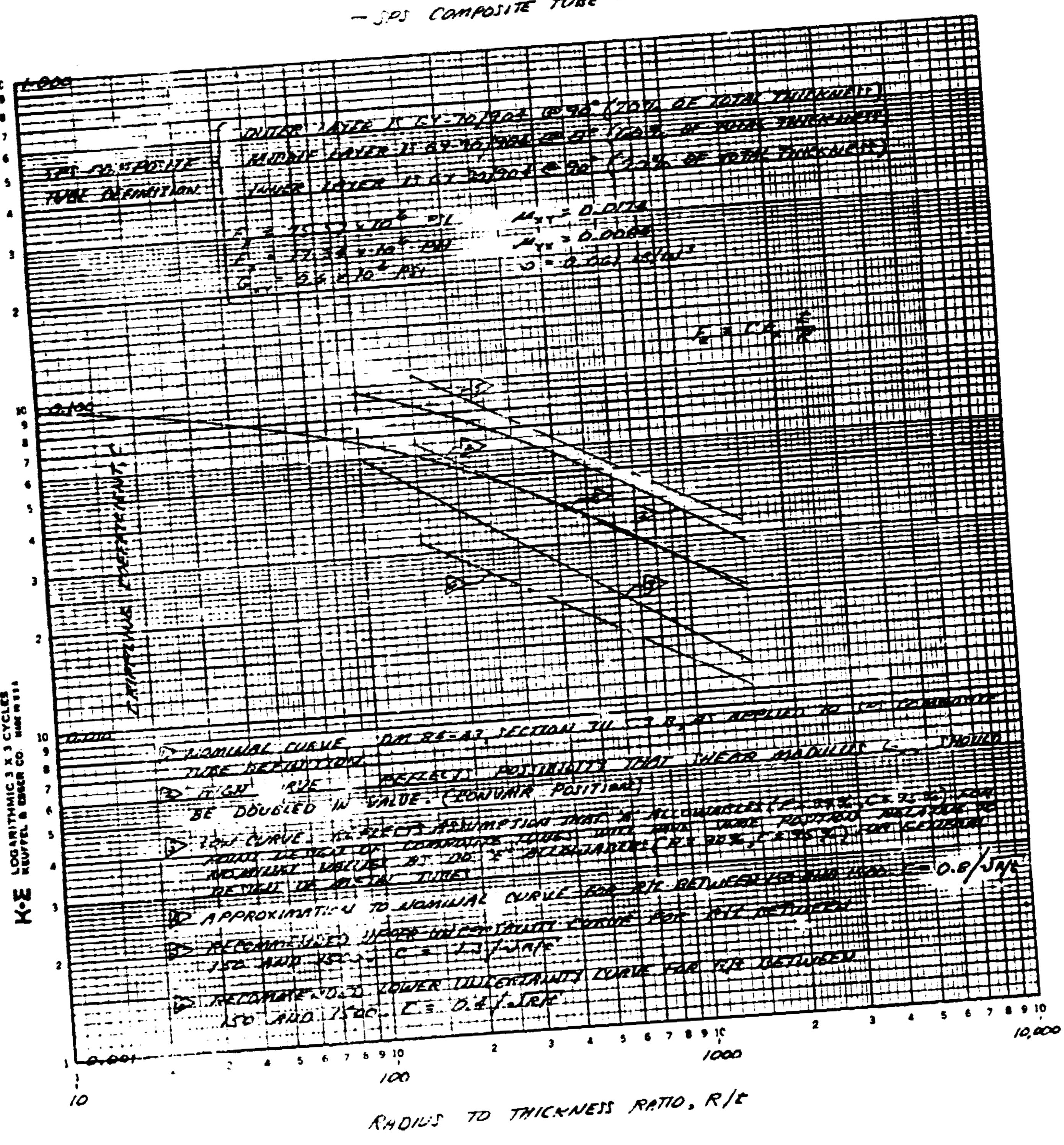


R.T. Conrad
7/28/77

FIGURE I-2

CRIPPLING COEFFICIENT UNCERTAINTY

— SPS COMPOSITE TUBE —



RADIUS TO THICKNESS RATIO, R/t

R.T. CONRAD

4.3.2 Thermal Engine Size/Mass Uncertainty

The thermal engine size uncertainty analysis was conducted similarly to the photovoltaic system. The efficiency chain worksheet is shown in Table 4.3.2-1.

