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Volume VI

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Phase I, Final Briefing
Space Construction
and Transportation

D180-25037-6

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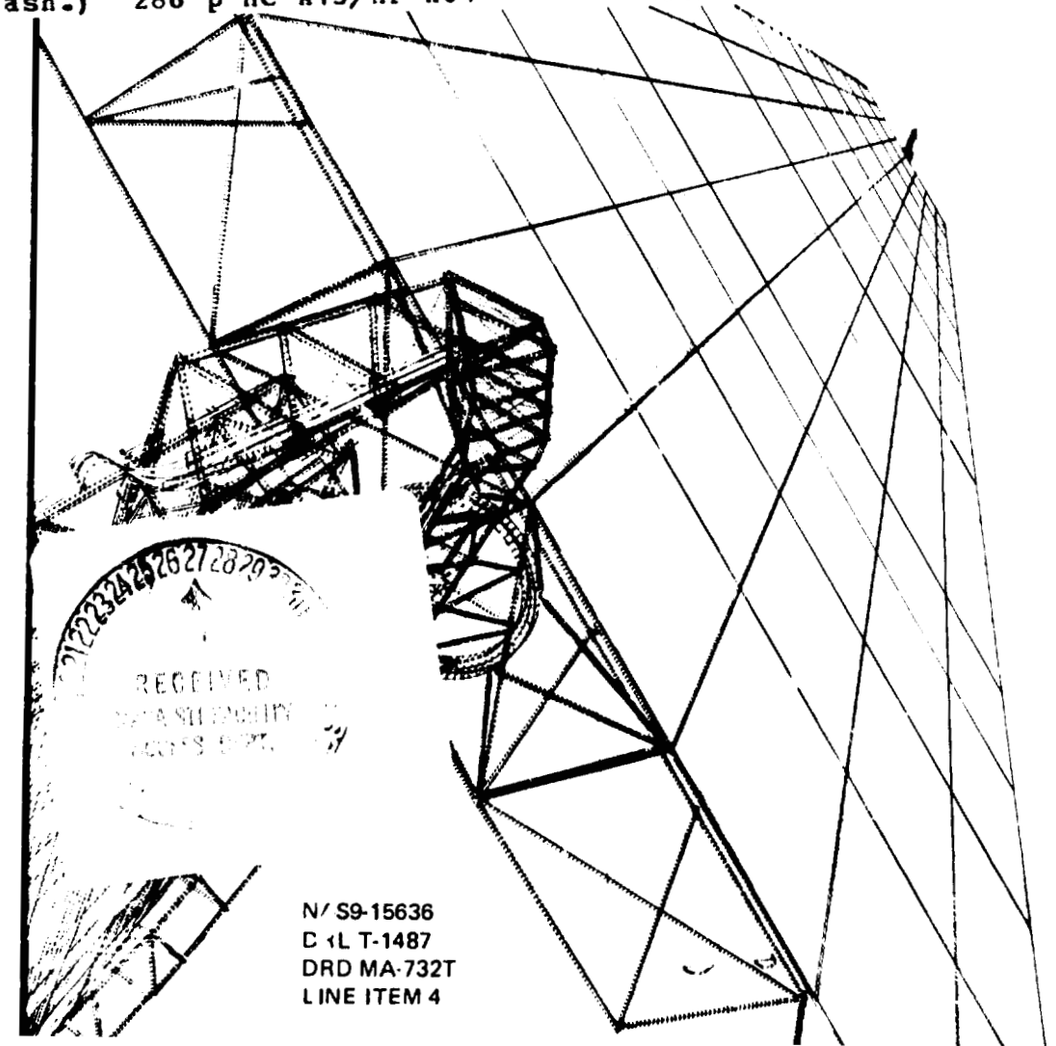

Solar Power Satellite System Definition Study

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GENERAL ELECTRIC

GRUMMAN

Arthur D Little, Inc

TRW

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Solar Power Satellite
System Definition Study

Volume VI
PHASE I FINAL BRIEFING
Space Construction and Transportation
D180-25037-6

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FOREWORD

The SPS System Definition Study was initiated in June of 1978. Phase I of this effort was completed in December of 1978 and is herewith reported. This study is a follow-on effort to an earlier study of the same title completed in March of 1978. These studies are a part of an overall SPS evaluation effort sponsored by the U. S. Department of Energy (DOE) and the National Aeronautics and Space Administration.

This study is being managed by the Lyndon B. Johnson Space Center. The Contracting Officer is Thomas Mancuso. The Contracting Officer's representative and Study Technical Manager is Harold Benson. The study is being conducted by The Boeing Company with Arthur D. Little, General Electric, Grumman, and TRW as subcontractors. The study manager for Boeing is Gordon Woodcock. Subcontractor managers are Dr. Philip Chapman (ADL), Roman Andryczyk (GE), Ronald McCaffrey (Grumman), and Ronal Crisman (TRW).

This report includes a total of seven volumes:

I - Executive Summary
II - Phase I Systems Analyses and Tradeoffs
III - Reference System Description
IV - Silicon Solar Cell Annealing Tests
V - Phase I Final Briefing Executive Summary
VI - Phase I Final Briefing: Space Construction and Transportation
VII - Phase I Final Briefing: SPS and Rectenna Systems Analyses

In addition, General Electric will supply a supplemental briefing on rectenna construction.

Agenda

SPS-2525

	THURSDAY, DEC 14TH	
* 0900	EXECUTIVE SUMMARY	G. WOODCOCK
	TOPICAL REPORT I: SPACE OPERATIONS	
▶ 1045	CONSTRUCTION LOCATION ANALYSIS	E. DAVIS
1200	(LUNCH)	
▶ 1300	SATELLITE CONSTRUCTION ANALYSIS	K. MILLER, R. McCAFFREY
● 1430	ALUMINUM SATELLITE STRUCTURE	R. McCAFFREY
	TOPICAL REPORT II: GROUND OPERATIONS	
▶ 1500	INDUSTRIAL INFRASTRUCTURE	P. CHAPMAN
▶ 1530	RECTENNA SITING	D. GREGORY
	FRIDAY, DEC 15TH	
	TOPICAL REPORT III: SATELLITE & RECETNNA SYSTEMS	
● 0900	SOLAR ARRAYS AND ANNEALING	O. DENMAN
● 0930	ONBOARD POWER HANDLING	O. DENMAN
● 0945	ONBOARD DATA & COMMUNICATIONS	R. CRISMAN
● 1015	POWER TRANSMISSION SYSTEM	E. NALOS
● 1100	POWER RECEPTION SYSTEM	R. ANDRYCZYK
1200	(LUNCH)	
	TOPICAL REPORT IV: DEVELOPMENT PLANNING	
* 1300	TECHNOLOGY ADVANCEMENT	G. WOODCOCK
▶ 1330	FLIGHT PROJECTS	D. GREGORY

* = VOLUME V

▶ = VOLUME VI

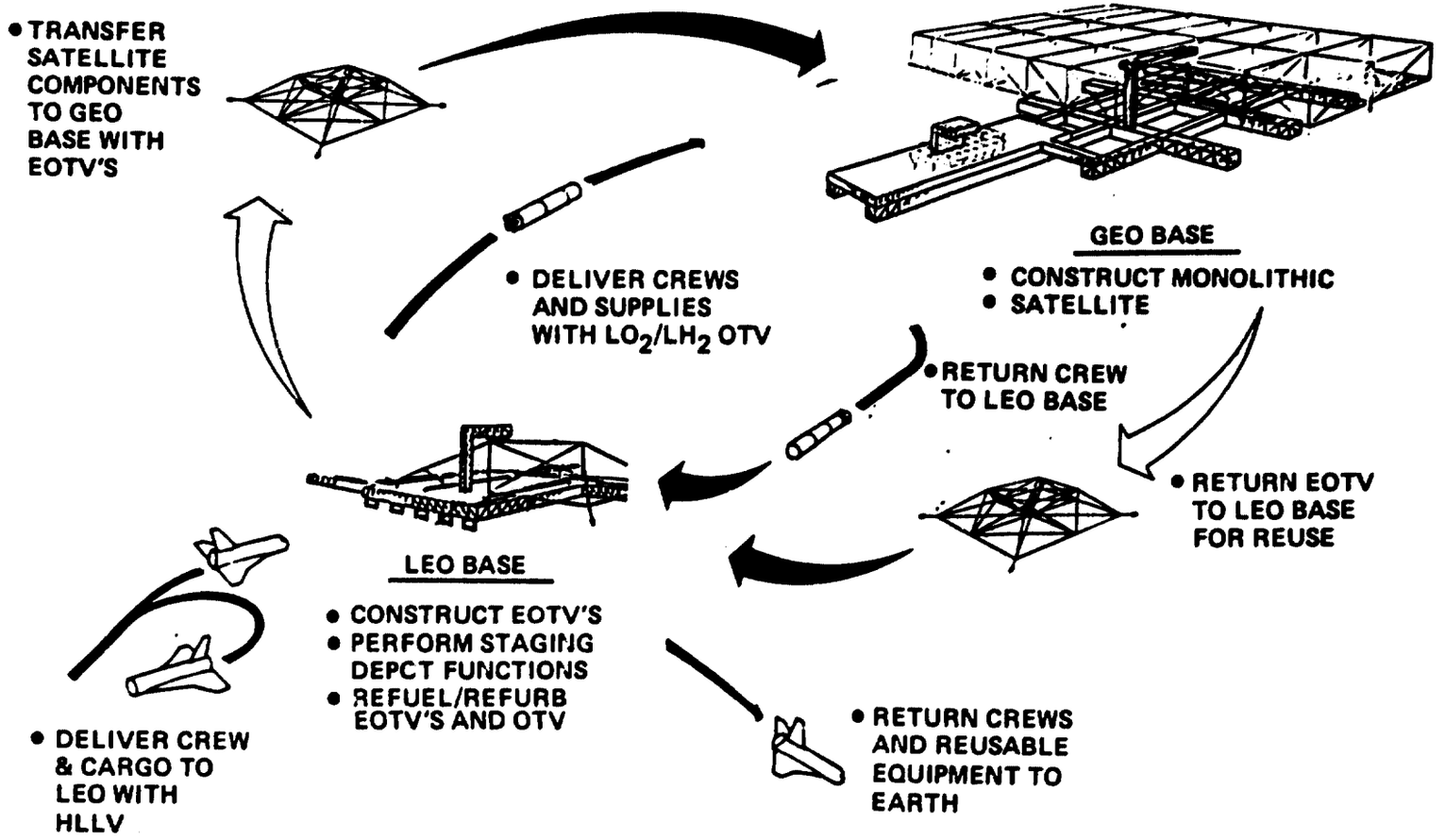
● = VOLUME VII

GEO CONSTRUCTION CONCEPT

ELECTRIC ORBIT TRANSFER VEHICLES

The major system elements and operations associated with the GEO construction concept using electric orbit transfer vehicles for SPS cargo delivery are indicated. This concept is to be compared with a LEO construction concept which uses self-power transportation of the modules to get them to GEO. The comparison between these two concepts will involve all aspects of transportation, construction and impacts on satellite design.

GEO Construction Concept
Electric Orbit Transfer Vehicles



PHASE I MID-TERM SUMMARY

The Phase I mid-term effort was confined to analyzing an electric orbit transfer vehicle (EOTV) using silicon solar cells. The payload had been established as equal to 10 HLLV payloads or 4,000 metric tons. The return payload requirement was related to the payload racks. Cost optimization was obtained with a specific impulse of 8000 sec and an up trip time of 180 days. Selection of a 10 round trip life for the EOTV's which corresponded to seven years of operation, was the result of cost optimization as well as risk considerations. A fleet size of 23 EOTV's including one spare was required to perform the 28 flights required per year. Mission operations concentrated on establishing where the solar array was to be annealed with GEO being the selected location because of the continous power availability and the determination of where the thruster should be refurbished with LEO being the selected location due to minimizing transportation cost. A total of 16 days of time was required to perform the maintenance operations as well as the operations associated with loading and unloading payload elements. Construction of the EOTV's occurred at a low earth orbit base that will have the additional role of serving as a staging depot during the construction of the satellites. Cost at the time of the mid-term was established by using scaling relationships associated with the satellite and self-power systems rather than an independent cost estimate. Using this approach and with the available technical definition, the GEO construction concept was cheaper than LEO construction at the mid-term.

Part 1 Midterm Summary
Electric Orbit Transfer Vehicle

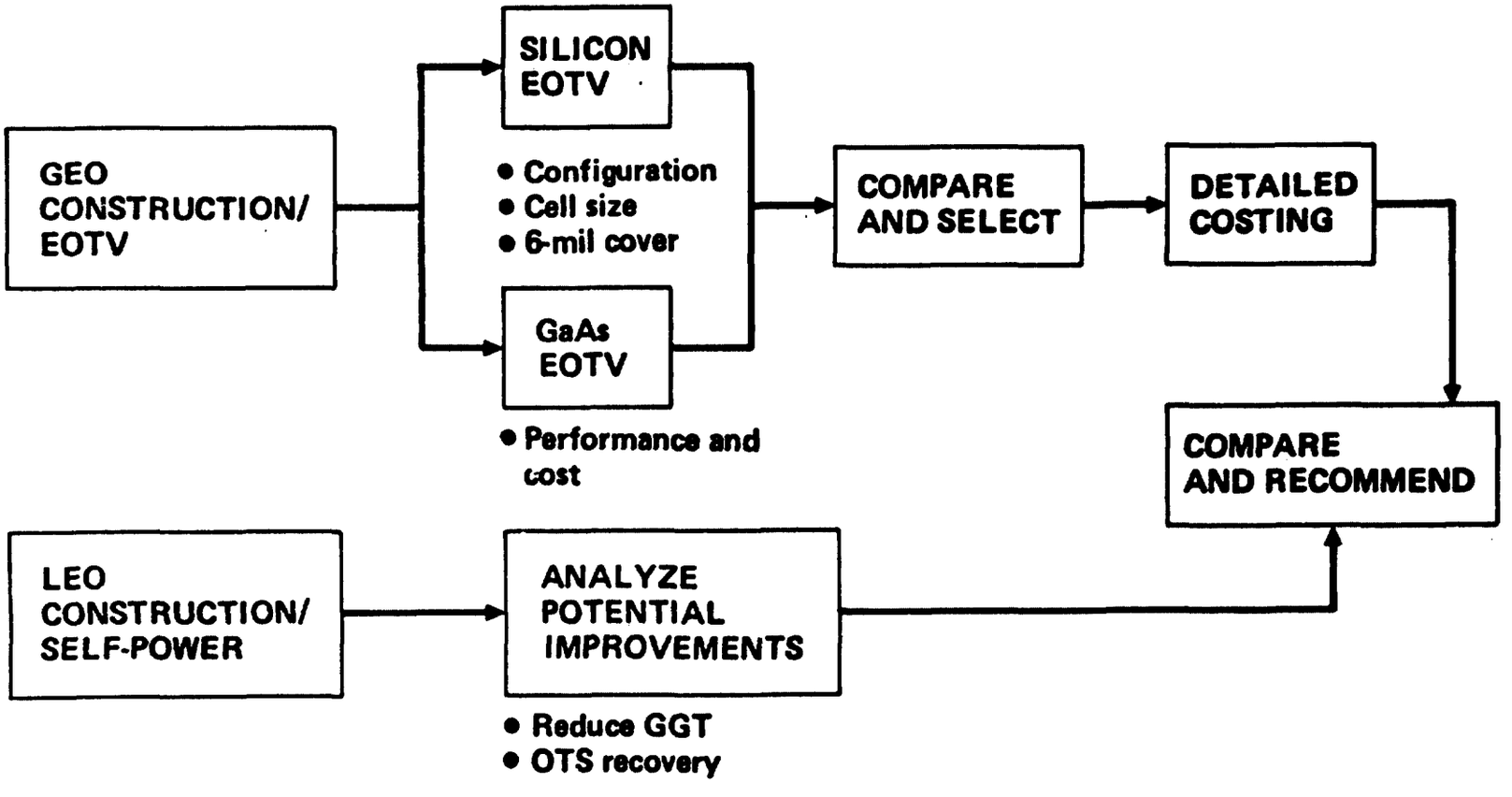
- ANALYZED AN EOTV USING SILICON SOLAR CELLS
- PAYLOAD – – UP 4000 MT
  DOWN 200 MT
- COST OPTIMIZATION – – – I_S = 8000 SEC
  TRIP TIME UP = 180 DAYS
  TRIP TIME DOWN = 39 DAYS
- NUMBER OF ROUND TRIPS – – – 10
- FLEET SIZE – – – 23
- CONFIGURATION – – – – CR = 1
  AR ≈ 1
  START BURN MASS = 1200 MT
- MISSION OPERATIONS
  - ANNEAL ARRAY AT GEO
  - REFURB THRUSTERS AT LEO
  - 16 DAYS TOTAL TURNAROUND
- CONSTRUCTION – – –AT LEO BASE
  23 DAYS/EOTV – – – CREW: 200
  1.5 YEARS FOR FLEET
- COST – – – SCALED TO SATELLITE AND SELF POWER SYSTEMS

CONSTRUCTION LOCATION ANALYSIS

Task Remaining at Mid-Term

Several tasks concerning GEO construction remained after the mid-term as well as additional analysis concerning improvements for the LEO construction/self-power option. In the case of the silicon EOTV, several configurations and cover glass sensitivities were to be analyzed. An EOTV using gallium arsenide cells was also to be analyzed to assess its performance and cost characteristics. These two EOTV's were to be compared and selected with the most desirable concept being used in establishing more accurate cost for the EOTV. Several potential improvements had also been defined for the LEO construction option. These basically included the improvement of the moment of inertia characteristics to reduce the gravity gradient torque associated with the transfer of the self-power module and also to investigate the cost benefits of recovering the expensive orbit transfer system propulsion elements. Finally, the GEO construction and LEO construction option would be compared on a total programmatic basis with a recommendation suggested.

Construction Location Analysis Tasks Remaining at Midterm



EOTV CONFIGURATION OPTIONS

The silicon EOTV configuration suggested at the mid-term involved a concentration ratio of 1 and an aspect ratio of approximately 1. This configuration is illustrated by option 1 on the adjacent chart. The key characteristics of this configuration are that there are four thruster module locations and the EOTV is approximately square (provides the most desireable moment of the inertia characteristics). Several variables exist however that could present different configuration options. These variables include the cell size to be used in the blanket and also the thruster module location. The first three options indicated, all use a 5 x 10 centimeter cell which differs from the basic satellite cell dimension which is approximately 6.5 by 7.4 centimeters. The reason for deviating from the satellite cell shape was that an array as nearly square as possible array was desired to provide the most favorable MOI and with the required voltage and power requirements this could best be obtained by changing the cell dimension. Option 4 shows the configuration that results if the basic satellite cell is used. In either case, a small penalty in cost per m^2 would occur due to provisions necessary to operate in the more severe operating environment; thrust provisions are provided at two locations. Option 3 also uses two thruster module locations but changes the aspect ratio of the satellite to approximately 5 to 1 in an attempt to decrease the control requirements for the Y axis.

EOTV Configuration Options

SPS-2493

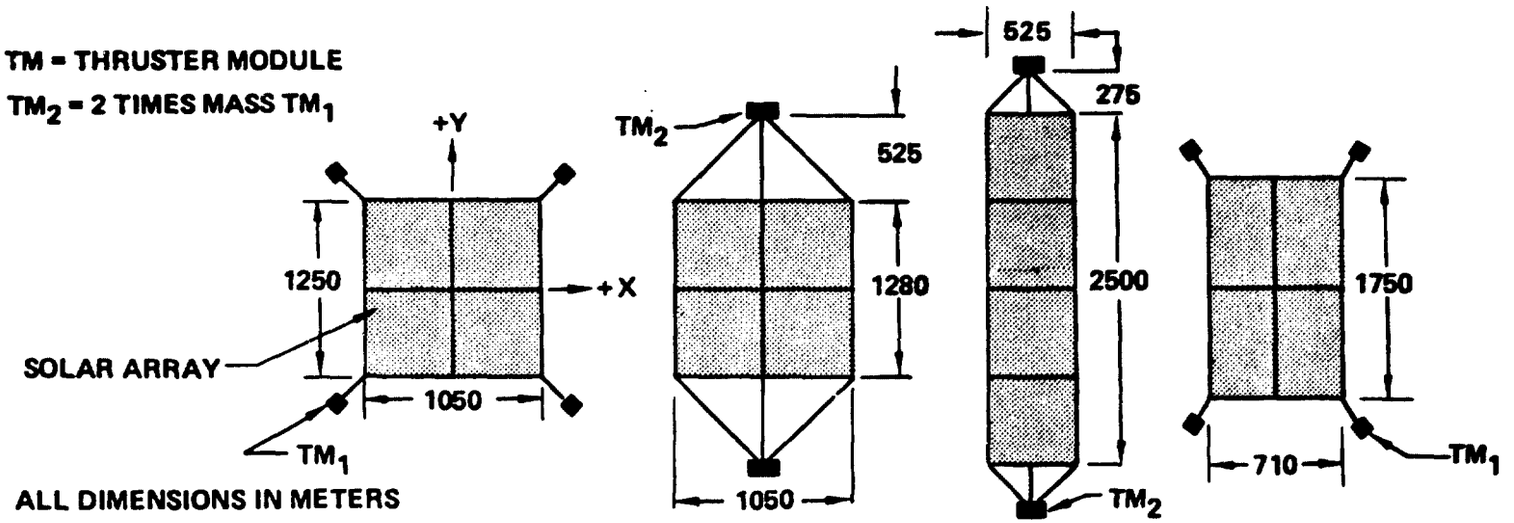
- KEY INPUTS (NOMINAL)
  - POWER: 230 MW
  - VOLTAGE: 2685
- KEY VARIABLES
  - CELL SIZE
  - THRUSTER MODULE LOCATION

- ASSESSMENT CRITERIA
  - THRUST PROVISIONS
  - ARRAY AREA
  - MASS
  - CONSTRUCTABILITY

OPTIONS → ① REFERENCE ② ③ ④

TM = THRUSTER MODULE

TM_2 = 2 TIMES MASS TM_1



ALL DIMENSIONS IN METERS

CELL SIZE (CM)	5X10	5X10	5X10	6.5 X7.4 (SATELLITE CELL)
THRUSTER MODULES	4	2	2	4

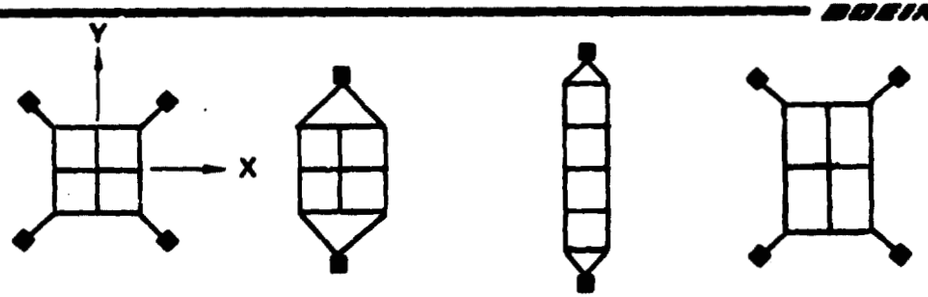
EOTV CONFIGURATION COMPARISON

The EOTV configuration options were compared using the mid-term configuration as the reference case. The parameters to be compared include the total amount of thrust required by the configuration to perform the mission and the difference in I^2R losses as result of changes in dimensions in the EOTV. These parameters will combine to reflect in the difference in the total array area requirements finally resulting in comparison of the mass, which reflects both the difference in the power bus mass as well as solar array mass. Finally, the concepts are to be evaluated for the differences in constructability.

The first items to be compared under thrust provisions is that associated with thrust vector pointing efficiency which is essentially the percent of available time that the thruster modules can be used at their full thrust. Orbit geometry and the need to continue to point the array at the sun while the earth is being orbited, results in configurations having 4 thruster modules to have small periods of time when one or two of the modules must be vectored away from their desired direction otherwise the high velocity plume would hit the vehicle and cause considerable damage. Options with only two thruster module locations such as 2 and 3, do not have this constraint and can operate at full power whenever the vehicle is in sun light. In terms of gravity gradient torque control requirement, the second option requires a thrust level of approximately twice that required to control the torque around the X axis is that required for the reference configuration. Control around the Y axis is about one-third, while control around the Z axis requires a torque level six times greater than the reference. This same approach is used in comparing option number 3. Option 4 was not analyzed in detail, but due to its elongated configuration it will be worse than the reference case. Another factor to be considered however is the fact that although Options 2 and 3 require far less torque control for the Y axis, some control is required and consequently thrusters in addition to those of the two modules must be provided. The net effect of comparing the amount of thrust required in terms of the thrust vector pointing efficiency compared to that of gravity gradient torque and full 3 axis control is such that little difference is evident at this time between four and two thrust module configurations. In terms of I^2R losses the extra length of the power buses required to reach the two thruster module locations or the length of the EOTV itself result in a small penalty for Options 2 and 3 over the reference case. The I^2R losses is reflected in terms of additional solar array area requirement and the associated mass plus the additional bus bar lengths results in a small mass penalty for option 2 and 3. In terms of constructability, the only significant difference would be that associated with the size of the construction base as influenced by the size of the bays making up the EOTV or the location of the thruster modules. In summary, there is not too much difference between the options investigated. A firm resolution as to which is better will require an additional level of detail regarding the amount of thrust necessary to satisfy all requirements. Consequently, the configuration using 5 x 10 cells and four thruster modules will be used for the remainder of the analysis.

EOTV Configuration Comparison

SPS-2494



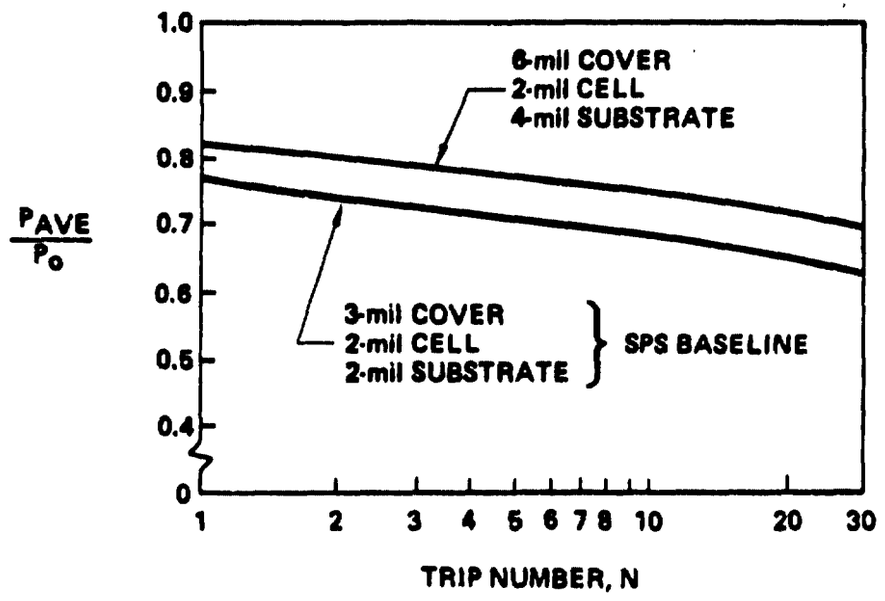
• OPTION	1	2	3	4
• THRUST PROVISIONS				
• T.V. POINTING EFF.	REF.	+6%	+6%	SAME AS REF
• GGT CONT REQ'T				
X AXIS	REF	> 2X	> 5X	WORSE THAN 1
Y AXIS	REF	< 3X	<100X	WORSE
Z AXIS	REF	>6X	>16X	WORSE
• OTHER FACTORS	–	SUPPLEMENTAL THRUSTERS REQ'D FOR Y AXIS CONT OPT 2 & 3		–
• NET EFFECT:	THRUST VECTOR POINTING AND GRAVITY GRADIENT CONTROL REQ'TS TEND TO OFFSET ONE ANOTHER			
• I^2R LOSSES (MW)	REF	+6.1	+7.2	NOT EVAL
• ARRAY AREA (KM^2)	REF	+0.035	+0.057	NOT EVAL
• MASS (MT)	REF	+51	+73	NOT EVAL
• CONSTRUCTABILITY	REF	TM INSTALLATION MORE DIFFICULT	SMALLER BASE	LARGER BASE

SILICON EOTV BLANKET CHARACTERISTICS
6 vs. 3 Mil Coverglass

The next point of refinement in the silicon EOTV analysis was that involving the benefits of using a thicker coverglass than the basic satellite blanket as a means to decrease the amount of degradation to the solar array. On the left hand portion of the chart, the power output is shown as a function of the number of trips flown by the EOTV and indicates a 5-6% improvement for the use of a 6 mil cover. The 6 mil coverglass blanket however does have a penalty in terms of the blanket mass per square meter and the cost per square meter. Mass per square meter is reflecting the fact that the blanket has gone from 7 mils to 12 mils in thickness, whereas the cost per square meter is primarily reflecting just the cost of the additional 5 mils of glass which in the basic blanket was only $5 per square meter of 5 mils of glass type material.

Silicon EOTV Blanket Characteristics
6 vs 3 Mil Cover

- POWER OUTPUT



- MASS AND COST

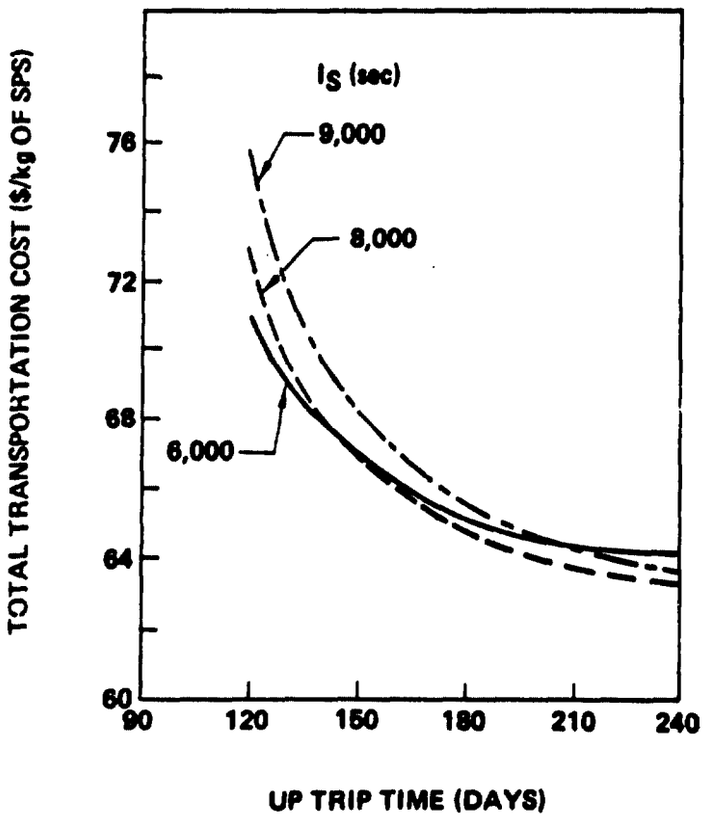
Blanket	kg/m^2	$\$/m^2$
3-2-2	0.628	62.6
6-2-4	1.06	68.0

SILICON EOTV COST OPTIMIZATION

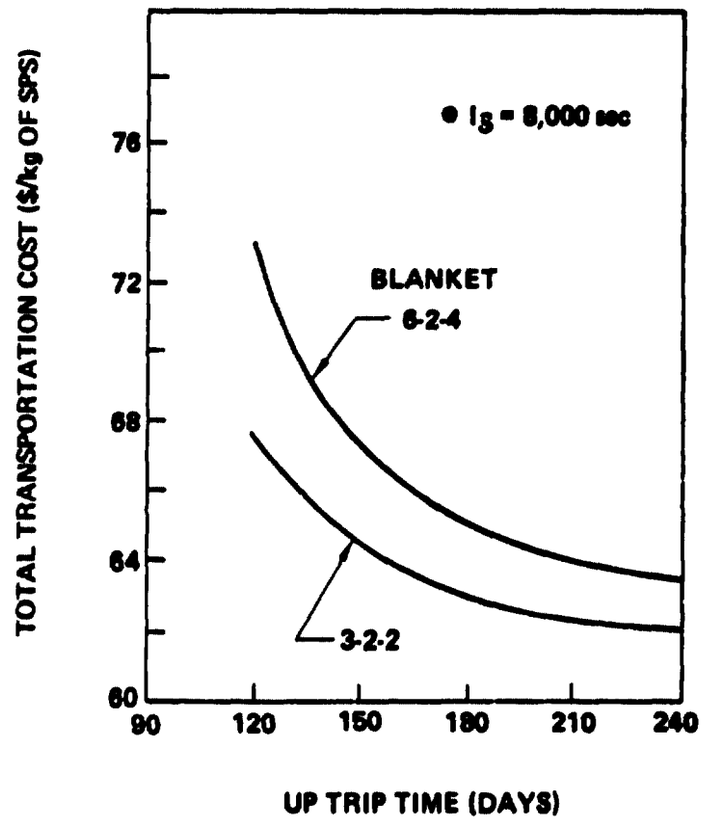
Transportation cost optimization is indicated for the EOTV using 6 mil cover in terms of the specific impulse and the uptrip time. Downtrip times are approximately 1/4 of the uptrip time. This comparison indicates that on fast trip times, such as 120 days, an I_S of 5,000 seconds is more desirable since the trip time itself requires large amounts of power and consequently it is not desirable to also at the same time require an I_s that requires large amounts of power, such as with 9,000 sec. The optimum I_s and trip time combination is I_s = 8,000 seconds and a trip time up of 240 days. The optimization curves for both blanket designs is shown in the right hand plot and indicates the EOTV using a 3 mil blanket to provide approximately $2 per kilogram of SPS savings at the optimum I_S and trip time. Further detail and the reason for the 3 mil blanket EOTV providing lower cost is discussed on the next chart.

Silicon EOTV Cost Optimization

- SILICON 6-mil EOTV



- SILICON 3- VERSUS 6-mil EOTV

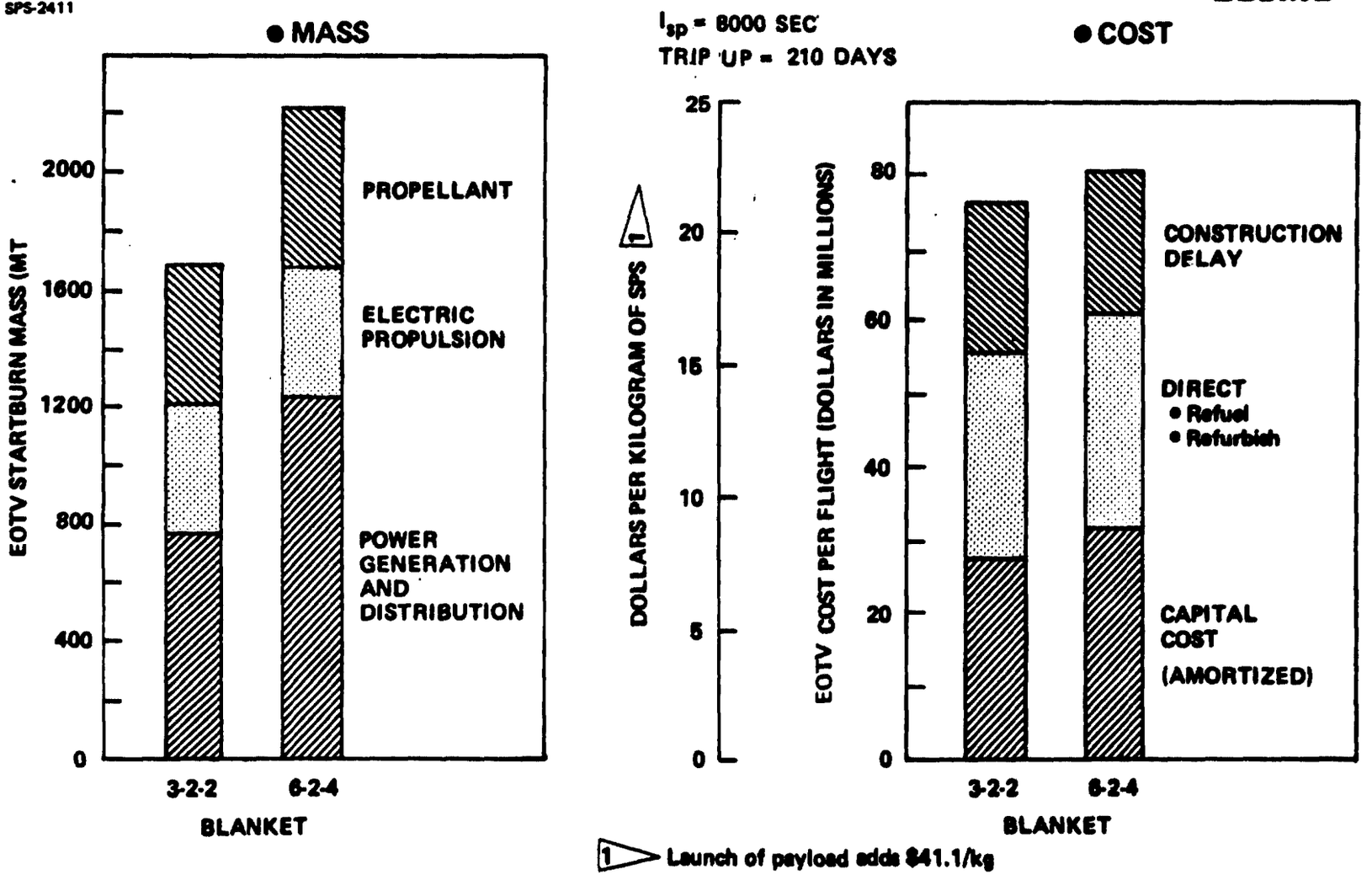


SILICON EOTV COMPARISON

On the left is presented the mass comparison of an EOTV using either a 3 mil or 6 mil blanket. This comparison as well as the cost is done for a specific impulse of 8,000 seconds and an uptrip time of 210 days. The mass comparison shows a significant penalty for the power generation and distribution system of the 6 mil blanket configuration primarily because of the heavier solar array. The propulsion and propellant requirements are approximately equal, although the 6 mil case has slightly greater requirements because of the heavier PGDS. The cost comparison reflects amortized capital cost and is expressed in terms of EOTV dollars per kilogram of SPS. Although the unit cost of the 6 mil blanket EOTV would be considerably greater than that for the 3 mil EOTV, when amortized over the life of the system, little difference occurs between the two concepts. Again, the propellant requirements were approximately equal so the direct costs in terms of refueling the EOTV's are approximately the same. Since both concepts use the same trip time, the construction delay cost is also the same. The net result is that the 3 mil blanket EOTV provides a $2 per kilogram of SPS benefit over that of the 6 mil case and will be used in the comparison with a GaAs blanket EOTV.

Silicon EOTV Comparison

SPS-2411



GALLIUM ARSENIDE EOTV

An alternative to the silicon EOTV is the use of gallium arsenide solar cell blankets. Several reasons are indicated for its consideration. The key factor in establishing the benefit of this type of solar blanket is the cost per square meter that will occur. This is significant since it will be done so in a program that uses silicon solar cells for the satellite thereby resulting in a relative small production rate for the gallium arsenide blanket. The key assumptions are indicated and particular emphasis is given to selecting an EOTV with a configuration concentration ratio of 1 rather than some higher concentration ratio. This is done in order to eliminate the problems associated with uneven illumination resulting from higher concentration ratios and elimination of the concern for the radiation degradation of the reflector.

GaAs EOTV

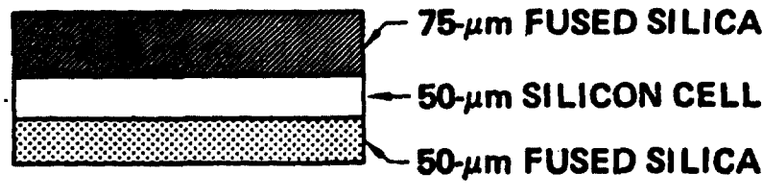
- Reasons for consideration
  - Higher cell performance
  - Lower mass/m^2
  - Better resistance to radiation
- Key factor in evaluation
  - Cost/m^2
- Key assumptions
  - Payload
    - Up = 4,000 MT
    - Down = 200 MT
  - Configuration concentration ratio = 1

BLANKET DESIGN CHARACTERISTICS

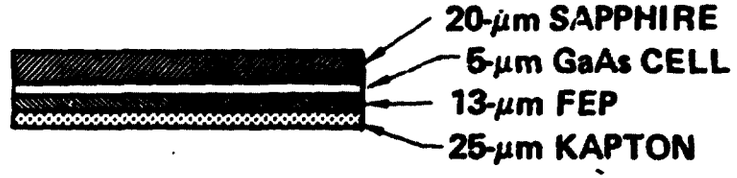
The makeup of the silicon blanket and gallium arsenide blankets are indicated with the gallium arsenide blanket being that as defined by Rockwell International for Marshall Space Flight Center. As indicated, the gallium arsenide blanket provides an improvement in terms of the efficiency and power output (before radiation is applied to the blanket) and for the basic blanket as defined by Rockwell, a considerable mass per square meter improvement over the silicon blanket. A second mass per square meter value is indicated for the gallium arsenide blanket that uses a 40 micron covergalss rather than a 20 micron coverglass. This option has been included in an attempt to provide better radiation characteristics for the gallium arsenide blanket.

Blanket Design Characteristics

SILICON BLANKET



GaAs BLANKET (RI BASELINE)

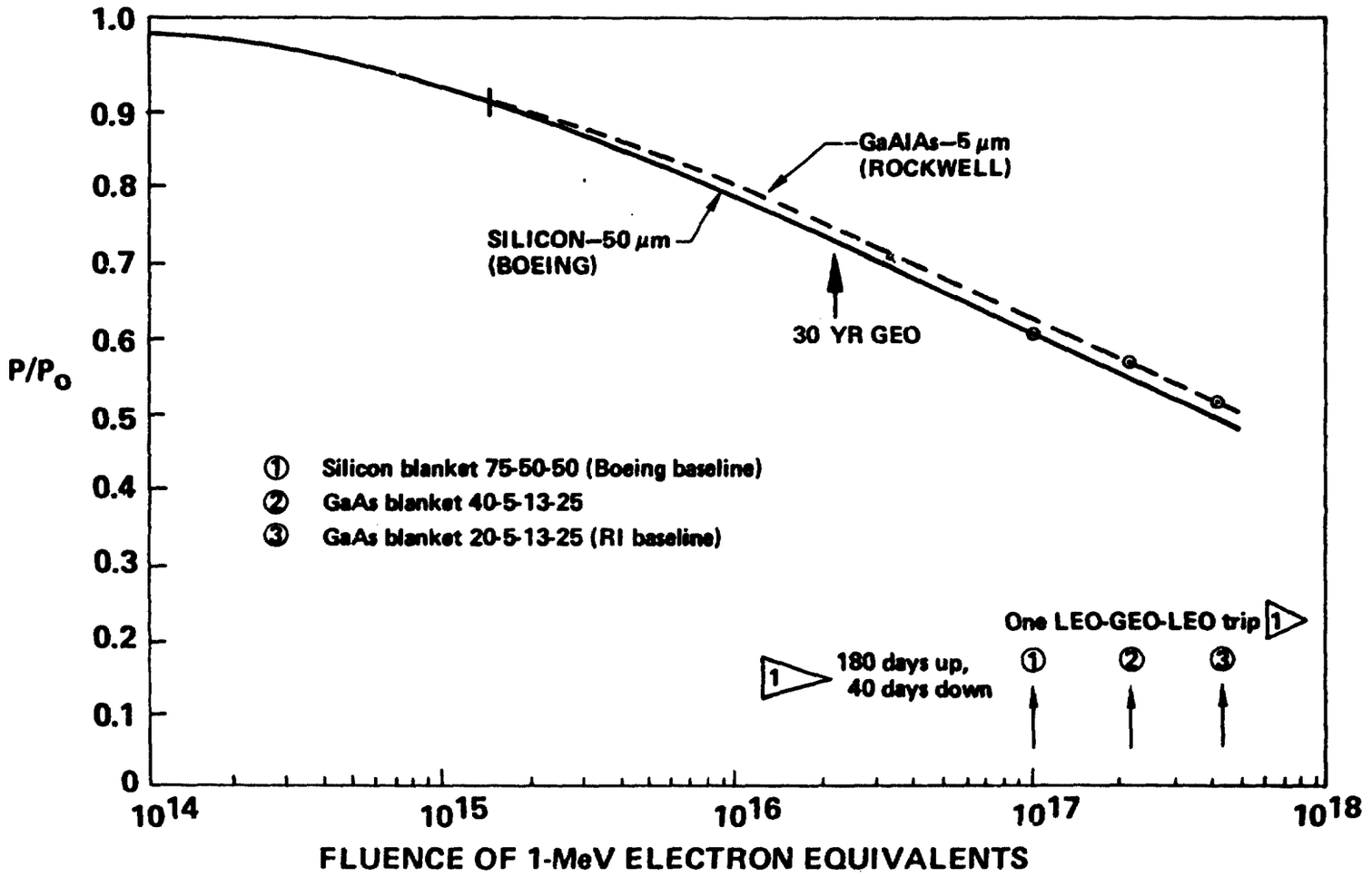


• Efficiency: 17.3%	19% TO 20%
• Power output: 197 W/m^2	237 W/m^2
• Mass (without growth: 0.427 kg/m^2)	0.252 kg/m^2 (20 - 5 - 13 - 25) 0.412 kg/m^2 (40 - 5 - 13 - 25)

SOLAR CELL RADIATION SENSITIVITY

The comparison of the power output of these two blankets as a function of fluence they will experience is indicated. The gallium arsenide prediction is taken directly from the Rockwell/MSFC study whereas the silicon cell data relates to that used by Boeing in the definition of the satellite. As would be expected, the gallium arsenide cell for a given amount of fluence provides a small power output benefit over the silicon cell. However, what is important is how the complete blanket performs when exposed to the orbit transfer environment. In the lower righthand portion of this chart are indicated the fluence levels expected to be experienced by the two blankets for 180 days uptrip and a 40 day downtrip. In the case of the silicon blanket, one round trip will provide about 10^{17} equivalents of 1 MeV electrons, which results in a power output of approximately 60%. Should the basic gallium arsenide blanket (20 micron coverglass) be used, a fluence level of approximately 4.4×10^{17} will be experienced resulting in a 52% power output value. This explains the rationale for investigating a thicker coverglass. The blanket considered was one using a 40 micron coverglass (Option 2) which experienced 2.2×10^{17} of fluence, resulting in a 58% power output, but still lower than the 60% provided by the silicon blanket. This also suggests that additional shielding around the gallium arsenide cell may be beneficial for the orbit transfer operations.