The thermal engine size/mass uncertainty analysis employed a parametric method. This method was also applied to the photovoltaic system and agreed with the more detailed mass estimator's result within 1%. The parametric method worksheet is shown in Table 4.3.2-2.

TABLE 4.3.2-1
THERMAL ENGINE EFFICIENCY CHAIN

ITEM	NOMINAL	MINIMUM	MAXIMUM	LOG MIN	LOG MAX	LOG MEAN	σ	Correlations
CONCENTRATOR	.877	.83	.95	-.1863	-.0513	-.1188	.0225	NO CORRELATIONS IDENTIFIED
REFLECT DEGR	1.0	.70	1.0	-.3567	0	-.1783	.059	
CPC	.865	.80	.865	-.2231	-.145	-.1841	.013	
CAVITY OPTICAL	.950	.95	.98	-.0513	-.0202	-.0357	.0052	
CAVITY RERADIATION	.917	.917	.934	-.0866	-.0683	-.0775	.0031	
CAVITY THERMAL	.995	.990	.998	-.010	-.003	-.0065	.0012	
CYCLE	.189	.189	.200	-1.666	-1.609	-1.6377	.0094	
GENERATOR	.984	.984	.986	-.0161	-.0141	-.0151	.0003	
PARASITIC	.962	.944	.98	-.0576	-.0202	-.0389	.0062	
POWER DISTR	.948	.93	.96	-.0753	-.0408	-.0567	.0053	
MPTS (from P/V)	.563	.412	.683	-.8853	-.3806	-.6331	.0304	
	.0628	.027	.095	-3.6143	-2.3525	-2.9834	.0726	
SIZES	$118 km^2$	$272 km^2$	$77.8 km^2$			$146 km^2$		

$+3\sigma = 181 km^2$

$-3\sigma = 117 km^2$

WBS #	ITEM	EQUATION	AREF = 118 REF VALUE (TONS)	A = 146 km^2 CONSTANT AREA (MOST PROB) WORST	BEST	AVG	σ AT CONST AREA	UNIT (= AREA OR POWER SLOPE, ETC)	AREA SCALING FACTOR	CORRECTED AREA SLOPE
1.01 SPS			81027	122435	71193	96822	3097			.33879
1.01.00 MULT/COM			8916	13297	9341	11319	477			
1.01.00	PRIMARY STRUCTURE	$M = M_{REF}\frac{A}{AREF}$	7262	10266	7704	8985	427	.0615	1	.0615
1.01.00.01	SATELLITE CONTROL	$M = M_{REF}\frac{A}{AREF}\frac{M}{M_{REF}}$	1450	2706	1458	2082	208			.0142
1.01.00.02	SATELLITE COM AND DATA		4	6	4	5	-			-
1.01.00.03	MECH SYS & OTHER		200	319	175	247	24			.0009
1.01.01	ENERGY COLLECTION		1837	5925	1215	3570	785			.0244
1.01.01.00	SUPPORT STRUC	(INCL IN MAIN STR)	0							
1.01.01.01	FACETS	$M = M_{REF}\frac{A}{AREF}$	1837	5925	1215	2570	785			
1.01.02	ENERGY CONV		40084	59268	29010	44147	2488			
1.01.02.00	SUPPORT STR.	(INCLUDED IN MAIN STR)	0							
1.01.02.01	CPC & LIGHT DOORS	$M = M_{REF}\frac{A}{AREF}$	324	500	300	400	35	0.0027	1	0.0027
1.01.02.02	CAVITY ABSORBER	$M = M_{REF}(1 + \frac{A-AREF}{AREF} F)$	1000	1300	900	1109	67		.46	.00349
1.01.02.03	THERMAL ENGINE SYS									
1.01.03.01	BOILERS	$M = M_{REF}(1 + \frac{A-AREF}{AREF} F)$	3296	5057	2918	3987	356		.45	.0123
1.01.03.02	TURBINES		13755	18269	9134	13701	1522		.45	.0422
	GENERATORS & COOLERS		3648	5765	2309	4037	576		.43	.0124
	PUMPS		1234	1666	1066	1366	100		.43	.004
	RADIATORS	$M = Pth/Pthref\ M_{ref}$	10769	17953	7645	12799	1718		.37	.0324
	POTASSIUM INVENTORY	$M = Pth/Pthref\ M_{ref}$	6058	8758	4738	6748	670		.37	.0171
1.01.03	POWER DISTR & SWG	$M = M_{REF}\ 1 + \frac{A-AREF}{AREF} F)$	4978	7133	3839	5486	549		.43	.0162
1.01.04	MPTS	FROM P/V ANALYSIS	25212	36812	27788	32300	1504		.43	.095