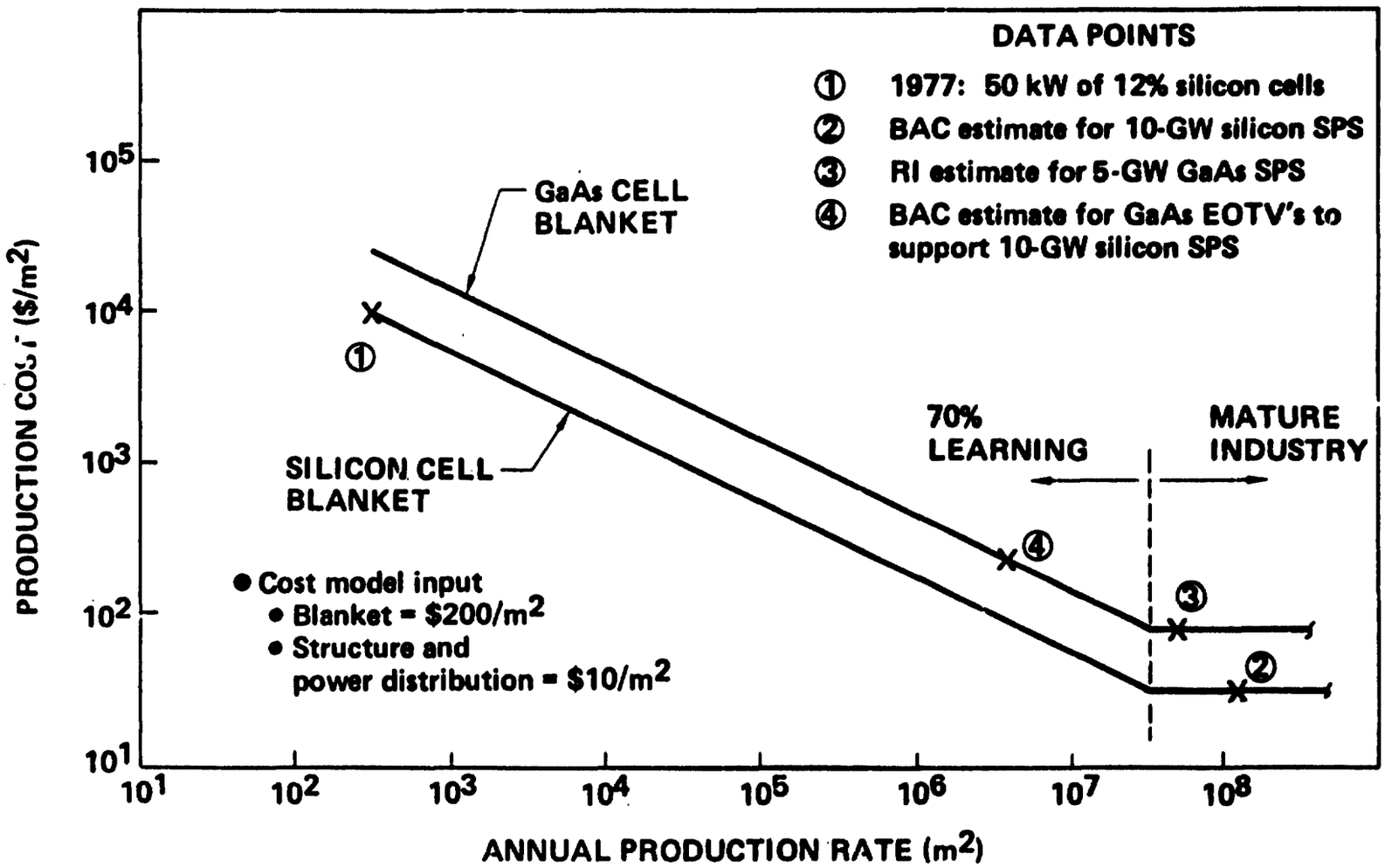
Solar Cell Radiation Sensitivity



GALLIUM ARSENIDE BLANKET COST

As suggested earlier, a key factor in assessing the benefits of the gallium arsenide EOTV as compared to silicon is the cost that must be paid per square meter. The method used to achieve this value is illustrated and includes a plot of production cost per square meter as a function of the annual production rate. The silicon cell blanket curve is indicated and again it is the same as what has been used in the past analysis of the Boeing silicon satellite. This curve is established by beginning with 50 kilowatts of solar array being produced in 1977 and following a 70% learning curve down to the point where the cost is approximately two times the material cost of the solar array at which point no further learning is possible and thereafter the cost per square meter will be the same regardless of the production rate. In the case of the 10 gigawatt silicon satellite indicated by Point 2, the basic cost is about $44 per square meter. The data point (#3) used to establish the gallium arsenide blanket cost was that predicted by Rockwell in their study for MSFC where approximately 52 million square meters of gallium arsenide solar array was produced per year at a cost of $71 per square meter. It was also assumed that the production rate resulting in mature industry cost would be the same as that for the silicon blanket. The quantity of the cell required for the gallium arsenide EOTV was established by taking the total fleet requirements and dividing equally over the seven years of operating life and adding a 20% margin per year. As a result, approximately 3.8 million square meters of the gallium arsenide blanket were produced per year, resulting in a cost of approximately $200 per square meter. That combined with the $10 per square meter associated with the structure and power distribution of the gallium arsenide EOTV resulted in a total of $210 per square meter versus approximately $60 per square meter for a silicon blanket EOTV that used a [illegible] 10 centimeter cell.

GaAs Blanket Cost



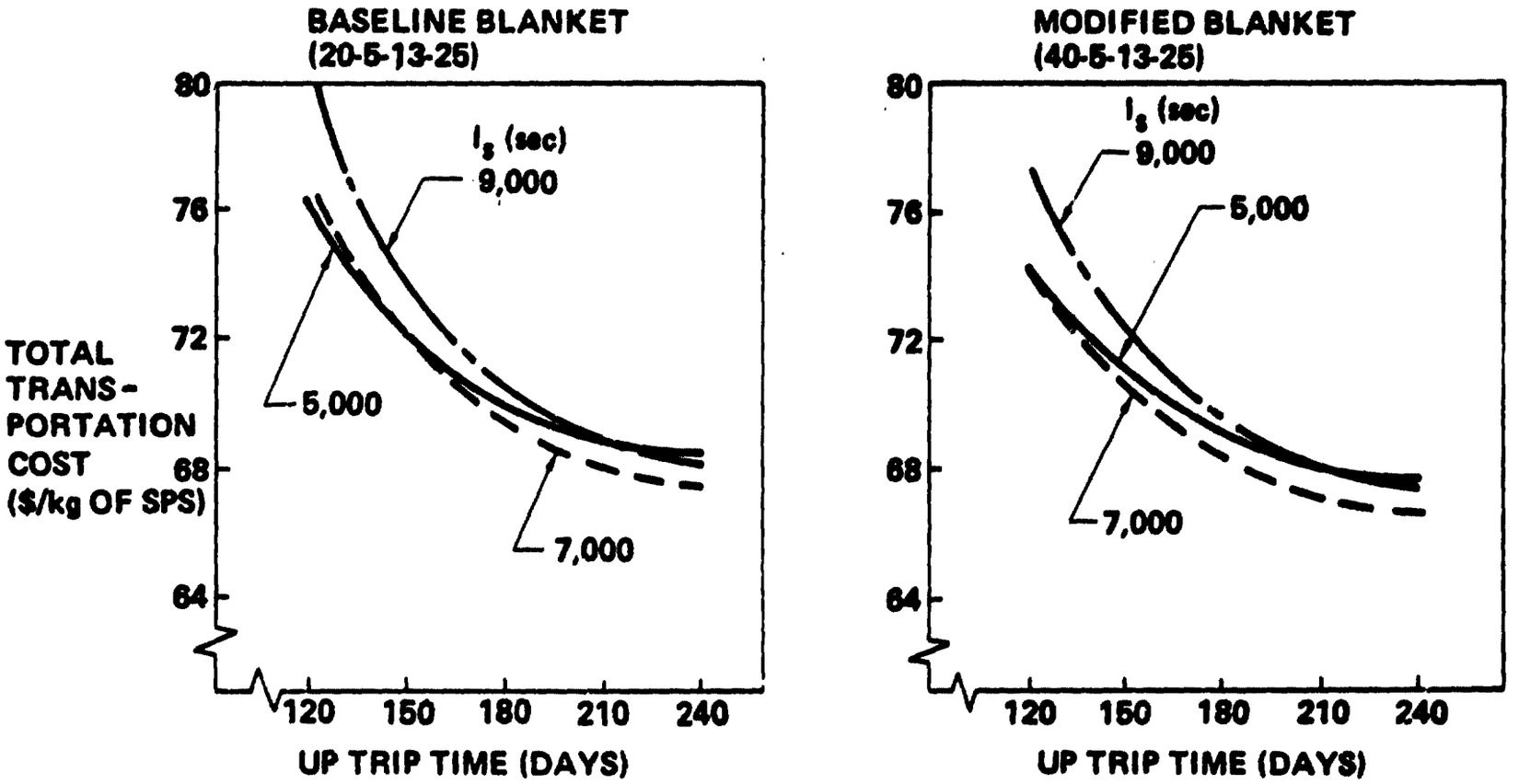
COST OPTIMIZATION

Gallium Arsenide EOTV

The transportation cost optimization of the two gallium arsenide blanket EOTV designs is indicated. In both cases, an ISP of 7,000 seconds and up trip time of 240 days is optimum with the modified blanket using a 40 micron coverglass providing an advantage of approximately $2 per kilogram of SPS. Further design and cost characteristics associated with these optimizations are presented in the two following charts.

Cost Optimization
GaAs EOTV

SPS-2424



EOTV DESIGN CHARACTERISTICS

Key characteristics which result from the optimization shown on the previous chart are indicated for both the gallium arsenide EOTV and the silicon EOTV. In terms of optimization, the key features are that of the specific impulse and trip time. As indicated, the baseline silicon EOTV uses a higher specific impulse and shorter trip time which will influence both electric power requirements, the degradation and eventually the propellant requirements for the EOTV. Also included in order to provide a direct comparison in terms of these parameters is an EOTV with the same trip times and specific impulses as the GaAs EOTV. In terms of design characteristics, the baseline EOTV has electric sizing power requirements considerably greater primarily because of its higher ISP and faster trip time. Power remaining after one round trip, however, is the highest for the silicon baseline for the reasons indicated on a preceding chart discussing radiation sensitivity. The design power required for the concepts reflect the basic electric power requirement to drive the electric thrusters, I^2R losses and also oversizing to cover the initial degradation. Array area requirements reflect the design power required as well as the power output of each square meter of the array. Empty mass characteristics includes the power generation distribution system and the electric propulsion system elements but excludes propellant.

EOTV Design Characteristics

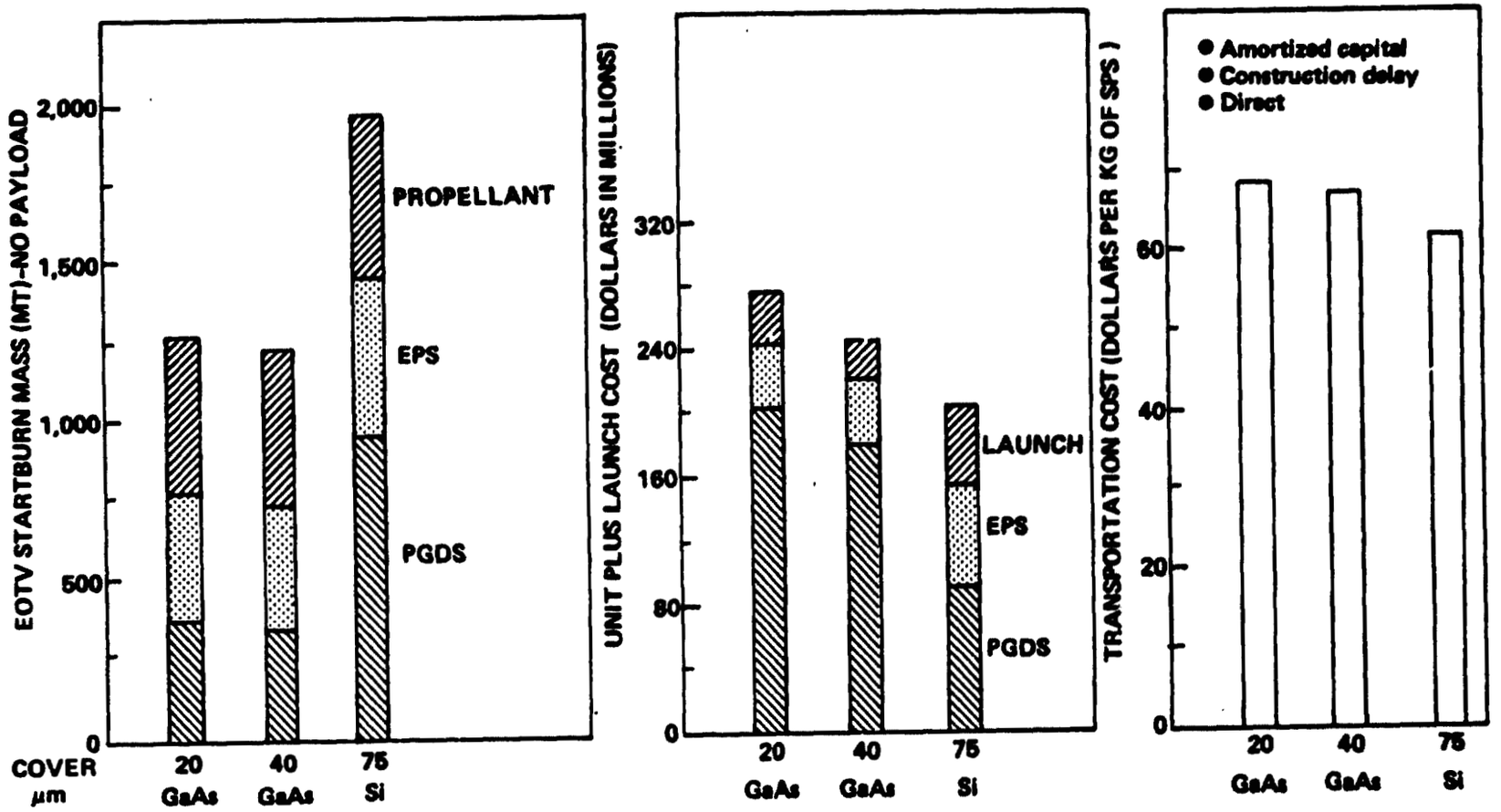
	GaAs EOTV		Silicon EOTV 75-50-50 blanket	
	Basic blanket 20-5-13-25	Modified blanket 40-5-13-25	Baseline	Direct Comparison
• Optimization				
• I_s (sec)	7,000	7,000	8,000	7,000
• Trip time up (days)	240	240	180	240
• Trip time down (days)	37	37	47	49
• Design characteristics				
• Electric sizing power (MW)	125	118	182	115
• P/P_0 after one round trip (%)	48	52	58	56
• Design power (MW)	230	203	296	187
• Array area (km^2)	0.97	0.85	1.5	0.95
• Empty mass (MT)	767	718	1,457	957

EOTV COMPARISON
Silicon vs. Gallium Arsenide

Comparison of the two EOTV's is examined in more detail through use of mass, unit cost and total transportation cost. In the case of mass, the silicon EOTV solar array is heavier per square meter and there is less power per square meter resulting in a much heavier vehicle. Propellant requirements are also larger due to the greater empty mass of the vehicle. Unit cost of the three candidates, however, show a benefit to the silicon EOTV primarily as a result of the cost per square meter of the array being approximately 1/4 that of the gallium arsenide blanket. The electric propulsion system, however, on the silicon system is greater because of the greater start burn mass of the system which also explains the higher launch cost. The total transportation cost amortizes the capital investment (unit cost plus launch of the EOTV's), and results in the silicon EOTV providing a savings of approximately $7 per kilogram of SPS over the baseline gallium arsenide and about a $6 per kilogram improvement over gallium arsenide with a thicker coverglass.

EOTV Comparison
Silicon Versus GaAs

SPS-2426



EOTV SOLAR ARRAY SUMMARY

With the level of definition conducted to date, the silicon cell blanket with 3 mil coverglass is recommended as the preferred solar array for the EOTV. Should future analysis indicate less optimism regarding radiation damage to the solar array and its recovery with the annealing, the 6 mil coverglass may require reassessment. The gallium arsenide cell with minimum coverglass does not appear to be worthwhile for orbit transfer operations. Again future analysis concerning radiation effects on the blanket may provide the rationale for investigating GaAs blankets with thicker coverglasses. Consequently, the EOTV to be further defined and updated for eventual comparison with the LEO construction option will be that employing a silicon 3 mil coverglass blanket.

This analysis considered the possibility of using a gallium arsenide EOTV to support a silicon satellite. Clearly, if gallium arsenide were selected for the satellite, it would also be the lobical choice for the EOTV.

EOTV Solar Array Summary

- SILICON CELL WITH 3 MIL COVER IS PREFERRED
- SILICON WITH 6 MIL COVER TO BE REASSESSED IF RADIATION RECOVERY IS LESS THAN ANTICIPATED
- GaAs CELL COVER AS DEFINED FOR GEO SATELLITE NOT ADEQUATE
- GaAs CELL WITH THICKER COVER ALSO TO BE REASSESSED IF RADIATION RECOVERY IS LESS THAN ANTICIPATED

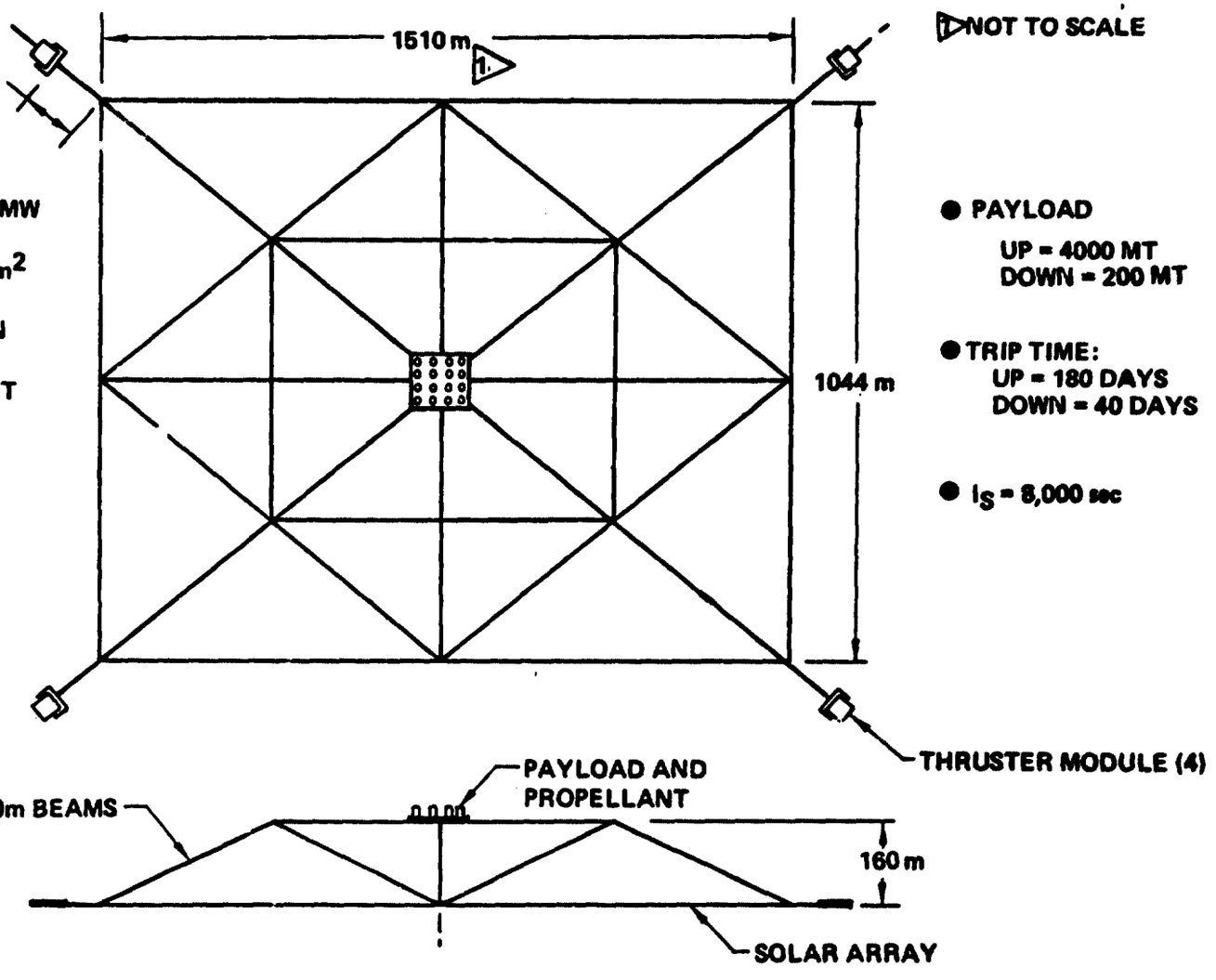
ELECTRIC OTV CONFIGURATION UPDATE

The selected electric OTV configuration consists of four independent solar array bays, each providing power to a thruster module. The overall dimensions of this configuration have been increased since mid-term as a result of the increases in the initial power requirements to perform the mission. Most notably this means the increase of power from 230 megawatts at mid-term up to 296 megawatts for the final configuration. This factor has increased the area from 1.2 up to 1.5 square kilometers and accordingly has changed the large dimension of the configuration from 1.2 kilometers to 1.5 kilometers. The width of the configuration has remained at approximately 1.044 kilometers since the dimension of each bay is determined by the cell size and the voltage requirements of the thrusters with the optimum voltage being 2765 when considering I^2R and plasma losses. Accordingly, the empty mass of the vehicle has gone from 1200 metric tons to 1462 metric tons resulting in an increase in electric thrust from approximately 3000 Newtons total to 3345 Newtons. Propellant requirements have changed very little from the mid-term.

Electric OTV Configuration Update

SPS-2423A

- INITIAL POWER = 296 MW
- ARRAY AREA = 1.5 Km^2
- ELEC THRUST = 3345 N
- EMPTY MASS = 1462 MT
- ARGON = 469 MT
- LO_2/LH_2 = 46 MT



NOT TO SCALE

- PAYLOAD
  UP = 4000 MT
  DOWN = 200 MT
- TRIP TIME:
  UP = 180 DAYS
  DOWN = 40 DAYS
- I_S = 8,000 sec

EOTV MASS SUMMARY UPDATE

The empty mass for the configuration is shown for both mid-term and final values. The most significant change has been that associated with the solar array mass, which has been increased for the reasons indicated with the most notably being the more accurate model reflecting the power requirements for I^2R losses, storage provisions, changing power conditioning efficiencies as a result of using solid state equipment rather than motor generator equipment and also a revision in the radiation degradation analysis. These changes to the solar array, in turn, have reflected or resulted in changes in all other elements of the vehicle resulting in approximately a 300 metric ton increase over the mid-term values. Accordingly, the startburn mass also reflects a 300 metric ton increase over the mid-term value.

EOTV Mass Summary Update

ITEM	• EMPTY MASS (M.T.) MIDTERM	FINAL
POWER GEN & DISTRIB	(736)	(951)
SOLAR ARRAY	608	780 1
STRUCTURE	95	122
DISTRIBUTION	33	42
ENERGY STORAGE	–	7
ELECTRIC PROPULSION	(447)	(496)
THRUSTERS	71	79
POWER CONDITIONING	195	219
THERMAL CONT	55	88
STRUCT/MECH	80	61
PROPELLANT FEED SYS	46	49
AUXILIARY SYSTEMS	(12)	(15)
TOTAL	1195	1462

• STARTBURN MASS (M.T.)

PAYLOAD	4000
EMPTY	1462
PROPELLANT	
ARGON	469
LO_2LH_2	46
	5977

1 MORE ACCURATE MODEL
- POWER REQ'T ADDITIONS
  - I^2R & STORAGE
  - PPU EFF
  - REVISED RADIATION DATA
- ARRAY AREA
  - BASED ON DESIGN POWER NOT ELEC
- OTHER CHANGES ARE RESULT OF 1

EOTV COSTING GUIDELINES

The guidelines used to establish more accurate EOTV costs than that shown at the mid-term are indicated. The fleet size and amortization period are the same as was used for mid-term. The chief difference in costing, however, deals with the method in which the costing was done. At the mid-term, a scaling relationship was used where the power generation and distribution system cost was scaled to similar systems of the satellite and the electric propulsion system cost for the EOTV was scaled to costs associated with the selfpower orbit transfer systems. As such, this scaling method presented an optimisitc cost primarily because of using a component production rate much higher than that possible when amortizing the hardware over a number of years. The final costing of the EOTV, included establishing detailed first unit costs using component mass and quantities directly associated with a single EOTV. These TFU costs were then used in conjunction with the annual production rate of the components for the entire EOTV fleet to establish the average cost of an EOTV.

EOTV Costing Guidelines

	MIDTERM	FINAL
• FLEET SIZE	23	23
• AMORTIZATION PERIOD (YR)	7	7
• FLIGHT [illegible] T COST	SCALING	DETAILED MODELING • DETAIL TFU MASS & QUANTITY • AVG. TO REFLECT COMPONENT ANNUAL PRODUCTION RATE
• POWER GEN & DISTRIB	SCALE TO SATELLITE ($95/KG)	
ARRAY CONTRIB	$44/M^2	$53/M^2 DUE TO 5 X10 CM CELL
• ELECTRIC PROPULSION	SCALE TO SELF POWER OTS ($117/KG)	
• PROGRAMMATIC	NOT CONSIDERED	CONSIDER

COMPONENT ANNUAL PRODUCTION RATE

This chart shows the influence of amortizing or spreading out the total hardware requirements over the operating life of the system. In the case of the GEO construction concept, the total components for the 23 vehicles has been spread out equally over 7 years of its operating life with an additional 20% added to the annual requirement to cover manufacturing problems, etc. As indicated, nearly all components for the GEO/EOTV case reflect a significant decrease in the annual production rate, which will eventually reflect in the average unit cost of the EOTV's.

Component Annual Production Rate

SPS-2481

KEY COMPONENT	ANNUAL PRODUCTION RATE (UNITS)		
	LEO/SPM	GEO/EOTV	LEO/SPM/EOTV
THRUSTERS	26800	5340	
PPU'S	384 (1 PER 80 THRUSTERS)	534 (1 PER 10 THRUSTERS)	
SWITCHGEAR	1920	534	
INTERRUPTERS	26800	16500	
CABLING	192	30	
TANKS–ARGON	32	8	
GIMBALL ASSY	32	15	
AVIONICS			
COMMUN	32	15	
COMPUTER	32	15	
THERMAL CONT	384	15	
POWER DIST	160	105	
STANDOFF STRUCT	32	15	

SILICON EOTV COST UPDATE

The EOTV hardware and cost per flight numbers are presented. In the case of the hardware costs, both mid-term and final costs are presented. The final flight unit cost have almost doubled from that of the mid-term, reflecting the influence of the lower production rate. The power generation and distribution system has not increased as much as electric propulsion system primarily because the solar array, which is the largest contributor, was and still is being costed on a mature industry basis with the increase over preceding mid-term values primarily the result of the 20% penalty paid for using the 5 x 10 centimeter cell and also the 21% cost growth factor. Electric propulsion costs, are greater by almost a factor of 3 and reflect a significant difference in the cost for individual elements as a result of lower production rate. As indicated earlier, programmatic costs were not indicated in the mid-term. On a cost per flight basis, including amortization of the capital, the change from the mid-term has been approximately $30 million per flight.

Silicon EOTV Cost Update

SPS-2483

- COST IN MILLIONS

EOTV HARDWARE

	PART 1 MIDTERM	PART 1 FINAL
• FLIGHT UNIT	(124)	(247)
• POWER GEN & DISTRIB	(69.9)	(99.7)
SOLAR ARRAY		79.6
STRUCTURE		12.1
DISTRIBUTION		1.6
ENERGY STORAGE		6.4
• ELECTRIC PROPULSION	(52.7)	(141)
THRUSTERS		15.4
POWER COND.		87.2
THERMAL CONTROL		22.1
STRUCT/MECH		11.3
PROPELLANT SYS		5.0
• AVIONICS	(1.0)	(6.5)
• PROGRAMMATIC		(36.6)

COST PER FLIGHT

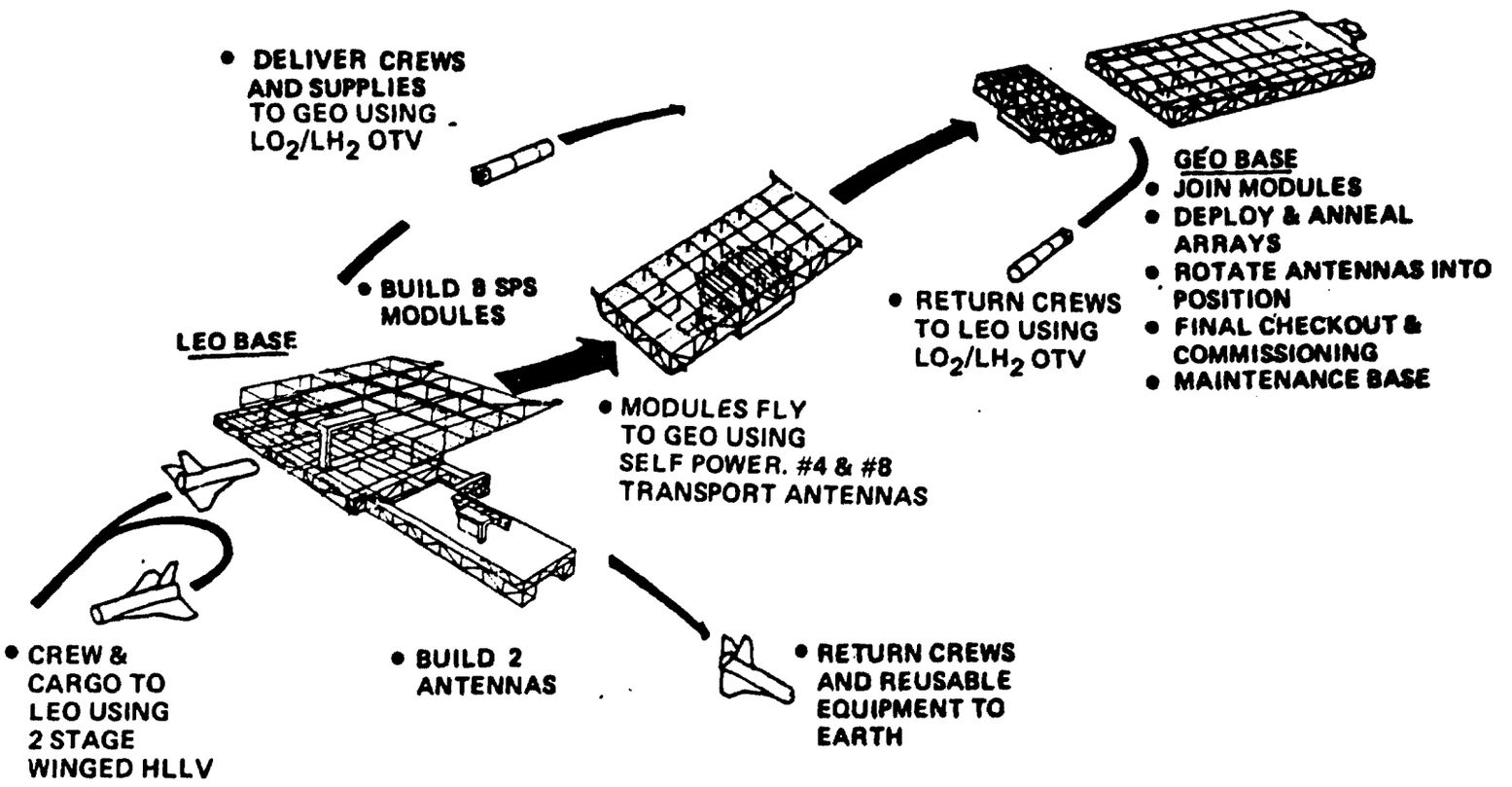
	BASIC	AMORT.
• CAPITAL	(347)	(52)
• EOTV HRDW	284	
• EOTV LAUNCH	54	
• CONST BASE	13	
• DIRECT		(29)
• REFUEL		19
• REFURB		10
• CONST TIME DELAY		(18)
• PAYLOAD LAUNCH		(148)
TOTAL		247

LEO CONSTRUCTION CONCEPT
SELF-POWER MODULES

This concept has been discussed extensively in documentation associated with JSC/Boeing contract NAS9-15196 The chart illustrates the overall construction and operation scenario associated with the LEO construction concept. In terms of transporting the satellite, eight separate modules are constructed in low Earth orbit with portions of the solar array deployed to provide power necessary to drive the electric thrusters that propel the vehicle to GEO where the modules are joined together to form the total satellite.

Several improvements have been considered for this concept. The first deals with improving the overall module configuration for the transfer operation. The second considers the cost benefits that might occur through recovery of the electric propulsion components and their subsequent reuse. Both of these improvements will be discussed on subsequent charts.

LEO Construction Concept
Self Power Modules

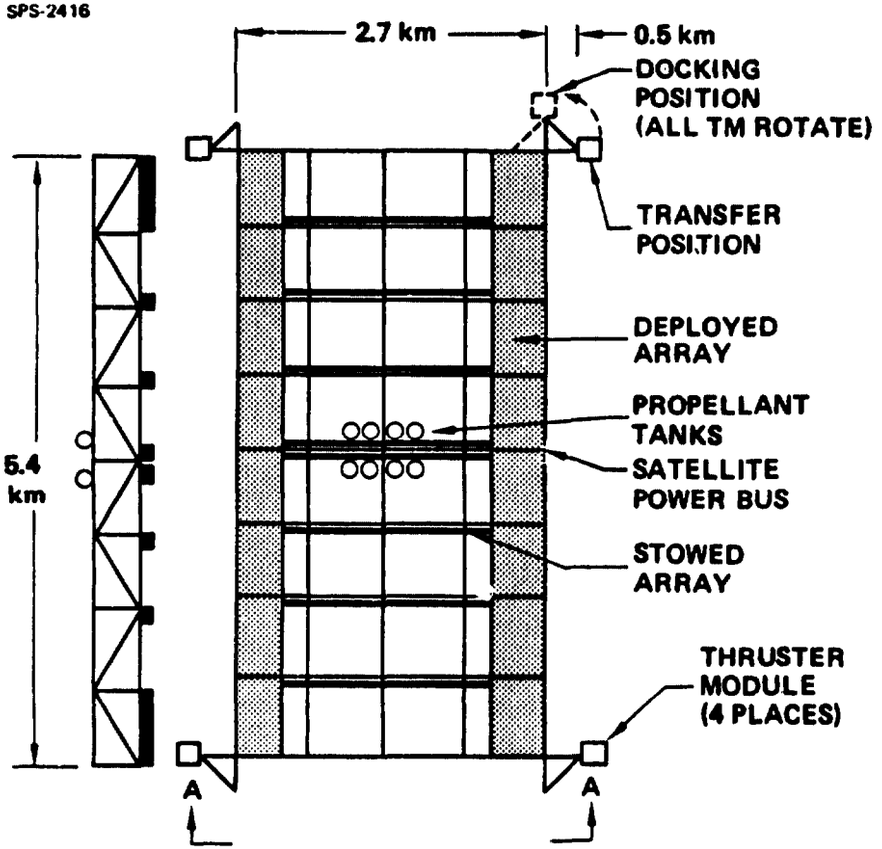


SELF-POWER CONFIGURATION
Photovoltaic Satellite

In an attempt to reduce the gravity gradient torque requirements and thereby reduce the propellant requirements several configuration changes have been incorporated. The first of these deals with the location of the deployed solar array. Prior self-power module configurations had the solar array deployed at both ends of the module and parallel with the x-axis. The new configuration however has the arrays deployed along the y-axis of the configuration and along both sides. This not only improves the moment of inertia characteristics of the configuration, but also eliminates the mismatch between cells that occurred with the previous deployment since some cells in the string had been exposed to radiation and others were not. The other change resulting in better moment of inertia characteristics and eventually lower gravity gradient torque penalty was that of positioning the thruster modules out along the X axis rather than the Y axis for the orbit transfer. Once GEO is reached, the thruster modules are rotated into a position where they are along the Y axis so no interference occurs during docking of one module to the other. The overall impact of the improved moment of inertia characteristics is that the propellant requirements decreased from about 34 million kilograms per satellite down to 29 kilograms per satellite.

Self-Power Configuration Photovoltaic Satellite

SPS-2416

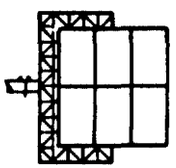


GENERAL CHARACTERISTICS

- 3% oversizing (radiation)
- Trip time = 140 days
- I_{SP} = 7,000 sec

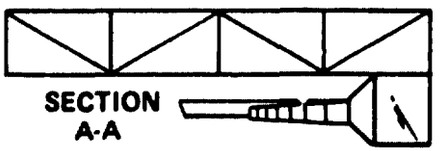
MODULE CHARACTERISTICS	NO ANTENNA	WITH ANTENNA
• Number of modules	6	2
• Module mass (10^6 kg)	8.7	23.7
• Power required (10^6 kW)	0.3	0.81
• Array (%)	13	36
• OTS dry (10^6 kg)	1.1	2.9
• Argon (10^6 kg)	1.0	5.1
• LO_2/LH_2 (10^6 kg)	1.4	2.2
• Electrical thrust (10^3 N) [1]	4.5	12.2
• Chemical thrust (10^3 N)	12.0	8.0

[1] 20% additional thrust available for GGT and thrust vector control



	NO ANTENNA	ANTENNA
Panel size:	24x38m	48x57m
Thrusters:	600	1,600

MODULE WITH ANTENNA



OTS RECOVERY MOTIVATION

The chief reason for considering recovery of the electric orbit transfer system components is the fact that there are approximately 1.3 billion dollars of components for each 10 GWe satellite. Consequently, each component has been investigated for its cost in terms of dollar per kilogram of value and for the ease in which it could be removed. Those components judged to be good candidates include the thrusters, processing units, gimbals, avionics and propellant tanks. Recovery of these components would result in 87% of the unit cost and 56% of the mass of the electric transfer system.

OTS Recovery Motivation

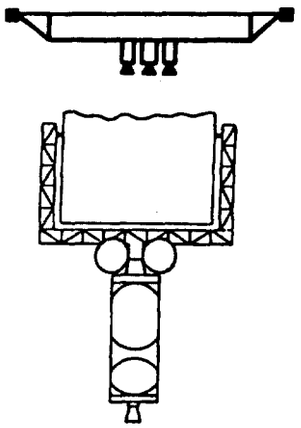
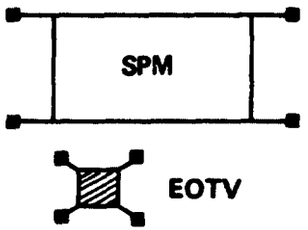
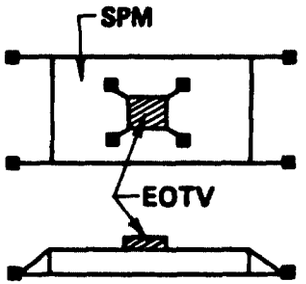
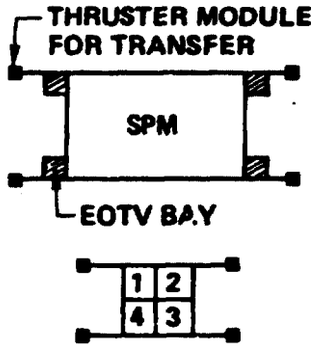
OTS components	One satellite per year			
	Cost($M)	Mass (10^6 kg)	$/kg	Recovery
Thruster panel thrusters, PPU, switchgear, yoke, interrupters	815	6.14	132	Yes
Gimbal	133	0.09	1,477	Yes
Avionics	46	0.003	15,300	Yes
Tanks	149	0.4	370	Yes
Standoff structure	35	0.6	58	No, low value
Propellant feed system	16	0.58	28	No, integral
Thermal control	98	1.0	98	No, attach to standoff
Power distribution	22	3.0	7	No, integral
Total	1,314	11.8		
Recovery %	87	56		

RECOVERY SYSTEM OPTIONS

Several methods have been considered in the past for the recovery of electric orbit transfer systems. Prior analysis by Boeing has considered the use of LO_2/LH_2 orbit transfer vehicles for the return of the components. The operating mode was to transfer up the OTV's piggyback on the self-power modules. Once GEO is reached, the electric propulsion elements would be attached to the chemical OTV's which would return the systems back to the LEO base where they would be refurbed and used on a subsequent self-power module. Chief disadvantage in this concept has been the long storage requirements for the LO_2/LH_2 requirements and the large propellant requirements for this type of system resulting in excessive launch cost. Another method of recovery is the use of small electric orbit transfer vehicles. Three different methods in employing this concept have been analyzed. The first of these is called the independent EOTV and consists simply of sending up a small EOTV independent of the self-power module. The second option has the EOTV sent up piggyback on the self-power module. Once GEO is reached, the components are placed on the EOTV and transferred back to LEO for refurb and reuse. The third method employs an EOTV concept that is more tightly integrated into the self-power module. In the case illustrated, the thruster modules of the EOTV would actually be used to propel the module to GEO. The thruster modules would be larger than that normally required for the EOTV operations by itself. The array of the EOTV would be used as well as a portion of the array of the self-power modules. Once GEO is reached, the four separate sectors of the EOTV must be reassembled to form an EOTV that can be transferred back down to LEO. The method selected for the recovery is that of the independent electric OTV, since it provides the most straightforward concept and the most flexibility at this point in time.

Recovery System Options

SPS-2421

	1 PIGGYBACK CHEMICAL OTV	2 INDEPENDENT EOTV	3 PIGGYBACK EOTV	4 INTEGRATED EOTV
				
				• FOUR BAYS ATTACH TO FORM RETURN EOTV
• CONCERNS/ COMPLEXITIES	• PROP STORAGE DURING UP TRIP	• MINIMUM	• ATTACHMENT OF EOTV TO SPM • LONGER ROUND TRIP FOR EOTV	• ASSY OF RETURN EOTV • POWER-BUS INTERFACE • STRUCTURE INTERFACE
• COST CONSIDERATION	• LARGE PROP REQ'T • LOW OTS PROD. RATE—HIGH UNIT COST	• LOWEST	• MORE OTS UNITS REQ'D	• HIGHEST OF THE EOTV'S
		* SELECTED • MOST STRAIGHT FORWARD • MOST FLEXIBLE		

EOTV SIZING OPTIONS

Several options exist in terms of the size of the EOTV. These options are brought about by several different payload requirements associated with the modules. As noted, six of the eight modules have a recovery payload mass of approximately 550 metric tons, while two of the eight modules have OTS components that total 1650 metric tons. A detailed analysis has not been conducted on the three options indicated but Option 2 which sizes the EOTV to return the largest payload appears to a reasonable choice and will be used in the remainder of the OTS recovery analysis.

EOTV Sizing Options

SP 7420

• REQUIREMENTS

Module	OTS mass (10^6kg) to be recovered
1	0.55
2	0.55
3	0.55
4	1.65
5	0.55
6	0.55
7	0.55
8	1.65

• OPTIONS

1. Size for 0.55×10^6 kg
   - 1.65×10^6 kg payload required three EOTV's
   - Large number of EOTV's

√ 2. Size for 1.65×10^6 kg
   - Can bring down three 0.55×10^6 kg payloads

3. Have two sizes of EOTV:
   - One for 0.55×10^6 kg
   - One for 1.65×10^6 kg

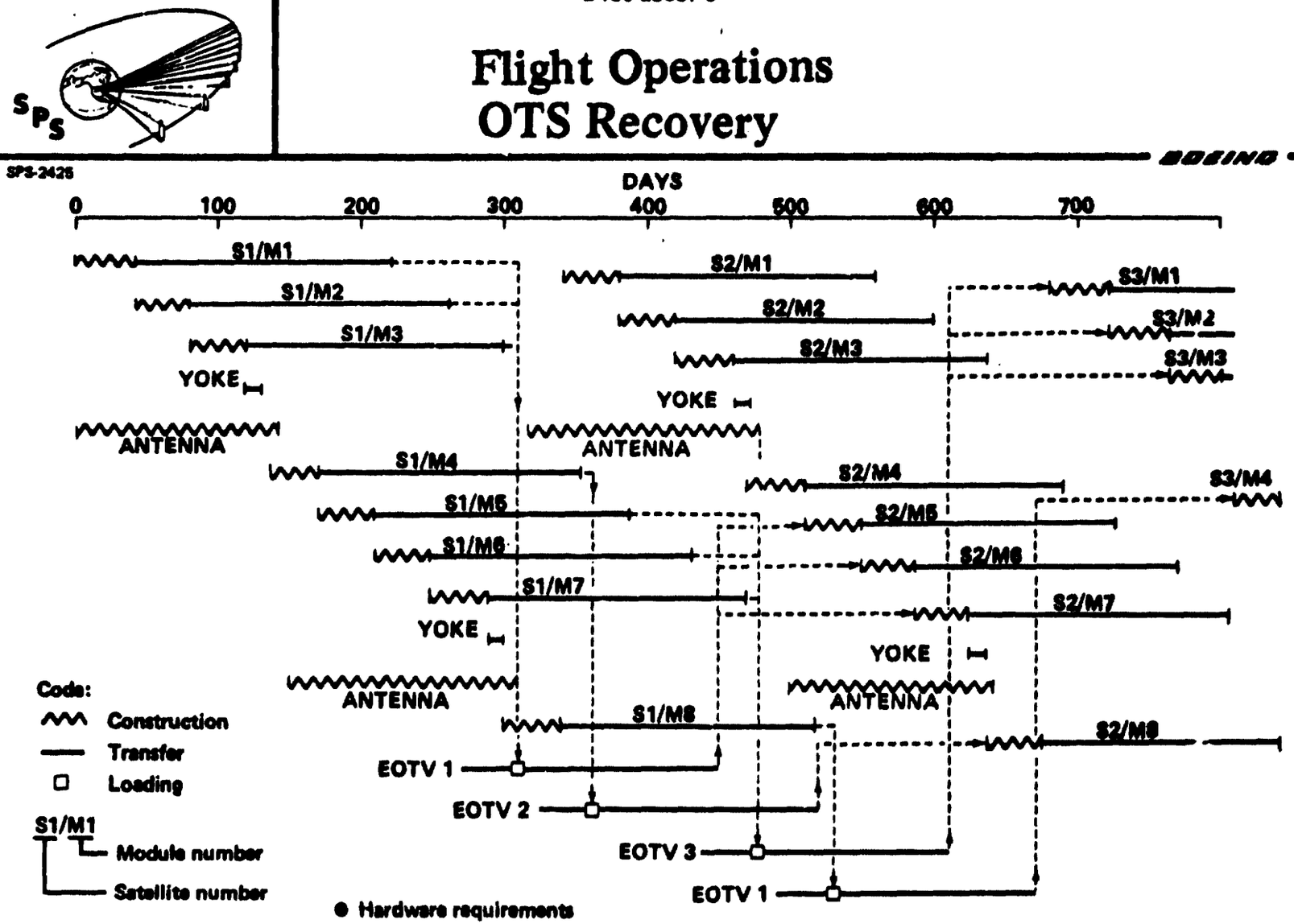
√ SELECTED

FLIGHT OPERATIONS

OTS Recovery

The flight operations schedule associated with use of independent electric orbit transfer vehicles for recovery of OTS systems is illustrated. This schedule includes that associated with the construction of the modules, the transfer of the modules and then at certain times the storage of the OTS requirements that are to be recovered. For example, components for the first three modules of the first satellite are removed from their modules and stored at the GEO base. Prior to the arrival of the third module at GEO, the first electric orbit transfer vehicle is sent to GEO. Once the EOTV reaches GEO, the components are loaded to form the full 1650 metric ton payload. That EOTV, then returns the components back to LEO where they are removed and taken to the LEO base for refurbishment and subsequent reuse. The fourth module of each satellite also transfers an antenna and consequently is a 1650 metric ton payload in itself. This requires a dedicated EOTV such as #2 to perform the recovery operations. The OTS units of satellite modules 5, 6 and 7 are also collected at GEO to form one payload package and are returned using the third electric orbit transfer vehicle. The OTS components of the eighth satellite module which also takes up an antenna is brought back through the use of the first EOTV. As can be seen from this schedule, module 1, 2, 3, and 4 of the second satellite cannot use any of the propulsion systems used on the first satellite modules. Consequently, they must also be provided with their own separate dedicated orbit transfer systems. As a result, the LEO construction concept using self power and recovery of the OTS components requires 12 modules of OTS equipment and three independent electric orbit transfer vehicles.