TITLE: TABLE 4.3.2-2
RANKINE THERMAL ENGINE PARAMETRIC SCALING UNCERTAINTY ANALYSIS

4.4 MASS/COST UNCERTAINTY NOTES:

CAPITAL COST UNCERTAINTIES

Preliminary analysis of cost estimates indicated five primary contributors to uncertainties: solar cells (or thermal engines), klystrons, the ground receiver, space construction operations, and space transportation. Estimates are as follows:

Item	Nominal	Range	Range Rationale
Solar Cells	3,731	2,050 to 6,870	\$20 to \$67 /m² from various solar cell cost estimates
Klystrons	1,048	600 to 2,000	\$40 to \$100/KWe
Ground Receiving Station	4,446	2,500 to 6,500	Part II Midterm Range
Construction	1,110	700 to 1500	Uncertainty in crew size and equipment costs
Transportation	6,445	4,834 to 8,050	Low value assumes less maintenance cost. High value includes 1% attrition and certain interest costs.

These ranges were treated as uncorrelated:

Item	Nominal	Mean (from range)	σ
Solar Cells	3,731	4,460	803
Klystrons	1,048	1,300	233
Ground Receiving Station	4,446	4,500	667
Construction	1,110	1,100	133
Transportation	6,445	6,445	536

The RSS is 1203, = ±6.2% (1 σ)

The RSS at the expected mass (with growth) is 1375. The cost escalation (Σ Mean − Σ Nominal) is 1025.

A similar procedure was followed for the thermal engine.

POWER COST UNCERTAINTIES

The power cost equation is,

$$C = \frac{C_c \cdot r}{8766 f} \text{, in \$/kwh}$$

where C_c is capital cost in \$/kw

r is capital charge factor (per annum)

f is plant factor

The figure 8766 is the number of hours in a year.

At the 1 SPS/year rate, values and uncertainties are:

Capital	2725 ± 480
r	$0.15 \pm .03$
f	$0.8 \pm .1$

The equation may be linearized by:

$$\ln C = \ln C_c + \ln r - \ln 8766 - \ln f$$

The calculation proceeds as follows:

Item	nominal value	$\log_e$	$\sigma(\log_e)$
C_c	2725	(+) 7.910	.0547
r	.15	(+) −1.897	.0608
f	.8	(−) −.2230	.0392
8766	8766	(−) 9.079	0
		−2.843	.0906

Power Cost Values are:

	−3σ	−2σ	−σ	Nom	+σ	+2σ	+3σ
log ¢	−3.1148	−3.0242	−2.9336	−2.843	−2.7524	−2.6618	−2.5712
$/kwh	.044	.049	.053	.058	.064	.070	.076

Similar calculations were used for the thermal engine and for the higher rates (4 sps/yr)

Note that the uncertainty in r is the largest contributor!

NOTES ON UNCERTAINTY ANALYSIS: CORRELATED VARIABLES

The normal distribution

All variables will be assumed randomly distributed according to the normal distribution,

$$p(x) = \frac{1}{\sqrt{2\pi}\,\sigma}\, e^{-V_x^2/2\sigma^2}$$

where σ is the standard deviation of x and V_x is the variance of x from its mean.

The bivariate normal distribution

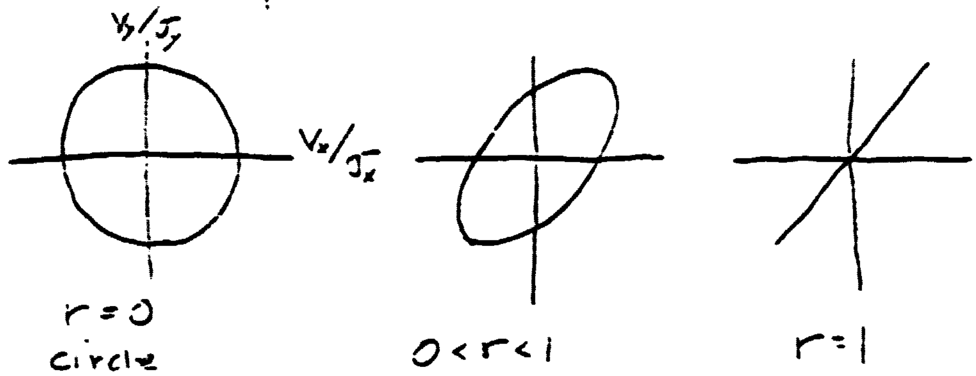
This distribution is expressed as follows:

$$p(x,y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-r^2}}\, e^{-G/2}$$

where $G = c^2 = \frac{1}{1-r^2}\left[\frac{V_x^2}{\sigma_y^2} - \frac{2rV_xV_y}{\sigma_x\sigma_y} + \frac{V_y^2}{\sigma_y^2}\right]$

The locus of V_x and V_y for a given value of c^2 is an equi-probability ellipse.

The ellipse can be sketched as follows



The value r is the correlation coefficient. It is a measure of the dependency of y on x. If r = 0 there is no dependency (no correlation). If r = 1 they are completely dependent and the problem can be reduced to one with only one uncertain variable.

Properties of the ellipse

The equation for the ellipse may be written:

$$x^2 - 2\rho xy + y^2 = (1-\rho^2)c^2$$

where $x = V_x/\sigma_x$ and $y = V_y/\sigma_y$. Note that the correlation coefficient is independent of scaling on x and y. If a new variable

$V_t = KV_x$ is introduced, we have

$x = V_x/\sigma_x = V_t/K\sigma_x$:

$$\frac{V_t^2}{K^2\sigma_x^2} - \frac{2\rho V_t V_y}{K\sigma_x\sigma_y} + \frac{V_y^2}{\sigma_y^2} = (1-\rho^2)c^2$$

It is evident that $\sigma_t = K\sigma_x$ and that ρ does not change.

We may also ask, what is the maximum value of x and where does it occur? If the ellipse equation is solved for x,

$$x = \rho y \pm \sqrt{(c^2-y^2)(1-\rho^2)}$$

The derivative is

$$\frac{dx}{dy} = \rho \pm \frac{1}{2}\left[(c^2-y^2)(1-\rho^2)\right]^{-1/2}\left[-2y(1-\rho^2)\right]$$

Setting the derivative to zero:

$$\rho = \mp \frac{y(1-\rho^2)}{\sqrt{(c^2-y^2)(1-\rho^2)}}$$

Which solves to:

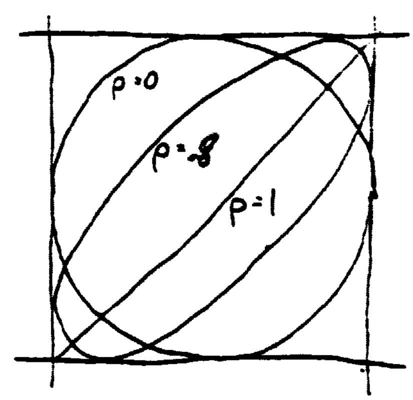
$$\boxed{y = \mp \rho c}$$

This can be substituted to find x_{max}:

$$x_{max} = \mp \rho^2 c \pm \sqrt{(c^2 - \rho^2 c^2)(1-\rho^2)}$$

which simplifies to

$$\boxed{x_{max} = \pm c}$$ not dependent on ρ



In the normalized ellipse equation (x and y rather than V_x and V_y), the ellipse is a circle if $\rho = 0$. If $\rho > 0$ the axis of the ellipse is tilted at 45°. If the non-normalized ellipse is considered, it can be shown* that the ellipse tilt angle is $\alpha = \frac{1}{2} \tan^{-1} \frac{2\rho\sigma_x\sigma_y}{\sigma_x^2 - \sigma_y^2}$.