Flight Operations
OTS Recovery



- Hardware requirements
  - OTS for twelve modules
  - Three EOTV's

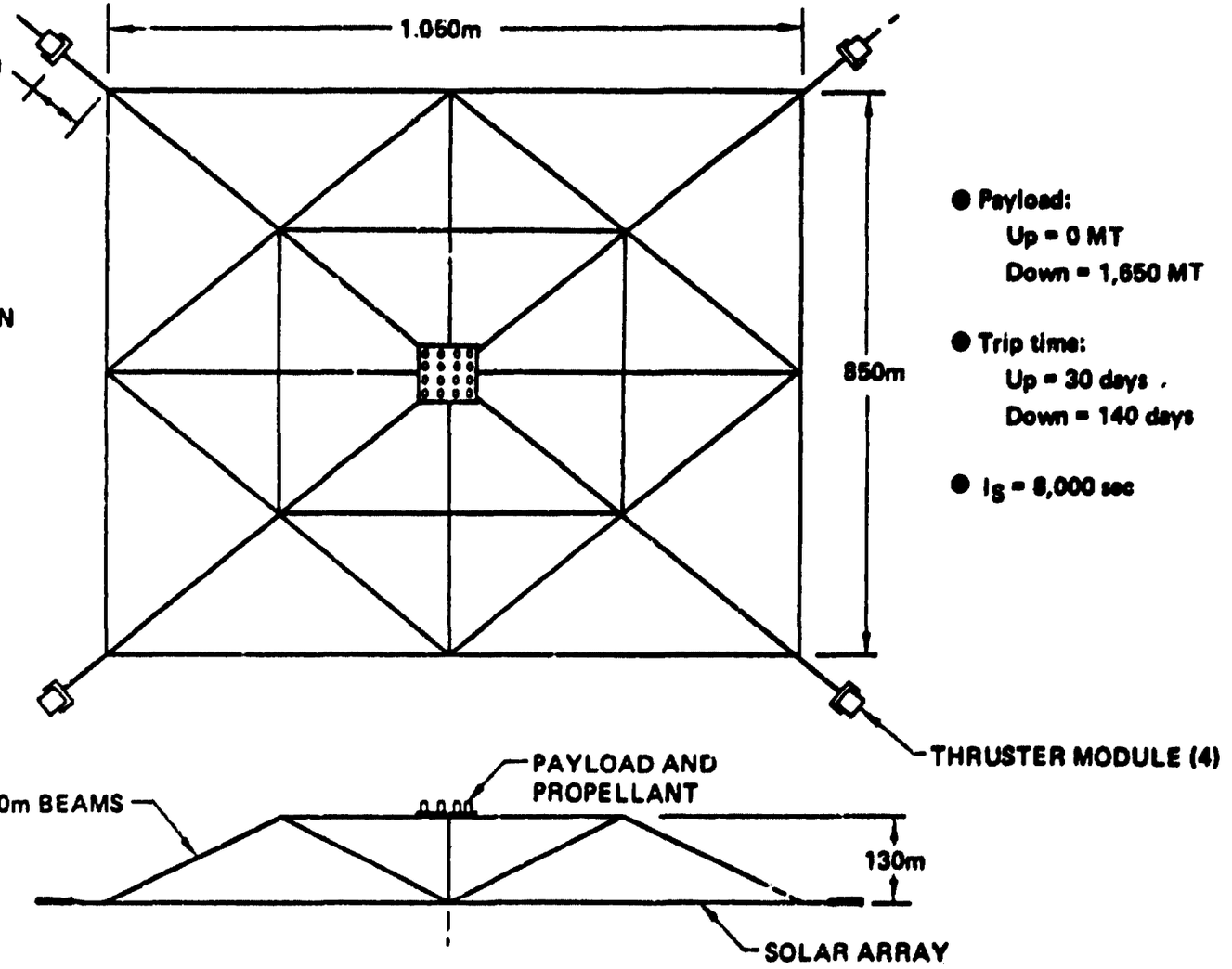
INDEPENDENT EOTV FOR SELF-POWER OTS RECOVERY

The configuration for the small independent electric orbit transfer vehicle is indicated. This configuration is generally the same as that for the EOTV used in the GEO construction concept. The primary difference has been that the payload requirements are smaller resulting in about 1/3 the power requirements and about 1/2 the solar array requirements resulting in a dry mass of 760 metric tons.

Independent EOTV for Self-Power OTS Recovery

SPS-2423

- Initial power = 122 MW
- Array area = 0.79 km^2
- Electrical thrust = 1,760N
- Dry mass = 760 MT
- Argon = 230 MT



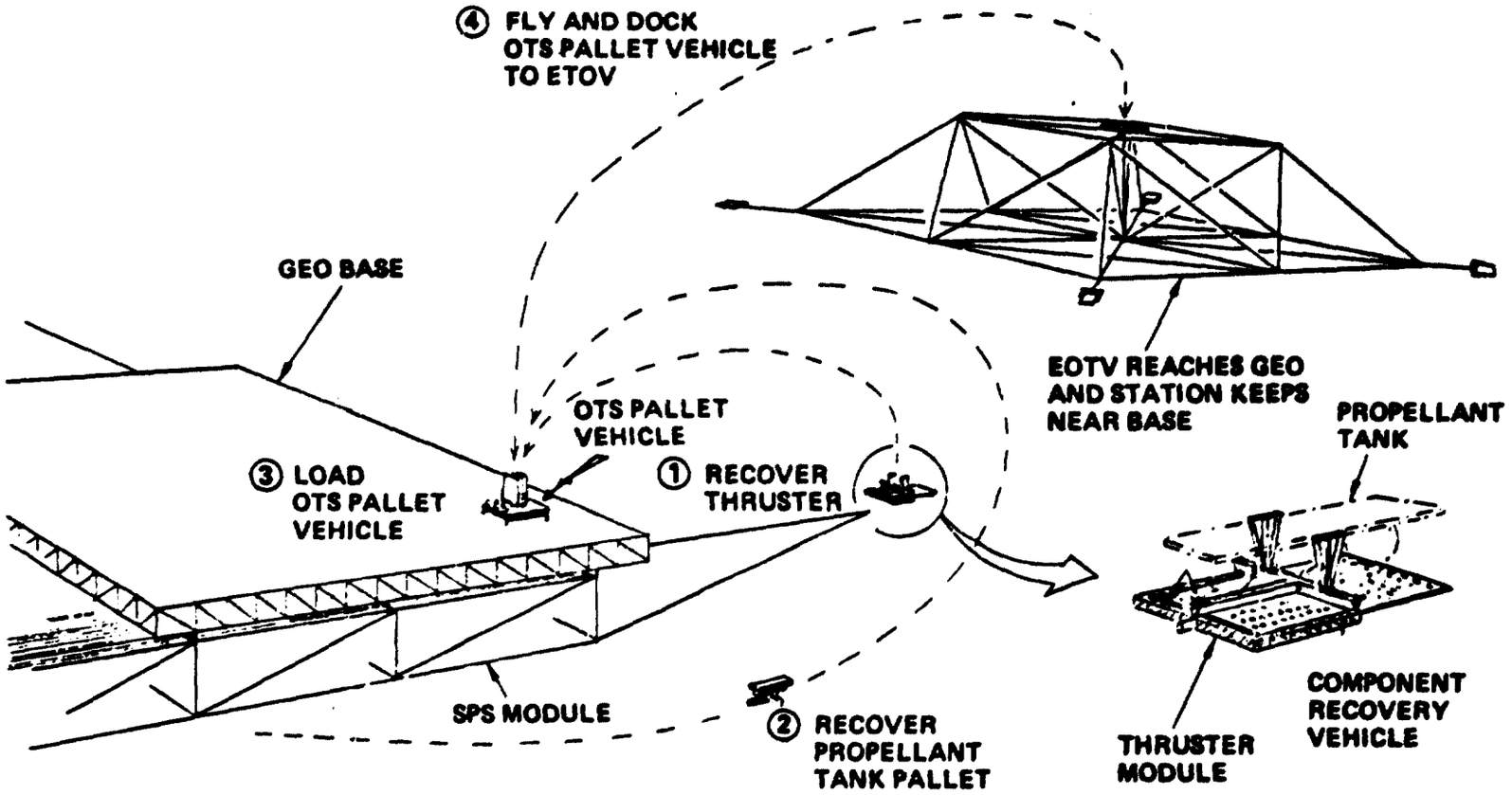
- Payload:
  Up = 0 MT
  Down = 1,650 MT
- Trip time:
  Up = 30 days
  Down = 140 days
- I_S = 8,000 sec

GEO OTS RECOVERY OPERATIONS

The primary operations associated with the recovery of the orbit transfer system elements at GEO are illustrated. Following the docking of the module with the already present modules, component recovery vehicles are flown out from the GEO base to the thruster modules of the self-power module. The complete thruster modules including gimbals are removed and flown back to GEO final assembly base where an OTS pallet vehicle is stationed. Propellant tanks are also removed as well as avionics, loaded on the transfer orbit pallet vehicle and flown to the EOTV which has been station keeping at a location near the GEO base.

GEO OTS Recovery Operations

SPS-2429

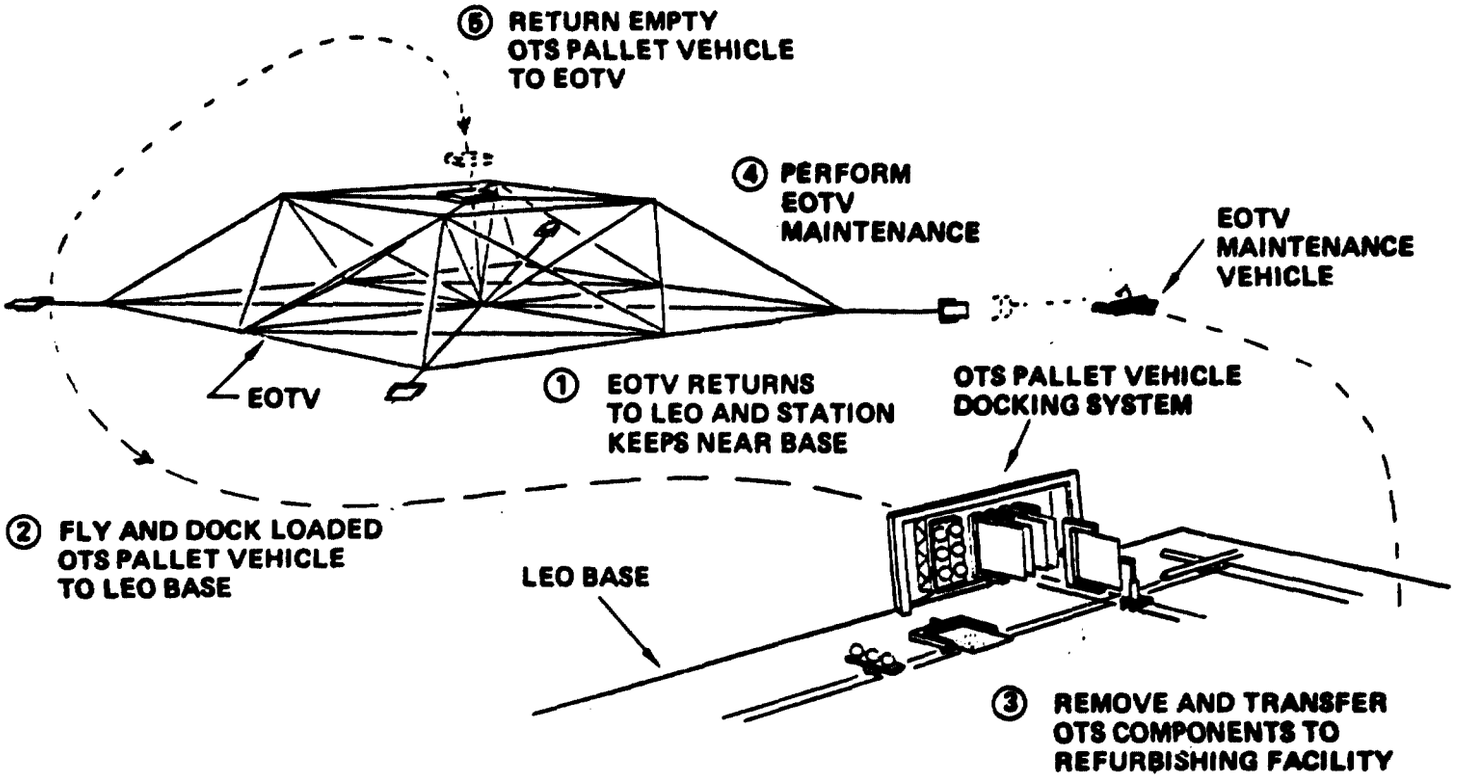


LEO OTS RECOVERY OPERATIONS

The EOTV returns to LEO at a location near the LEO construction base. The OTS pallet vehicle is then flown from EOTV over to the LEO base where components are removed and taken to the refurbishment facility. The empty OTS pallet is flown back to the EOTV for a subsequent trip to GEO. Meanwhile, maintenance vehicles from the LEO base are flown to the EOTV to perform maintenance on the thruster modules of that vehicle.

This concludes the definition of the improvements for the self power module concept. Cost for the concept will be presented as part of the overall comparison of the LEO versus GEO construction concepts which will occur in the following charts.

LEO OTS Recovery Operations



CONSTRUCTION LOCATION COMPARISON PARAMETERS

The parameters to be used comparing GEO construction using electric orbit transfer vehicles for SPS cargo delivery with LEO construction that uses self power transfer of satellite modules will use the parameters indicated.

Construction Location Comparison Parameters

PARAMETER

- CONSTRUCTION PREPARATION TIME
- SATELLITE DESIGN IMPACT
- ORBITAL BASES/CONST EQUIP
- CONSTRUCTION OPERATIONS
- CREW REQUIREMENTS
- ENVIRONMENTAL FACTORS
- ORBIT TRANSFER OPERATIONS
- LAUNCH OPERATIONS
- RISK/UNCERTAINTY
- COST
  - CONST PREPARATION
  - FIRST SATELLITE TRANSP.
  - AVERAGE PER SATELLITE

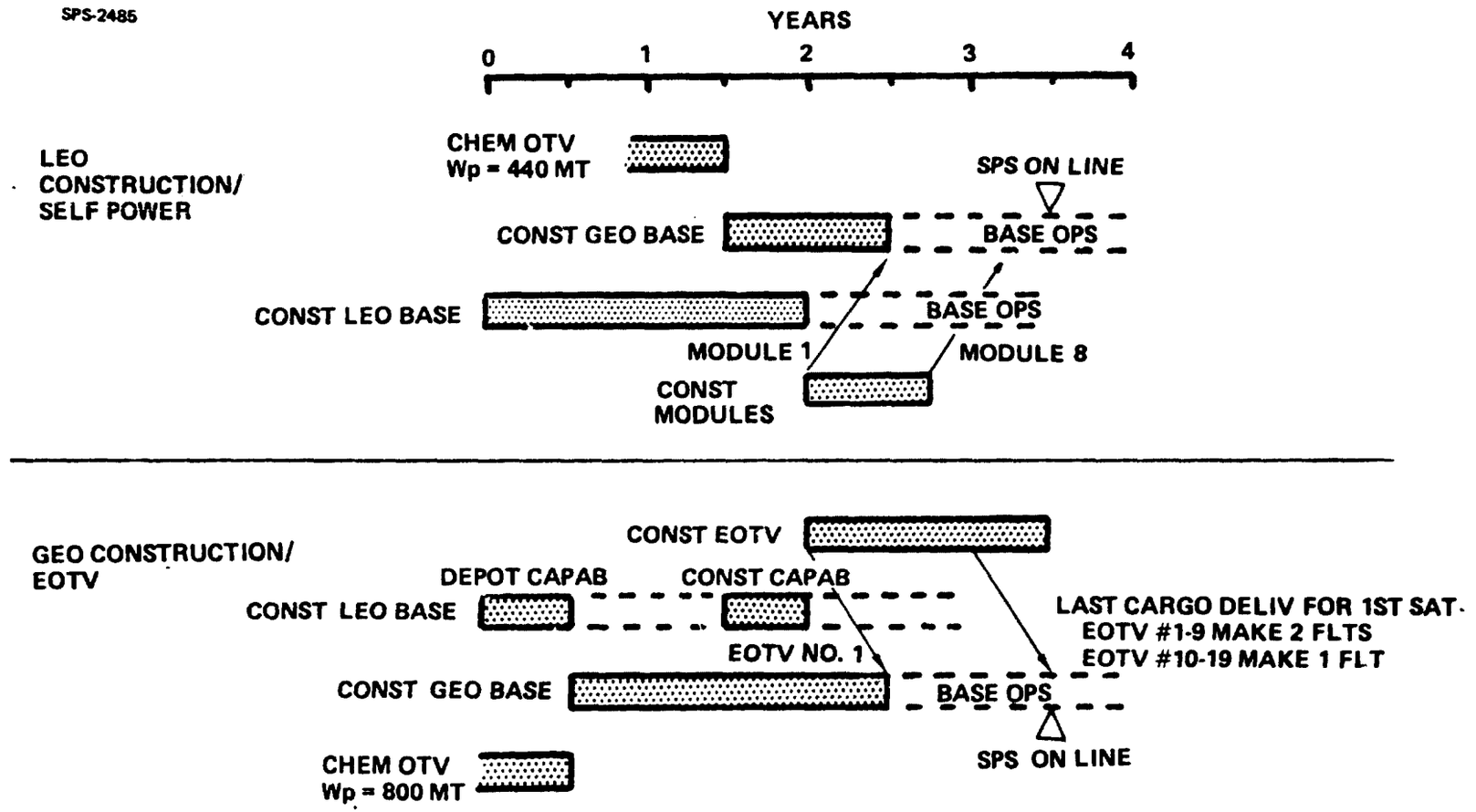
CONSTRUCTION PREPARATION

Initially it was thought that GEO construction using EOTV's for cargo delivery would require a longer preparation time in terms of when the first SPS can be put on line. Analysis indicates however that this method can have its system elements arranged in a manner that results in the first satellite coming on line at the same as the LEO construction method. The only difference between these two options at this point in time appears to be the time when the chemical orbit transfer vehicle must be available. For the case of the LEO construction concept, the chem (LO_2/LH_2) OTV is not required until approximately 1½ years after the first system element payload is launched and is used to support the construction of the GEO final assembly base.

In the case of GEO construction, the chem OTV must be available at the end of the first half year in order to provide the capability to deliver components of the satellite construction base which will be assembled at GEO. In addition to the difference in the availability date for the chem OTV, the GEO construction chem OTV will also be about twice as large in terms of propellant capacity.

Construction Preparation

SPS-2485



SATELLITE DESIGN IMPACT SUMMARY

Leo Construction

This chart indicates the key differences between a satellite that would be constructed in LEO using a modular approach with one that would be constructed at GEO and be monolithic. For the LEO construction case, an additional mass penalty will result in terms of the solar array due to the oversizing for the radiation degradation on that solar array which is deployed for the self-power transfer. The mass indicated reflects about a 3% oversizing penalty. The structural penalty reflects both the fact that the array will be oversized because the radiation degradation as well as the modularity which means redundant additional members in additional strength in the structure. Finally, because of the oversizing of the solar array there will be a small power distribution penalty for a total mass penalty of approximately 3 million kilograms for a 10 GWe satellite built at LEO versus GEO. This mass penalty has been included in all transportation cost analysis.

Satellite Design Impact Summary
LEO Construction

SELF POWER TRANSFER

IMPACT	REASON	PENALTY
• SOLAR ARRAY	• OVERSIZING FOR RADIATION DEGRADATION	• 1.75M Kg (1)
• STRUCTURE	• MODULARITY • OVERSIZING	• 1.07M Kg • 0.25M Kg (1)
• POWER DISTRIBUTION	• EXTRA LENGTH DUE TO OVERSIZING	• 0.07M Kg (1)

≈ 3M Kg PENALTY OVER GEO CONST

(1) FUNCTION OF SELF POWER PERFORMANCE CHARACTERISTICS

ORBITAL BASES

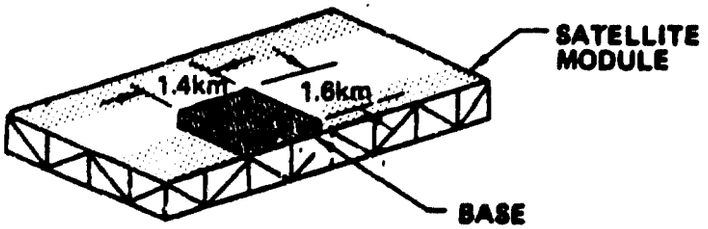
LEO Construction Concept

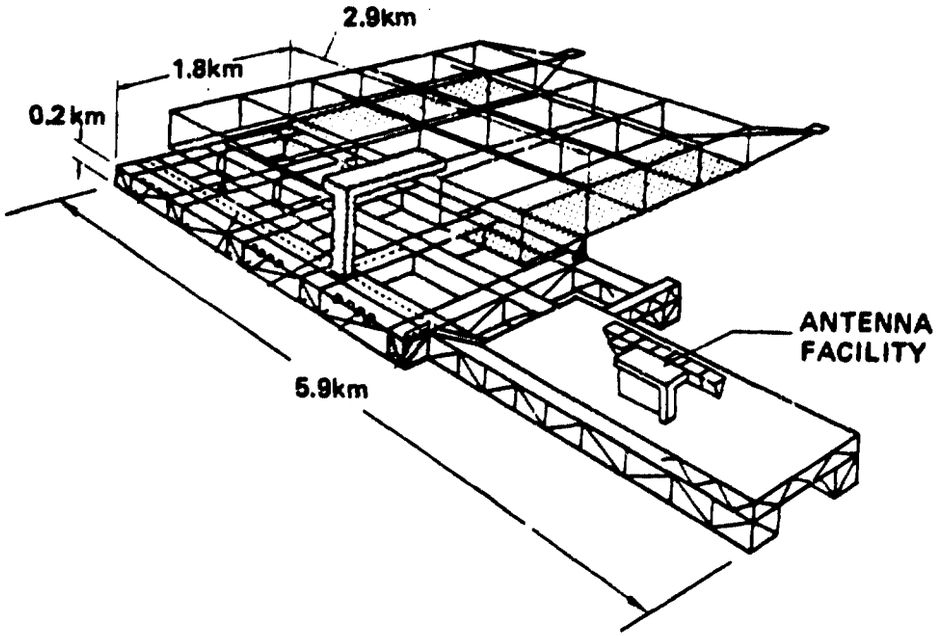
Primary characteristics of the orbital bases associated with LEO construction are indicated. The LEO base is used for the construction of the self-power module. It has a mass of approximately 5,550 metric tons and requires a construction crew of 407. The overall dimensions of the base are approximately 5.9 kilometers by 1.8 kilometers. A GEO final assembly base is also required and has a mass of approximately 850 metric tons and a crew size of 65.

Orbital Bases
LEO Construction Concept

SPS-2488

- GEO FINAL ASSEMBLY BASE
  - MASS = 855 MT
  - CREW = 65





- LEO CONSTRUCTION BASE
  - MASS = 5550 MT
  - CREW = 407

ORBITAL BASES

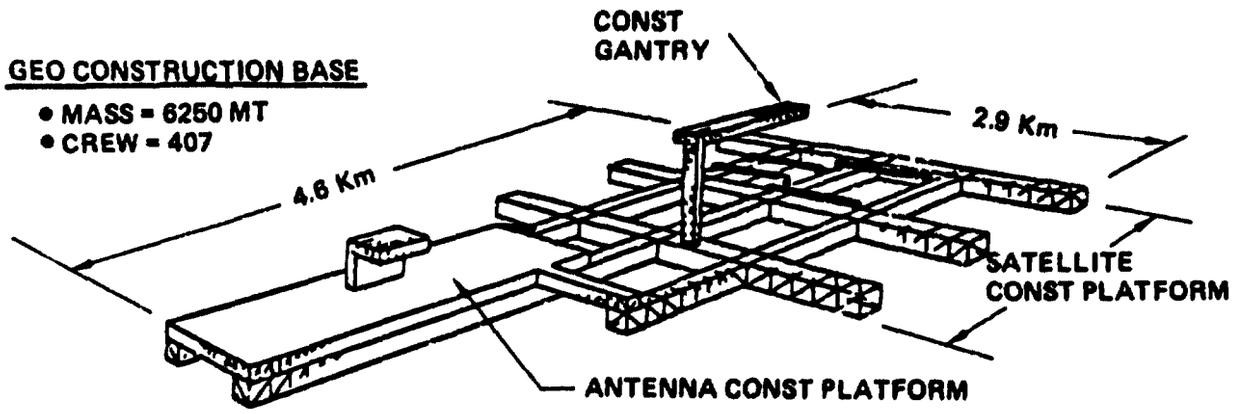
GEO Construction

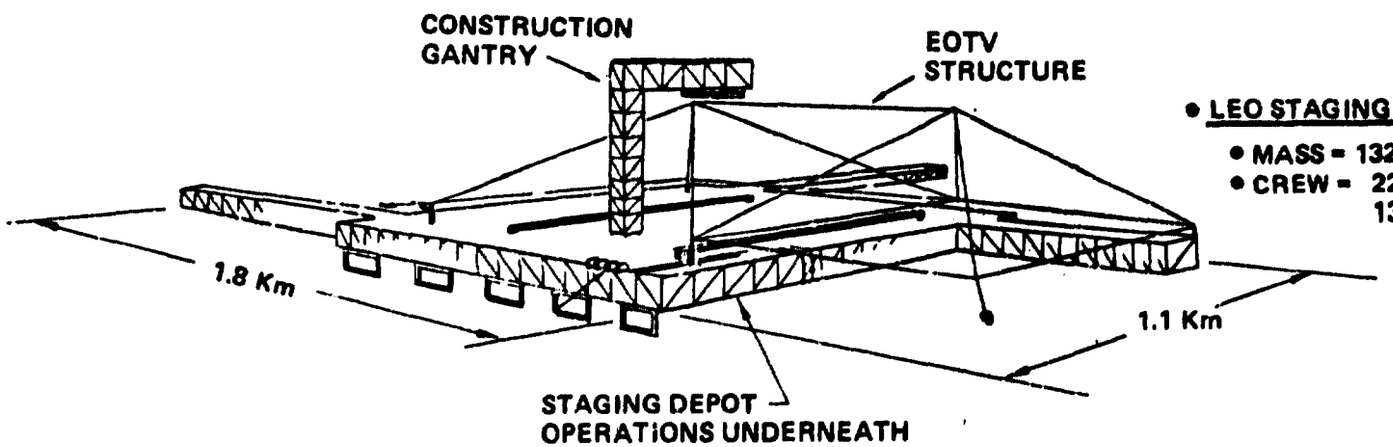
The GEO construction concept requires a LEO staging base that has a mass of approximately 1300 metric tons and requires a crew size of around 200 during the construction phase of the EOTV. Once the program is underway, the crew size can be reduce to 130 people since only depot type operations are performed. The GEO construction base has the task of constructing a monolithic 5 gigawatt or 10 gigawatt satellite. The mass at this base is 6,250 metric tons with the increase over the LEO satellite construction base being primarily that related to additional radiation shelters for the crew.

Orbital Bases
GEO Construction

SPS-2487

- GEO CONSTRUCTION BASE
  - MASS = 6250 MT
  - CREW = 407





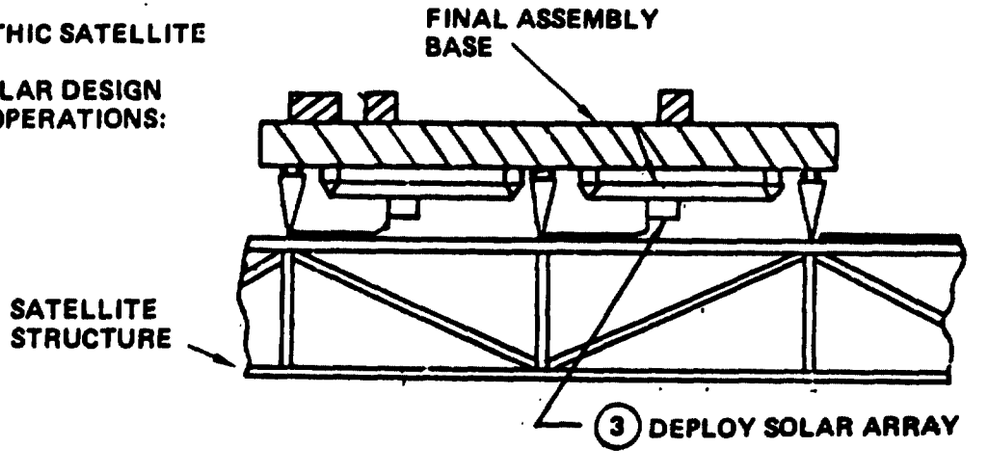
- LEO STAGING BASE
  - MASS = 1320 MT
  - CREW = 220 CONST PHASE
    130 OPS PHASE

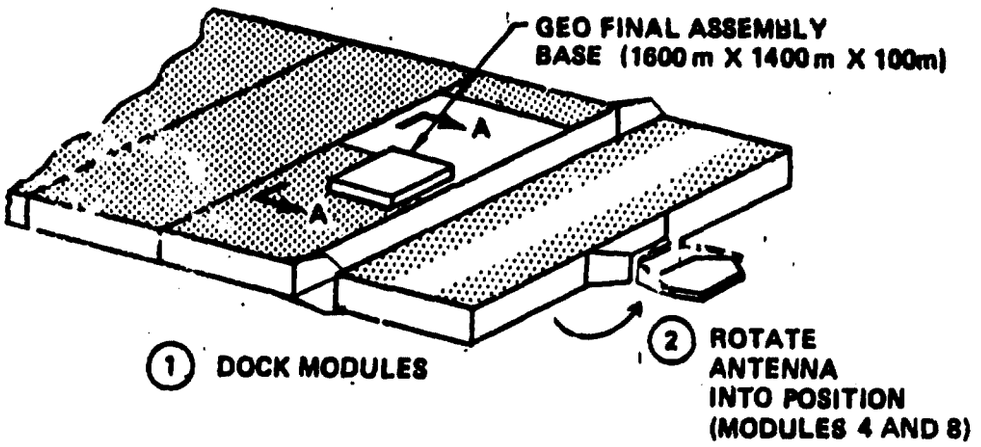
CONSTRUCTION OPERATIONS

As indicated earlier, the GEO construction concept has been associated with the construction of a monolithic satellite. LEO construction, however, uses a modular satellite design which means modules are constructed at LEO and use self-power electric propulsion transfer to GEO. Consequently, the LEO construction option has several additional construction requirements. The first of these is the docking of the modules once GEO is reached. Another requirement is that on both the 4th and 8th modules the antenna is transfered in a position underneath the module in order to improve the moment of inertia characteristics and as a result, once the modules are docked the antenna must be rotated up into its operating position. The final difference in the LEO construction approach is that those solar arrays not deployed for the self-power transfer must be deployed through the use of deployment machines at the final assembly base.

Construction Operations

- GEO CONSTRUCTION ALLOWS MONOLITHIC SATELLITE
- LEO CONSTRUCTION UTILIZES A MODULAR DESIGN AND REQUIRES THE FOLLOWING GEO OPERATIONS:





ENVIRONMENTAL FACTORS SUMMARY

The indicated factors primarily are those that influence the construction of the satellite. In the case of radiation, all crew modules located at GEO will have a substantial penalty in terms of protection against solar flares. A shielding density of 20 to 25 grams per square centimeter is required in the radiation shelters. EVA operations would be worse at GEO although for LEO construction should any EVA be required it should be restricted time periods when the construction base is not passing through the South Atlantic anomoly. Occultation of the construction bases has several impacts with one being in terms of the base power generation system. The GEO construction base requires the same amount of operational power but require less total power because of nearly continuous sunlight on the solar array that is used to generate power for the base. Lighting will be required at both locations either due to the base being occulted by the earth or the construction base itself will cast shadows so that lighting will be required. Should graphite type structure be used, the thermal effects on the structure should be minimum in both cases. Gravity gradient and drag penalties associated with LEO construction are larger although the difference of 600-700 kilograms a day is less than one HLLV flight per year. Collision with manmade objects is judged to be greater for the LEO construction concept during the satellite (module) construction phase . However, the total collision probability must also include collisions that may occur during the transfer between LEO and GEO; this comparison is presented on the next chart.

Environmental Factors Summary

SPS-1611

FACTOR	LEO BASE	GEO BASE
• RADIATION		
• SOLAR FLARE	2-3 GM/CM^2	20-25 GM/CM^2 (115 000 KG/100 PEOPLE)
• EVA	SO. ATLANTIC ANOMALY RESTRICTION	STEADY STATE IS WORSE
• OCCULTATION		
• BASE POWER REQ'TS:	3600 KW	2500 KW
• LIGHTING:	• REQ'D AT BOTH LOCATIONS (Δ OF 100-150 KW)	
• THERMAL EFFECTS:	• NO SIGNIFICANT DIFFERENCE IF GRAPHITE TYPE STRUCTURE IS USED	
• GRAVITY GRADIENT & DRAG:	• GRAVITY GRADIENT CONST MODE USED FOR BOTH LOCATIONS • LEO CONST PROPELLANT IS GREATER BY 600-700 KG/DAY	
• COLLISION WITH MAN-MADE OBJECTS	• POTENTIAL GREATER FOR LEO CONST (SEE ORBIT TRANSFER FLIGHT OPERATIONS) BUT AVOIDANCE MANEUVERS CAN REDUCE PROBABILITY TO NEAR ZERO	

ORBIT TRANSFER OPERATIONS

Flight mechanics associated with the self-power module method and the electric orbit transfer vehicle are essentially the same. There are some factors, however, which will differ between the two approaches; one being the collision with manmade debris, another being t' potential of interupting the power beams coming down from operating satellites. The key inputs into these two factors are the size of the modules being transfered and the amount of time that they are exposed to the environment. In the case of the potential collisions per year (with no avoidance maneuvers), the LEO construction concept is predicted to have 18 collisions while the GEO construction approach would have only one. However, in terms of the transfer of vehicles from low orbit to high orbit, the GEO construction approach with the large fleet of 23 vehicles has a (area) (time) exposure value approximately 3 times that of the self-power module concept, resulting in approximately 3 times as many potential collisions. As a result, the GEO construction concept has approximately 50% more potential collisions if no avoidance is done. It should be emphasized, however, that prior analysis in the solar power satellite study has indicated that sufficient avoidance maneuvers are possible to prevent any collisions with manmade debris.

The second item to be compared is that dealing with potential interuptions of power beams originating from operating power satellites. The potential problem occurs since the modules or vehicles transporting cargo depart from a 30 degree inclination orbit and have a destination of 0 degrees at GEO. The exact number of interruptions is not known at this time, however, it is known that these interruptions will be proportional to the number of revolutions that the vehicles make in the transfer from low orbit to high orbit. Again, the total number of flights plays a key part in this estimate. The LEO construction concept using self-power modules is estimated to require a total of 6,400 revolutions to get one 10 gigawatt satellite to GEO. In the case of GEO construction using 23 EOTV's flying 28 flights per year, a total of 28,000 revolutions is required or approximately 4 times revolutions per year, which should indicate approximately 4 times as many interruptions of beams coming down as for the LEO construction option.

Orbit Transfer Operations

- FACTORS
  - COLLISION WITH MAN-MADE DEBRIS
  - SATELLITE POWER BEAM INTERRUPTIONS
- KEY DATA
  - SELF POWER MODULES ..... 8 FLIGHT PER YEAR
    2.75 KM^2 PER MODULE
    0.5 YR EXPOSURE PER MODULE
  - GEO EOTV'S ..... 22 VEHICLES
    1.5 KM^2 PER VEHICLE
    1.0 YR EXPOSURE PER VEH.
- POTENTIAL COLLISIONS PER YEAR (WITH NO AVOIDANCE MANEUVERS)

	LEO/SPM	GEO/ETOV
CONST	18	1
TRANSIT	22	66
TOTAL	40	67

- POTENTIAL POWER BEAM INTERRUPTIONS PER YEAR
  (QUANTITY NOT AVAILABLE BUT WILL BE PROPORTIONAL TO NO. OF REV'S)
  - LEO/SPM - - - 8 FLIGHTS @ 800 REV/FLT = 6400 REV
  - LEO/EOTV - EQUIV TO 21 FLTS UP @ 1200 REV
    16 FLTS DOWN @ 200 REV } = 28400 REV

RISK/UNCERTAINTY

Orbit Transfer System

As stated previously, the LEO construction concept uses self-power and as such the orbit transfer system is used only once although recovery and reuse is possible as discussed previously. The construction concept using EOTV's, however, requires multiple use for each EOTV. Components presenting a concern for the multiple use EOTV's are indicated. In the case of the solar arrays, the cost optimum transfer time for each flight will result in degradations as low as 40 to 45% as compared with 30 years of satellite operation which will degrade approximately 10%. The impact of this deep degradation is not known in terms of overall power generation capability nor in terms of the number of annealings which can be made nor the level of recovery. Cell to cell mismatch occurs even though annealing has been performed since each cell has its own unique characteristics. With excessive cell to cell mismatch there would be non-optiumum power characteristics from the solar array. The impact of the large number of thermal cycles the solar array will be exposed to is unknown both in terms of occultations and certainly in terms of the annealing cycles suggested for the system. Finally, as the power output degrades during the missions, so will voltage degrade which will present some complication in terms of power conditioning equipment. The other components indicated also offer some concern, however they are judged to be less significant. In the case of avionics, one typical 180 day transfer presents a dose of approximately 10^4 rads. This radiation level will require use of radiation hardened electronics particularly when 10 flights (10^5 rads) are planned. The impact of radiation hardened electronics is twofold. One, the system will be slightly more expensive then standard avionics, and two, the number of design solutions will be restricted. The final item to be considered is that of the structure. For a typical transfer of 180 days, approximately 5×10^9 rads will be experienced at the surface of the graphite type structure. Previous data has indicated that decomposition will occur beginning with about 10^9 rads. This decomposition results from the outgassing and constitutes a form of contamination which may have an impact on the solar cells performance. The extent of this impact is not known at this time.

Risk/Uncertainty
Orbit Transfer System

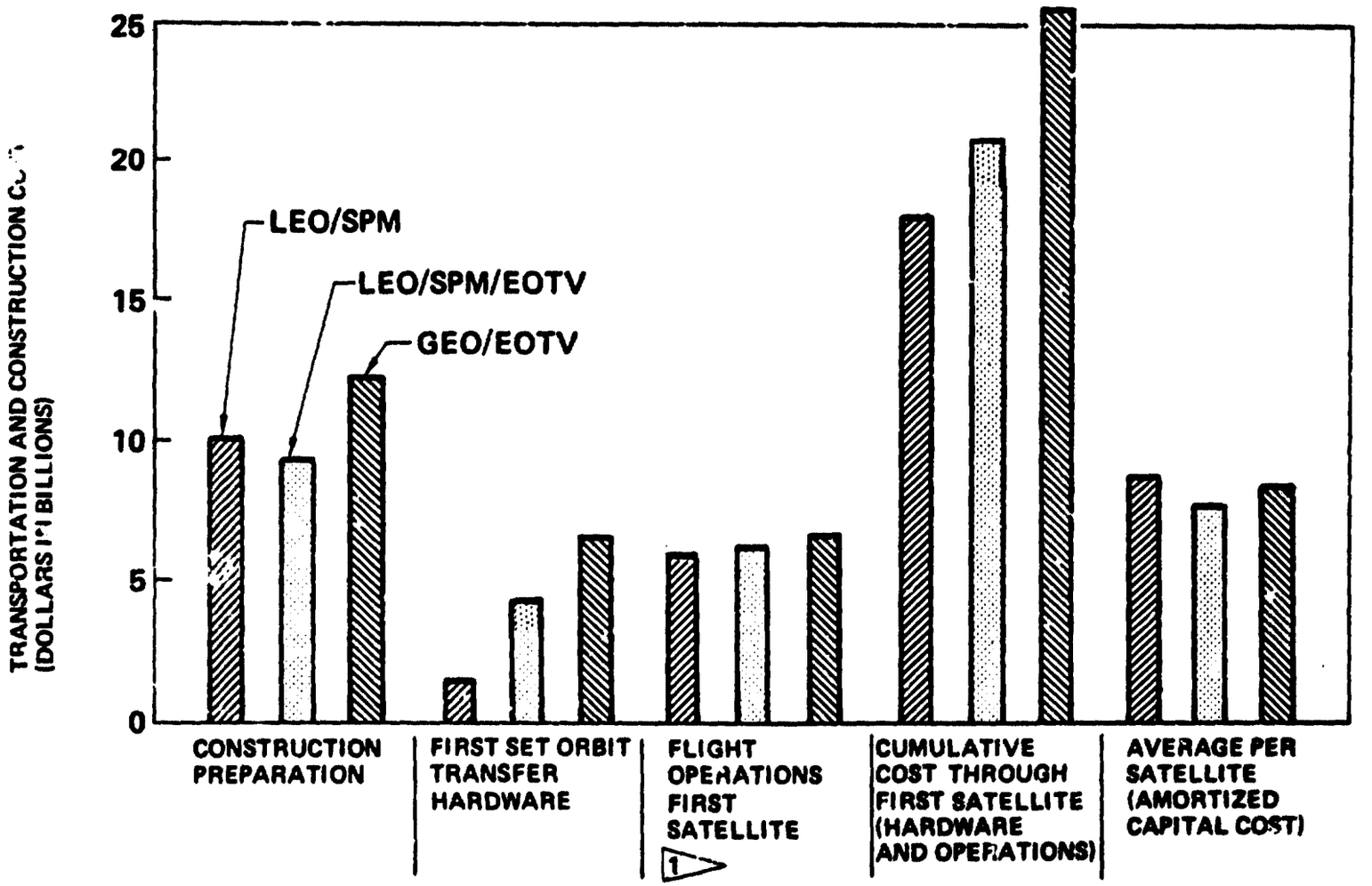
- LEO CONSTRUCTION
  - SELF POWER SYSTEM IS USED ONLY ONCE
- GEO CONSTRUCTION
  - EOTV IS A MULTI USE SYSTEM IN A HOSTILE LEO-GEO ENVIRONMENT
- KEY FACTORS OF ONE LEO-GEO-LEO TRIP
  - RADIATION IS MORE SEVERE
    - 10 TIMES THAT OF 30 YRS AT GEO FOR SOLAR ARRAY
  - NUMBER OF THERMAL CYCLES (OCCULTATIONS) IS THE SAME AS 18 YRS GEO OPS
- COMPONENT CONCERNS
  - SOLAR ARRAY
    - DEEP DEGRADATION
    - RECOVERY
    - CELL TO CELL MISMATCH
    - THERMAL/ANNEALING CYCLES
    - VOLTAGE FLUCTUATIONS
  - AVIONICS
  - STRUCTURE

CONSTRUCTION/TRANSPORTATION COST COMPARISON

The final parameter to be compared in the LEO vs. GEO construction trade is that of cost associated with all elements of the construction and transportation systems. This chart indicates several cost divisions, with each division including cost for three construction options: 1) LEO construction with self-power modules and no recovery 2) LEO construction with self-power modules in conjunction with recovery of the electric transportation system elements and 3) the GEO construction concept using electric orbit transfer vehicles. All costs are plotted as a function of total transportation and construction cost. Details of each of these divisions and each bar is provided on the next chart. In summary, for the construction preparation portion of the program which includes placement of the construction bases and buying any necessary ground facilities for the orbit to orbit transportation elements, the LEO construction concept using recovery of the electric components provides the least cost. The procurement of the first set of orbit transfer hardware, however, gives a considerable advantage to the LEO construction concept with self-power and no recovery. Flight operations associated with the first satellite, namely that of launching of the propellant to perform the delivery of the first satellite is approximately equal. When all three of these increments are added together, one gets the cumulative cost through the first satellite. At this point, the LEO construction concept with self-power transfer provides approximately a $3 billion savings over the LEO concept with recovery of the electric system and approximately a $7 billion savings over that of the GEO construction concept. When the capital costs are amortized the total operating cost of all three concepts is quite comparable with the LEO construction using recovery of the electric propulsion systems providing a slight margin.

Construction/Transportation Cost Comparison

SPS-2413



1 Satellite(s) producing 10 GW

DETAILED COST COMPARISON

Construction/Transportation

Cost presented on the preceding chart are presented in greater detail. During the construction preparation period, the chief difference between the options is that associated with the placement of the orbital bases including the unit cost of the bases. The second difference is that of the amount of ground production facilities for the orbit transfer hardware. The cost penalty reflects $1 for each $1 of recurring costs that shows up under the average per satellite column. In terms of direct cost during the construction preparation period, the numbers reflect approximately half the crew size used in the normal construction operation but spread out over a two year time period. The GEO construction case has the majority of the orbital crew at GEO thus resulting in the highest cost. Total cost for the construction preparation period indicates that the LEO construction approach with recovery of the electric transportation system to be the lowest cost.

The second major cost comparison covers the transportation cost associated with placement of the first satellite. In terms of capital costs, the LEO construction approach with no recovery of the electric transportation system provides the least cost primarily because it has a very small fleet investment. A LEO construction case with recovery reflects a somewhat higher cost primarily as a result of low production rate on the electric propulsion components. The GEO construction case, with a fleet of 23 vehicles results in the highest capital cost. In terms of the direct cost for this period, the LEO construction case with no recovery has slightly higher costs although not significant. The propellant required for the transfer of each satellite in the LEO case is approximately twice that of the GEO construction concept, however, such factors as lower costs associated crew rotation and resupply and no refurbishment during the first year, offset this to some degree resulting in the small difference between the concept in terms of direct cost. Construction delay time primarily reflects the fact that for LEO construction, the trip is optimized at around 140 days of transfer while the GEO construction is more optimum at 180 days of transfer resulting in slightly larger interest payment. The total cost during this phase shows that LEO construction without recovery being nearly $3 billion cheaper than the LEO construction with recovery and approximately $5.5 billion cheaper than the GEO construction concept.

The final comparison of these concepts deals with the average per satellite cost which amortizes all capital costs. In the case of LEO construction with no recovery, the cost indicated is the same as that for the first satellite since a complete set of orbit transfer systems is needed for each satellite. The LEO construction with recovery concept and GEO construction using EOTV's both amortize the unit cost of the electric propulsion equipment and its placement. The total average per satellite cost shows that approximately $130 million savings per satellite for the LEO construction with revovery of OTS over the GEO construction case and approximately $700 million over the construction with no recovery.