It can also be shown that the major and minor axes of the ellipse ~~are~~ given by:

* Hald, Statistical Theory With Engineering Applications, Wiley, 1952

$$a = \frac{1}{2}\left\{\sqrt{\sigma_1^2+\sigma_2^2+2\sigma_1\sigma_2\sqrt{1-\rho^2}} + \sqrt{\sigma_1^2+\sigma_2^2-2\sigma_1\sigma_2\sqrt{1-\rho^2}}\right\}$$

$$b = \frac{1}{2}\left\{\sqrt{\sigma_1^2+\sigma_2^2+2\sigma_1\sigma_2\sqrt{1-\rho^2}} - \sqrt{\sigma_1^2+\sigma_2^2-2\sigma_1\sigma_2\sqrt{1-\rho^2}}\right\}$$

In the normalized ellipse, these simplify to

$$a = \sqrt{1+\rho}$$

$$b = \sqrt{1-\rho}$$

Drawing the ellipse; estimating ρ.

These relations can be used to sketch the ellipse: Example - suppose $\sigma_x = 1$, $\sigma_y = 2$, and $\rho = 0.5$. Draw the 1σ ellipse.

The maxima occur at V_x/σ_x and $V_y/\sigma_y = \rho c$. (For the 1σ ellipse, $c=1$.)

When either variable is zero, the values of the other are

$$V_x/\sigma_x = V_y/\sigma_y = \sqrt{(1-\rho^2)c^2}$$

The major & minor axes are 2.07 and ~~2.02~~ 0.834

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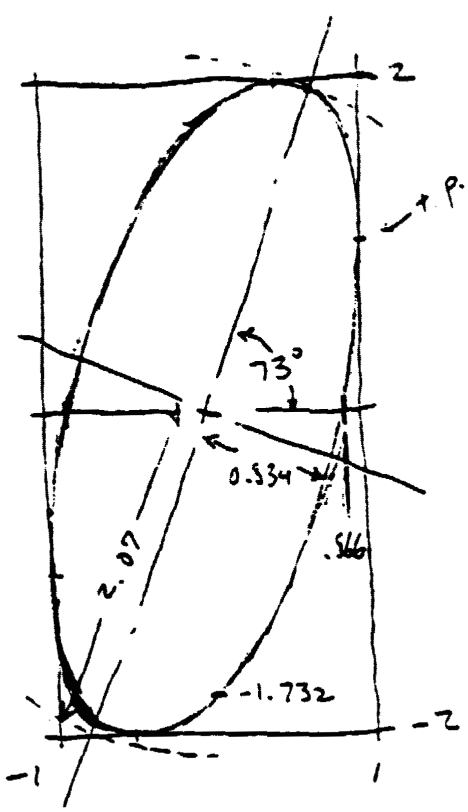
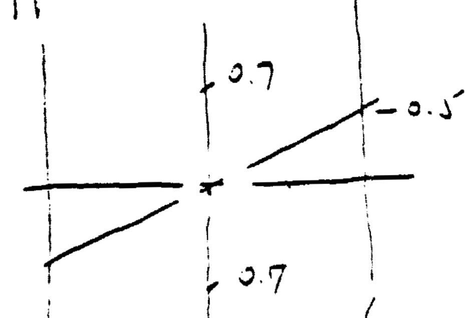
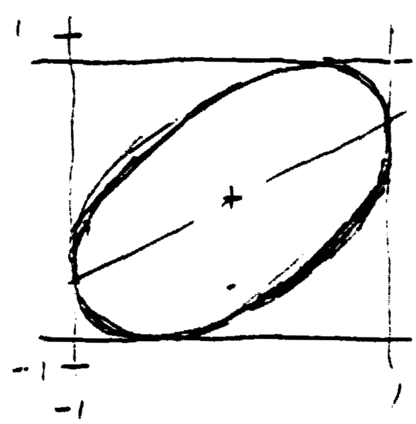


These values allow the ellipse to be sketched reasonably accurately as illustrated above. Similarly, if some estimates are available regarding the variances, these may be used to estimate ρ. For example, suppose that the information in the sketch is available, representing 3σ limits. Then σ_x is 0.333.