Detail Cost Comparison Construction/Transportation

SPS-2480

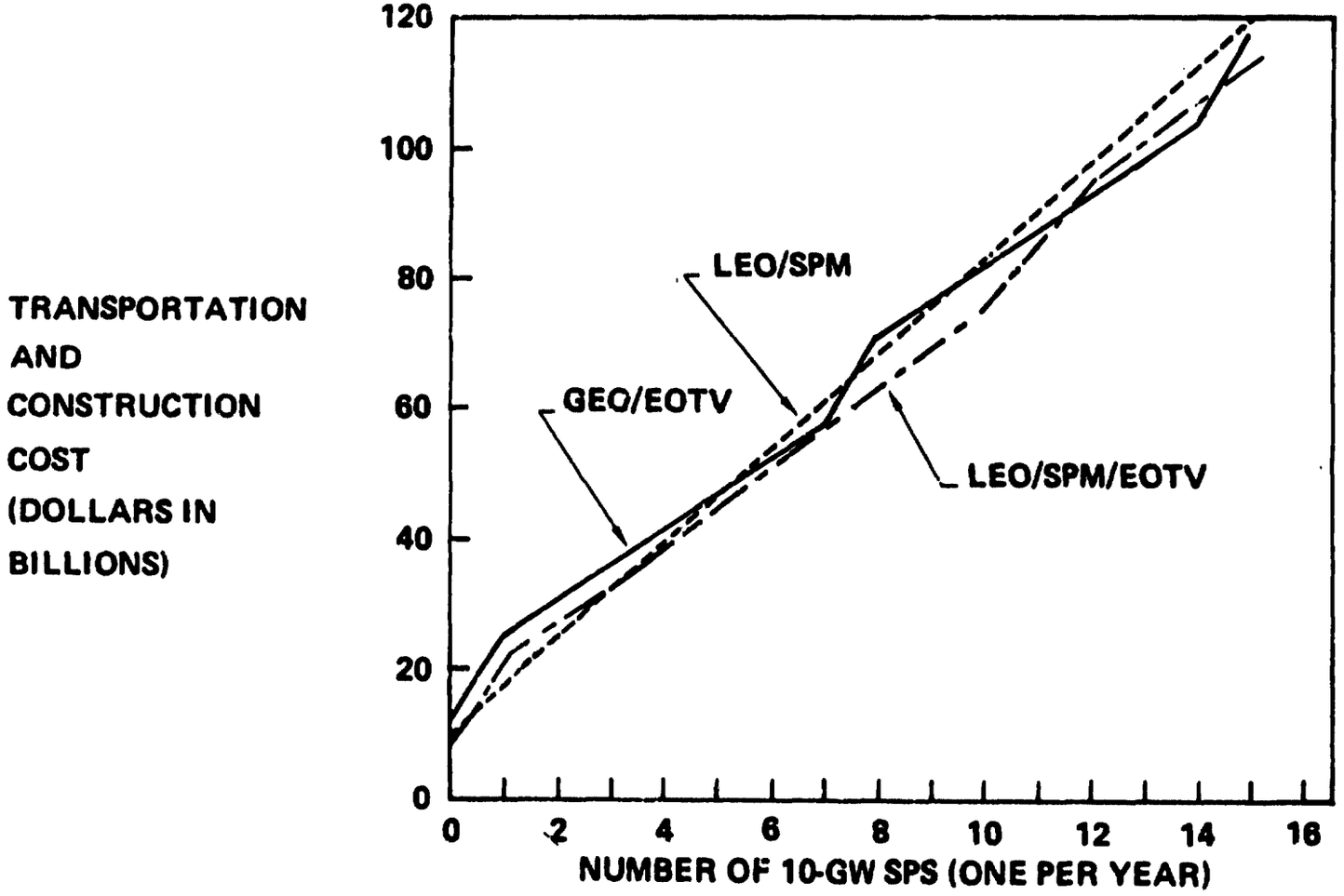
NR = NO RECOVERY OF OTS R = RECOVERY OF OTS

ITEM	CONSTRUCTION PREPARATION			TRANSPORT THRU FIRST SATELLITE (HRDW + OPS)			AVG PER SATELLITE (AMORTIZED CAPITAL)		
	LEO/NR	LEO/R	GEO	LEO/NR	LEO/R	GEO	LEO/NR	LEO/R	GEO
CAPITAL COST	(9795)	(9015)	(11185)	(2010)	(5615)	(7830)	(2715)	(1565)	(2290)
SAT OTV LAUNCH	–	–	–	560	840	1310	560	120	1450
SAT OTV HRDW	–	–	–	1450	4350	6520	1450	630	
RECOV OTV LAUNCH	–	–	–	–	75	–	–	20	–
RECOV OTV HRDW	–	–	–	–	350	–	–	85	–
ORB BASE HRDW	7895	8035	9300	–	–	–	705	710	840
ORB BASE TRANS.	360	350	675	–	–	–			
OTV PROD. FACIL	1450	630	1210	–	–	–	–	–	–
DIRECT	(430)	(450)	(750)	(5515)	(5440)	(5315)	(5515)	(6020)	(5315)
SAT LAUNCH	–	–	–	3880	3765	3850	3880	3765	3850
SAT OTV PROPL.	–	–	–	1045	1015	535	1045	1015	535
SAT Δ HRDW	–	–	–	160	160	–	160	160	–
SAT OTV REFURB	–	–	–	–	–	180	–	570	180
RECOV OTV REFURB & PROP LAUNCH	–	–	–	–	50	–	–	60	–
CREW/SUPPLY	430	450	750	430	450	750	430	450	750
CONST TIME DELAY				(380)	(380)	(490)	(380)	(380)	(490)
TOTAL	10225	9465	11935	7905	11435	13635	8610	7965	8095
$/KG OF SATELLITE				79.8	115.5	137.7	86.9	80.4	81.8

CUMULATIVE COST COMPARISON

The total transportation and construction cost can be plotted as a function of the number of 10 gigawatts satellites placed on-line. In the case indicated, one 10 gigawatt satellite is added per year. The initial point on the cost curves reflect the procurement of the construction bases followed by the procurement of the first set of orbit transfer hardware to deliver the first 10 gigawatt SPS. Cost thereafter essentially reflects recurring cost per satellite for each of the construction options except in those cases where the orbit transfer fleet must be replenished. From this plot it can be seen that there is a relatively narrow band of cost for all three construction options and possibly it is not until approximately 150 gigawatts of capacity has been procured that the LEO construction concept using self-power transfer of the modules with recovery of the electric systems starts to provide an advantage.

Cumulative Cost Comparison



COST SENSITIVITY

No Recovery from Radiation Damage

Another cost comparison that can be shown deals with the uncertainty associated with the electric OTV concept and particularly to the cost sensitivity to the amount of radiation damage that can be removed with annealing. Previous analysis has assumed 95% of the damage is removed with each annealing. A limit case occurs if one assumes that no recovery is possible in terms of annealing. In the case of the LEO construction concept, this will result in a cost penalty of approximately $740 million per satellite which is a result of having to oversize by approximately 8%. For the GEO construction concept using EOTV's, there must be an assumption regarding the number of uses for each EOTV before it is discarded. In this analysis it is assumed that once the power output falls to 50% of initial power output, sufficient damage has been done to the array and probably to supplemental systems that further use is not possible. The 50% level is reached after 4 EOTV trips if no recovery is possible. The average trip time during these four trips will be 280 days resulting in an amortization period of 3.5 years rather than 7.1 years in the baseline EOTV case that uses radiation damage recovery. As a result, the cost penalty per satellite will be 1230 million which is approximately 70% greater than the LEO construction concept using self-power. Consequently, it is judged that the GEO construction EOTV concept is much more sensitive to the understanding of radiation and its damage removal through the use of annealing.

Cost Sensitivity
No Recovery From Radiation Damage

- LEO CONSTRUCTION/SELF POWER (NO RECOVERY)
  - 22% OF SATELLITE SOLAR ARRAY DEPLOYED FOR TRANSFER
  - RADIATION LOSS IS 40%
  - RESULTS IN 8.8% OVERSIZING
  - Δ COST/SATELLITE (AVG) = $740 MILLION

- GEO CONSTRUCTION/EOTV
  - ASSUME EOTV DISGARDED WHEN $P/P_O < 50\%$
  - NUMBER OF EOTV TRIPS = 4
  - AVERAGE TRIP TIME = 280 DAYS
  - AMORTIZATION PERIOD = 3.5 YRS
  - PRINCIPAL IS $7,800 MILLION PER FLEET
  - Δ COST/SATELLITE (AVG) = $1,230 MILLION

CONSTRUCTION LOCATION SUMMARY

This chart contains a summary of all the comparison parameters used in the construction location comparison. Some of these parameters have indicated little or no difference between the construction option. The GEO construction option using EOTV's has been declared to have an advantage in terms of impact on the satellite design and also in terms of the construction operation. LEO construction with no recovery of the electric transportation system is judged to be better in terms of orbit transfer operations and uncertainties associated with orbit transfer hardware design. In terms of construction cost, the LEO construction approach has an advantage while the LEO construction concept with no recovery has a cost advantage through placement of the first satellite. On a recurring cost basis, LEO construction with recovery of the orbit transportation system and the GEO construction concepts are approximately equal in cost.

Construction Location Summary

BOEING

SPS-2486

COMPARISON PARAMETER	① LEO/SPM	② LEO/SPM/EOTV	③ GEO/EOTV	RATIONALE
• CONST PREPARATION	• NO SIGNIF DIFF			• SAME TIME FOR FIRST SATELLITE
• SATELLITE DESIGN IMPACT			✓	• NO MODULARITY • SMALLER LOADS
• ORBITAL BASES/CONST EQUIP	• NO SIGNIF DIFF			• SAME CONST BASE • STAGING DEPOT VS FINAL ASSY BASE
• CONSTRUCTION OPS			✓	• NO MODULE BERTHING OR ANTENNA HINGING
• CREW REQ'TS	✓			• SAME SIZE BUT MAJORITY AT LEO
• ENVIRONMENTAL FACTORS	• NO SIGNIF DIFF			• ALL CAN BE HANDLED WITH ACCEPTABLE SOLUTIONS
• ORBIT TRANSFER OPS	✓			• FEWER POTENTIAL COLLISIONS AND BEAM PENETRATIONS
• LAUNCH OPS	• SO SIGNIF DIFF			• APPROX SAME NO. LAUNCHES
• RISK/UNCERTAINTY	✓			• MULTI USE IN HOSTILE ENVIRONMENT NOT REQ'D
• CONST COST	✓	✓		• CHEAPER ≈ $2B
• FIRST SAT. TRANS COST	✓			• CHEAPER $3B OVER ② $7B OVER ③
• AVG. COST PER SAT		✓	✓	• CHEAPER ($0.6B)

✓ INDICATES MOST PROMISING

CONCLUSIONS TO DATE

Construction Location

The LEO construction concept using self-power transfer of the modules and no recovery is recommended for the initial stages of the operational program. The most dominating reasons for this recommendation are that it has significantly lower front end cost with recurring cost being competitive out to at least 150 gigawatts of installed power. In addition, this concept does not require reuse of the power generation system which may be quite sensitive to the environment between LEO and GEO. Finally, this concept allows natural evolution to the recovery of the electric propulsion system, which would result in the lowest recurring costs of any of the concepts evaluated.

Construction Location Conclusions To Date

- LEO CONSTRUCTION WITH SELF POWER TRANSFER IS RECOMMENDED.
  - FRONT-END COSTS ARE $2 AND $7 BILLION (13% & 29%) CHEAPER
  - CUMULATIVE COST REMAINS COMPETITIVE OUT TO 150 GW_E OF INSTALLED SATELLITE POWER
  - OPERATIONS NOT DEPENDENT ON MULTIPLE REUSE OF HARDWARE EXPOSED TO SEVERE LEO-GEO ENVIRONMENT
  - ALLOWS EVOLUTION TO THE LOWEST RECURRING COST CONCEPT WHICH IS LEO CONSTRUCTION WITH SELF POWER AND RECOVERY OF THE PROPULSION SYSTEMS THROUGH USE OF EOTV'S

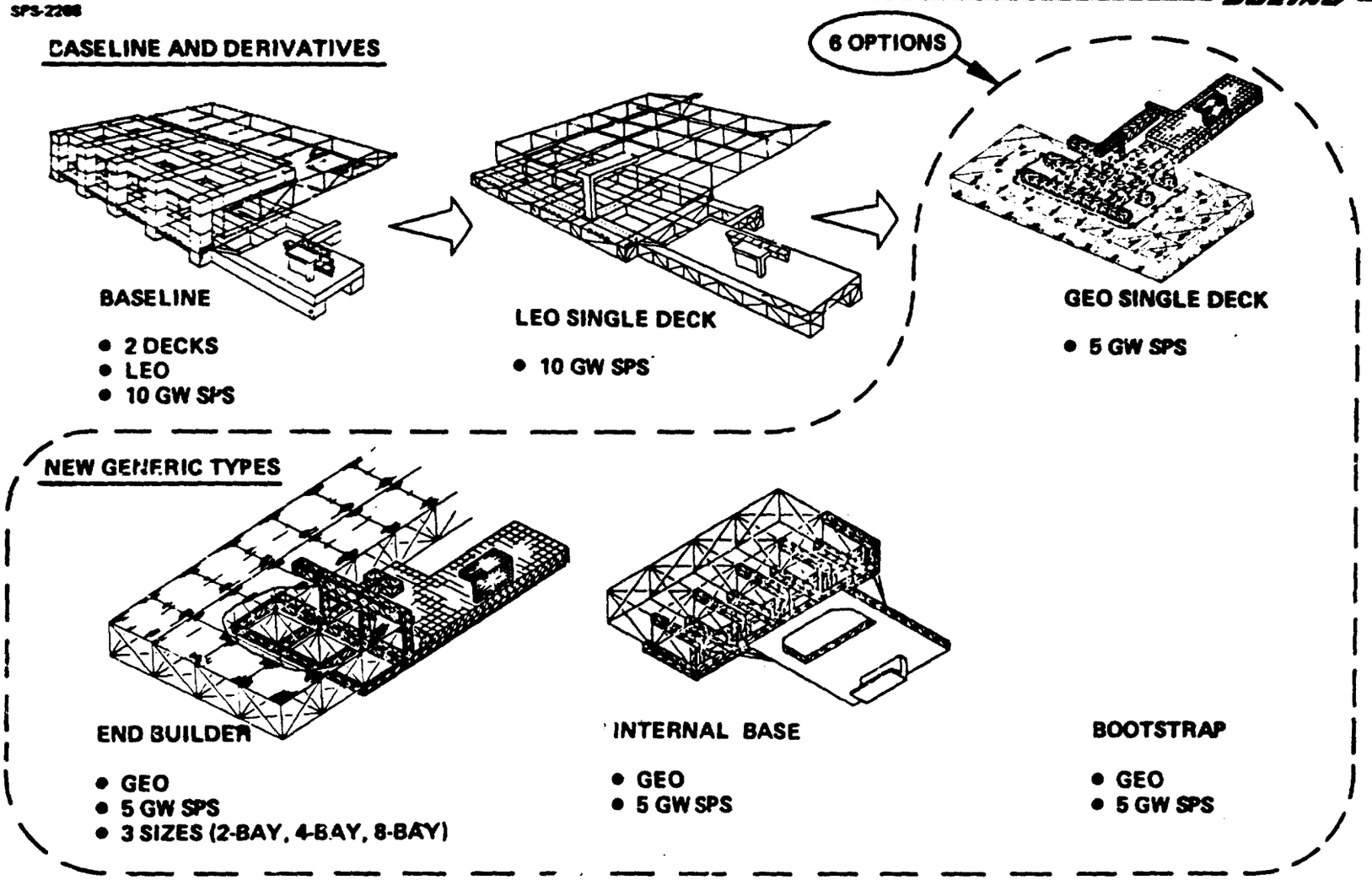
ALTERNATIVE CONSTRUCTION CONCEPTS

This figure illustrates the spectrum of facility concepts that were explored during Phase I of this study. The LEO Single Deck construction base is the one that is recommended to be used as the baseline in Phase II.

The Single Deck base was selected based on a comparison study which considered the six options shown within the dashed lines. The GEO Single Deck and the 2-Bay and 4-Bay End Builders were the most viable candidates and their characteristics will be described in ensuring charts.

Alternative Construction Concepts

SPS-2268



ALTERNATIVE CONSTRUCTION CONCEPTS

EVALUATION GROUNDRULES

In order to make a fair comparison between the competing construction base concepts, it was necessary to legislate some common groundrules. The most significant groundrules are summarized in the figure. This is a summary of over 100 detailed groundrules. The three viable construction base options are consistent with all of the groundrules.

Alternative Construction Concepts Evaluation Groundrules

- 5 GW, MONOLITHIC, PHOTOVOLTAIC SPS
- GEO CONSTRUCTION
- 180 DAYS ±5% CONSTRUCTION TIME
- CONTIGUOUS FACILITY (ANTENNA AND POWER COLLECTION MODULE CONSTRUCTION AREAS ATTACHED)
- USE NEW ANTENNA CONST FACILITY
- CONSTRUCTION EQUIPMENT RATES LESS THAN OR EQUAL TO BASELINE RATES
- 2 SHIFTS, 10 HRS/SHIFT, .75 PRODUCTIVITY
- 100-MAN CREW HABITAT MODULES + 5 OTHERS
- COMMON MASS AND COST FACTORS
- COMMON EQUIPMENT MANNING

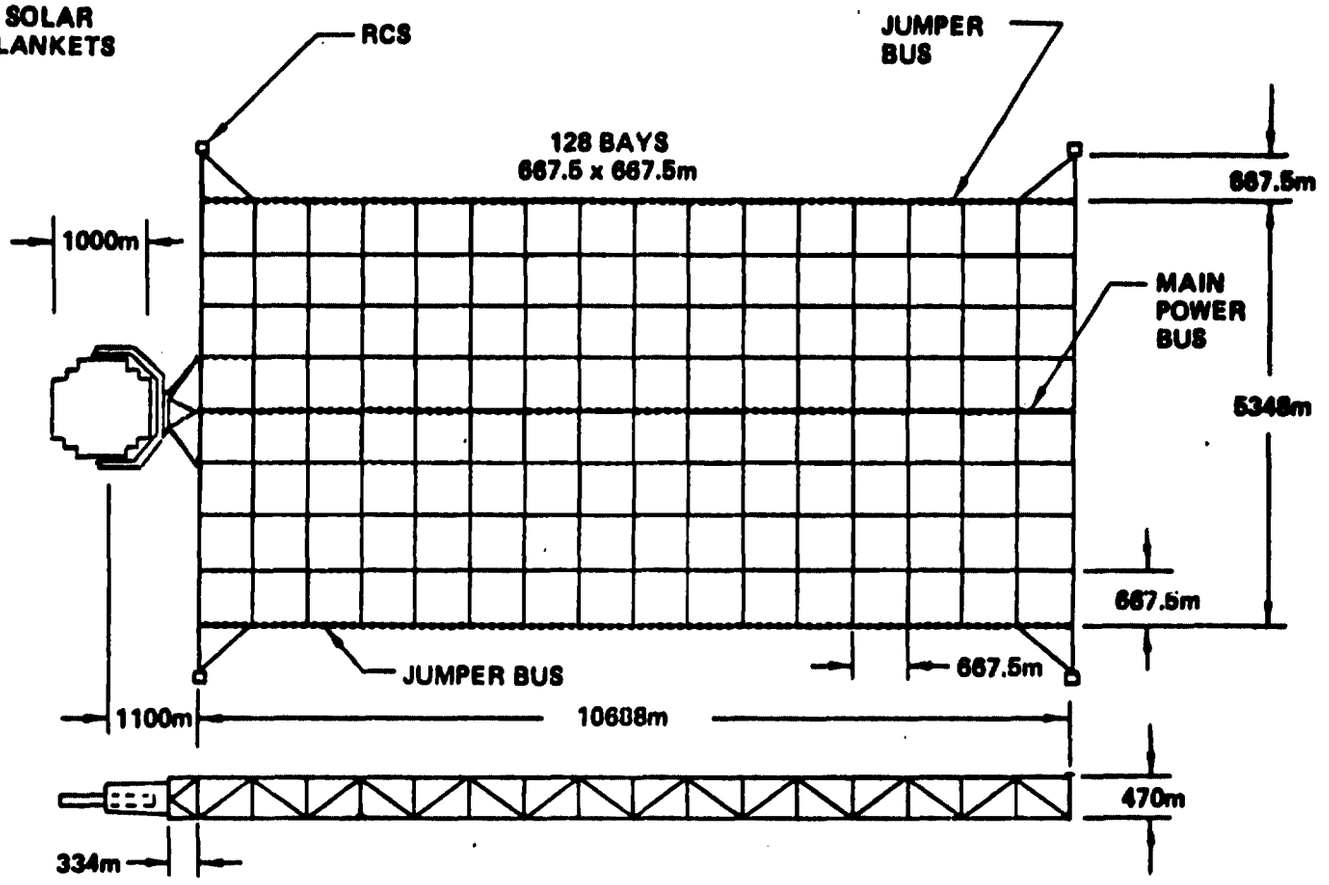
5 GW SPS REFERENCE CONFIGURATION

(SILICON CELLS)

This figure shows the SPS configuration that is to be constructed by each of the construction base concepts. This is constructed as a monolithic (non-modular) system at GEO. This SPS and the GEO construction location were legislated by NASA as the basis for the alternative construction concept analysis. This arose because GEO construction had not been analyzed to the same level of detail as LEO construction and going into this study GEO construction was the NASA preferred concept. It was acknowledged that the preferred construction approach was most likely insensitive to where the satellite was built, as has been substantiated by this study.

5 GW SPS Reference Configuration (Silicon Cells)

- 15m WIDE SOLAR ARRAY BLANKETS

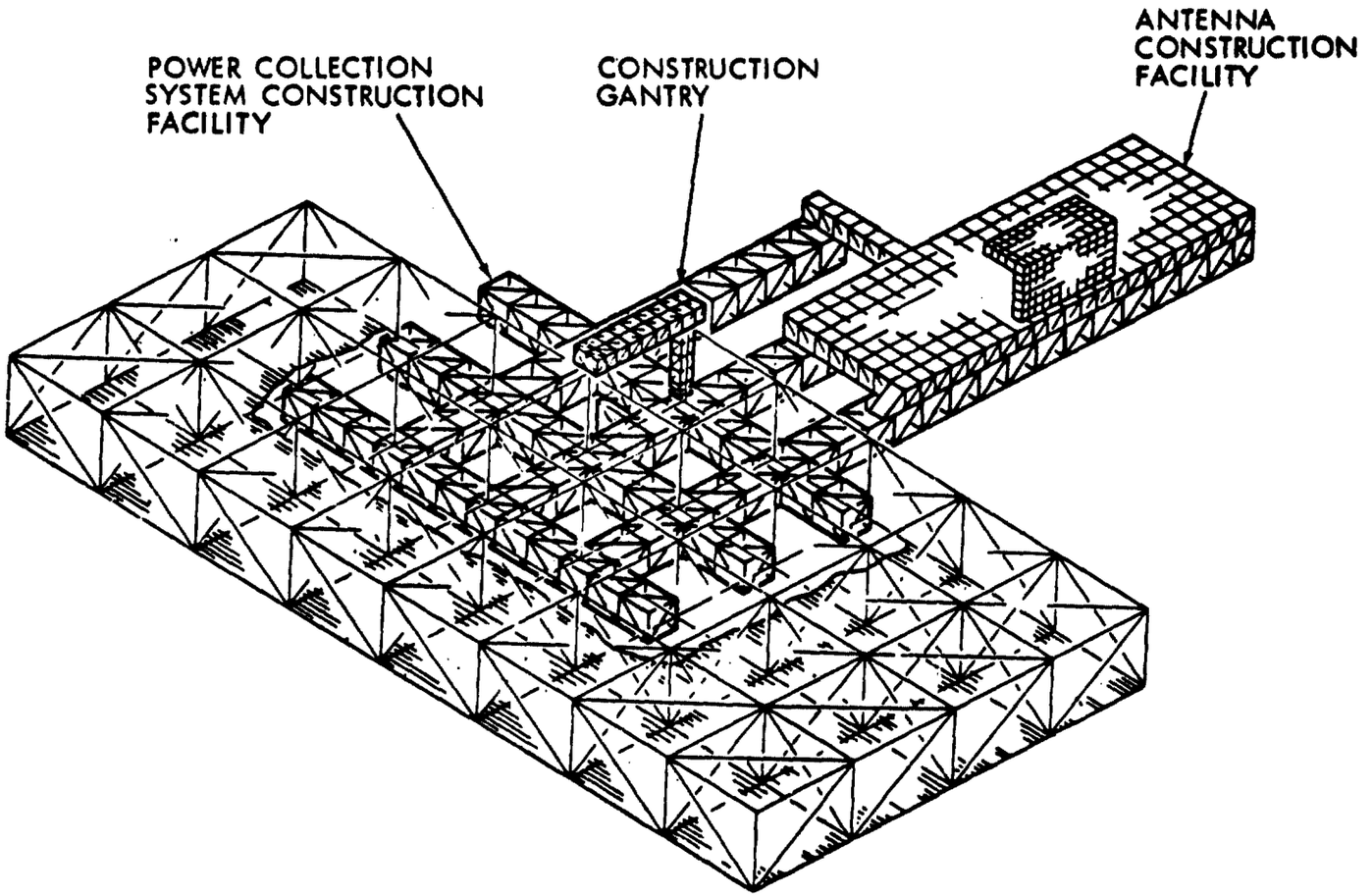


GEO SINGLE DECK CONSTRUCTION BASE

This base concept is depicted in the figure. The most notable feature is the mobile construction gantry. This gantry has replaced the "back wall" and "roof" of the C-shaped construction base described in earlier studies. The antenna construction platform and facility is an updated configuration that resulted from another construction analysis task (refer to Tasks 42117 & 42118 in MPR #5).

GEO SINGLE DECK CONSTRUCTION BASE

SPS-2565

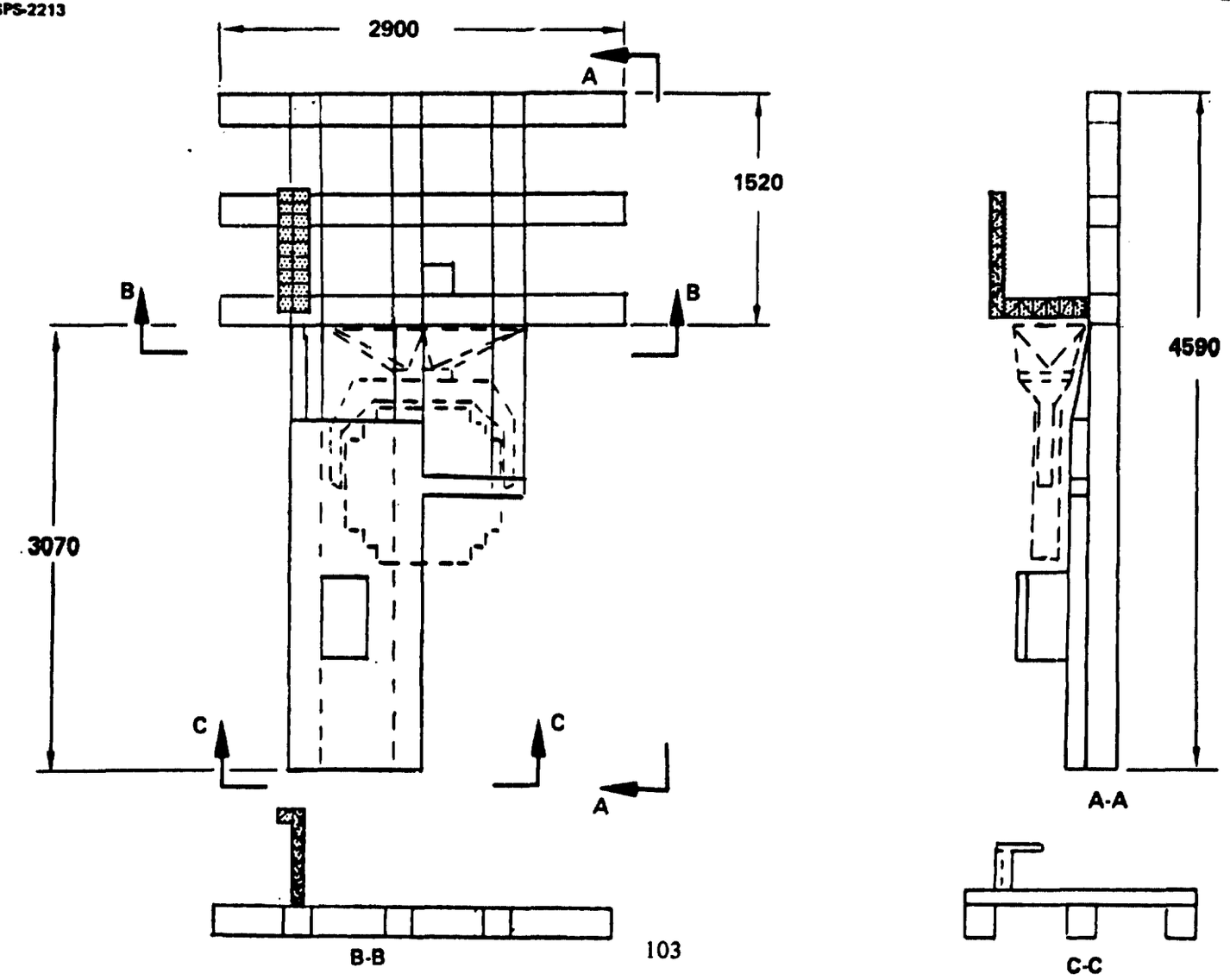


GEO SINGLE DECK CONSTRUCTION BASE

The configuration of the GEO Single Deck Construction Base in indicated by the figure.

GEO Single Deck Construction Base

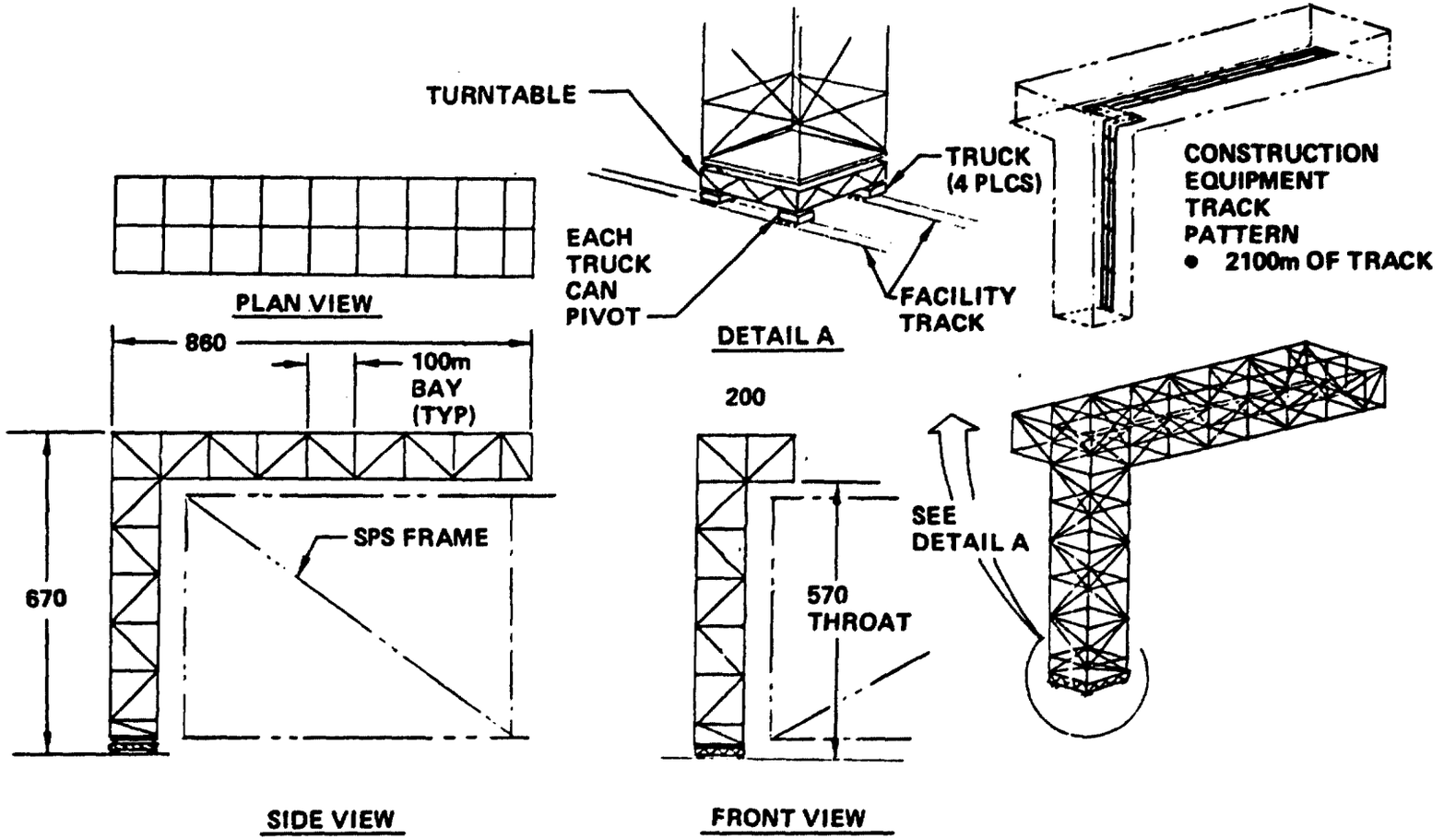
SPS-2213



CONSTRUCTION GANTRY CONFIGURATION

This figure shows the configuration of the construction gantry. Note that the gantry is capable of translation along the facility tracks and can pivot about its carriage. The gantry incorporates a track system that allows the attached construction equipment to maneuver about during the construction operations.

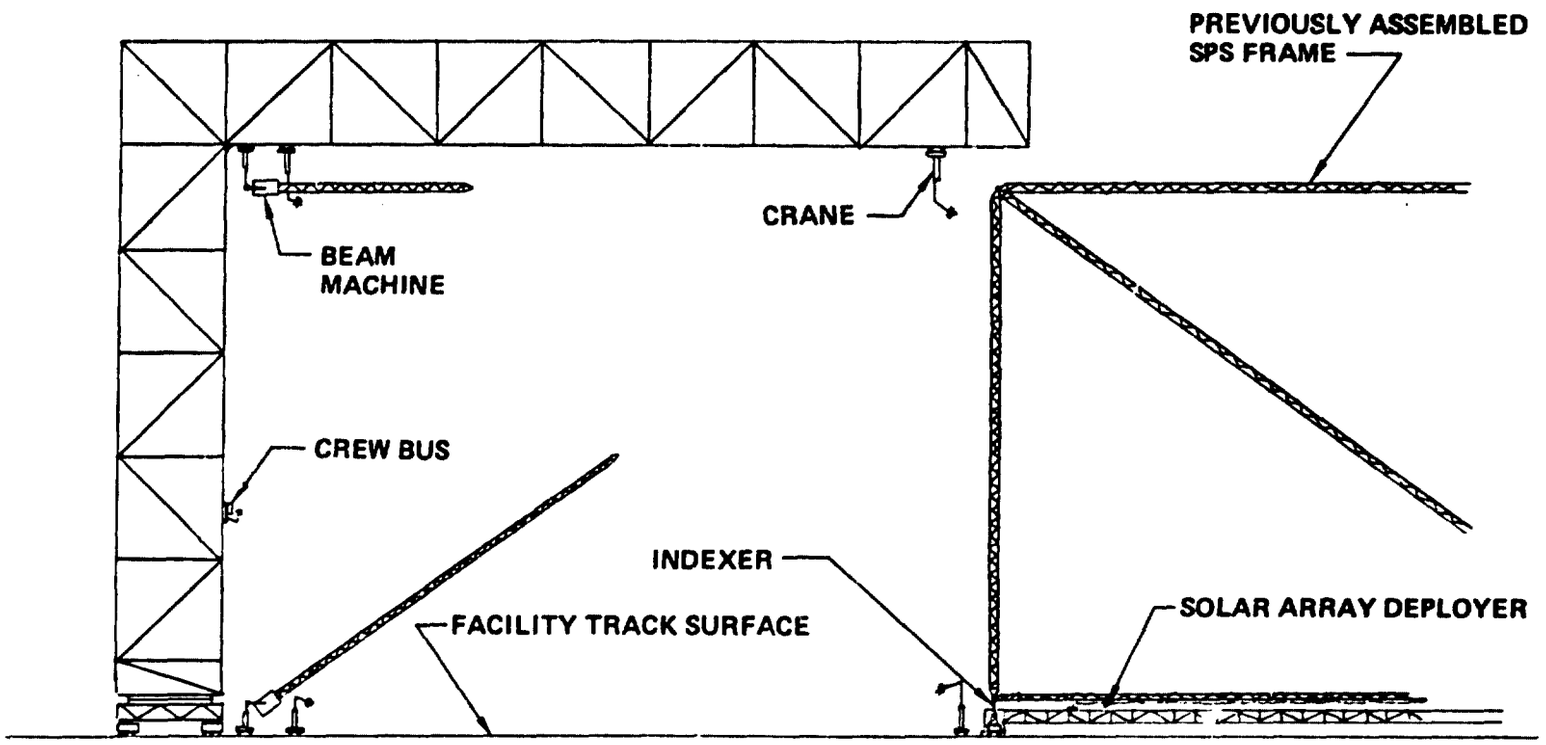
Construction Gantry Configuration



CONSTRUCTION GANTRY

This figure shows the locations of the construction equipment upon the gantry. There is one beam machine, two cherrypickers, and a crew bus attached to the gantry track system.

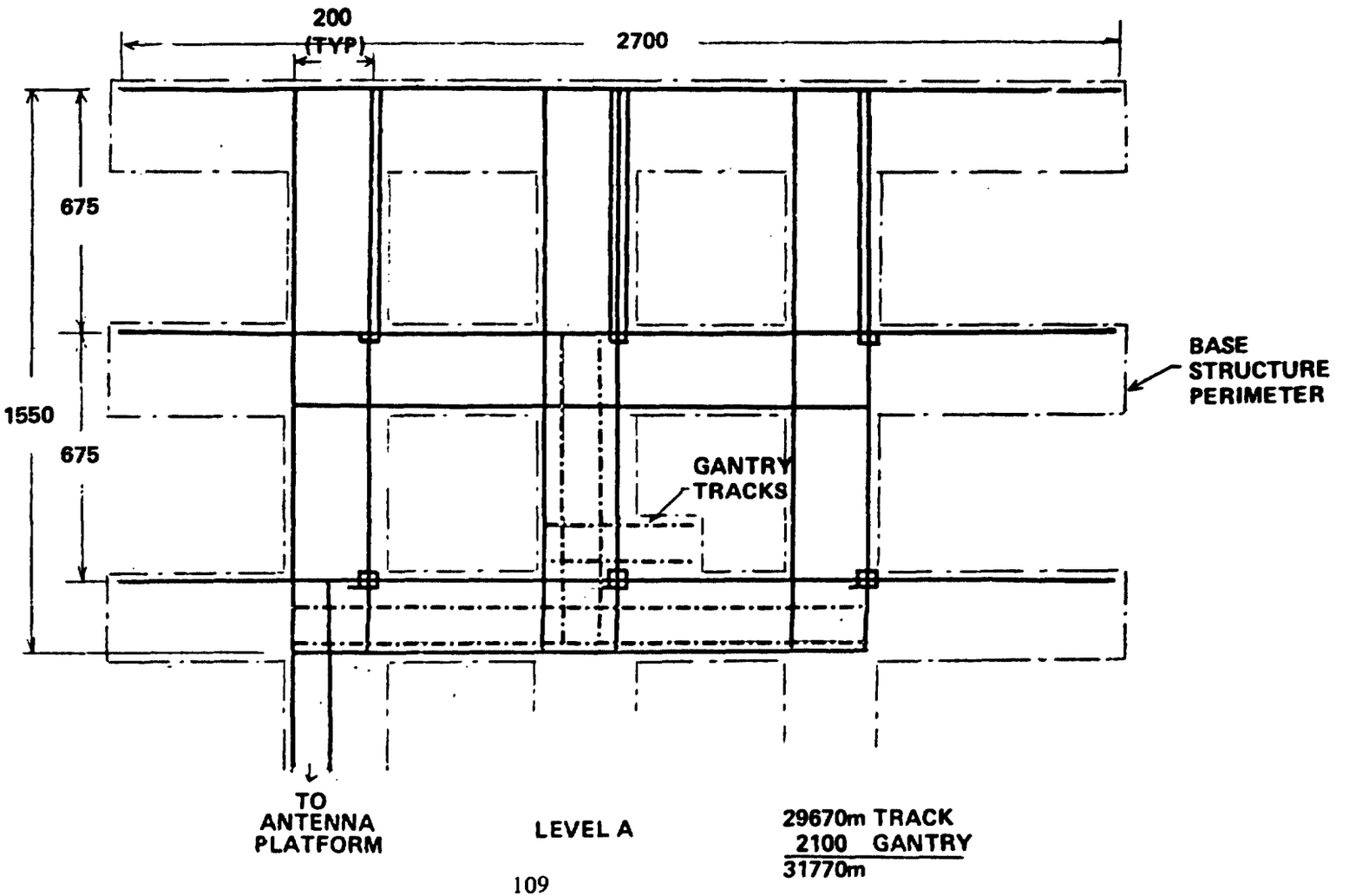
Construction Gantry



GEO SINGLE DECK TRACK SYSTEM

The track network on the base provides the pathways upon which the construction equipment, the SPS indexers, the cargo transporters, and the crew transporters maneuver around the base. The base structural configuration is created by the track network configuration.

GEO Single Deck Track System



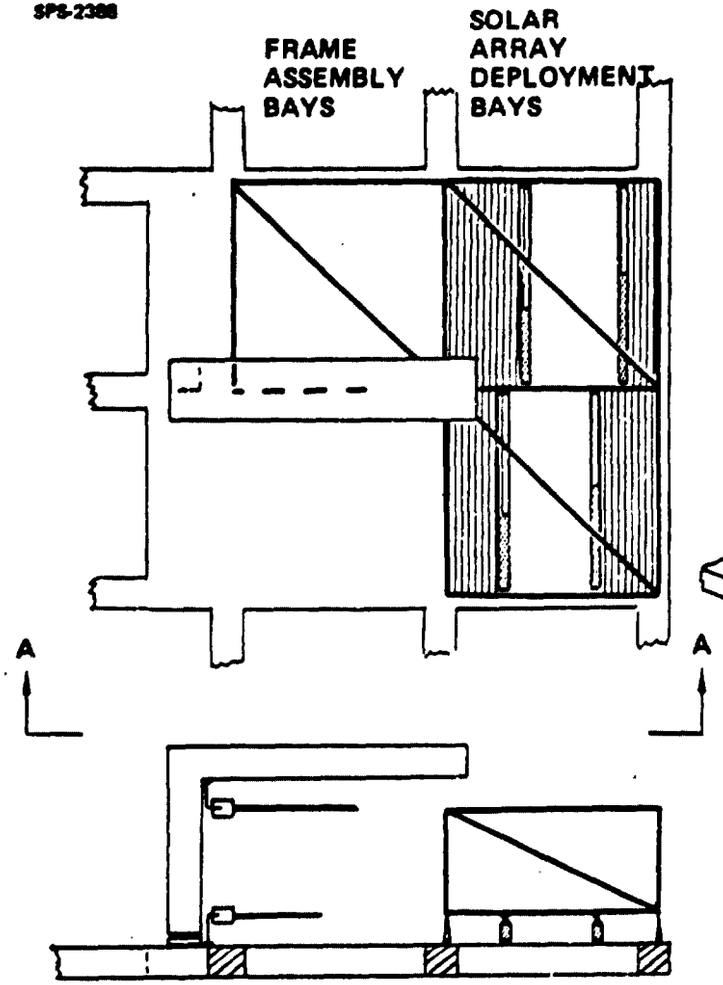
SINGLE DECK FRAME ASSEMBLY/SOLAR ARRAY DEPLOYMENT

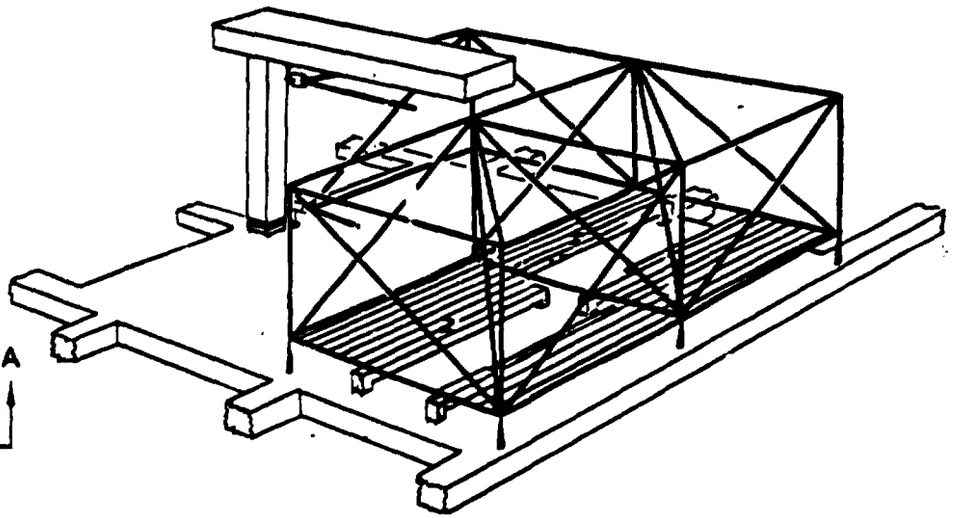
The Single Deck and the End Builder concepts are distinguished by the approach used to construct the SPS frame and to deploy the solar array. In the Single Deck base, the frame assembly operations are independent of the solar array deployment and operations (de-coupled operations).

When making the frame, each of the beam machines operate independently of each other. Each of the solar array deployers are independent. The only coupling of operations is that all of the machines must complete their appointed jobs before the satellite can be indexed so that the construction operations can begin on the next two bays.

Single Deck Frame Assembly/ Solar Array Deployment

SPS-2388





- FABRICATE AND INSTALL EACH BEAM SEPARATELY
- DEPLOY EACH SOLAR ARRAY BLANKET SEPARATELY

(DE-COUPLED OPERATIONS)

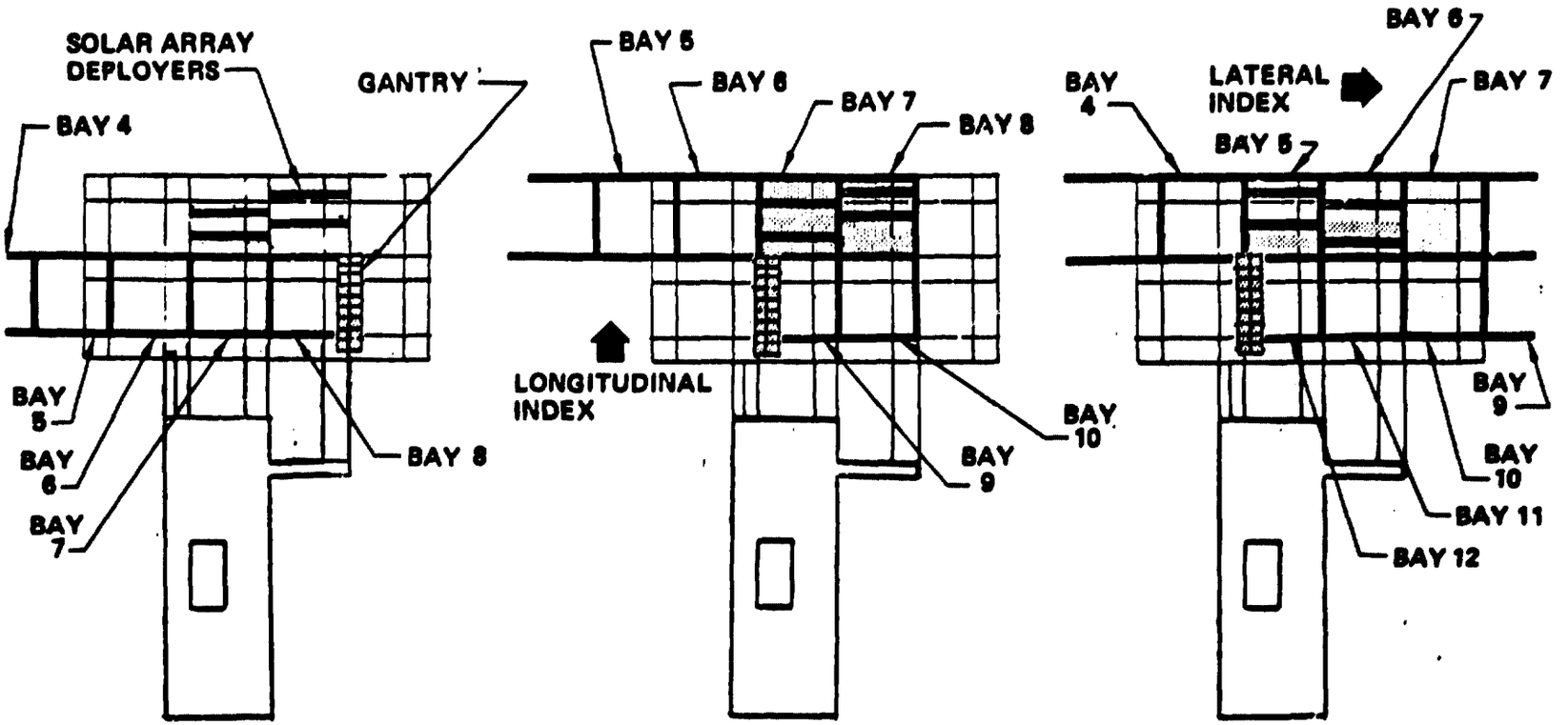
POWER COLLECTION SYSTEM CONSTRUCTION

SEQUENCE (GEO CONSTRUCTION)

This figure shows the frame assembly, solar array deployment, and indexing operational sequence. It should be noted that the construction gantry is required to move laterally along the base and to pivot 90° during various steps in the construction sequence.

Power Collection System Construction Sequence (GEO Construction)

SPS-2214



①

- FIRST ROW OF BAYS COMPLETED (8 BAYS WIDE)

②

- FRAME INDEXED LONGITUDINALLY ONE BAY
- SOLAR ARRAY DEPLOYED IN BAYS 7 AND 8
- ASSEMBLE FRAMES FOR BAYS 9 AND 10 (SECOND ROW OF BAYS)

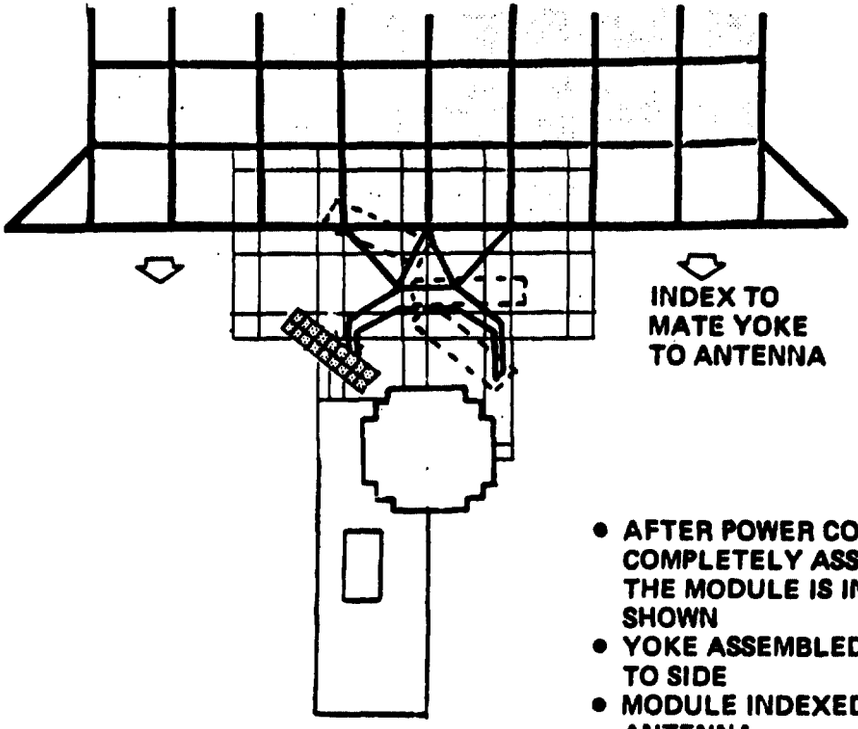
③

- LATERALLY INDEX FRAME 2 BAYS
- DEPLOY SOLAR ARRAY IN BAYS 5 AND 6
- ASSEMBLE FRAME BAYS 11 AND 12

YOKE ASSEMBLY AND MATING OPERATIONS

The construction gantry is employed in the assembly of the antenna yoke as is shown in the figure.

Yoke Assembly and Mating Operations



- AFTER POWER COLLECTION MODULE HAS BEEN COMPLETELY ASSEMBLED AND CHECKED OUT THE MODULE IS INDEXED TO ORIENTATION SHOWN
- YOKE ASSEMBLED AND THEN GANTRY MOVED TO SIDE
- MODULE INDEXED TO MATE YOKE TO ANTENNA
- AFTER COMPLETED SPS IS CHECKED OUT, THE SATELLITE IS INDEXED LATERALLY AND THE FACILITY IS FLOWN AWAY

GEO SINGLE DECK CONSTRUCTION BASE CREW SIZE

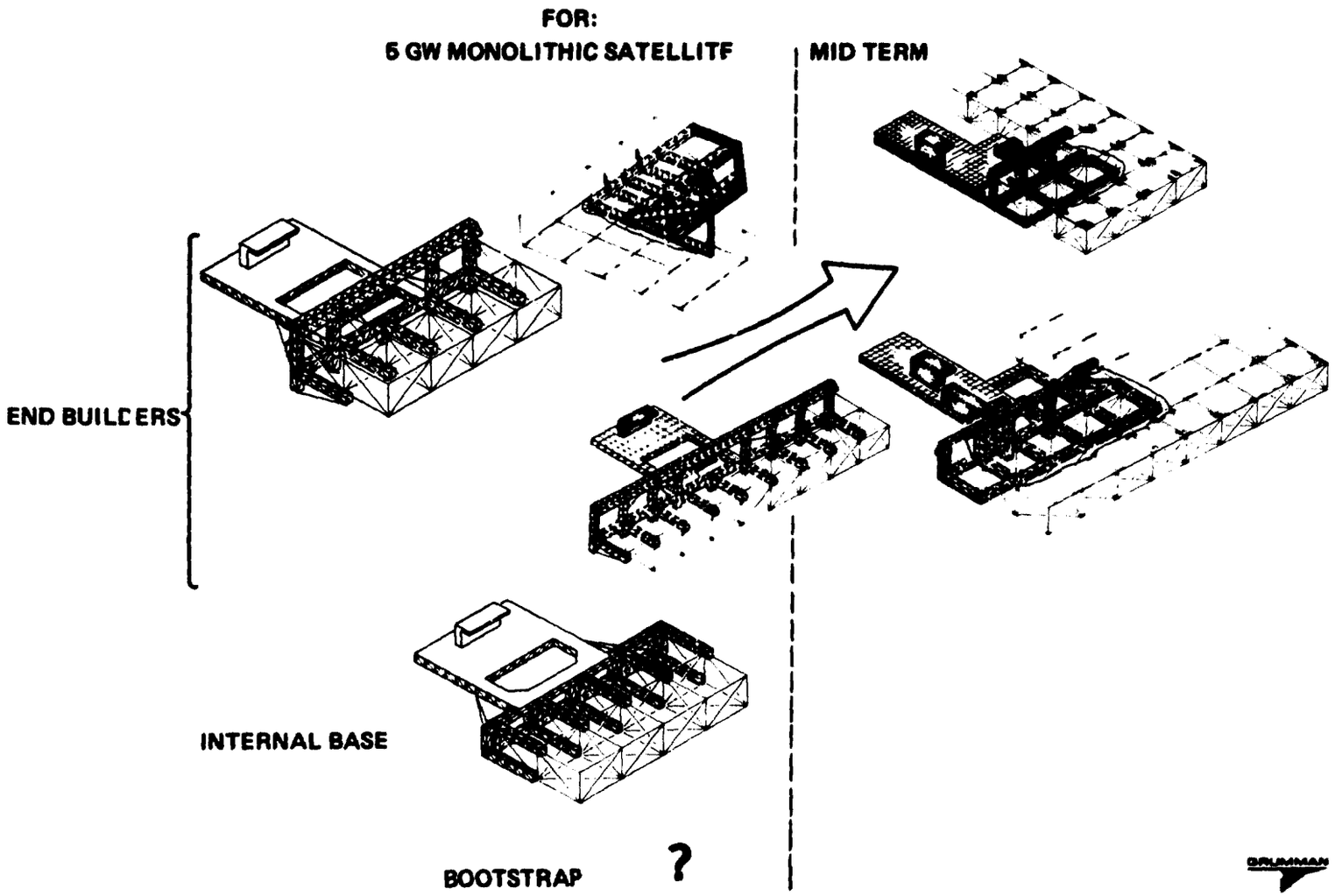
GEO SINGLE DECK FACILITY - CREW SIZE

BASE MANAGEMENT	(10)
CONSTRUCTION	(297)
MANAGEMENT	22
MODULE CONSTRUCTION	62
ANTENNA CONSTRUCTION	40
SUBASSEMBLY	46
MAINTENANCE	37
LOGISTICS	42
TEST/QC	40
BASE OPERATIONS	(41)
BASE SUPPORT	(67)
TOTAL	407

ALTERNATE GEO CONSTRUCTION CONCEPT DEVELOPMENT

During Phase I, Grumman investigated several different methods for constructing the baseline SPS 5GW satellite in geosynchronous orbit. These concepts were to be developed for direct comparison with Boeing's baseline single deck construction concept. Three different approaches were examined at the outset of the study, which included the end builder, internal base and bootstrap concepts. The bootstrap idea was dropped, as no practical concepts could be identified. Feasible design solutions were found, however, for both the end builder and internal base concepts, which were compared at the Mid-Term. The internal base was subsequently dropped because it offered no clear cut advantage over the end builder approach. In addition, the internal base was limited to building certain types of structure, such as those using hexahedral bracing. Since the Mid-Term Briefing, further work was done on both the 2 bay and 4 bay end builder construction bases.

ALTERNATE GEO CONSTRUCTION CONCEPTS DEVELOPMENT



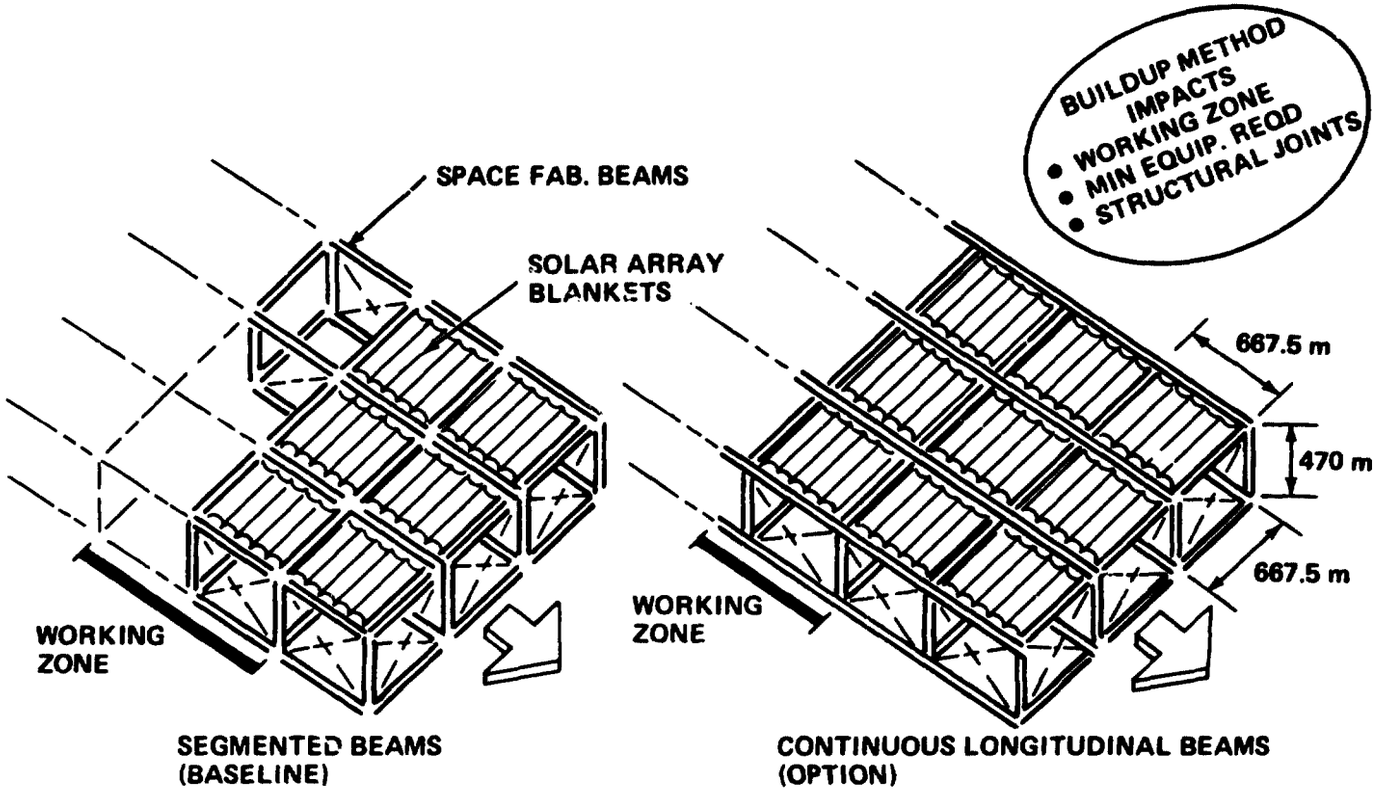
ALTERNATE SPS CONSTRUCTION METHODS

The method of construction selected for building the full size Solar Power Satellite (5 to 10 GW) will directly impact the size of the construction work area and the minimum equipments needed for space fabrication and assembly. The method of construction can also impose constraints on the design of SPS subsystems. Two alternate construction methods, using segmented beams and continuous longitudinal beams are shown for a typical SPS solar array module.

The baseline method, for example, follows a two step process which allows minimal equipment to be used for structural assembly, while other time consuming subsystem functions, such as installing solar array blankets, are performed on fully assembled structural bays. The solar array structural bays are constructed with space fabricated beam elements joined at the corners. Accordingly the construction work zone needs a two bay facility depth to accomodate both structural and non-structural construction operations.

The alternate approach, however, is keyed to the continuous fabrication of longitudinal structural elements which allows the buildup of other subsystems to be more closely coupled. While this method of construction may require more automatic construction equipment than the segmented build-up concept, it also needs less construction work area, hence, a smaller base to implement. Providing more automated equipments can be used to increase overall crew productivity and hence cost effectiveness. The use of continuous longitudinal elements of course requires a different joint design for assembling the structural framework. Overall production efficiency could be improved further by aligning the solar blanket installation with the longitudinal structure to facilitate multiple blanket deployment operations.

ALTERNATE SPS CONSTRUCTION METHODS



GRUMMAN

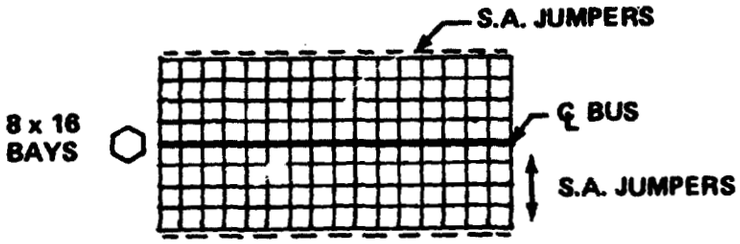
2955-049V

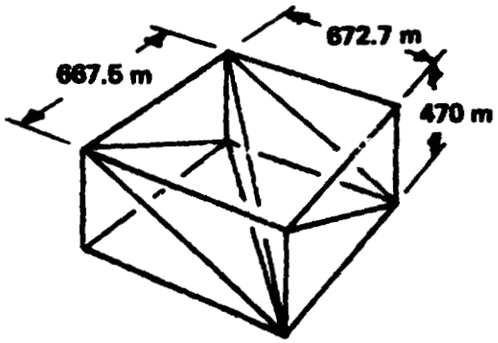
SPS SPACE CONSTRUCTION REQUIREMENTS AND ISSUES

The alternate GEO construction concepts are developed to assemble the baseline 5GW satellite in 6 months. The baseline satellite has a single antenna located at one end of large power collection module. This 8 X 16 bay power collection module features a hexahedral braced structure, a centerline power bus and lateral solar array blanket installation. Major emphasis was focused on the construction of this satellite power collection module. The Boeing antenna construction approach was used on all construction concepts. The end builder concept received the greatest emphasis and was developed by analyzing the major construction issues related to the satellite construction approach, structural assembly sequence, joints, automatic beam fabrication, satellite support, solar array/structure assembly, antenna construction site and installation and base indexing.

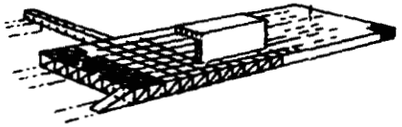
SPS SPACE CONSTRUCTION REQUIREMENTS & ISSUES

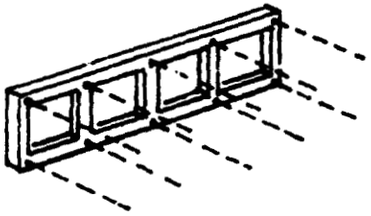
- ASSEMBLE BASELINE 5 GW SATELLITE IN 6 MONTHS





- USE CONTINUOUS LONGITUDINAL MEMBERS
- USE BOEING ANTENNA CONSTRUCTION APPROACH
- MAJOR END BUILDER ISSUES
  - SATELLITE CONSTRUCTION APPROACH
  - STRUCTURAL ASSEMBLY SEQUENCE
  - STRUCTURAL JOINTS
  - AUTOMATIC BEAM FABRICATION REQUIREMENTS
  - SATELLITE STRUCTURAL SUPPORT
  - SOLAR ARRAY/STRUCTURE ASSEMBLY METHODS
  - ANTENNA CONSTRUCTION SITE & INSTALLATION
  - BASE INTEGRATING





2955-050V

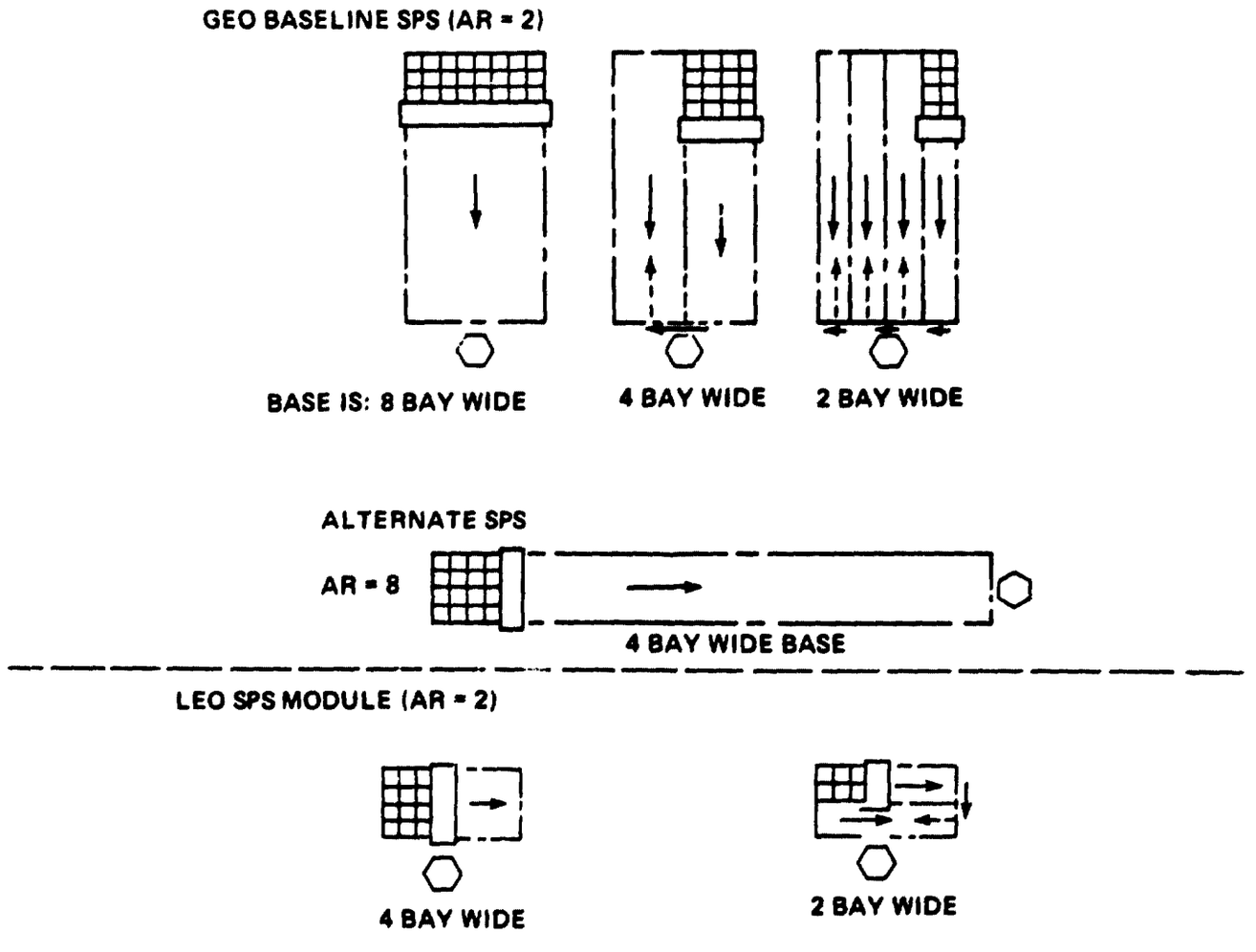
END BUILDER SATELLITE CONSTRUCTION OPTIONS

Several options for building the SPS with continuous structural beams are shown on the facing page. The end builder construction base has been allowed to vary in size from 8 bays wide (maximum) to 2 bays wide (minimum) to permit identification of critical aspects in the production buildup of the baseline SPS. In addition, other SPS configurations were examined (ie alternate SPS aspect ratio = 8 and the smaller LEO constructed module) in order to assess the interaction of base-size and SPS configuration.

The baseline 8 x 16 bay SPS can be constructed by using either 8 bay wide, 4 bay wide, or 2 bay wide construction bases. The large 8 bay wide end builder constructs the satellite on a single pass. It can install the antenna at the beginning or the end of power collection module construction. The other bases require 2 or more passes to complete the satellite and can phase the antenna installation to coincide with either the mid point or completion of power collection module construction. The 8 bay wide and 2 bay wide options encompass the lowest and highest levels of production activity to meet the 6 month build cycle.

The two remaining options address alternate SPS designs which favor single pass production buildup for the 4 bay wide option. The LEO constructed modules also require that the antenna be installed normal to the direction of construction.

END BUILDER SATELLITE CONSTRUCTION OPTIONS



2955-052V

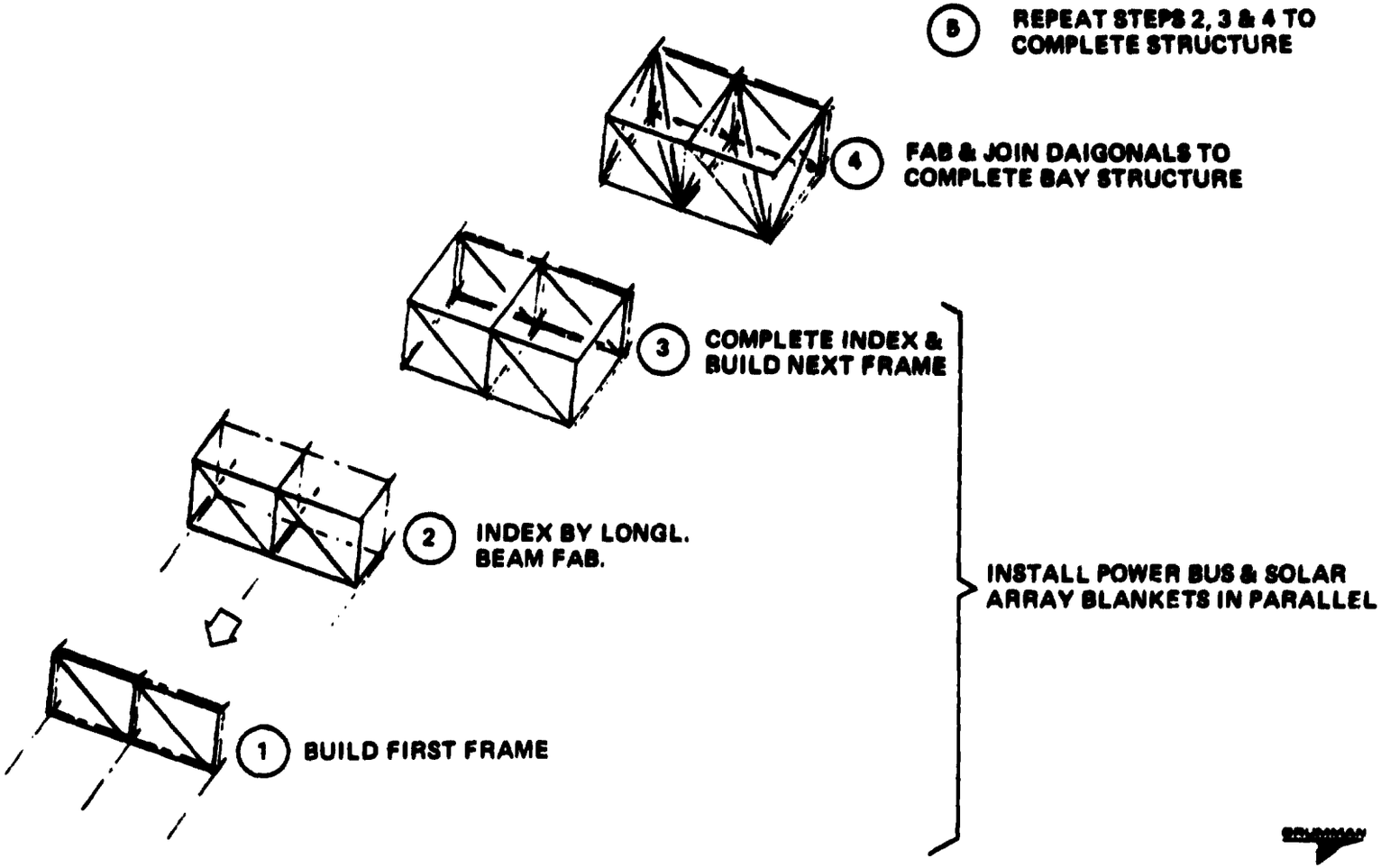
TYPICAL END BUILDER STRUCTURAL ASSEMBLY SEQUENCE

The end builder construction system is tailored to the structural cross section of the satellite and uses dedicated beam machines to a tomatically fabricate continuous longitudinal members. Additional beam machines are needed to fabricate the other required lateral and diagonal members used in the structural assembly. A typical assembly sequence is shown for the first construction pass of a 2 bay end builder. It is also typical for a 4 bay and 8 bay end builder.

As shown the assembly process begines when the first frame is built up on the longitudinal members. The structural members of the frame can be fabricated by separate beam machine; located next to each longitudinal member or with mobile beam machines that travel from one position to the next. The upper and lower horizontal beams are fabricated in parallel and then positioned for assembly. As these members are being joined, the beam machines are, pivotted and the other members of the frame are fabricated as needed to complete the assembly. Step 2 indexes the frame for one bay length by fabricating the continuous longitudinal beams from dedicated beam machines. In Step 3, the next frame is built as in Step 1. During these three steps, power busses and solar array blankets can be installed in parallel. If solar array blankets are to be deployed in the direction of build, they are fed out as the structure indexes. If they are laterally strung, then the structure is indexed incrementally and blankets strung across the structure, from the base, at each increment. Longitudinal busses are installed "on the fly" as the structure is indexed; lateral busses are installed before a bay is indexed.

Step 4 fills in the bay structure with diagonal beams to complete that structure. This bay is then indexed, as in Step 2, and the whole process repeated until the solar array structure is built.

TYPICAL END BUILDER STRUCTURAL ASSEMBLY SEQUENCE



2955-053V

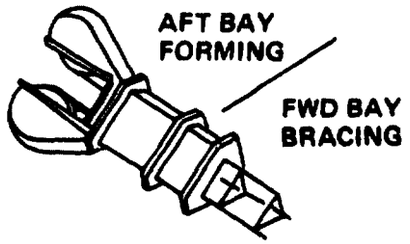
SPS COMPOSITE BEAM FABRICATION

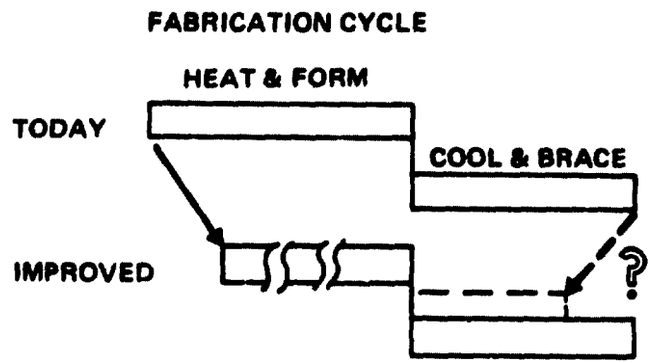
Early in the study a detailed production rate analysis was performed on the composite beam builder (beam machine) since related design data were readily available and because this equipment is common to all SPS segmented and continuous construction concepts. Automatic beam fabrication rates were estimated for SPS by investigating potential areas of growth for the current beam builder technology contracts at Grumman (NAS8-32472) and General Dynamics (NAS9-15310) This preliminary study showed that somewhat higher rates may be achieved in fabricating the large SPS structural beams than the 5 meters per minute ground rule used for operations timelines.

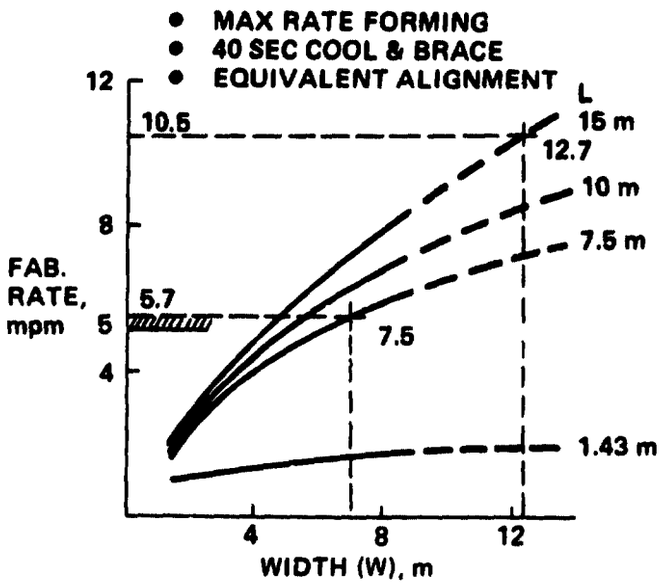
Projected beam builder output rates were determined for a range of possible SPS space fabricated beam sizes. For example a production rate of 5.7 meters/min. for the 7.5 m beam, and 10.5 meters/min. for the 12.7 m beam (both composites) can be reasonably expected from a study of growth potentials available in the current technology.

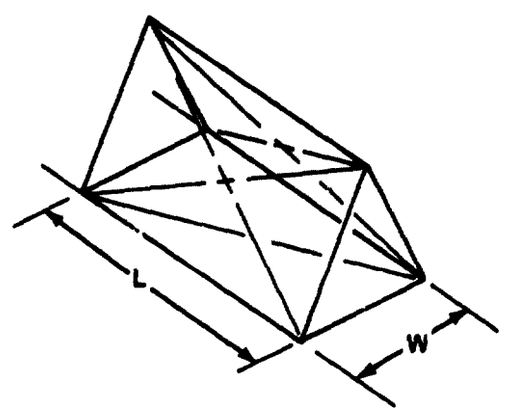
Growth potential areas include: higher cap forming rates, permissable because larger depth beams are less sensitive to beam geometery (bow effect) problems than beams of shallower depth; and, larger batten spacings permit the beam machine (which operates on a run/stop cyclic basis) to operate in the run mode a proportionately greater amount of time for the same unit bay construction.

SPS COMPOSITE BEAM FABRICATION









2955-054V

LONGITUDINAL BEAM FABRICATION REQUIREMENTS

Beam fabrication and satellite indexing are closely related in the end-builder construction operations. The longitudinal beam builders provide the driving force to index the satellite structure, while performing their basic function of beam-element fabrication. This end builder characteristic leads to the necessity for certain requirements regarding beam builder performance. Those requirements identified to date are:

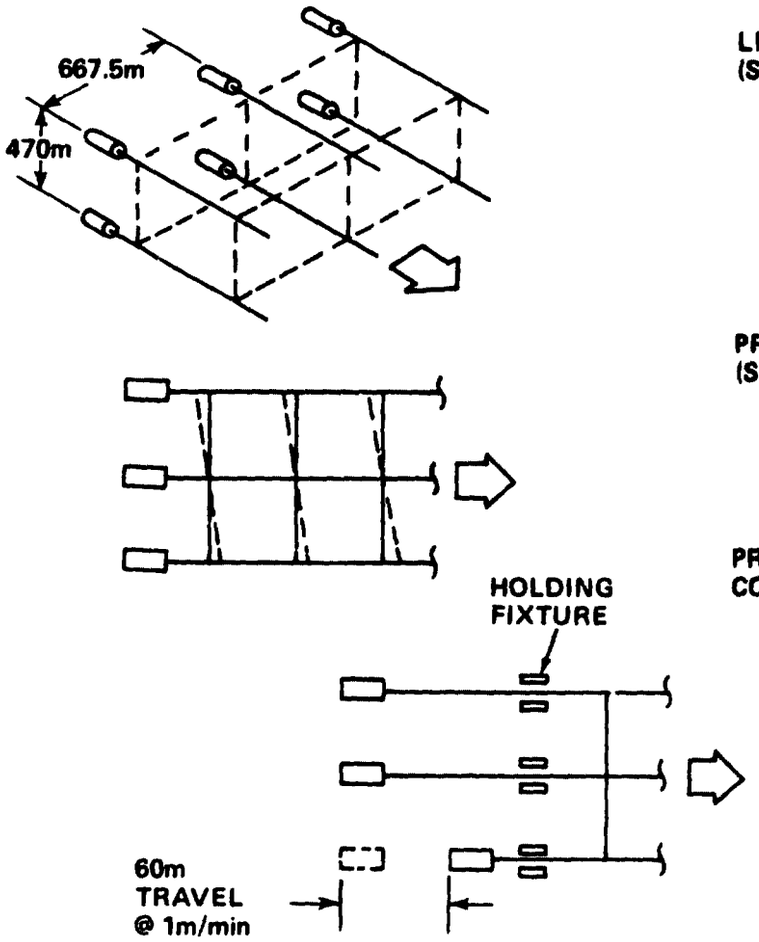
(a) Limit startup and shutdown accelerations to insure that beam builder subsystem machinery will safely sustain forces induced during indexing. Include the affect of mass differences in the 2, 4, and 8-bay end-builder configurations as well as the progressive mass increase in the satellite under construction.

(b) Provide for synchronized indexing. Tolerances in the simultaneously operating beam builders produce variations in beam builder forces during indexing. These variations shall be limited to safe levels as determined by allowable forces not only on subsystem machinery but on the base structure and satellite structure as well.

(c) Design for construction continuity in the event of a beam builder failure. Emphasis shall be placed on reliability of subsystem machinery including redundant operating modes, where possible, to avoid beam builder shutdown. In addition, consideration shall be given to subsystem designs that limit repair time to approximately 60 minutes, while the shutdown beam builder tracks along at the same rate as the indexing structure. Holding fixtures to facilitate on-line/off-line maintainance & repair shall also be considered.

It should be noted that the above requirements for limitation of accelerations and for synchronization apply to any base assembly function where simultaneity of operation is critical, including the use of multi-indexers driving simultaneously to propel either the base (in the end-builder construction approach) or to propel the satellite (in the single-deck construction approach). For all such functions, centralized control is necessary to limit locomotion forces to acceptable values.

LONGITUDINAL BEAM FABRICATION REQUIREMENTS



LIMIT STARTUP & SHUTDOWN ACCELERATIONS
(SIMILAR TO SINGLE-DECK SATELLITE INDEXING)

ISSUES FOR STUDY:

- LOADING COND'S. (C.G. OFFSET, S/A TENSION, ETC)
- IMPACT OF LOADS ON:
  - BASE & SATELLITE STRUCTURE
  - BEAM-BUILDER S/S OPERATION
- CENTRALIZED CONTROL

PROVIDE FOR SYNCHRONIZED INDEXING
(SIMILAR TO SINGLE-DECK SATELLITE INDEXING)

- CONTROL TOLERANCES GENERATE BASE/SATELLITE INTERFACE LOADS
- CENTRALIZED CONTROL

PROVIDE FOR CONTINUITY OF CONSTRUCTION OPS

- RELIABILITY/REDUNDANCY
- 60 MIN REPAIR TIME
- ON LINE/OFF LINE MAINTENANCE & REPAIR

GRUMMAN

2955-062V

SYNCHRONIZED INDEXING

Control tolerances in the simultaneously operating longitudinal beam machines generate interface loads between the base and satellite as a function of the satellite's structural stiffness. If it is assumed that one of the beam machines has a slightly higher output rate than the rest, this rate difference can be seen as a difference in beam length and can be treated as a deflection induced on the satellite structure.

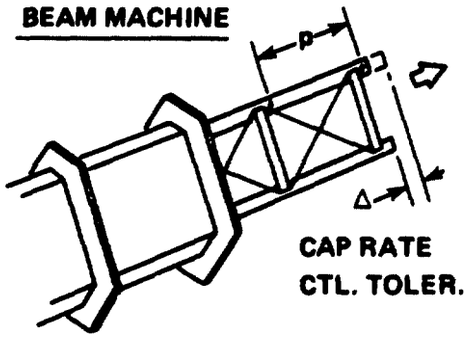
A preliminary study of beam synchronization requirements suggests that the control technique presently used within the beam machine itself to synchronize the 3 cap rates can also be used to control multiple machines by increasing the number of feedback control loops to include all caps in those machines operating simultaneously. Assuming tolerance levels achieved to date in the GAC/MSFC (NAS 8-32472) beam builder, estimates of beam length differences between machines are derived. The induced loads shown are based on deflections imposed on an elastic structure idealized in the curve also included in the chart. (Beam properties used were E=20,000,000 PSI and A = 3.75 in^2). Preliminary load values computed are given parametrically based on the frequency (7.5m, 5.0m, and 2.5m) with which recalibration checks in the control system are performed. For example, a slotted hole spacing of 7.5 m along the caps limits the accummulation of error in the encoder device to .533 cm max. this deflection produces a maximum load of 2670 newtons which, for the present, is well under the 13000 N allowable.

It should be noted that the affects of thermal gradients in the construction base, which are a necessary consideration in this kind of analyses, have not been included.

SYNCHRONIZED INDEXING

MULTI MACHINE CTL.
SAME AS CAP RATE CTL.

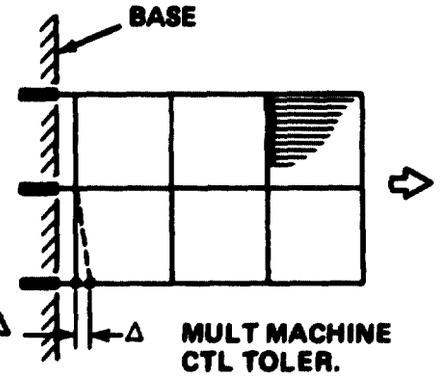
BEAM MACHINE



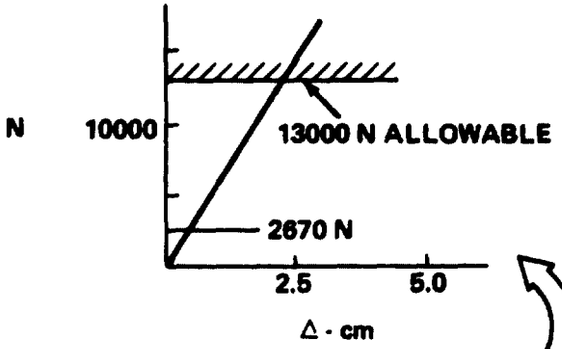
CAP RATE
CTL. TOLER.

CLOSED LOOP
FEEDBACK CTL

- ENCODER DEVICE
- SLOTTED HOLE DETECTOR



MULT MACHINE
CTL TOLER.



RELATIONSHIP OF CTL
TOLER AXIAL LD
IN 7.5 m BEAM

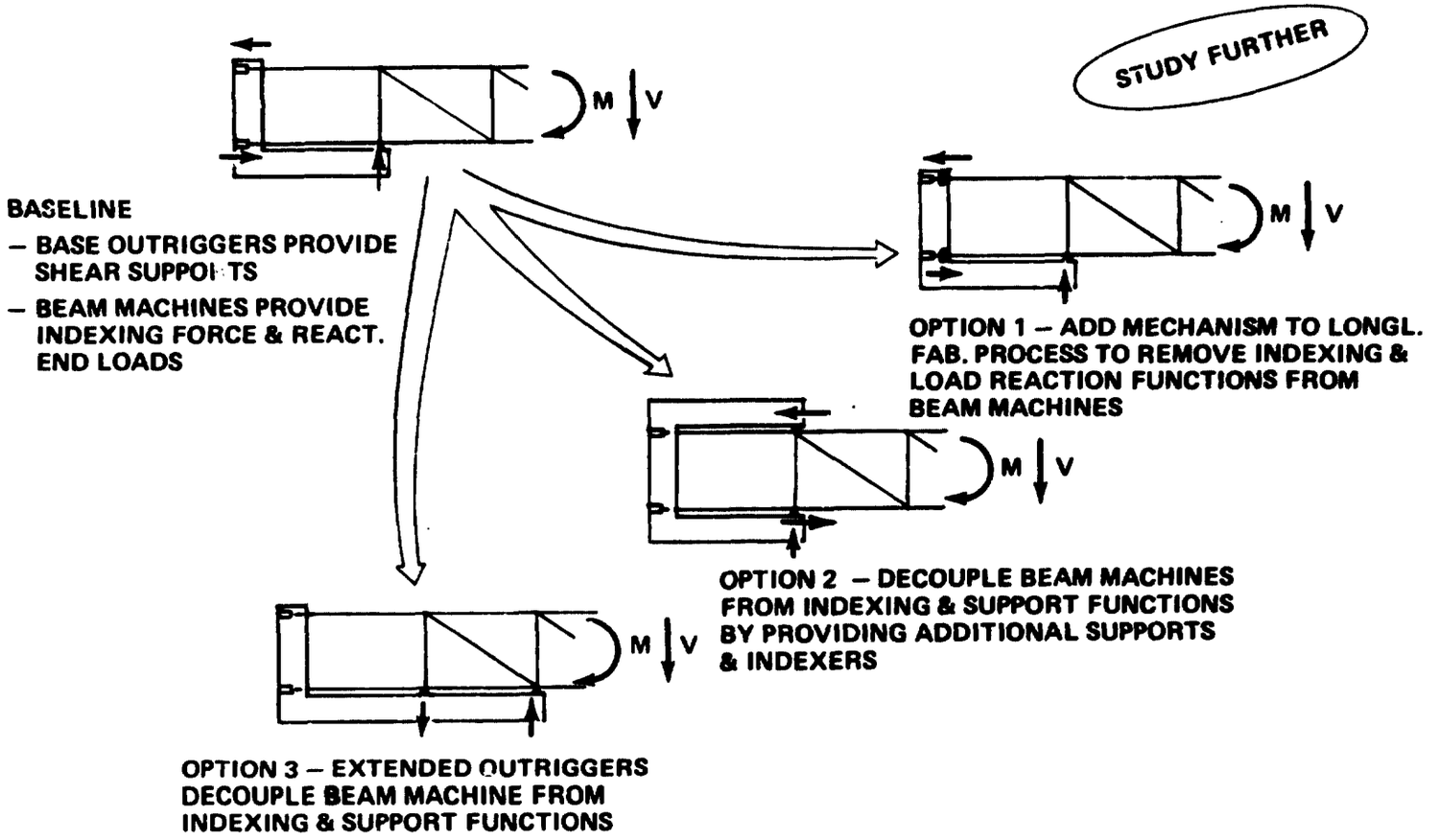
PITCH (P)	MAX ERROR	INDUCED LOAD
7.5 m	± 0.533 cm	± 2670 N
5.0	± 0.355	± 1780
2.5	± 0.178	± 890

SATELLITE SUPPORT DURING END BUILDER CONSTRUCTION

As presently conceived, the L shaped facility for building the solar array carries beam machines on one leg of the L and supports for emerging structure on the other leg. As illustrated, distrubance of the structure already built will result in moments reacted by end loads in the beams and beam machines and by shears reacted by the supports on the other leg. The beam machines also provide the forces for indexing the structure, as it is built, by fabricating the longitudinal beams. The capability of the beam machines to provide the forces necessary to react disturbance torques and to index the assembled satellite structure requires further study.

Three options are presented on this chart for relieving the beam machines of this function. Option 1 adds on-line indexing mechanisms to the process of fabricating the longitudinal beams. These synchronized mechanisms are dedicated to indexing the beams and to reacting disturbance end loads similar to the indexers used on the single deck baseline. Shears are still reacted by the leg supports. Option 2 adds a leg to the top of the L to make a C section base. Thus, the structure has supports on two opposite faces which react all disturbance loads and index the structure. The third option extends that leg of the base which mounts the supports. Additional supports are provided on the extension at one bay distant from the originals. These two sets of supports react all distrubance loads and index the structure.

SATELLITE SUPPORT DURING END BUILDER CONSTRUCTION



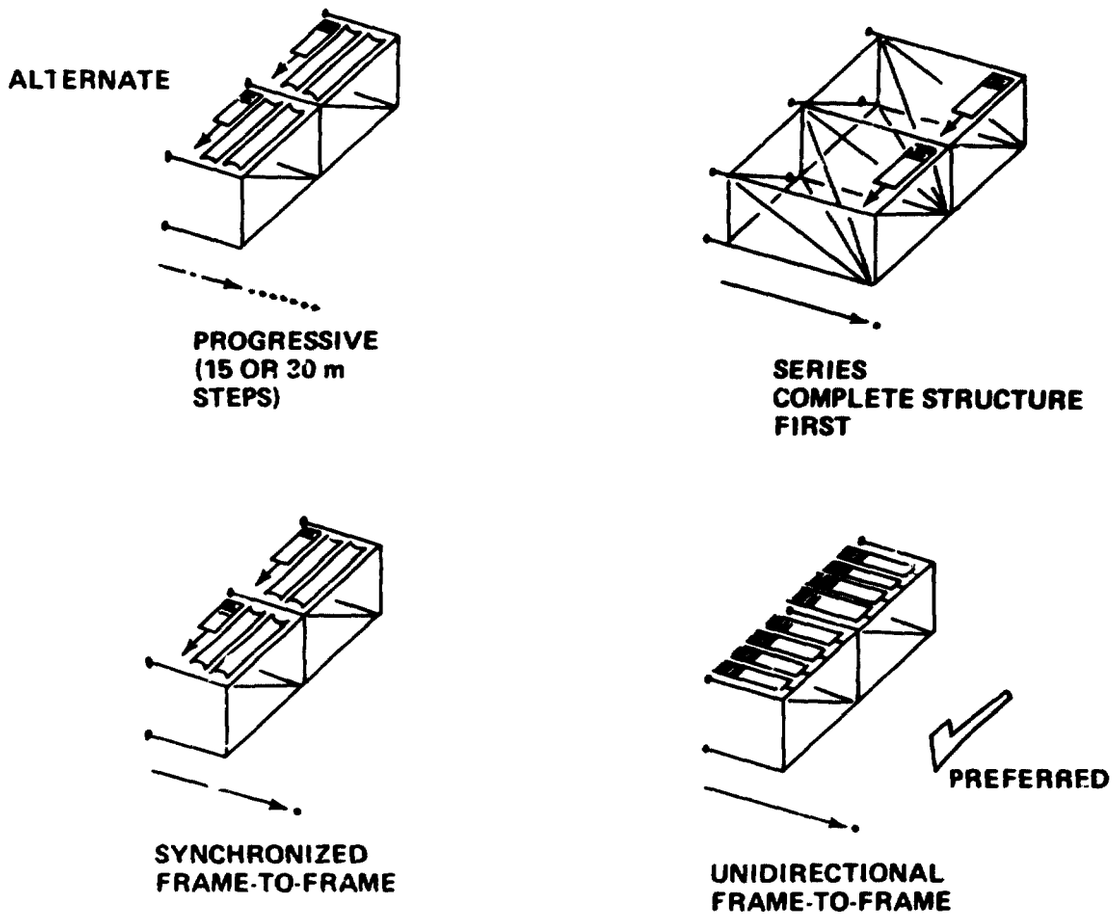
2955-055V

SOLAR ARRAY/STRUCTURE ASSEMBLY METHODS

Four methods are shown for coupling the installation and deployment of solar array blankets with the end builder structural assembly sequence. The baseline solar array segments are oriented normal to the continuous longitudinal beams. Hence, the arrays may be either installed during progressive stop-and-go beam fabrication operations (i.e., build 15m length-deploy array-build 15m, etc.), installed in series with the completed structural bay (as in the segmented build-up approach), or installed during synchronized operations with continued beam fabrication. A unidirectional method is also shown which aligns the solar array segments with the direction of construction. In this method, all the solar arrays in the bay can be automatically deployed, as the beam fabrication process continues from one frame to the next frame. Reorienting the arrays in this manner, however, requires the satellite to be designed with a different power bus routing. Recent Boeing analysis indicates that the power bus can be rerouted with no weight penalty.