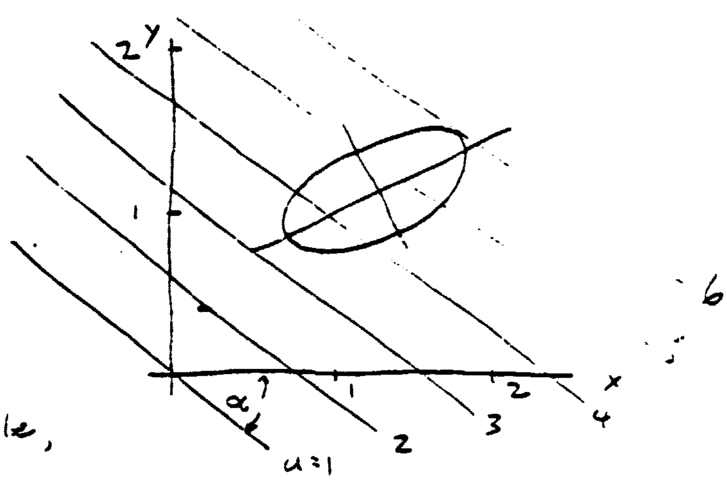
A trend line for V_y dependence on V_x is shown, as are estimated 3σ limits on V_y when $V_x = 0$. Since these are 3σ limits, we know $C = 3$. Also, if the trend line's intercept at the V_x limits are the ellipse tangency points, $V_y/\sigma_y = \rho C = 3\rho.$ The limits on V_y when $V_x = 0$ allow setting $V_y/\sigma_y = 3\sqrt{1-\rho^2}.$ These may be solved to find $\rho = 0.581$ and $\sigma_y = 0.287$ $(3\sigma_y = 0.862)$. The 3σ ellipse can then be sketched:



Note that the trend line is not the semimajor axis of the ellipse. The trend line is at 26.5°. The SMA is at 38°.

Functions of correlated variables

Suppose we have a variable U that is a (definite) function of x and y. The problem may be sketched as follows:



We are interested in finding the uncertainty in U. (σ_u)

In this example, suppose that $\partial U/\partial x = 1.3$ and $\partial U/\partial y = 1.8$. The angle α between the lines of constant U and the x-axis is given by $\tan\alpha = -\frac{\partial U/\partial x}{\partial U/\partial y}$, about $-36°$ in the example.

We will determine σ_u by application of a co-ordinate rotation through the angle α. Consider co-ordinates t, u with the same grid spacing as x and y.

Then $V_x = V_t \cos\alpha - V_u \sin\alpha$

$V_y = V_t \sin\alpha + V_u \cos\alpha$.

Substituting into the ellipse equation;

$$G = \frac{1}{1-\rho^2}\Bigg[V_t^2\left(\frac{\cos^2\alpha}{\sigma_x^2} - \frac{\sin^2\alpha}{\sigma_y^2} - \frac{2\rho\sin\alpha\cos\alpha}{\sigma_x\sigma_y}\right)$$

$$+ V_u^2\left(\frac{\sin^2\alpha}{\sigma_x^2} + \frac{\cos^2\alpha}{\sigma_y^2} + \frac{2\rho\sin\alpha\cos\alpha}{\sigma_x\sigma_y}\right)$$

$$- V_t V_u\left(\frac{2\sin\alpha\cos\alpha}{\sigma_x^2} - \frac{2\sin\alpha\cos\alpha}{\sigma_y^2} + \frac{\cos^2\alpha - \sin^2\alpha}{\sigma_x\sigma_y}\right)\Bigg]$$