The unidirectional solar array/structure assembly method is preferred because it allows shorter construction times to be achieved while also permitting significantly slower rates for thin film solar array blanket deployment. This method requires the least equipment to implement. The progressive method of assembly is the alternate approach since it can also be implemented with little impact on construction base design.

SOLAR ARRAY/STRUCTURE ASSEMBLY METHODS

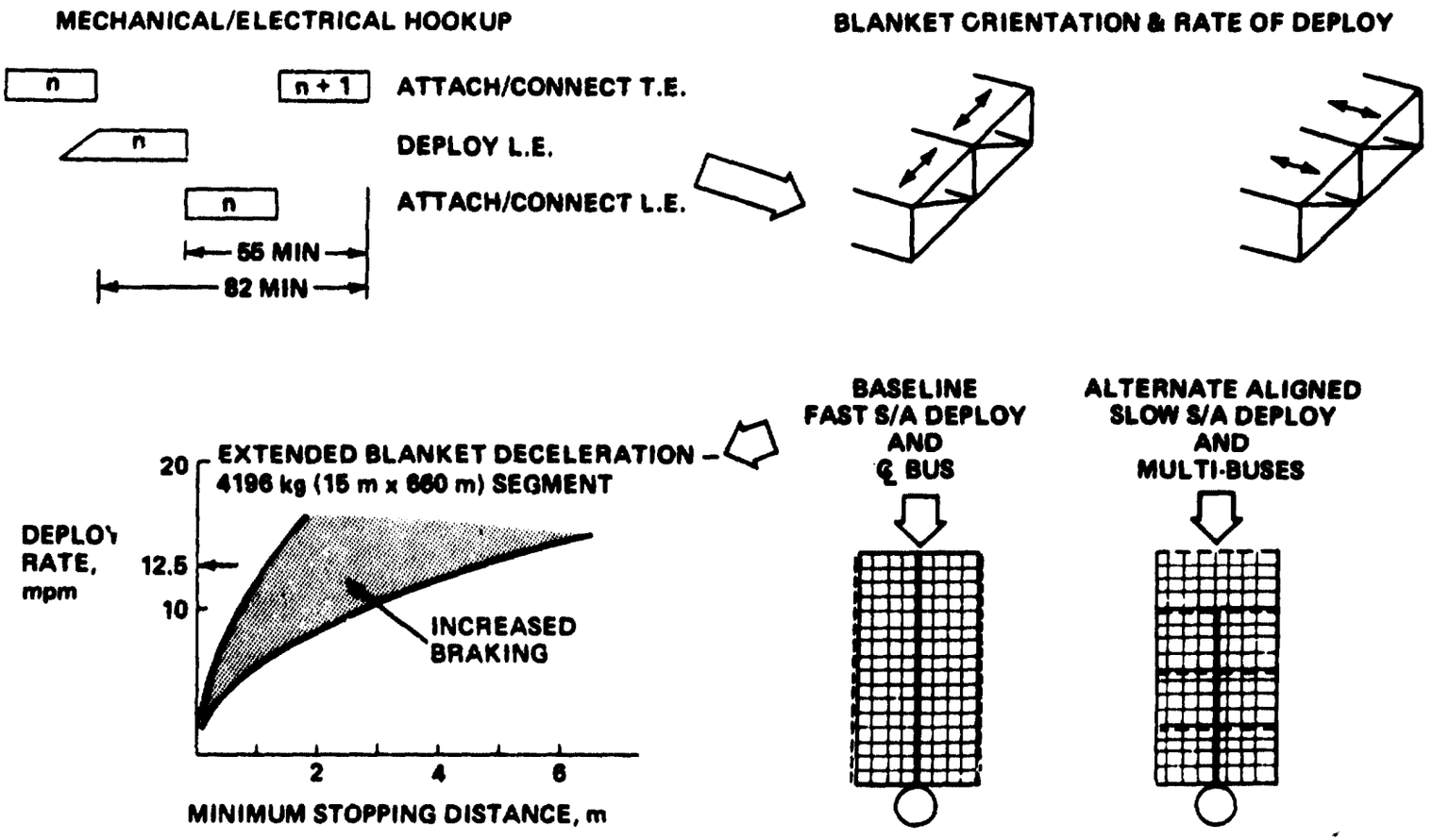


2955-056V

SOLAR ARRAY BLANKET INSTALLATION CONSIDERATIONS

The solar array installation method must deal with the mechanical and electrical requirements for hooking up the opposite ends of each blanket and the required rate of deployment. The baseline solar array installation cycle takes 82 minutes, which includes 55 minutes for attaching and connecting the trailing edge (TE) and the leading edge (LE). The trailing edge connections are made in parallel as the leading edge deploys. With the blanket oriented normal to the direction of construction it must be deployed at a faster rate than if it were aligned with the emerging longitudinal beams. High rates of deployment are generally undesirable since they impose increased braking requirements during extended blanket deceleration. The baseline deployment rate of 12.5 mpm can be reduced significantly by aligning the solar array segments with the direction of build-up. It is recognized that re-orienting the arrays also requires the power distribution system to be designed with multi-busses in lieu of the baseline centerline bus.

SOLAR ARRAY BLANKET INSTALLATION CONSIDERATIONS



2955-057V

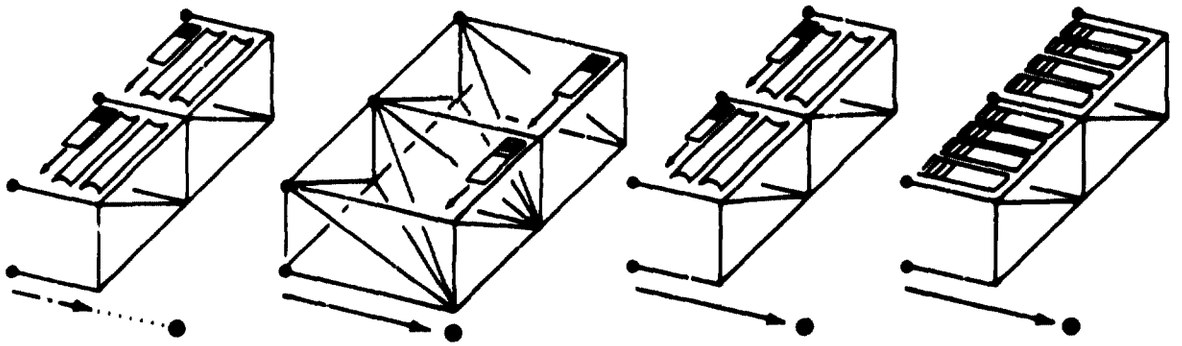
SOLAR ARRAY/STRUCTURE ASSEMBLY COMPARISON (128 BAYS)

The four assembly methods (progressive, series, synchronized, and unidirectional) are compared in terms of their structural fabrication method, blanket installation direction, required deployment rates, solar array installation equipments, construction base impact and related satellite impact.

Approximately 148 days are available for constructing the power collection module, within the specified six months, when yoke assembly, antenna/yoke mating and final test and check out are considered. The required rates for fabricating the longitudinal beams and deploying the solar array blankets in 128 bays are shown for the 8 bay, 4 bay, and 2 bay wide construction bases. The analysis includes the time for fabricating and assembling satellite frames and diagonal supports and performing solar array mechanical and electrical hook-ups. It should be noted that the longitudinal beams are fabricated at much lower rates than the 5 mpm rate used to fabricate laterals and diagonals. For the cases examined, it was not possible to apply either the progressive or series methods for the 2 bay wide base since it took too long to accomplish. Both the synchronized and unidirectional methods, however, were able to work within the available time. The unidirectional method exhibits the same low rates, of course,for beam fabrication and blanket deployment. Therefore it was selected for the 2 bay base design. The alternate progressive method of assembly was selected for the 8 bay and 4 bay base designs for the mid term to demonstrate that it could be made to work in 6 months.

The unidirectional method is also attractive for the 4 bay and 8 bay designs because it requires the least equipment and has little impact on the construction base. Recent Boeing analysis has indicated that the satellite power bus can be reconfigured with no weight penalty. An assessment of structural impact due to end builder construction methods and realigned solar blanket preloading however remains to be performed.

SOLAR ARRAY/STRUCTURE ASSEMBLY COMPARISON (128 BAYS)



ASSY METHOD	PROGRESSIVE	SERIES	SYNCHRONIZED	UNDIRECTIONAL
STRUCTURAL FAB	15 m STEPS	COMPLETE BAY	FRAME-TO-FRAME	FRAME-TO-FRAME
BLANKET INSTALLN	BASELINE-LAT.	LATERAL	LATERAL	ALIGNED
148 DAY INDEX/DEPLOY 8-BAY WIDE RATES (mpm) 4-BAY WIDE RATES 2-BAY WIDE RATES	(L. BEAM & S/A) 0.17 & 12.5 0.36 & 12.5* –	(L. BEAM & S/A) 0.17 & 12.5 0.36 & 12.5* –	(L. BEAM & S/A) 0.09 & 5.8 0.18 & 12.3 0.42 & 28.4	(L. BEAM & S/A) 0.12 & 0.12 0.54 & 0.54 1.47 & 1.47
S.A. INSTALL. EQUIP.	INSTALLERS & DEPLOYER	INSTALLERS, DEPLOYER & CROSS BAY GANTRY	INSTALLERS & DELOYERS	INSTALLERS
CONSTR BASE IMPACT	STRAIGHT TRACK LEDGE	667 m SUPPORT ARMS	CURVED RETURN TRACK OVERHANG	STRAIGHT TRACK LEDGE
SATELLITE IMPACT	STRUCT. – TBD	STRUCT. – TBD	STRUCT. – TBD	STRUCT. – TBD PWR BUS – NONE

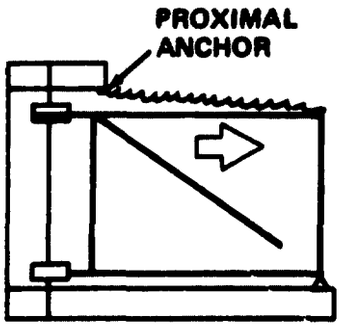
*DEPLOY 2 BLANKETS/BAY

ALTERNATE

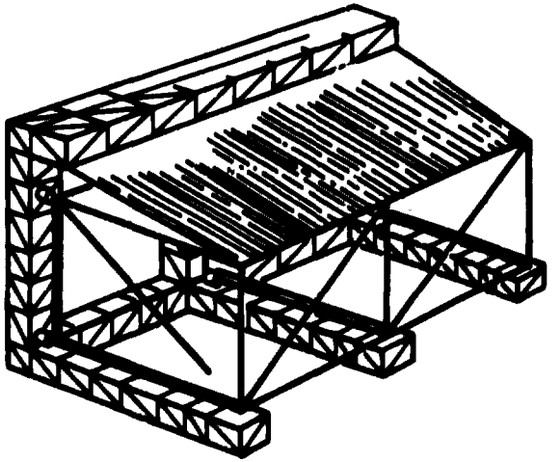
PREFERRED

2955-058V

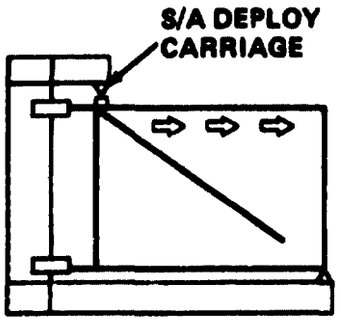
END BUILDER FRAME ASSEMBLY/SOLAR ARRAY DEPLOYMENT (COUPLED OPERATIONS)



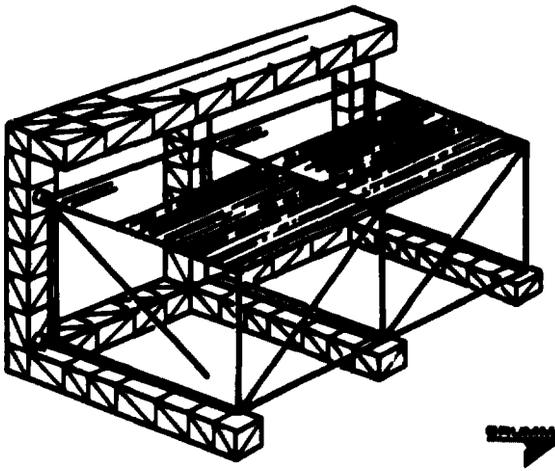
88 SOLAR ARRAYS
DEPLOYED
WITH CONTINUOUS
LONGITUDINAL
BEAM FABR.



– OR –



4 SOLAR ARRAYS
DEPLOYED
WITH INCREMENTAL
LONGITUDINAL
BEAM FABR.

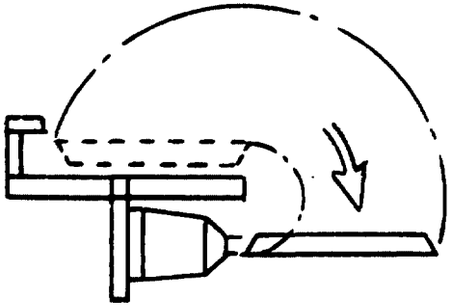


2955-077V

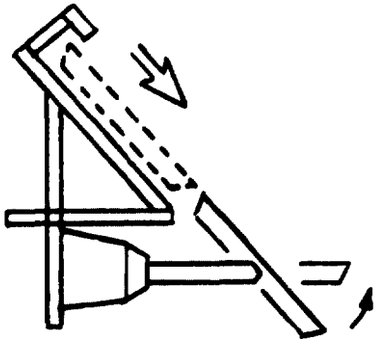
END BUILDER ANTENNA INSTALLATION CONCEPTS

Several options were investigated for locating the antenna construction site. These options included top deck (horizontal and canted), back side, and rear deck (forward and lateral pass) as shown. The top-deck horizontal, originally selected as the baseline approach because of base size and weight consideration, was later discarded because of undesireable off-site antenna assembly procedures necessitated by this approach. The top-deck canted concept exhibits the same problems. The back side approach contained excessive antenna handling and was also discarded. The rear deck - forward pass has the desireable feature of in-line antenna handling,however the slide-through feature imposes critical requirements for satellite support and satellite clearance and further requires the construction base to be greater than 2-bays wide. The preferred approach is the rear deck lateral pass because of its in-line characteristic and its much simpler mating procedure. After mating the antenna, the base is indexed clear of the antenna in a simple, straight forward manner.

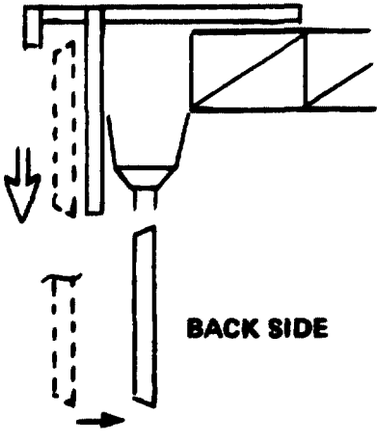
END-BUILDER – ANTENNA INSTALLATION CONCEPTS



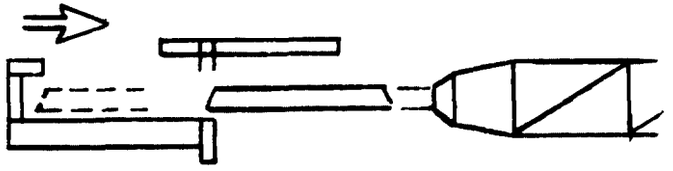
TOP DECK



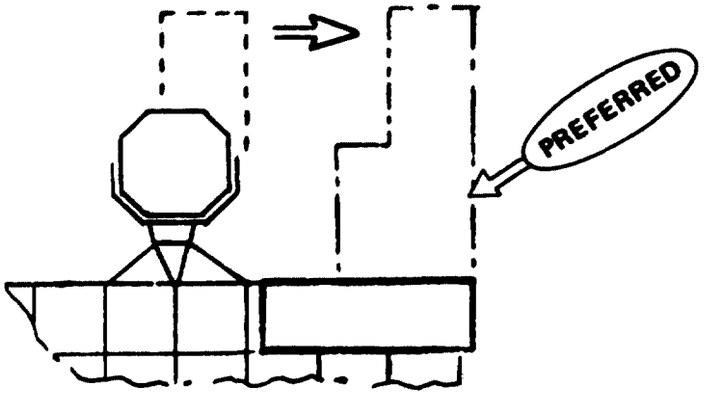
CANTED



BACK SIDE



REAR DECK
FWD PASS



REAR DECK LATERAL PASS

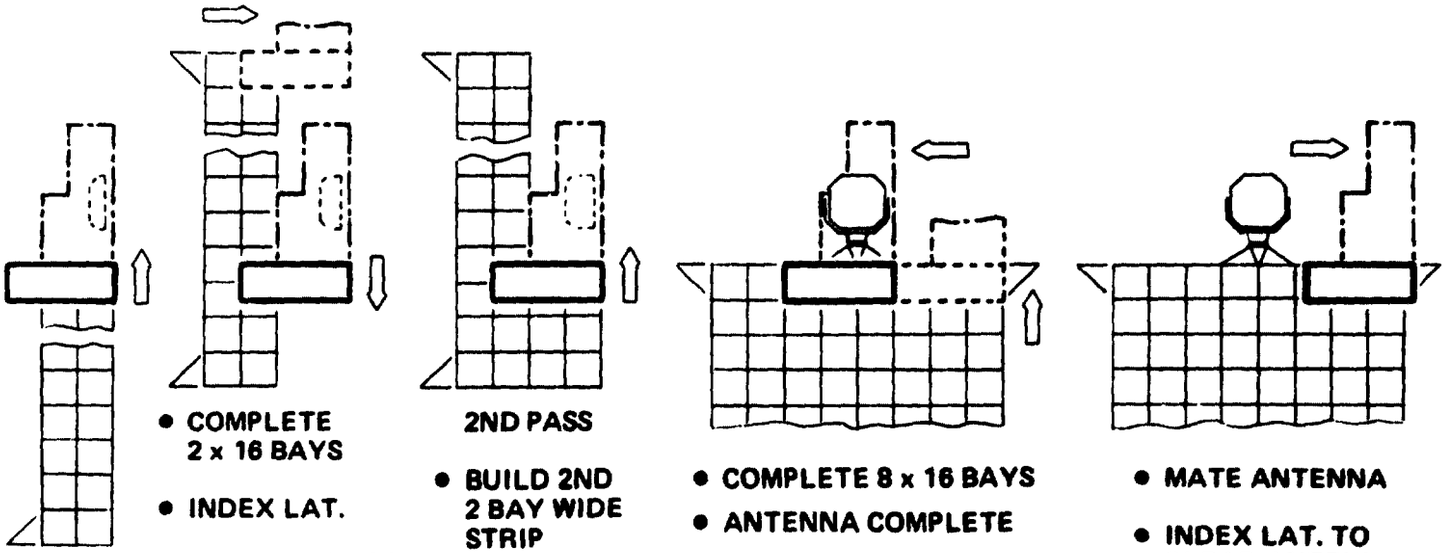
2955-021V

2 BAY END BUILDER CONSTRUCTION SEQUENCE (UPDATE)

The 2 bay base constructs the 8 x 16 bay satellite in 4 passes, fabricating a 2 bay strip in each pass. Both longitudinal and lateral indexing rails are provided for. After completing the first pass, the base is indexed laterally (2 bays) and then longitudinally (16 bays) to begin, at that point, the second pass. Note that the antenna is constructed in parallel. This procedure is repeated until the power generation and distribution system structure and S/S is completed.

At the end of the 4th pass, the antenna, yoke, etc are also completed. The base is then indexed laterally to a position with the antenna on satellite centerline. Mating operations are then begun to transfer the antenna mass from the construction base to the satellite. When the antenna is completely mated the base is then indexed away from, and clear of, the antenna.

2 BAY END-BUILDER – CONSTRUCTION SEQUENCE (UPDATE)



1ST PASS

- BUILD 2-BAY WIDE STRIP
- PARALLEL ANTENNA BUILDUP

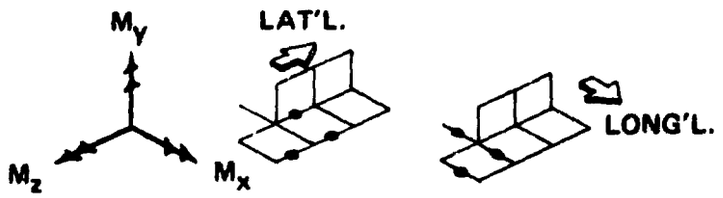
- COMPLETE 2 x 16 BAYS
- INDEX LAT.
- GO BACK-TO-GO

2ND PASS

- BUILD 2ND 2 BAY WIDE STRIP

- COMPLETE 8 x 16 BAYS
- ANTENNA COMPLETE
- INDEX LAT.
- BUILD ANT. SUPPT. STRUCT.

- MATE ANTENNA
- INDEX LAT. TO CLEAR ANTENNA



INDEXER SUPPORTS

GRUMMAN

2955-045V

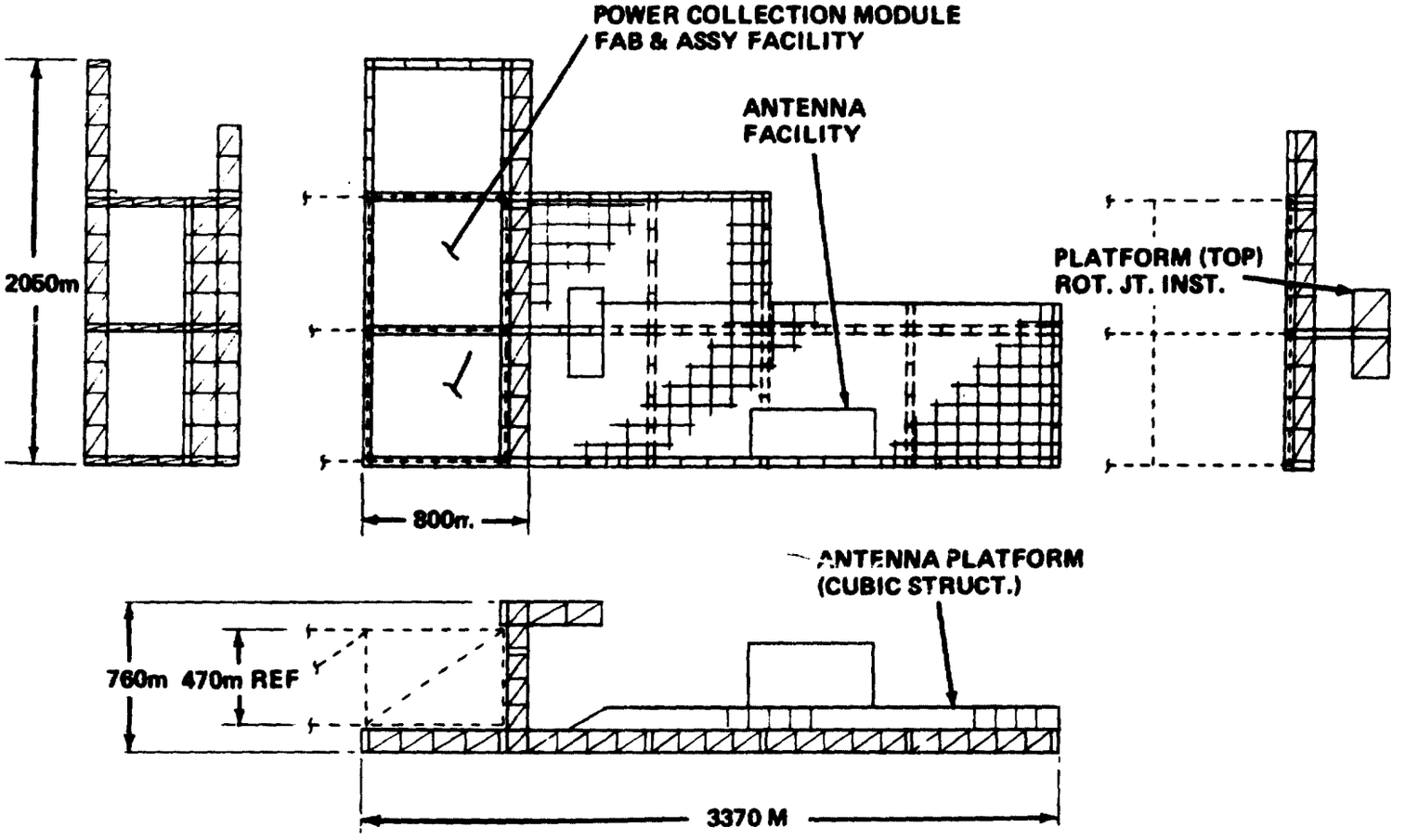
2 BAY END BUILDER CONSTRUCTION BASE

The 2 bay end builder construction base builds an 8 bay wide SPS, 16 bays long in four passes. The only difference from the SPS baseline configuration is the continuous, rather than segmented, fabrication of all longitudinal beams. Solar arrays are deployed parallel to the longitudinal beams, and the antenna facility conforms to all aspects of the baseline antenna construction scenario, except that it includes a yoke fabrication and assembly area.

While defined as a 2 bay base, its width (2050m) encompasses a 3 bay segment of the power collector structure to provide a one bay overlap for lateral and longitudinal indexing operations. The 760m high base, built in the form of an open truss "L" - shaped framework, is sufficient to house necessary equipment and machinery to construct the power collector module. The antenna construction site is located at the rear of the base, making its total length 3370m although only approximately 800m is required for power collection module construction. Note that a short platform extends into the antenna work area to facilitate rotary-joint assembly.

Further details of the 2 bay base operation are described in the following pages.

2 BAY END-BUILDER – CONSTRUCTION BASE (REVISED)



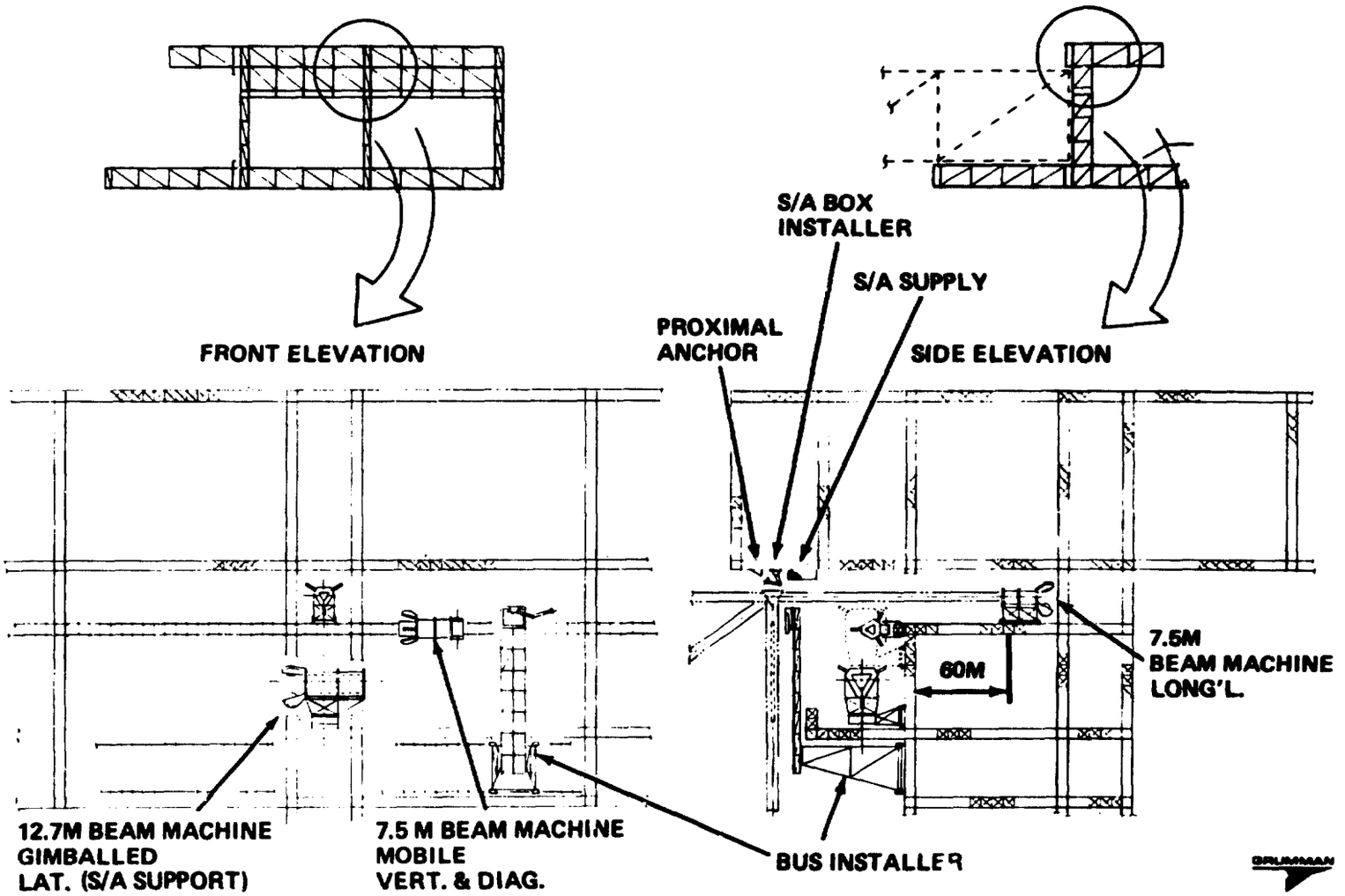
2955-047V

2 BAY END BUILDER CONSTRUCTION SYSTEM

Major equipment functions and their specific locations in the base are identified. Note that a 60 m travel distance provided the longitudinal beam builders to permit failure correction in a 60 min period (assuming a fabrication rate c lm/min).

The two views shown represent what is probably the most active location in the base. The 12.7 m beam machines gimbals 180° to provide the required S/A support beams, while nearby a mobile (track mounted) 7.5 m beam machine is shown at its mid point of travel between one end of the base and the other. In addition, the 7.5 longitudinal beam machine; bus installer and solar array implacement equipments are shown.

2 BAY END-BUILDER – CONSTRUCTION SYSTEM

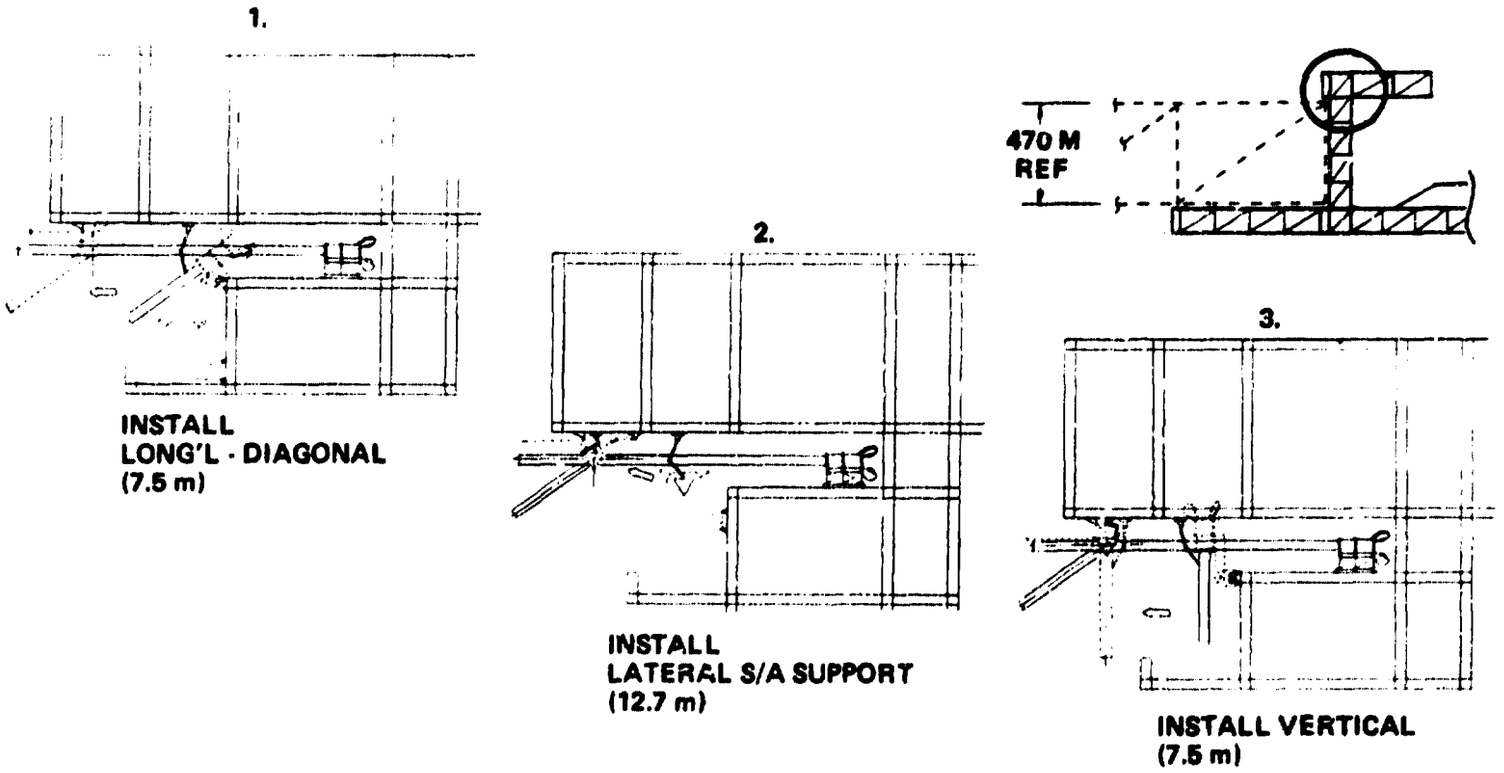


2955-046V

2 BAY END BUILDER CONSTRUCTION APPROACH (PRI STRUCT.)

The production buildup of the power collection module starts with assembly of 7.5 m and 12.7 m structural tri-beams. The figure opposite depicts major beam installation activity at each frame-station with the forward longitudinal-diagonal (7.5m) being installed before the lateral S/A support beam (12.7m) to facilitate cherry-picker accessibility & mobility in the end-attachment process. Note that the 12.7 m beam machine shuttles up and down on a short length of track to preclude interference with the beam machine producing the vertical beam elements. The beam elements in the plane of each frame (verticals, lateral diagonals, and lower-tranverse elements) are installed last and complete the structural buildup of each bay.

2 BAY END-BUILDER CONSTRUCTION APPROACH (PRI STRUCT)



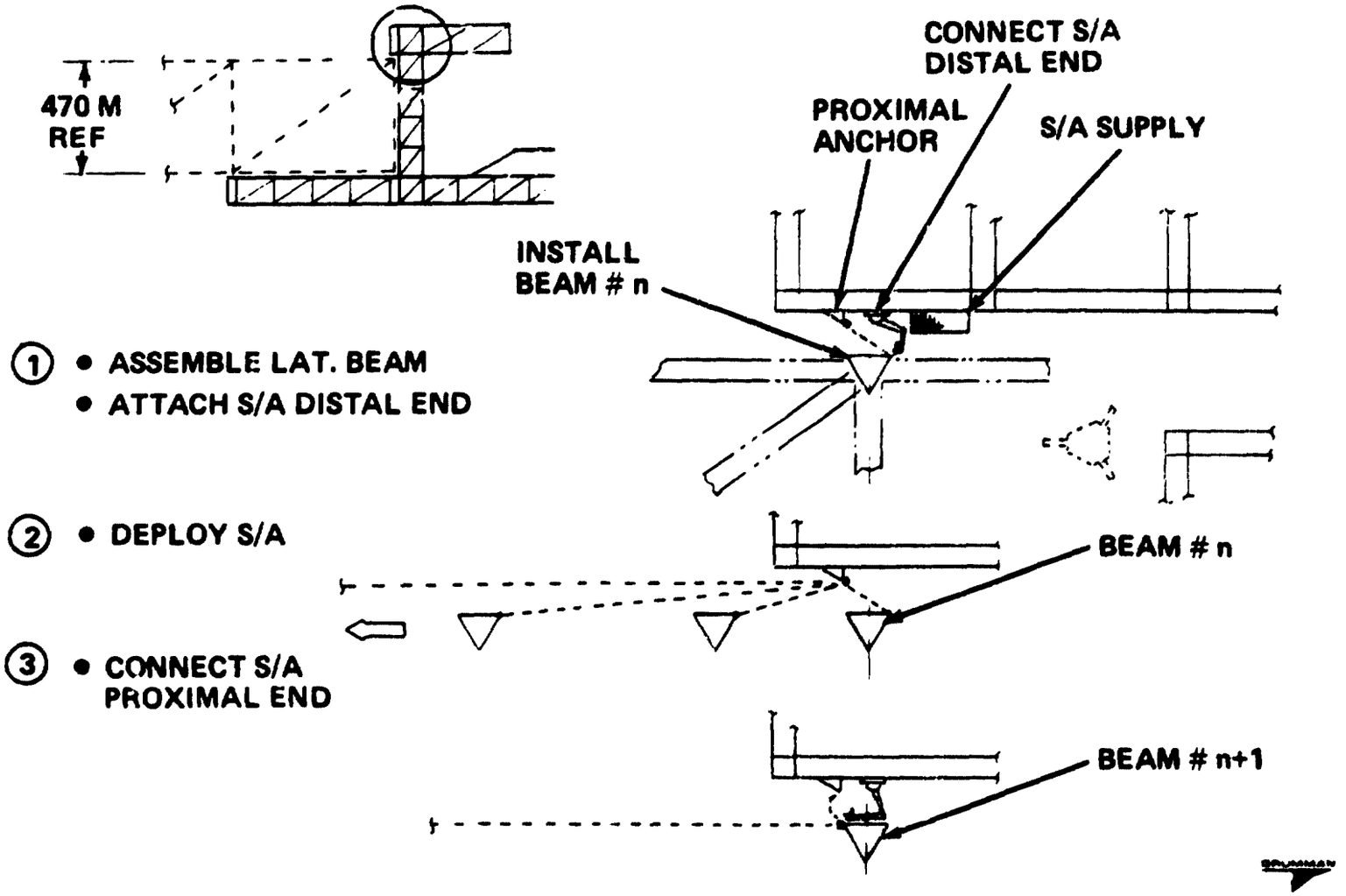
2955-065V

2 BAY END BUILER CONSTRUCTION APPROACH (SOLAR ARRAY)

The installation of solar arrays occurs at the same work station in the base as the assembly of in-plane structural frame elements, described in the preceding chart, to obtain maximum time-line benefits from parallel activities.

Subsequent to the installation of a 12.7 m solar array support beam, the cherry picker removes a S/A box from the supply crib shown and fastens it to the proximal anchor. The distal-end of the blanket is then connected to the beam. When the frame has been indexed one bay away, the blankets are fully deployed and the box is removed from its anchor support fittings and fastened to the next 12.7 m support beam to complete the cycle.

2 BAY END-BUILDER CONSTRUCTION APPROACH (SOLAR ARRAY)



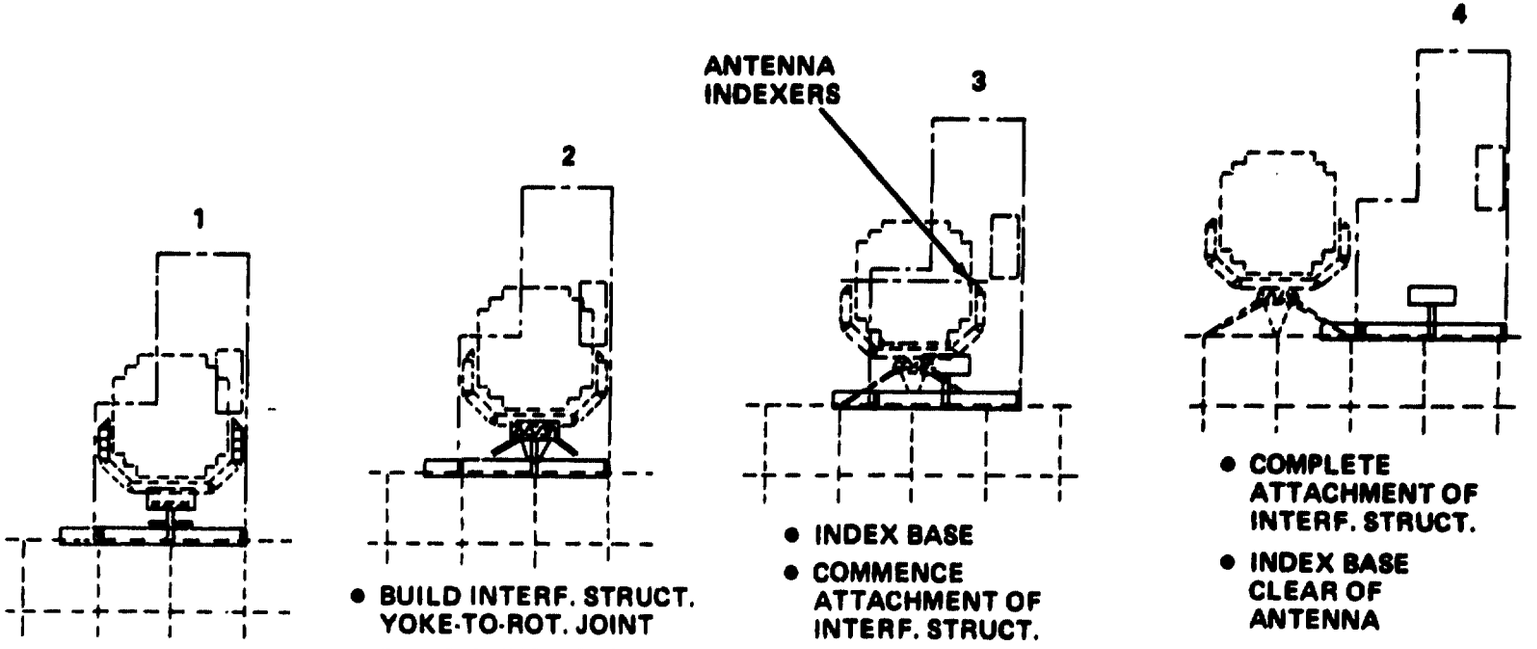
1. • ASSEMBLE LAT. BEAM
   • ATTACH S/A DISTAL END
2. • DEPLOY S/A
3. • CONNECT S/A PROXIMAL END

2955-064V

2 BAY END BUILDER YOKE CONSTRUCTION/ANTENNA MATING (REVISED)

With the antenna facility in its revised location in the construction base, antenna mating operations are performed after the completion of the 8 x 16 power collection module. The antenna is constructed inparallel with the S/A so that after the 4th pass, it is ready for installation. At the end of the 4th pass, the base is indexed to the left 3-bays to put the antenna on the S/A centerline. The interface structure between rotary joint and solar array is attached in incremental steps to permit the base to gradually transfer the antenna mass while indexing itself away from, and clear of, the antenna.

2 BAY END-BUILDER
YOKE CONSTRUCTION/ANTENNA MATING (REVISED)



- 8 x 16 BAYS COMPLETE
- BASE IN POSITION
- ANTENNA, YOKE, & ROTARY JOINT COMPLETE

- BUILD INTERF. STRUCT. YOKE-TO-ROT. JOINT
- BUILD & JURY RIG INTERF. STRUCT ROT. JOINT-TO-S/A

- INDEX BASE
- COMMENCE ATTACHMENT OF INTERF. STRUCT.

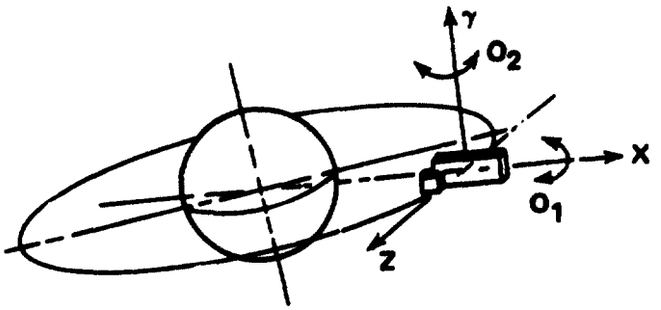
- COMPLETE ATTACHMENT OF INTERF. STRUCT.
- INDEX BASE CLEAR OF ANTENNA

2955-063V

5GW SPS GEO CONSTRUCTION-END BUILDER GRAVITY GRADIENT CONDITION

Preliminary studies were made to assess the structural design of the end builder construction base in geosynchronous orbit. This case shows the configuration evaluated for gravity gradient induced loads; the solar array is 4 by 16 bays, the construction base is in position at the antenna end and the microwave antenna fully constructed is located in the aft position of the base. Mass data and orbital orientation are as shown in the figure. A worst case gravity gradient torque was assumed with $\theta_2 = 45°$ and $\theta_1 = 0$ was assumed.

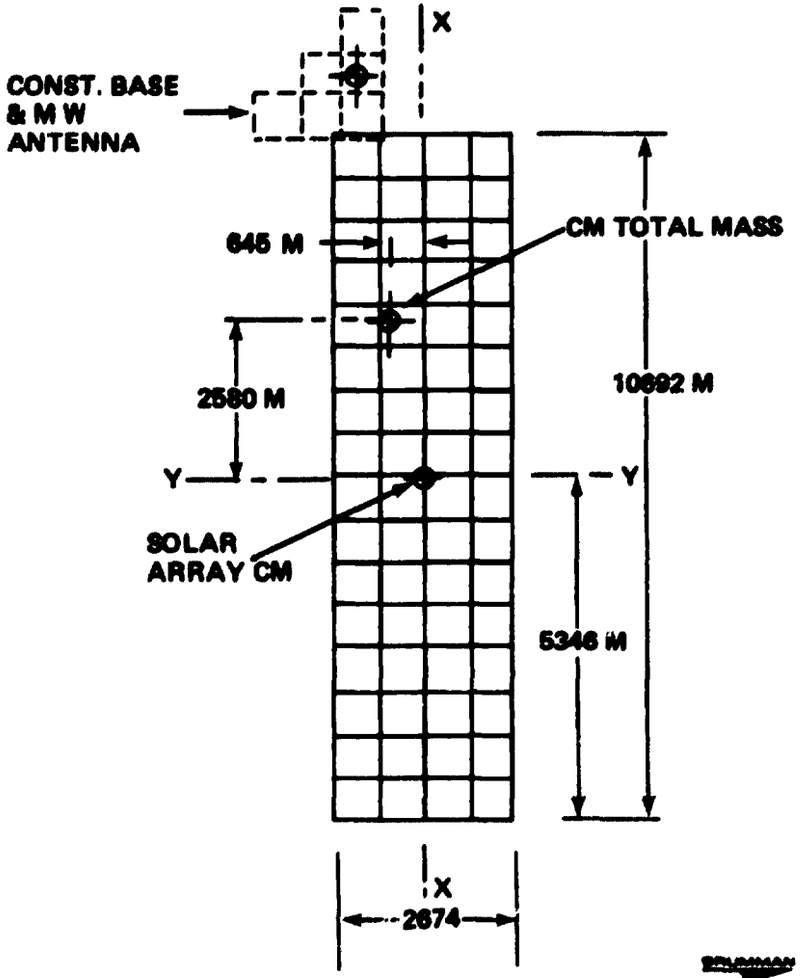
5GW SPS GEO CONSTRUCTION – END BUILDER GRAVITY GRADIENT CONDITION



SATELLITE ORIENTATION DURING CONSTRUCTION

MASS DATA

- CONSTRUCTION BASE — 5×10^6 kg
- MW ANTENNA — 12.5×10^6 kg
- 1/2 SOLAR ARRAY — 18.75×10^6 kg

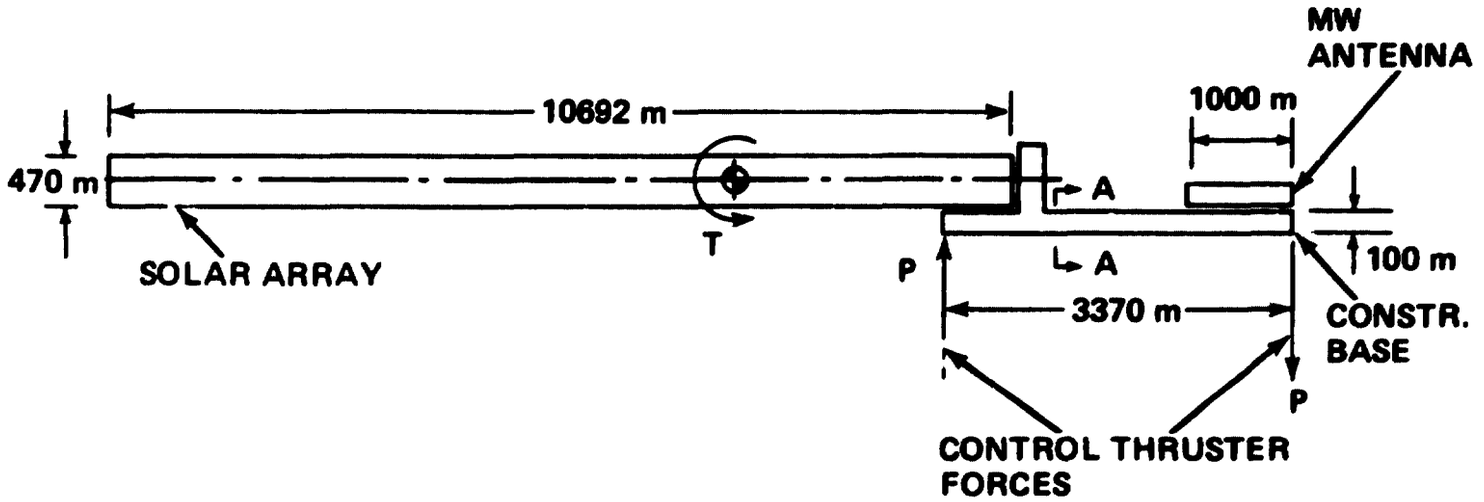


2955-034V

5 GW SPS END BUILDER CONSTRUCTION BASE GRAVITY GRADIENT CONDITION

This figure shows the free-body diagram of the solar array/construction base/antenna configuration. The control thrusters were assumed located as shown at each end of the construction base. The moment at the section A-A would not exceed the strength of a composite material beam.

5GW SPS
END BUILDER CONSTRUCTION BASE
GRAVITY GRADIENT COND.



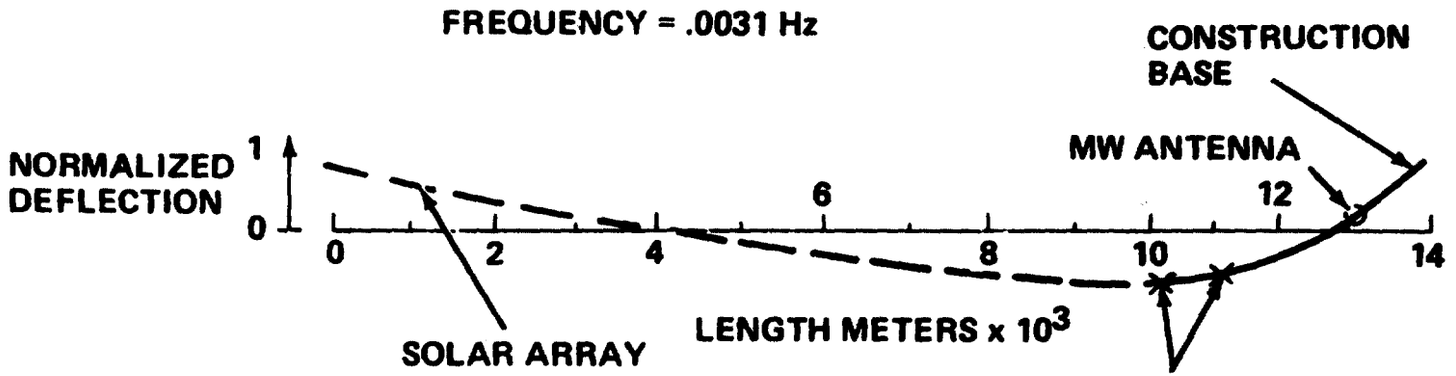
- ESTIMATED BENDING MOMENT AT SECTION A-A $M = 1.46 \times 10^6$ Nm
- ULTIMATE LOAD PER BEAM CHORD MEMBER $P = \pm 4857$ N
- LOAD NOT CRITICAL FOR CLOSED CHORD COMPOSITE MEMBER

5GW SPS GEO CONSTRUCTION END BUILDER NATURAL FREQUENCY & MODE SHAPE

The frequency for the selected configuration shown in the previous figure was calculated using the given mass data. The stiffness data was calculated for the Boeing selected composite cap member with an area of 8.065×10^{-4} m^2 and a modulus of elasticity of 1.378×10^{11} N/m^2. The array was assumed attached to the base at the indicated locations; the total antenna mass was located at its center of gravity.

The results show the frequency of 0.0031 Hz is well above the required 0.00124Hz.

5GW SPS
GEO CONSTRUCTION END BUILDER
NATURAL FREQUENCY AND MODE SHAPE



MASS DATA:

CONSTRUCTION BASE	5×10^6 kg
SOLAR ARRAY	18.75×10^5 kg
MW ANTENNA	12.5×10^6 kg

STIFFNESS DATA:

EI_{ARRAY} 1.48×10^{14} Nm^2

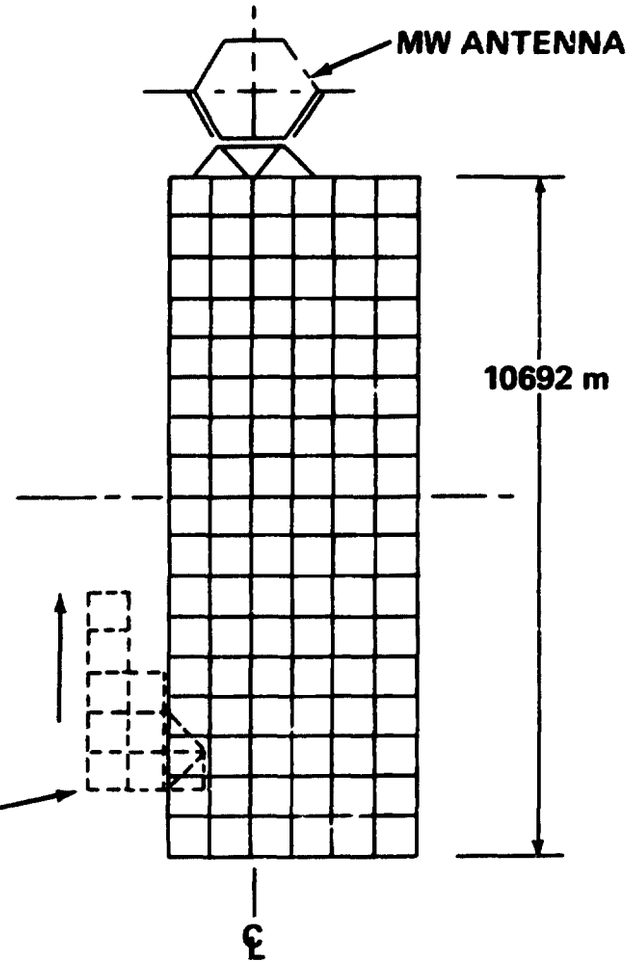
$EI_{CONST.\ BASE}$ 5×10^{12} Nm^2

5GW SPS END BUILDER CONSTRUCTION BASE INDEXING CONDITION

Preliminary estimates were made of the loads acting on the end builder construction base during construction and are presented in the next two figures. The satellite array/antenna configuration are shown in the first figure. Since the satellite mass is very much greater than the construction base, it can be assumed that the relative motion of the satellite is zero.

A force-time curve is shown in the second figure for an index rate of 20 m/minute. Additional study is required to evaluate the effect of the impulse on the construction base.

5GW SPS
END BUILDER CONSTRUCTION BASE
INDEXING CONDITION



INDEXING RATE:

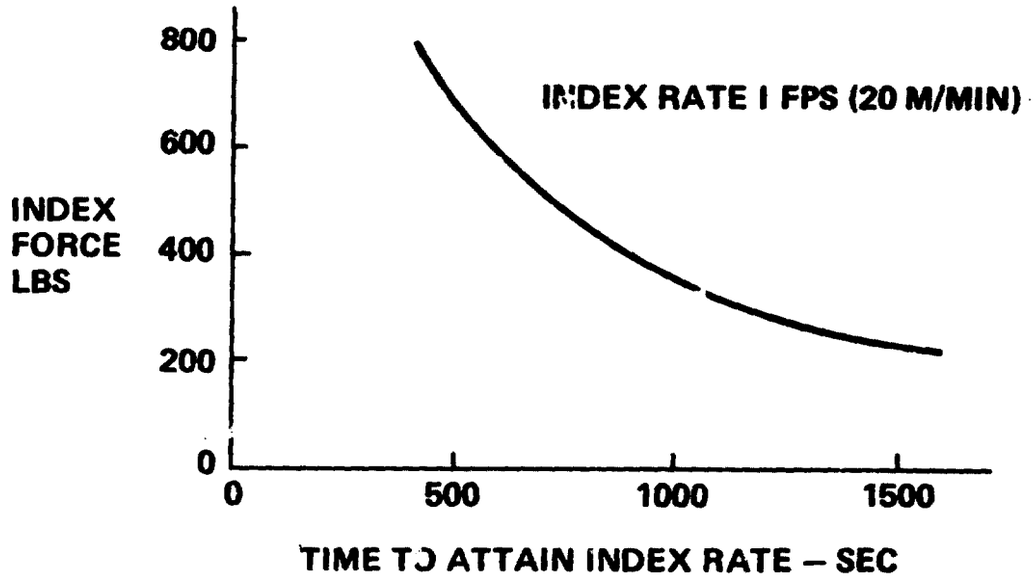
10 M/M TO 20 M/M

MASS DATA:

SOLAR ARRAY 28 x 10^6 kg
ANTENNA 12.5 x 10^6 kg
BASE 5 x 10^6 kg

CONSTRUCTION BASE

5GW SPS
END BUILDER CONSTRUCTION BASE
INDEXING FORCE



ASSUMPTIONS:

CONSTRUCTION BASE MASS IS A SMALL PERCENT OF TOTAL MASS; RELATIVE MOTION OF SATELLITE IS NEGLECTED

2955-038V

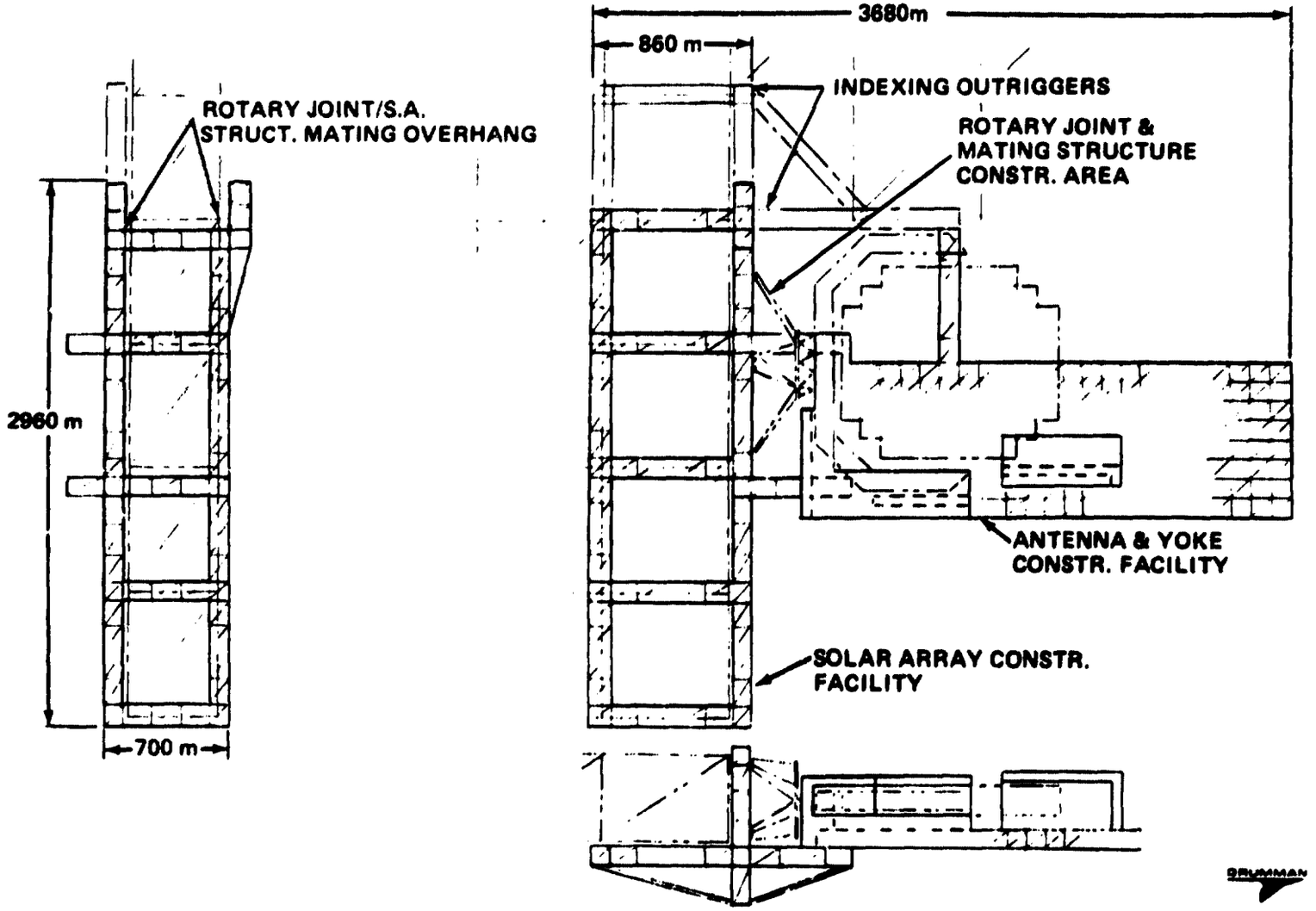
4 BAY END BUILDER CONSTRUCTION BASE

This concept builds an 8 bay wide SPS, 16 bays long, in GEO. The solar array structural configuration is the SPS baseline, with the exception of the longitudinal beams which are continuous. It requires two passes to build the solar array which approximates the construction scenario previously described for the 2 bay end builder. Solar arrays are deployed in the direction of build. The antenna construction platform conforms to the baseline in area but includes a yoke construction facility. This base mates the antenna to the solar array in the preferred location with the antenna aligned with the longitudinal centerline of the solar array.

Construction of the solar array takes place in an L-shaped facility, 2.96 Km long with 700 m and 860 m side legs. This facility is constructed from the joining of square section open truss beams, provisionally sized at 100 m per side. Mounted on the 700 m deep leg are such construction equipments as beam machines and handling devices, solar blanket installation facilities, and bus installation mechanisms, as well as habitation, docking, storage, etc. Beam machine and solar blanket installations are similar to the 2 bay end builder. The other leg of the facility guides and supports the longitudinal beams of the SPS until the bay structure is completed and self supporting.

The antenna and yoke construction platform is mounted at a distance from the solar array facility to provide an area in which the rotary joint and mating structure can be built. It is also located so that during second pass construction, the first pass solar array structure does not foul the antenna under construction. When the antenna and yoke have been built, they are then assembled to the rotary joint. The mating structure to the solar array is then build but not completed at its solar array end. This entire assembly is then indexed along the backface of the solar array facility until one set of legs of the mating structure is at the mating overhang for structural completion of those legs and mating to the solar array. The base is now indexed outboard so that the center mating legs can be completed and attached in the mating overhang. This sequence of indexing and mating is repeated to complete the mating of the solar array and antenna assemblies. Indexing of the base, laterally across the solar array, is continued until the base is separated from the satellite.

4 BAY END BUILDER CONSTRUCTION BASE (REVISED)



2955-022V

EVOLUTION OF TIMELINE PARAMETERS

This chart identifies the major timeline parameter and ground rules which have been updated since the Mid Term Briefing. The impact of these changes on the overall requirements for usage of crews and equipment are also provided.

Some of the changes shown are interrelated. For example, as a result of a revised ground rule, whereby the reindex rate was increased from 1 mpm to 10 mpm, there was a significant saving in time. That time was applied to the solar array attachment phase, which could then be accomplished with less cherry pickers and crew.

As a result of reevaluating the manning requirements for the cherry pickers and the beam machines, there was a significant saving in manpower. Originally, each cherry picker and each beam machine required a two man crew to provide safety and reliability through redundancy. However, the minimum staffing requirements is one operator for a cherry picker or for a mobile beam machine. In the end builder concept, where stationary beam machines are used, one man can operate either 8 on-line, longitudinal beam machines or 4 gimbled, segmented-beam machines or any combination thereof, e.g., 6 on-line and 1 gimbled, such as required for the 2 bay end builder configuration.

By orienting the solar array deployment longitudinally for the 4 bay end builder (similar to the orientation of the 2 bay end builder), it was possible to (1) delete the solar array deployer, (2) lower the solar array deployment rate from 12.5 mpm to 1 mpm, thus minimizing the inertia problem that had existed and (3) shorten the overall construction time by eliminating that time previously used for the actual deployment of the solar arrays, since the deployment is now performed in parallel with the longitudinal indexing.

At the midterm, it was considered that the subsystems assembly operations would be performed by sharing cherry pickers and operators that were assigned to other tasks. However, since the subsystems assembly tasks have not yet been analysed, four dedicated cherry pickers and operators were assigned to this function. Upon further analysis, this crew may be either increased or reduced.

EVOLUTION OF TIMELINE PARAMETERS

	FACTOR	MIDTERM	FINAL	IMPACT
OPERATIONS	I.O.C.	180 DAYS	180 DAYS	NO CHANGE
	ON-LINE MACH. FAB. RATE	AS REQD. (<5 mpm)	AS REQD. (<5 mpm)	NO CHANGE
	SEG-BEAM MACH. FAB. RATE	5 mpm	5 mpm	NO CHANGE
	MATE ANTENNA	MIDPOINT OPS	FINAL OPS	AVOIDS EARLY START UP
	REINDEX RATE	1 mpm	10 mpm	REV. GRND. RULE – REDUCE TIME
	STRUCT. ASSY.	DEDICATED CPs (4BAY)	MOBILE CPs	REDUCE C & E
	SUB SYS. ASSY.	UNDEFINED	4 DEDICATED CPs	ADDS CPs & CREW
	S/A ORIENTATION	LONG(2BAY)LAT(4BAY)	LONG (2 & 4 BAY)	REDUCE EQUIP., LOWER S/A DEPLOY. RATE, SHORT CONST. TIME
CREW	REMOTE WORK STATIONS	2 MEN/CAB	1 MAN & CHANGE-OVER	MIN. STAFFING REQT.
	AUTO. BEAM MACHINES	2 MEN/MACHINE	8 FIXED OR 4 GIMBLED OR 1 MOBILE/MAN	MIN. STAFFING REQT.
EQUIPMENT	ON-LINE MACH.	7.5 m FIXED	7.5 m FIXED	NO CHANGE
	SEG. - BEAM MACH.	DEDICATED	MOBILE	REDUCE EQUIP.
	INDEXERS	8 (2BAY)	5	CONFIG. UPDATE
	BEAM ASSY. CPs	6 CPs (2BAY)	4 CPs	MIN. SUPT. REQT.
	S/A ATTACH, CPs	6 CPs (2BAY)	4 CPs	USES TIME FROM 10 mpm INDEX

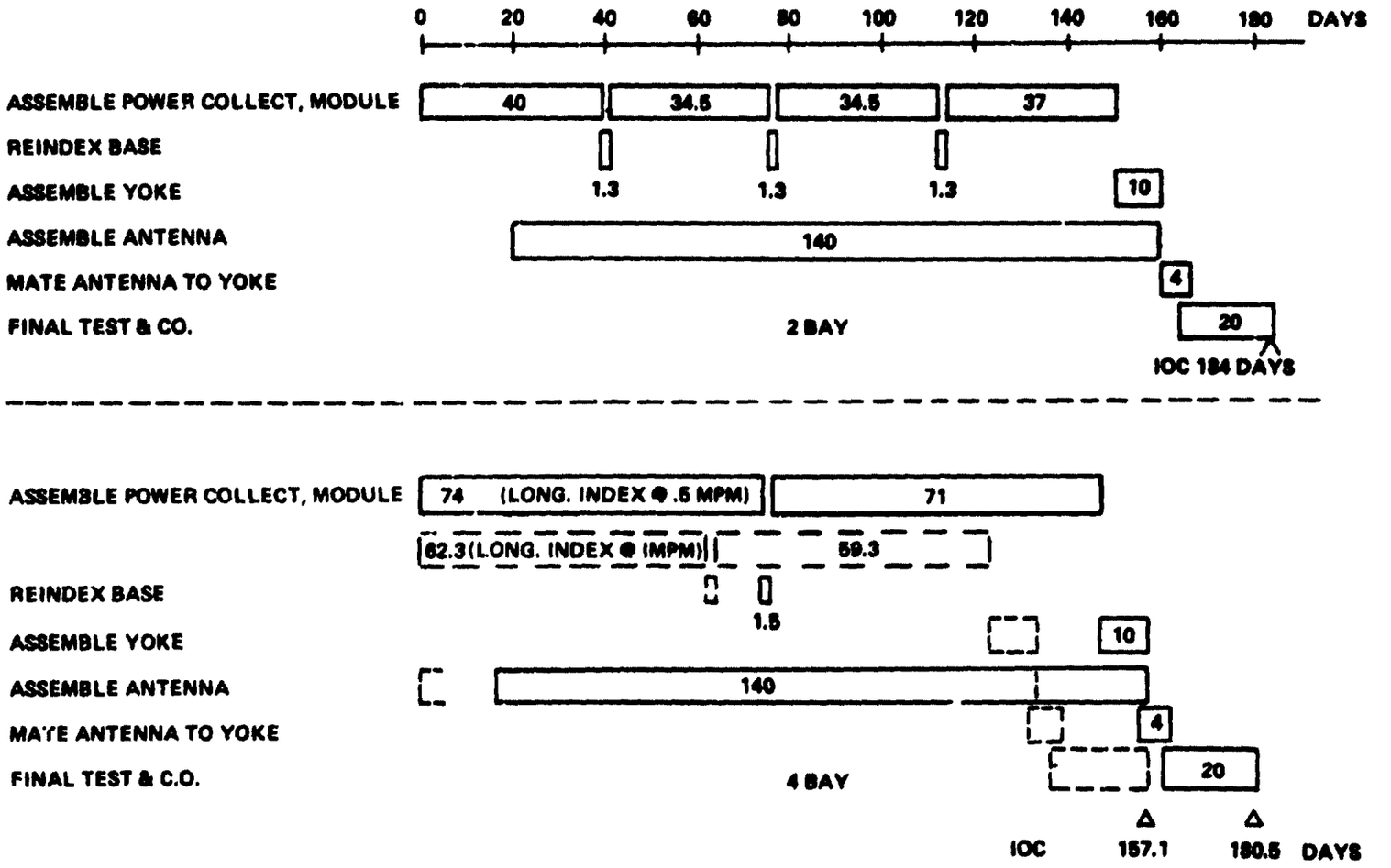
2955-075V

2 BAY & 4 BAY END BUILDER TIMELINES

For the 2 bay endbuilder configuration, the power collection module is constructed in four passes through the construction base. Each pass provides a 2 x 16 module. The first pass construction operations continue, as described on the following chart. However, bays 8 and 16 require the addition of lateral busses. The second pass requires time allocated for installation of the main busses, however this is done during indexing operations, so no serial time is added. Satellite thrusters are also installed during the first pass. The second and third pass timelines are shorter because one side of the modules are common with the structure previously assembled, therefore 2 fewer beams are built. The last pass assembly operations take the same time as the previous two passes, however the total time is increased to accomodate the remaining thruster installations. Allowing additional time beyond collector construction for reindexing the base and mating the yoke to the collector and antenna and for checkout, the total two bay end builder construction time is 184 days.

The 4 bay endbuilder operates identical to the 2 bay endbuilder, except that more time is required for attaching the solar arrays and for fabricating and attaching the beam segments, because the same amount of equipment is now used for four bays instead of two. There is, of course, only one reindexing phase. If longitudinal indexing occurs at 0.5 mpm, the total 4 bay endbuilder construction time is 180.5 days. However, if longitudinal indexing is accellerated to one mpm, then the total construction time is decreased to 157.1 days.

2 BAY & 4 BAY END BUILDER TIMELINES



2955-040V

2 BAY END BUILDER SATELLITE MODULE ASSEMBLY OPERATIONS

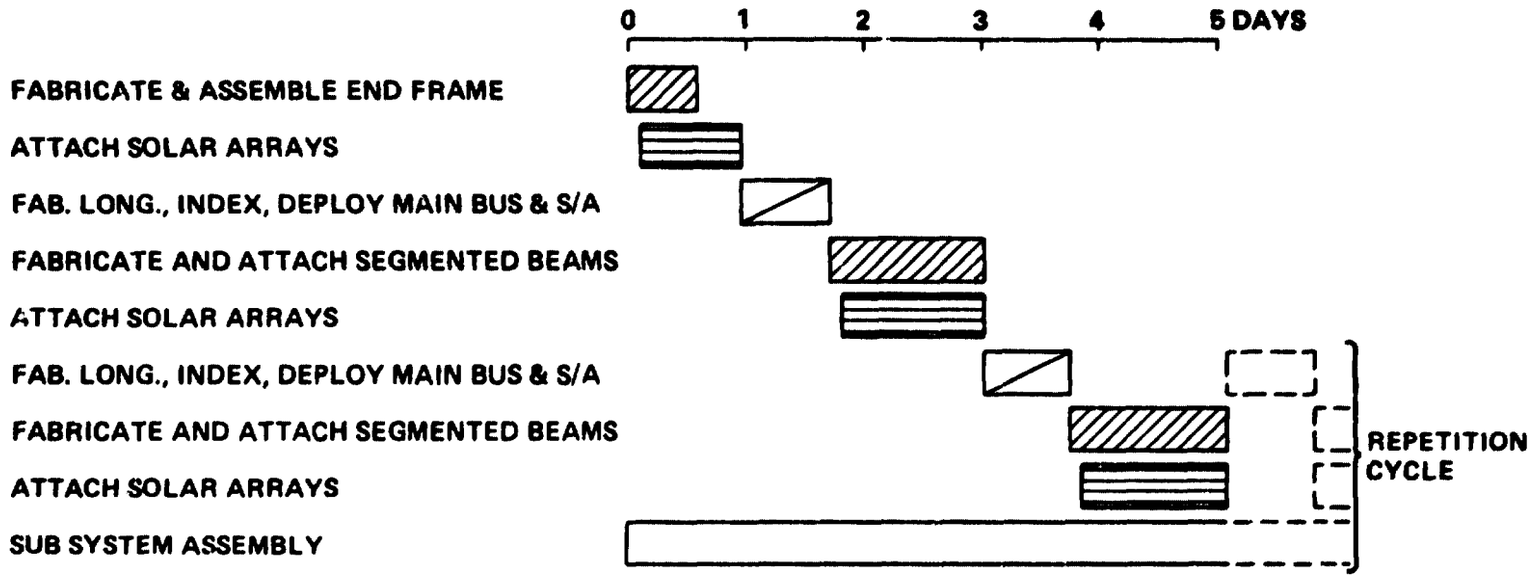
In the 2 bay construction approach, the solar array panels are deployed parallel to the longitudinal beams during the indexing phase. As a result, no solar array deployers are needed and no extra time is required for deployment. However, this approach requires the addition of lateral busses that connect the solar arrays to the main bus at the longitudinal center of the collector.

The assembly operations commence with the fabrication of short lengths of the longitudinal beams for implacement of the joints to which the lateral and diagonal beam segments of the end frame will be connected. Then, the 12.7 meter upper lateral beams for the end frame are fabricated and joined to the longitudinal beams. Next, the mobile beam machines begin fabricating the beam segments, which comprise the remainder of the end frame and simultaneously solar array canisters are anchored on the construction base and the distal end of the solar arrays are attached to the upper laterals.

Upon completion of the end frame assembly and solar array attachment, the structure is indexed longitudinally at one mpm. Meanwhile, the fixed beam machines fabricate the 667 meter longitudinal beams, the main bus is deployed (on the second pass) and the solar array panels are also being deployed.

After completion of the indexing phase, the upper lateral beam segments of the next frame are fabricated and installed. Then, collector busses and switches are attached. Next the solar array canisters are detached from the construction base, mounted on the upper laterals and the proximal ends are connected to collector busses. Simultaneously, new solar array canisters are anchored on the construction base and the distal ends are attached to the upper laterals and connected to collector busses. Finally, pigtails are installed across the upper laterals to provide electrical connection between the busses.

2 BAY END BUILDER SATELLITE MODULE ASSEMBLY OPERATIONS



40	TOTAL CONST. CREW
2	SHIFTS
10	HOUR SHIFT
75%	PRODUCTIVITY

2955-074V

EVOLUTION OF COST METHODOLOGY

The evolution of cost methodology and revison of equipment quantities from the midterm to the final report resulted in the following changes. The total length of beams and track was recalculated for the final 2 bay and 4 bay end builder. The quantity of related logistic and construction equipment was also revised.

Beam Builder and Cherry Picker/crane costs include Grumman costs and weight estimates for the automated beam machines and manned work stations and Boeing's cost and weight estimates for gimbals, carriages, and booms. A 90% unit cost learning curve was used.

The final cost methodology includes a 47% wraparound factor which represents costs for spares, installation, assembly, and check out, SE & I, Project Management, System Test, and GSE. Only some of these costs were estimated on a separate basis for the mid term report. Ground rule changes allow fractional crew modules to fit crew sizes, whereas only full modules of a nominal capacity of 100 and a maximum capacity of 115 people were used for the midterm report. The fractional crew modules are based on the nominal capacity of 100 people.

Base transportation costs were revised from $148/Kg. to $155/Kg. Crew salaries, previously excluded, were added to the final cost estimates.

EVOLUTION OF COST METHODOLOGY

	MIDTERM	FINAL
BASE STRUCTURE TRACK TURNTABLES		REVISED TOTAL BEAM LENGTH REVISED TOTAL LENGTH REVISE QUANTITY
BEAM BUILDERS	CONSTANT COST OF $34M EA	ESTIMATED SEPARATE COSTS FOR BEAM MACHINES, GIMBALLING, MOVEABILITY, AND MANNED WORK STATION. USED 90% LEARNING CURVE.
CRANES/CHERRY PICKERS	CONSTANT COST FOR EACH BOOM LENGTH, BASED ON GRUMMAN AND BOEING ESTIMATES	ESTIMATED SEPARATE COSTS SIMILAR TO BEAM BUILDERS. USED 90% LEARNING.
WRAPAROUND	SPARES NONE INST, ASS'Y, C/O –% OF GWT. SE & I NONE PROJ. MGMT NONE SYS TEST % OF WGT GSE 10% OF LAUNCH COST	47% OF BASE UNIT COST
CREW MODULES BASE TRANSPORT CREW SALARY	NO FRACTIONAL MODULES 148 $/Kg NOT INCLUDED	USED FRACTIONAL MODULES 155 $/Kg INCLUDED

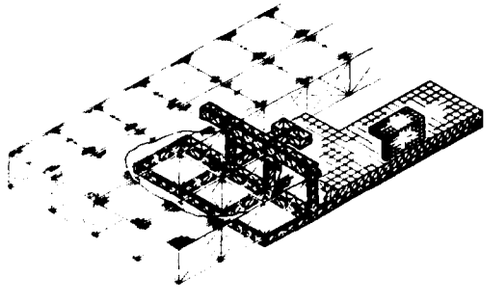
GRUMMAN

2955-076V

2 BAY END BUILDER BASE FEATURES

The main features of this base are listed here. The baseline SPS is constructed by multiple passes of the end builder, which builds a 2 bay wide strip, 16 bays long, then indexes over to build successively, three more strips. Construction system features cover cost, mass and crew information. Major construction equipment for the solar array module is itemized. Lastly, the impacts of this construction system on the satellite baseline are listed.

2 BAY END BUILDER BASE FEATURES

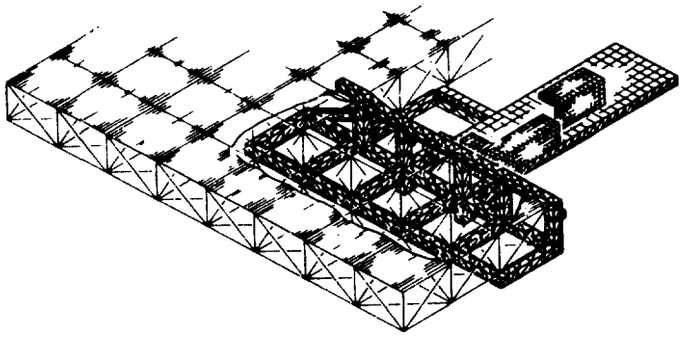


- MULTI-PASS CONSTR. OF 8 x 16 BAY SPS
- CONSTR. SYS
  - UNIT COST (1977 $) = $8.63B
  - SIZE L x W x H = 3.37 x 2.05 x .76 km
  - MASS
    - STRUCTURE = 2.40×10^6 kg
    - TOTAL BASE = 5.74×10^6 kg
  - CREW TOTAL = 383
- ARRAY MODULE CONSTR. EQUIP.
  - BEAM MACHINES = 9
  - CRANE/C.P. = 11
  - INDEXERS = 5
  - BUS DEPLOYERS = 1
  - SOLAR BLANKET DEPLOYERS = 0
- SATELLITE DESIGN
  - SOLAR ARRAY ORIENTATION = LONGITUDINAL
  - LONGITUDINAL BEAMS = CONTINUOUS

4 BAY END BUILDER BASE FEATURES

This chart follow the features format of the 2 bay end builder. The baseline 8 x 16 bay SPS is constructed in two passes by the 4 bay end builder, which bulds half the width of the satellite on successive passes. The construction system features, major equipments and their impacts on the satellite are listed.

4 BAY END BUILDER BASE FEATURES (UPDATE)



- MULTI-PASS CONSTR. OF 8 x 16 BAY SPS
- CONSTR. SYS
  - UNIT COST (1977$) = $9.07B
  - SIZE L x W x H = 3.68 x 2.96 x .70 km
  - MASS
    - STRUCTURE = 2.93×10^6 kg
    - TOTAL BASE = 6.37×10^6 kg
  - CREW TOTAL = 385
- ARRAY MODULE CONSTR. EQUIP.
  - BEAM MACHINES = 13
  - CRANE/C.P. = 11
  - INDEXERS = 4
  - BUS DEPLOYERS = 1
  - SOLAR BLANKET DEPLOYERS = 0
- SATELLITE DESIGN
  - SOLAR ARRAY ORIENTATION = LONGITUDINAL
  - LONGITUDINAL BEAMS = CONTINUOUS

2955-071V

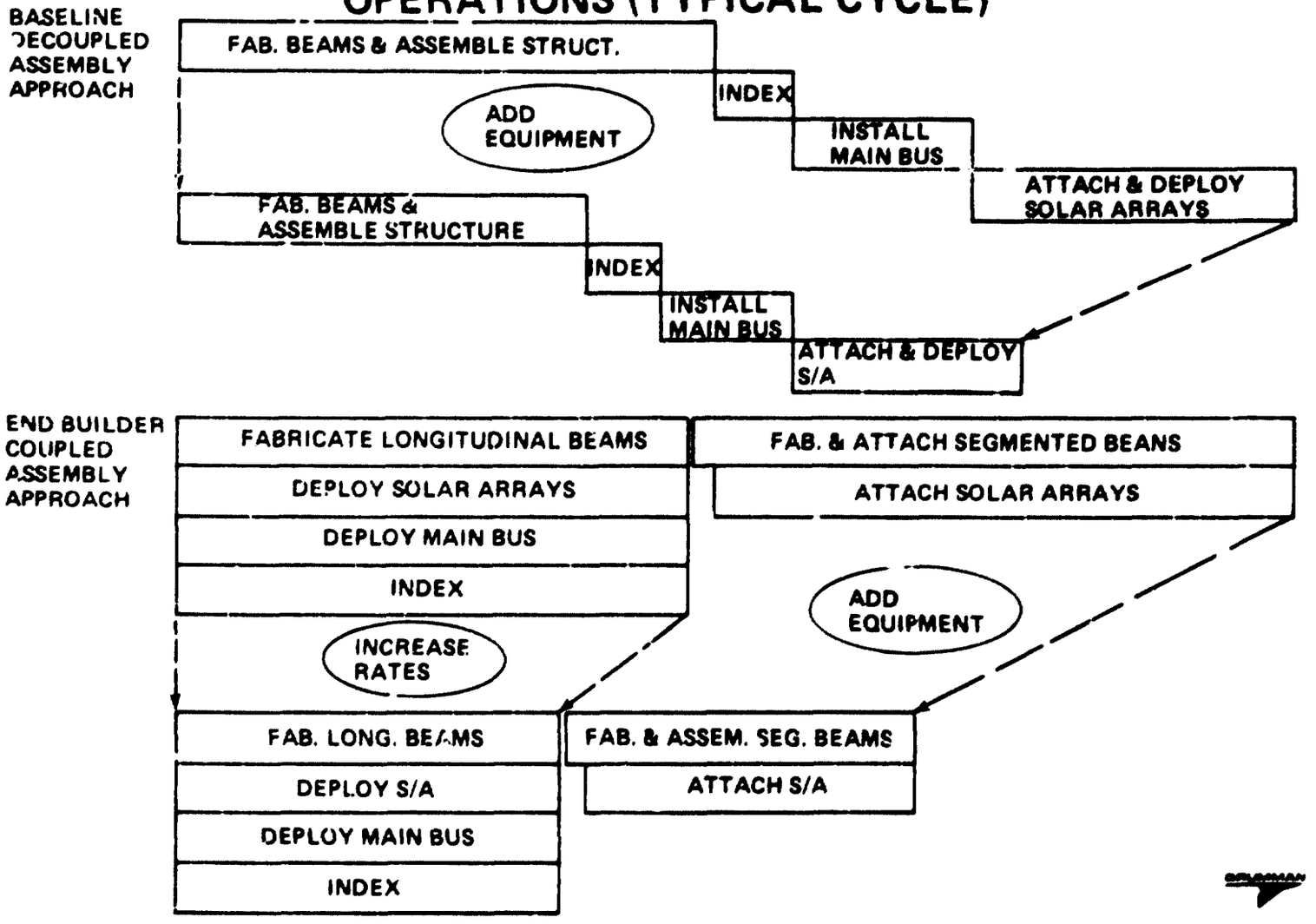
TECHNIQUES FOR ACCELERATING SPACE CONSTRUCTION OPERATIONS

The baseline configuration was a four phase decoupled assembly approach. Accellerating space construction operations can be accomplished by adding equipment to shorten the time required for any phase (except the index phase) or by coupling operations.

The end builder configuration uses a two phase coupled assembly approach. Those operations that can be accomplished while the structure is being indexed are grouped together in the first phase and the indexing rate controls the operation. Accellerating space construction operations in this phase can not be accomplished by adding more equipment. It can only be done by increasing the indexing rate and yet it is limited by the maximum rate for fabrication of the longitudinal beams and deployment of the solar arrays and the main bus.

During the second phase of the endbuilder construction approach the controlling operation is the fabrication and attachment of the segmented beams. The amount of crew & equipment required for the solar arrays is adjusted to finish that installation concurrent with the segmented beam operation. Accellerating space construction operations during this phase requires a coordinated increase of equipment for both operations. To be specific, increasing cherry pickers for solar array attachment will not accellerate this phase unless additional beam machines are provided.

TECHNIQUES FOR ACCELERATING SPACE CONSTRUCTION OPERATIONS (TYPICAL CYCLE)

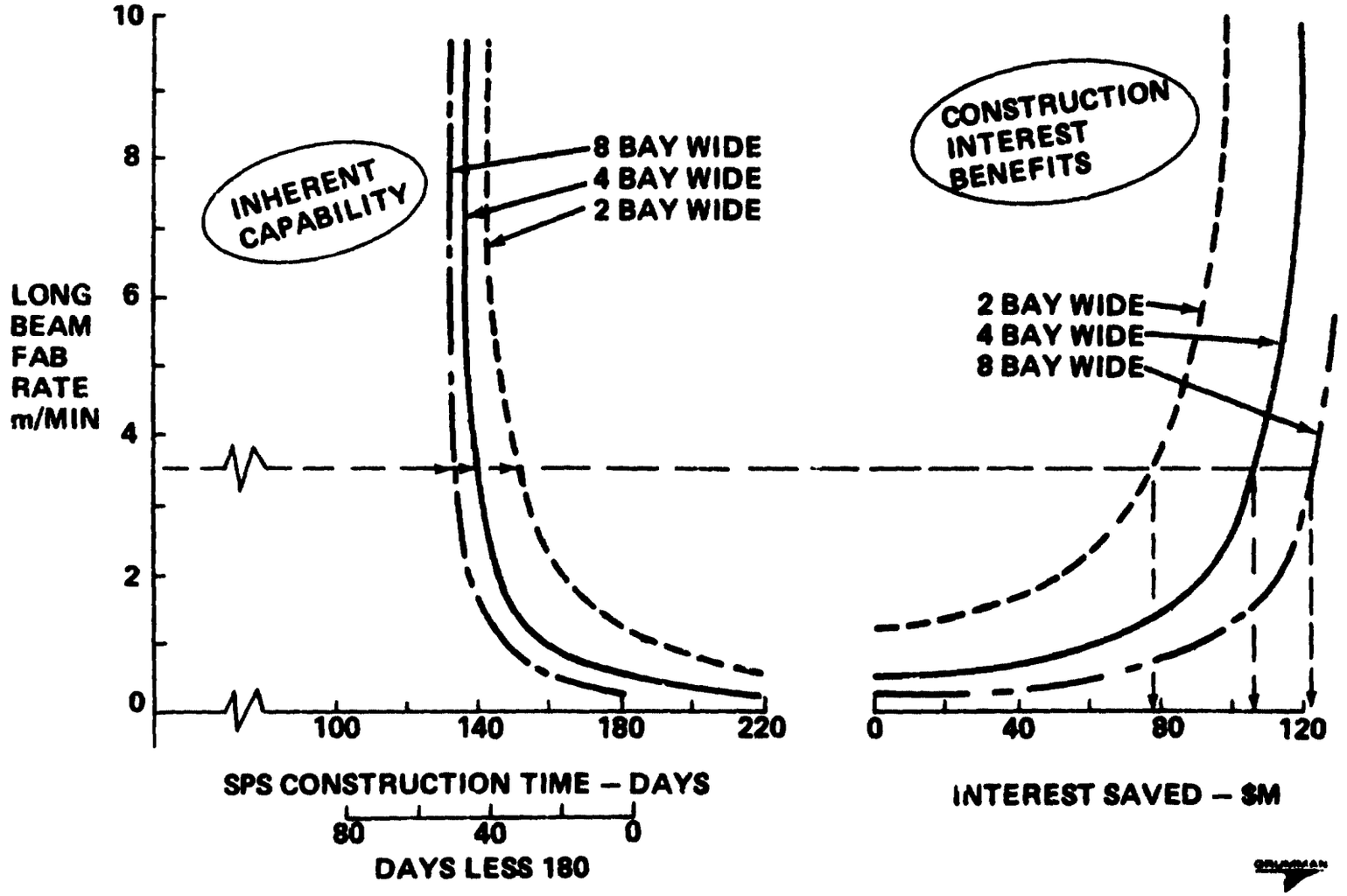


END BUILDER LONGITUDINAL BEAM PRODUCTION CAPABILITY AND BENEFITS
FIXED CREWS AND EQUIPMENTS

In order to satisfy the ground rule which limits GEO assembly of the 5GW satellite to 6 months, it was necessary to operate with skeleton crews, use minimal equipments and slow the operating rates of on line beam machines. The impact on total satellite construction time is shown in the facing page for various longitudinal beam fabrication rates with the 2 bay, 4 bay, and 8 bay end builder concepts. A significant reduction in overall construction time can be realized by simply operating these on line machines a little faster, such as at 3.5 meters per minute rather than the .25 to 1.5 meters per minute shown at 180 days. It is not efficient to operate these machines at much higher rates since other construction operations are constrained by limited crews and equipments. (eg for solar array hook up)

The benefit of being able to shorten the time of construction without adding additional crews and equipments can be reflected in reduced payments for construction interest. Using a daily interest rate of $2.7 M, the 4 bay end builder can complete construction 40 days early (at 3.5 m/min) at a saving of $107M per satellite. Equivalent savings in construction interest are also shown for other fabrication rates and the three end builder concepts.

END BUILDER LONG BEAM PRODUCTION CAPABILITY & BENEFITS FIXED CREWS & EQUIPMENT



2955-025V

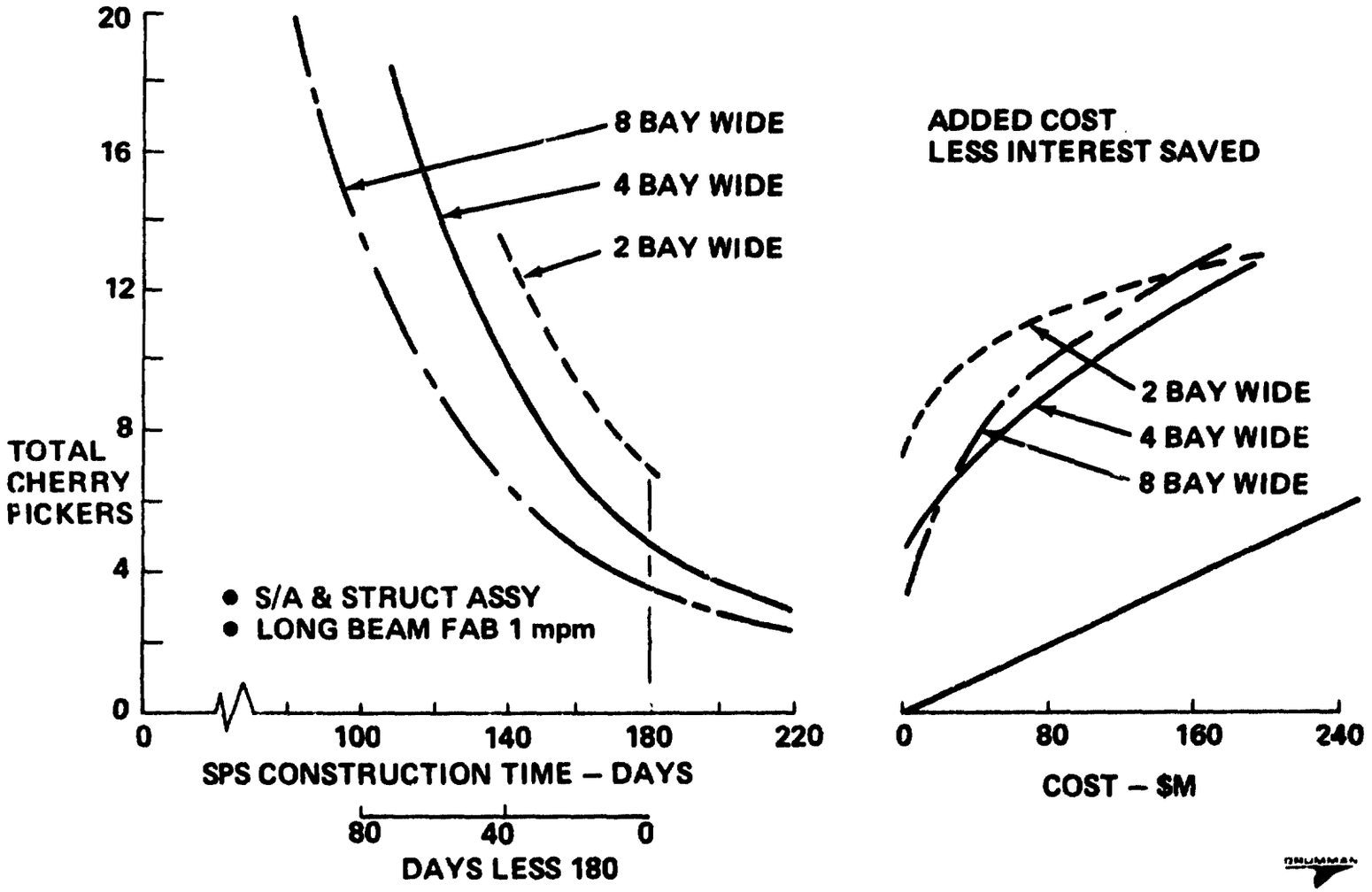
END BUILDER PRODUCTION SCALE UP POTENTIAL - ADDED CREWS AND 30 METER CHERRY PICKERS

The performance improvement that can be achieved by adding crews and equipments to the end builder concept is shown on the facing page Increasing cherry picker crews can speed up the solar array hook-up times. Both the 2 bay and 4 bay end builders are currently defined with 7 cherry pickers for solar array hook-up and structural assembly. The 4 bay end builder, however, could have been defined with 5 cherry pickers by relying upon a greater shared usage between these various solar array and structural assembly operations. Available resources however did not allow this option to be adequately explored to develop this multi-usage timeline further. Nevertheless, significant improvements in overall construction time can be achieved by increasing the crews and equipments in selective construction activities.