We conclude that

$$\frac{1}{1-r^2}\frac{V_t^2}{\sigma_t^2} = \frac{1}{1-\rho^2}V_t^2\left(\frac{\cos^2\alpha}{\sigma_x^2} - \frac{\sin^2\alpha}{\sigma_y^2} - \frac{2\rho\sin\alpha\cos\alpha}{\sigma_x\sigma_y}\right)$$

etc. and that therefore,

$$\frac{1/\sigma_t^2}{1/\sigma_u^2} = \frac{\dfrac{\cos^2\alpha}{\sigma_x^2} + \dfrac{\sin^2\alpha}{\sigma_y^2} - \dfrac{2\rho\sin\alpha\cos\alpha}{\sigma_x\sigma_y}}{\dfrac{\sin^2\alpha}{\sigma_x^2} + \dfrac{\cos^2\alpha}{\sigma_y^2} + \dfrac{2\rho\sin\alpha\cos\alpha}{\sigma_x\sigma_y}}$$

Rearranging;

$$\sigma_t^2/\sigma_u^2 = \frac{\cos^2\alpha\,\sigma_x^2 + \sin^2\alpha\,\sigma_y^2 + 2\rho\sigma_x\sigma_y\sin\alpha\cos\alpha}{\sin^2\alpha\,\sigma_x^2 + \cos^2\alpha\,\sigma_y^2 - 2\rho\sigma_x\sigma_y\sin\alpha\cos\alpha}$$

We know* that $\sigma_u^2 + \sigma_t^2 = \sigma_x^2 + \sigma_y^2$

So that $\sigma_u^2\left(1 + \sigma_t^2/\sigma_u^2\right) = \sigma_x^2 + \sigma_y^2$

* op cit

The parenthesis term simplifies to

$$\frac{\sigma_x^2 + \sigma_y^2}{\sin^2\alpha\,\sigma_x^2 + \cos^2\alpha\,\sigma_y^2 - 2\rho\sigma_x\sigma_y \sin\alpha\cos\alpha}$$

and

$$\sigma_u^2 = \sin^2\alpha\,\sigma_x^2 + \cos^2\alpha\,\sigma_y^2 - 2\rho\sigma_x\sigma_y \sin\alpha\cos\alpha .$$

To get σ_U, we need to scale by

$$\sigma_U^2 = \sigma_u^2\left(\frac{\partial U}{\partial u}\right)^2$$

The value $\partial U/\partial u$ is the length of a unit vector along the u axis in terms of U. This length is $\sqrt{(\partial U/\partial x)^2 + (\partial U/\partial y)^2}$

Therefore,

$$\sigma_U^2 = \left(\sin^2\alpha\,\sigma_x^2 + \cos^2\alpha\,\sigma_y^2 - 2\rho\sigma_x\sigma_y \sin\alpha\cos\alpha\right)\left[\left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial U}{\partial y}\right)^2\right]$$

We next use trigonometric identities:

$$\sin^2\alpha = \tan^2\alpha/(1+\tan^2\alpha);$$
$$\cos^2\alpha = 1/(1+\tan^2\alpha); \quad \sin\alpha\cos\alpha = \tan\alpha/(1+\tan^2\alpha)$$

And note that $\tan\alpha = -\partial U/\partial x \,/\, \partial U/\partial y$

Then
$$\sigma_U^2 = \frac{\dfrac{(\partial U/\partial x)^2}{(\partial U/\partial y)^2}\sigma_x^2 + \sigma_y^2 + 2\rho\sigma_x\sigma_y \dfrac{\partial U}{\partial x}/\partial U/\partial y}{-\,(\partial U/\partial x)^2/(\partial U/\partial y)^2}\left[\left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial U}{\partial y}\right)^2\right]$$

Which simplifies very nicely to

$$\sigma_U^2 = \sigma_x^2\left(\frac{\partial U}{\partial x}\right)^2 + \sigma_y^2\left(\frac{\partial U}{\partial y}\right)^2 + 2\rho\sigma_x\sigma_y\frac{\partial U}{\partial x}\frac{\partial U}{\partial y}$$

In the example sketched a few pages prior, assume $\sigma_x = 0.55$, $\sigma_y = 0.35$, $\rho = 0.5$

Then

$$\sigma_U^2 = .55^2 \times 1.3^2 + .35^2 \times 1.8^2 + 2 \times .5 \times 1.3 \times 1.8 \times .55 \times .35$$

$$= 1.359$$

and $\sigma_U = 1.166$