The cost penalty for adding these crews and equipments is also shown on the facing page. This cost penalty reflects the added costs for cherry pickers, crew modules, crew operations, and related transportation costs. The interest saved by adding these additional equipments is also shown for each end builder in terms of the added cost less interest saved.

Similar data could also be developed for the single deck baseline.

END BUILDER PRODUCTION SCALE UP POTENTIAL ADDED CREWS & 30 M CHERRY PICKERS

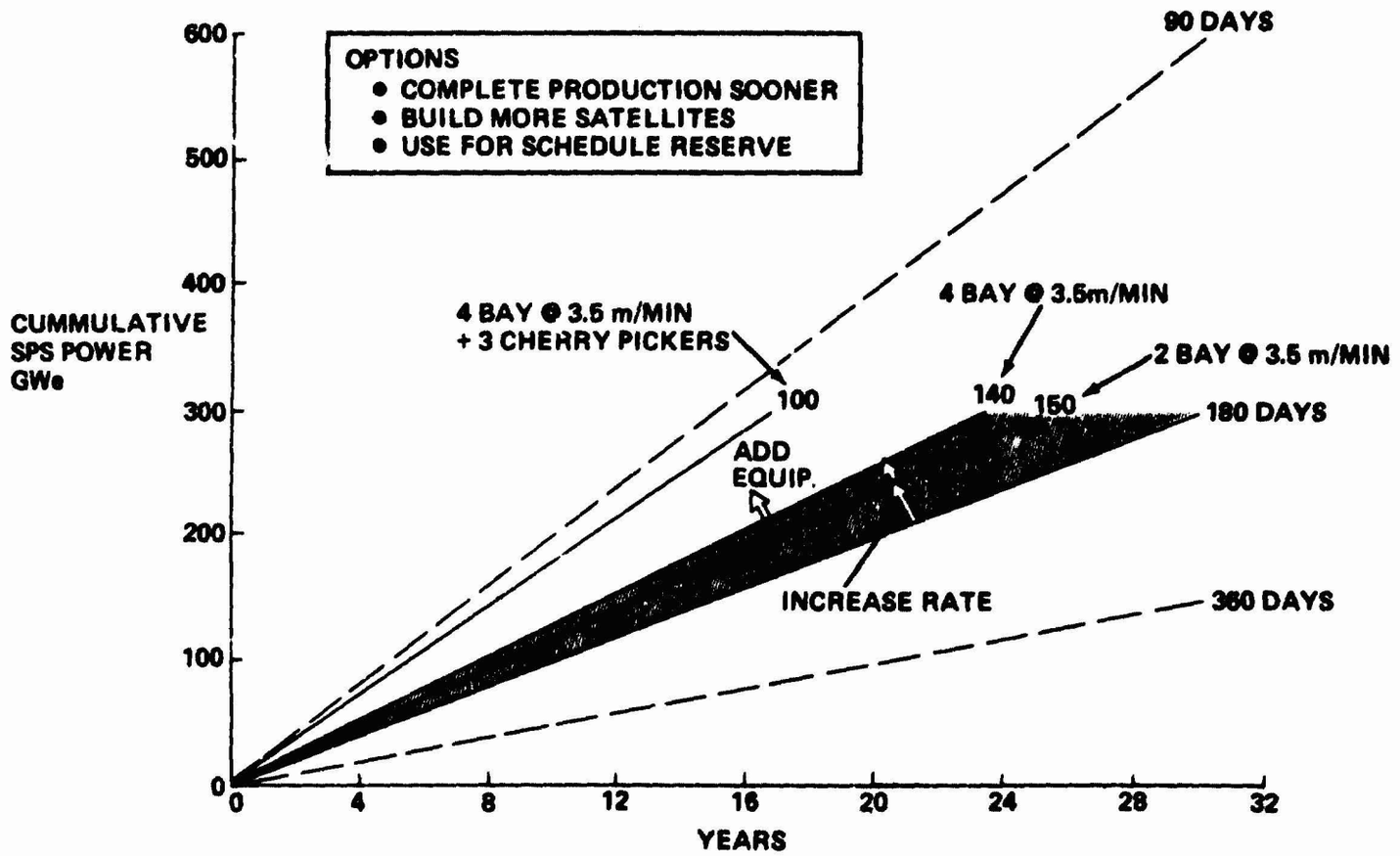


2955-027V

END BUILDER SATELLITE CONSTRUCTION POTENTIAL

The cummulative effect of faster end builder production capabilities are illustrated on the facing page. Assuming that the SPS program requires 10 GW to be added each year, then 30 years are needed to reach 300 GW by constructing one 5GW satellite every 6 months. By operating the 4 bay end builder at 3.5 meters per minute the same number of satellites could be completed at least 6½ years sooner. This performance advantage can either be used to complete production sooner, build more satellites or be applied as a production schedule reserve to cope with unscheduled delays (ie weather strikes, etc).

END BUILDER SATELLITE CONSTRUCTION POTENTIAL



2955 026V

ALTERNATE CONSTRUCTION BASE EVALUATION CRITERIA

- COST
- PERFORMANCE CAPABILITY
- SYSTEM COMPLEXITY
- OPERATIONS COMPLEXITY
- DEVELOPMENT RISK
- GROWTH POTENTIAL

SPS GEO CONSTRUCTION BASE COST COMPARISON (1977 $)

Comparative costs are shown on the facing page for the alternate satellite construction approaches using segmented and continuous longitudinal beams. The nominal construction time and maximum construction capabilities are also shown for the alternate bases. Total base costs and the related annual amortization costs are shown. Potential construction interest that can be saved each year by operating at faster rates are also shown and the net annual cost with this interest benefit is provided.

Although the total cost difference is not great, the 2 bay end builder features the least total base cost and a low annual amortization cost with interest benefit .

SPS GEO CONSTRUCTION BASE COST COMPARISON (1977 $)

	SINGLE DECK BASELINE	4 BAY END BUILDER	2 BAY END BUILDER
LONG. BEAM DESIGN	SEGMENTED	CONTINUOUS	CONTINUOUS
5GW SPS CONSTR TIME	185 DAYS	181 DAYS	184 DAYS
MAX CONSTR CAPABILITY	185 DAYS	141 DAYS	154 DAYS
TOTAL BASE COST	$9278 M	$9067 M	$8634 M
ANNUAL AMORTIZATION	$ 845 M	$ 830 M	$ 785 M
ANNUAL INTEREST SAVED (@ 3.5m/MIN LONG FAB)	———	$ 215 M	$ 155 M
ANNUAL COST WITH INTEREST BENEFIT	$ 845 M	$ 615 M	$ 630 M

PREFERRED

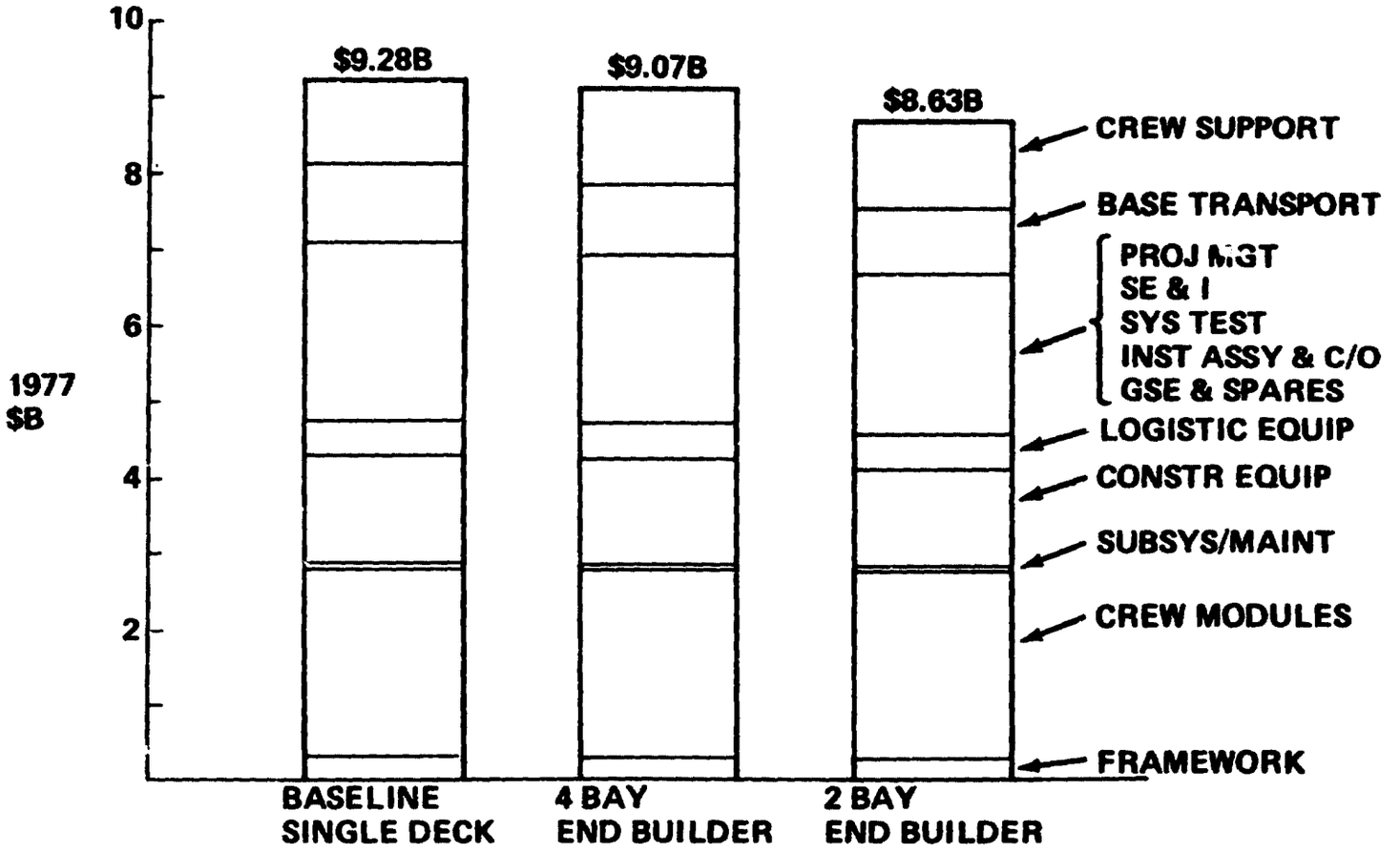
GEO CONSTRUCTION BASE COSTS

The same methodology was used to develop comparable cost data for Boeing's single deck baseline and Grumman's alternate end builder concepts. Cost estimates were developed to the level of base frame work, crew modules, construction equipment and logistic equipment (i.e. tracks, turntables and vehicles). Common subsystem and maintenance costs were included in all concepts, as were costs related to antenna construction, yoke construction and sub-assembly construction activities. A 47% wraparound factor is also included to account for subject management, system engineering and integration, system test, and the other cost elements noted in the figure. The added costs for transporting base hardware to GEO and conducting recurring crew operations are also included.

The estimates shown on the facing page were jointly reviewed and adjusted, if needed, to assure that comparable design definitions were used across the board. Base framework costs, for example, assume that each configuration employs 100 meter deep structural sections in lieu of the range of as drawn dimensions, which await initial loads and stress analysis.

The 2 bay end builder exhibits the lowest cost primarily because it features less costly construction equipment and related crew modules. The 4 bay end builder has more eqipment but is slightly less costly than the single deck baseline because of its smaller crew size.

GEO CONSTRUCTION BASE COSTS



2955-042V

SPS-2567

COST COMPARISON - 10^6

BOEING

ITEM	SINGLE DECK		2-BAY END BUILDER	WHY THE DELTA
Structures	303	(Δ 63)	240	. 2x4 bay vs 1-2/3 x 3 . Gantry included
Crew Modules	2582	(Δ 78)	2504	. Δ 22 people
Construction Equip.	1397	(Δ 115)	1282	. Dedicated solar array deployment equip.
Logistics Equip.	535	(Δ 80)	454	. 151 vx 68 turntables
Other	25		25	-
Wraparound	2275	(Δ 138)	2117	. Reflects above
Base Transport	968	(Δ 78)	890	
Crew Costs	1192	(Δ 70)	1122	. Δ 22 people @ $3M/man
TOTAL	9278		8634	

WHY THE COST DELTA?

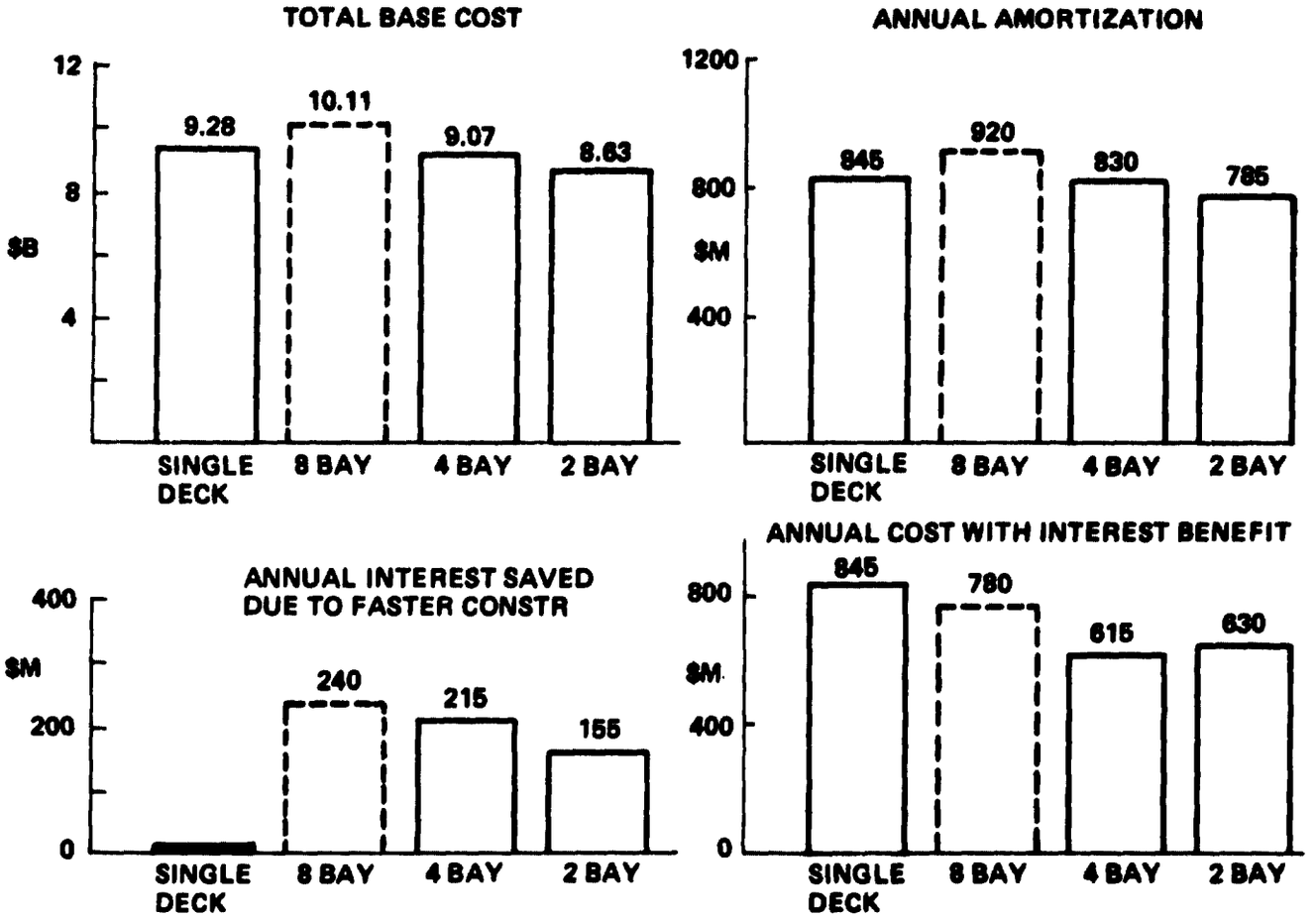
- The real difference between the Single Deck and the End Builder cost are the result of the difference in solar array deployment techniques.

	SINGLE DECK	END BUILDER
EQUIPMENT		
. Beam Machines	$307M	$420M
. Cherrypickers	$580M	$600M
. Solar Array Deployers	$248M	
CREW		
. Structural Assembly		
- Beam Machine Op	4	6
- Cherrypicker Op	16 (should be 8)	8
. Solar Array Deploy	24	8

GEO BASE COST COMPARISON

This chart provides a graphic comparison of the major cost differences between the alternate construction bases. Total base cost, annual amortization and related interest benefits due to faster construction are shown for the single deck and end builder concepts. Total base costs for the 8 bay end builder were derived from earlier 8 bay versus 2 bay end builder cost comparisons. Accordingly, the 8 bay end builder is projected to cost almost 10% more than the single deck baseline and have an equivalent increase in annual amortization costs. It is interesting to note, however, when annual interest benefits are considered, the 8 bay end builder exhibits lower net annual costs than the single deck. Never-the-less, the 4 bay and 2 bay end builder still show the lowest net annual cost with the interest benefit.

GEO BASE COST COMPARISON



SPS GEO CONSTRUCTION BASE PERFORMANCE COMPARISON

Comparative performance data are provided on the facing page for the alternate construction bases. The base characteristics related to longitudinal beam design, satellite construction approach and nominal construction times are shown together with their comparative masses and maximum construction capabilities. The on line beam machines, which are used for continuous fabrication of end builder longitudinal beams, provide an inherent capability for increasing the overall rate of construction. By operating the longitudinal beam machines at 3.5 meters per minute it ic possible to save up to 40 days of satellite construction time. The baseline single deck segmented beam method of construction is not able to shorten the rate of construction without adding additional crews and eqipments. By building two 5GW satellites a year, the 4 bay end builder therefore can offer a 80 day advantage in faster performance over the single deck.

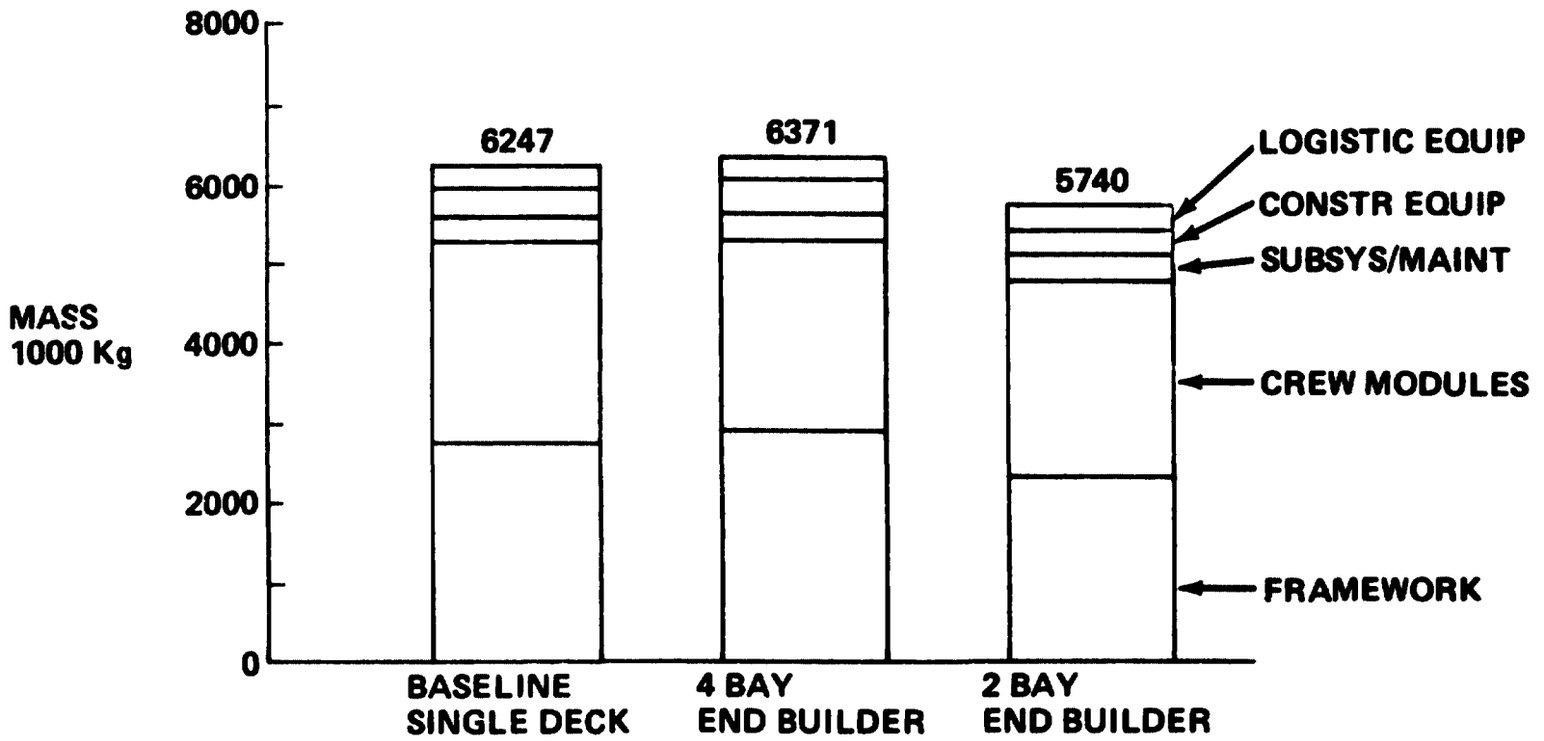
Comparison of the total base relative masses shows that most of the weight difference is attributed to the difference in base configuration framework. As previously noted, the w ight of base framework listed herein is normalized to the extent each base was assumed to employ 100 meter deep structural sections, rather than the various deeper and shallower "as drawn" sections which have not been analyzed and sized.

SPS GEO CONSTRUCTION BASE PERFORMANCE COMPARISON

	SINGLE DECK BASELINE	4 BAY END BUILDER	2 BAY END BUILDER
SATELLITE CONSTR APPROACH	MULTI INDEX	MULTI PASS	MULTI PASS
LONG BEAM DESIGN	SEGMENTED	CONTINUOUS	CONTINUOUS
5GW SPS CONSTR TIME	185 DAYS	181 DAYS	184 DAYS
MASS – TOTAL BASE	6247×10^3 Kg	6371×10^3 Kg	5740×10^3 Kg
– BASE FRAMEWORK	2792×10^3 Kg	2927×10^3 Kg	2399×10^3 Kg
– CONSTR EQUIP	340×10^3 Kg	387×10^3 Kg	337×10^3 Kg
MAX CONSTR CAPABILITY	185 DAYS	141 DAYS*	154 DAYS
SPS CONSTR TIME SAVED		40 DAYS	30 DAYS
ANNUAL CONSTR ADVANTAGE		80 DAYS	60 DAYS
*3.5m/MIN LONG BEAM FAB		PREFERRED	

2955-059V

GEO CONSTRUCTION BASE MASS COMPARISON



SPS GEO CONSTRUCTION BASE SYSTEM COMPLEXITY COMPARISON

The major system differences between the alternate construction bases are compared on the facing page. The single deck builds the segmented beam design and constructs the satellite by performing multiple lateral and longitudinal indexing operations. The end builder concepts, in turn, build the continuous longitudinal beam design and construct the satellite by fabricating in one direction and then re-indexing for a subsequent pass. Other system differences are characterized in terms of the overall base size (with and without the antenna construction facility), module construction work station, major module construction equipment, total crew size, and logistic track. The end builder concepts are generally smaller in size and can be operated with fewer people than the single deck. However, the single deck requires fewer automatic beam machines and cherry pickers than the two end builder concepts. It should be noted, however, that the end builder uses some of its cherry pickers to perform solar array installation functions, using simple proximal anchors from its built in logistic track, in lieu of the large cross bay gantries and related installation/deployment equipment used by the single deck.

SPS GEO CONSTRUCTION BASE SYSTEM COMPLEXITY COMPARISON

	SINGLE DECK BASELINE	4 BAY END BUILDER	2 BAY END BUILDER
SATELLITE CONSTR APPROACH	MULTI INDEX	MULTI PASS	MULTI PASS
LONG BEAM DESIGN	SEGMENTED	CONTINUOUS	CONTINUOUS
BASE SIZE – TOTAL	4.59 x 2.9 x .87 Km	3.68 x 2.96 x .70 Km	3.37 x 2.5 x .76 Km
– W/O ANT PLATFORM	2.9 x 1.52 x .87 Km	.86 x 2.96 x .70 Km	.80 x 2.05 x .76 Km
MODULE CONST FACILITY	FLAT DECK W UPPER LEVEL GANTRY STA	FIXED UPPER/ LOWER LEVEL WORK STA	FIXED UPPER/ LOWER LEVEL WORK STA
MODULE CONST EQUIP DELTA			
AUTO BEAM MACHINES	3 MOBILE	3 PLUS 10 SYNC	3 PLUS 6 SYNC
CHERRY PICKERS (30 & 80m)	8	11*	11*
INDEXERS	6	8	8
S/A INSTALL EQUIP	4 INSTALLER, DEPLOYER & CROSS BAY GANTRIES	PROXIMAL ANCHORS & SHARED C.P.S*	PROXIMAL ANCHORS & SHARED C.P.S*
CREW SIZE	407	385	383
LOGISTIC TRACK	60800 Km	77700 Km	60800 Km

GRUMMAN

2955-073V

SPS GEO CONSTRUCTION BASE OPERATIONS COMPLEXITY COMPARISON

The major differences in alternate GEO base construction operations are summarized on the facing page. All of the alternate bases build the satellite by indexing the base either laterally or longitudinally as permitted by the longitudinal beam design. The single deck segmented longitudinal beam assembly method allows either decoupled or coupled construction techniques to be employed. The baseline single deck approach uses decoupled solar array structure assembly operations. On the other hand coupled solar array/structure assembly operations are facilitated by the end builder continuous longitudinal beam approach. This end builder approach necessitates that all automatic longitudinal beam machines be synchronized and be capable of being maintained and repaired both on and off line. The end builder solar blankets can either be deployed longitudinally (88 or 176 strips) or laterally (single strip) as the baseline. Each alternate base uses a similar method for translating and mating the satellite antenna.

SPS GEO CONSTRUCTION BASE OPERATIONS COMPLEXITY COMPARISON

	SINGLE DECK BASELINE	4 BAY END BUILDER	2 BAY END BUILDER
LONG BEAM DESIGN	SEGMENTED	CONTINUOUS	CONTINUOUS
SATELLITE ASSY MODE	16 ROW LATERAL BUILDUP	2 PASS LONG BUILDUP	4 PASS LONG BUILDUP
SOLAR ARRAY/STRUCTURE ASSY	DECOUPLED	COUPLED	COUPLED
LONG BEAM FAB	AS REQD	SYNCHRO-NIZED	SYNCHRO-NIZED
BEAM MACHINE MAINTENANCE	OFF LINE	ON/OFF LINE	ON/OFF LINE
S/A BLANKET DEPLOY	SINGLE STRIP @ A TIME	176 STRIPS OR SINGLE STRIP	88 STRIPS OR SINGLE STRIP
ANTENNA MATING MODE	TRANS LONG	TRANS LATERAL	TRANS LATERAL

SPS GEO CONSTRUCTION BASE DEVELOPMENT REQUIREMENTS

The major construction elements that must be developed for either the single deck or the end builder concepts are listed on the facing page. Some of the differences in system development requirements include single deck upper level gantry control, end builder automatic longitudinal beam machine synchronization, and other differences in single deck/end builder solar array installation and deployment equipments. None of the above differences are judged to be significant, hence all concepts are cited to have a medium development risk.

SPS GEO CONSTRUCTION BASE DEVELOPMENT REQUIREMENTS

	BASELINE SINGLE DECK	4 BAY END BUILDER	2 BAY END BUILDER
MAJOR CONSTR ELEMENTS	• FLAT DECK SYS • UPPER LEVEL GANTRY CTL • MOBILE BEAM MACH ——— • CHERRY PICKERS • INDEXERS • SOLAR ARRAY INSTALLER • S/A DEPLOYER • S/A CROSS BAY GANTRY • BUS DEPLOYERS • LOGISTIC EQUIP	• 4 BAY SYS ——— • MOBILE BEAM MACH • BEAM MACH SYNC • CHERRY PICKERS • INDEXERS ——— • PROXIMAL ANCHOR ——— • BUS DEPLOYERS • LOGISTIC EQUIP	• 2 BAY SYS ——— • MOBILE BEAM MACH • BEAM MACH SYNC • CHERRY PICKERS • INDEXERS ——— • PROXIMAL ANCHOR ——— • BUS DEPLOYERS • LOGISTIC EQUIP
DEVELOPMENT RISK	• MEDIUM	• MEDIUM	• MEDIUM

SPS GEO CONSTRUCTION BASE GROWTH CAPABILITY

The ability of the alternate construction bases to be adapted to other requirements than those studied for GEO construction are summarized on the facing page.

Growth in SPS production rate requirements implies added crews and equipments for the single deck. For the end builders these added costs can be deferred until the longitudinal beam fabrication rate capability is reached. (i.e. about 3.5 meters/min).

All alternate bases can be expanded if needed to build the 8 x 16 bay satellite in one pass. Each concept can also build pentahedral structures or be adapted for use in LEO construction. In addition they can readily build smaller or larger satellites which require fewer or more bays of the same size. Should smaller or larger satellites be required with different size bays after the base has been built, then the single deck approach is probably easiest to adapt.

SPS GEO CONSTRUCTION BASE GROWTH CAPABILITY

	SINGLE DECK BASELINE	4 BAY END BUILDER	2 BAY END BUILDER
PRODUCTION RATE SCALE UP (FASTER PRODUCTION)	• ADD EQUIP & CREWS	• INCREASE L BEAM FAB RATES (0.5 TO 3.5 m/MIN) • ADD EQUIP & CREWS	• INCREASE L BEAM FAB RATES (1.0 TO 3.5 m/MIN) • ADD EQUIP & CREWS
SINGLE PASS 8 x 16 BAY SATELLITE CONSTR	EXPAND BASE TO SUIT	EXPAND AS REQ	EXPAND AS REQ
SUITABLE FOR PENTAHEDRAL CONSTR	OK	OK	OK
ADAPTABLE TO LEO CONSTR	OK – MOVE ANT PLATFORM TO END	OK – EITHER TURN ANT PLATFORM SIDEWARD OR LOCATE ON TOP	
SMALLER SATELLITE – FEWER BAYS – SMALLER BAYS	OK RESIZE UPPER LEVEL GANTRY	OK RESIZE BASE	OK RESIZE BASE
LARGER SATELLITE – MORE BAYS – LARGER BAYS	OK RESIZE DECK & GANTRY	OK RESIZE BASE	OK RESIZE BASE

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ALTERNATE CONSTRUCTION CONCEPT SUMMARY COMPARISON

The major differences identified in the evaluation of alternate GEO construction bases are summarized on the facing page. Each concept is compared in terms of its major costs (total base cost and annual amortization with interest benefits) system characteristics (base mass and crew size), operations complexity, performance capability, development risk and growth capability related to SPS size. Both the 2 bay and 4 bay end builders provide higher performance capability for some what lower cost than the single deck. The 2 bay end builder features the lowest cost, whereas the 4 bay end builder features the highest satellite construction performance capability (40 days faster at 3.5 m/min.). Hence if faster production capability is important then the 4 bay end builder is preferred.

However, the single deck appears simpler to operate due to having less construction equipment. The single deck is probably also easier to adapt to major changes in satellite design. Therefore, if simple operations are more important than faster production capability then the single deck is preferred.

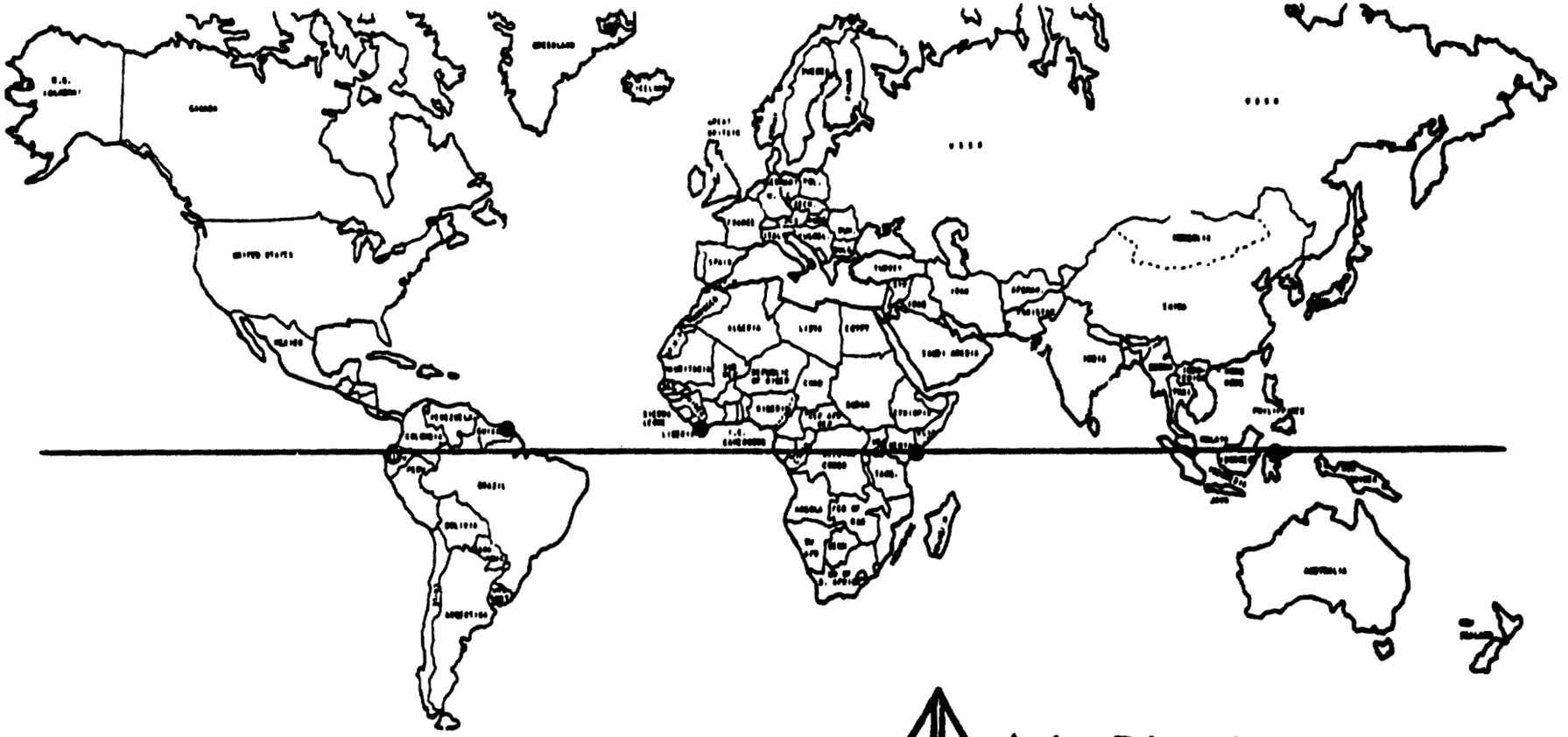
ALTERNATE CONSTRUCTION CONCEPT SUMMARY COMPARISON

CRITERIA	SINGLE DECK	4 BAY END BUILDER	2 BAY END BUILDER
BASE COST	$9.28B	$9.07B	$8.63B
ANNUAL AMORT W INTEREST BENEFIT	$845M	$615M	$630M
BASE MASS	6247 x 10^3Kg	6371 x 10^3Kg	5740 x 10^3Kg
CREW SIZE	407	385	383
OPERATIONS COMPLEXITY	DECOUPLED S/A-STRUCT ASSY	COUPLED S/A STRUCT ASSY	COUPLED S/A STRUCT ASSY
PERFORMANCE CAPABILITY	ADD EQUIP FOR FASTER PRODUCTION	40 DAY FASTER INHERENT	30 DAY FASTER INHERENT
DEVELOPMENT RISK	MEDIUM	MEDIUM	MEDIUM
GROWTH (SPS SIZE)	EASIEST TO ADAPT	MODIFY AS REQ	MODIFY AS REQ

RECOMMENDATION

SIMPLE OPS IMPORTANT	✓	
FASTER PROD IMPORTANT		✓

POTENTIAL EQUATORIAL LAUNCH SITES



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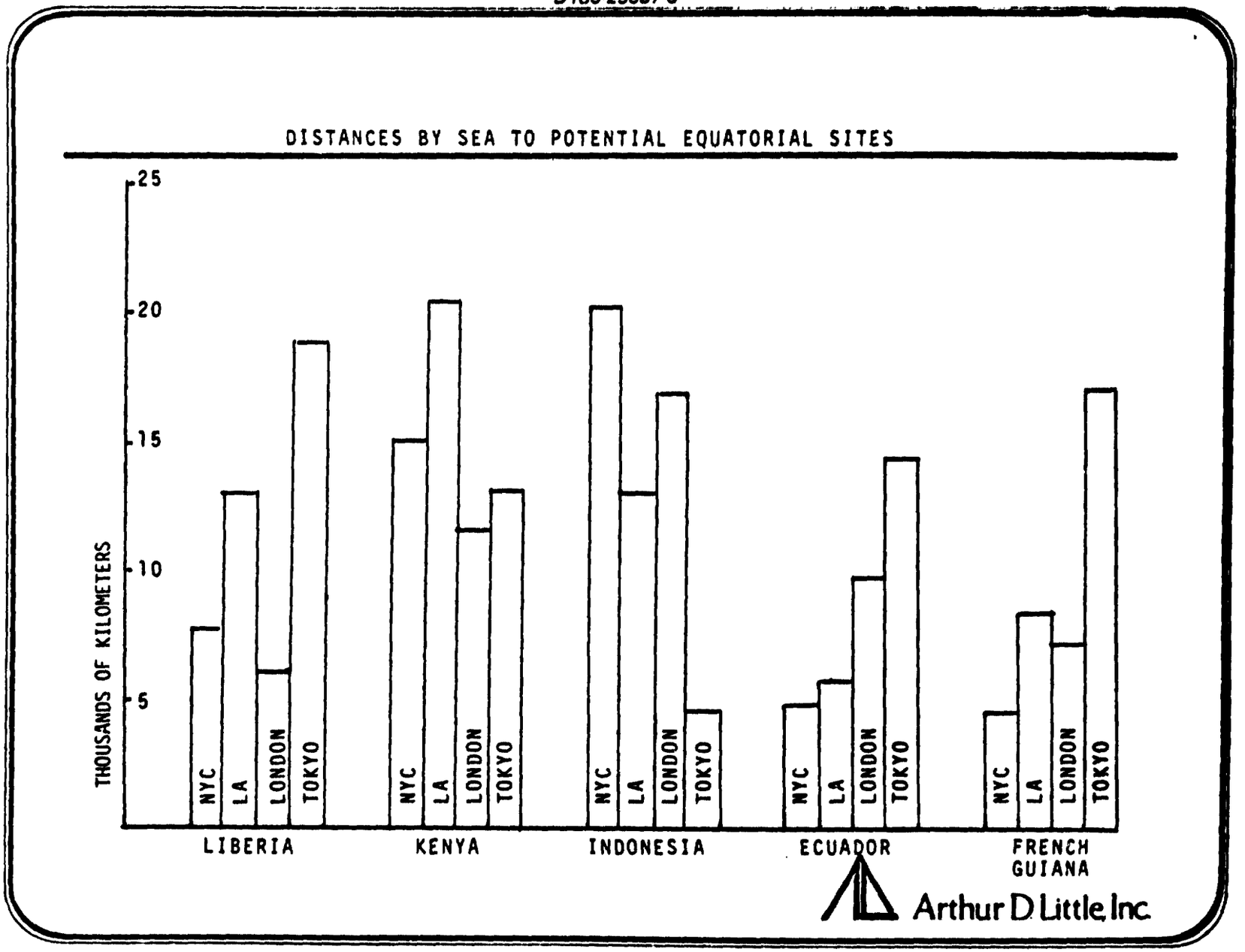
DISTANCES BY SEA TO POTENTIAL EQUATORIAL SITES
THOUSANDS OF KILOMETERS
25
20
15
10
5
NYC
LA
LONDON
TOKYO
LIBERIA
KENYA
INDONESIA
ECUADOR
FRENCH GUIANA
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RANKINGS OF POTENTIAL EQUATORIAL LAUNCH SITES (TENTATIVE)

	Liberia	Kenya	Indonesia	Ecuador	French Guiana
Existing Launch Facilities	3	2	3	3	1
Overwater Range, East	2	1	1	-	1
Access to Inclined Orbits	2	1	1	?	1
Access to Oil/Gas Field	3	2	2	1	3
Downrange Tracking Sites	1	3	1	2	4
Industrial Base, Energy, etc.	3	2	1	2	4
Logistics, Port Facilities, etc.	2	1	3	2	4
Sea Route Distance	3	5	4	1	2
Climate	4	2	3	1	5
High Mountains	-	2	2	1	-

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TRANSPORTATION COSTS TO EQUATORIAL SITE (ONE 5GW SPS)

Distance to Launch Site	4600	20500	km
SHIP			
Freight Cost	$ 4.2	$ 18.7	million
Time in Transit (@ 15 knots)	165	738	hours
Lost Revenues	$24.8	$110.7	million
Total Cost	$29.0	$129.4	million
AIR			
Freight Cost	$61.3	$273.2	million
Time in Transit	7	31	hours
Lost Revenues	$ 1.1	$ 4.7	million
Total Cost	$62.4	$277.9	million

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EOTV SAVINGS AT EQUATORIAL LAUNCH SITE (ONE 5GW SPS)

EOTV ΔV Reduction (no plane change)	350	m/sec
EOTV I_{SP}	7000	sec
Argon saved	255	tons
Argon cost saving	$0.5	million
Launch to LEO of Argon	$5.1	million
LEO-GEO Transit Time Reduction	132	hours
Revenue Gained	$19.8	million
Total Savings	$25.4	million

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EQUATORIAL LAUNCH SITES: CONCLUSIONS

- TERRESTRIAL TRANSPORTATION COSTS ARE MODEST BUT NOT NEGLIGIBLE.
- LOSS OF REVENUES DUE TO TIME IN TRANSIT MAY BE COST DRIVER FOR SEA FREIGHT.
- AIR FREIGHT TO CLOSE SITE MAY BE CHEAPER OVERALL THAN SEA FREIGHT TO REMOTE SITE.
- FREIGHT MODE FASTER THAN SEA BUT CHEAPER THAN AIR SHOULD BE USED IF AVAILABLE (HOVERCRAFT, HYDROFOIL, DIRIGIBLE?)
- ECUADOR, GUIANA/BRAZIL, LIBERIA PREFERABLE SITES.
- TERRESTRIAL TRANSPORTATION COSTS AND DELAYS MAY BE OFFSET BY REDUCTION IN EOTV COSTS AND DELAYS

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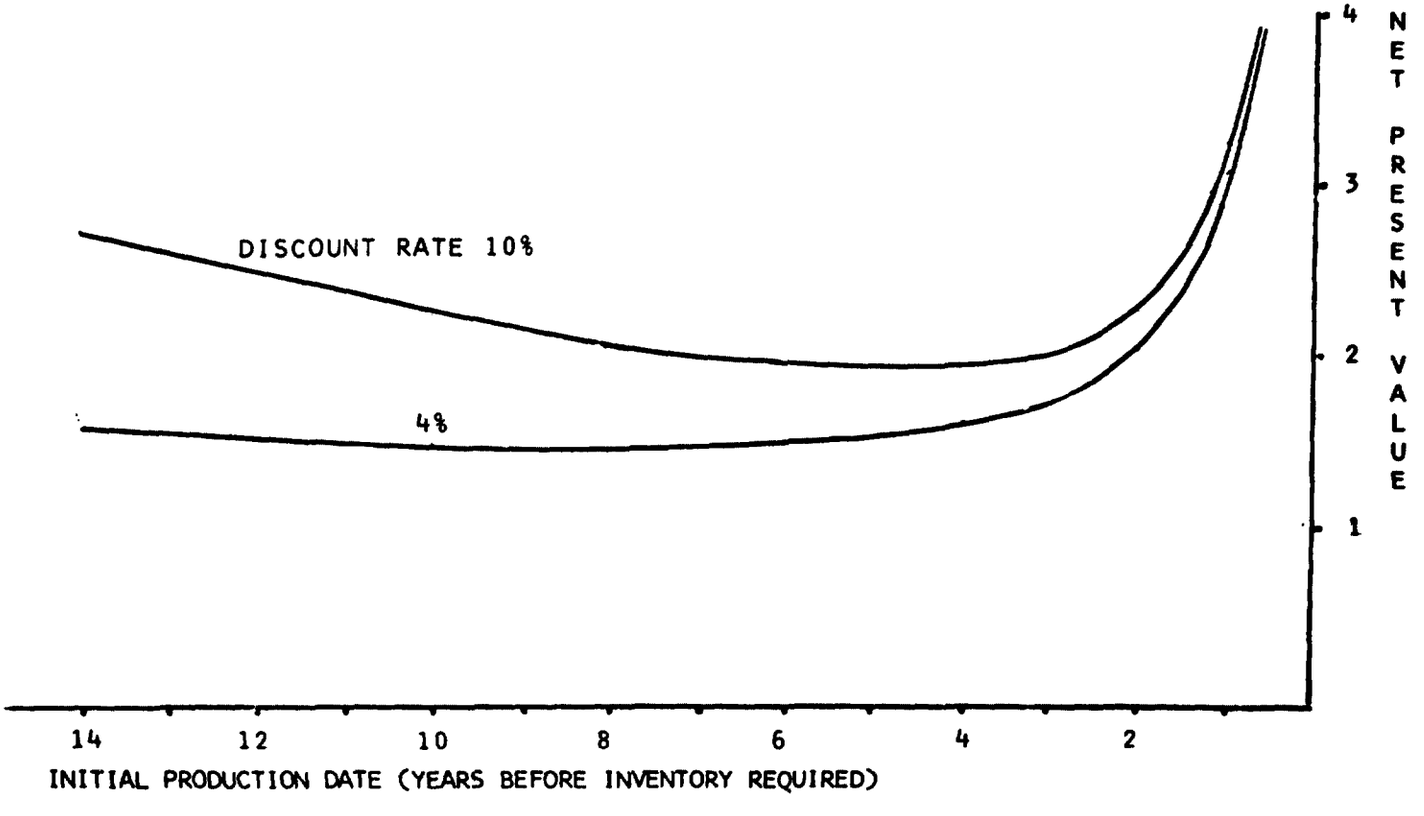
If it is necessary to have a certain inventory of a component at a specified time (e.g., for prototype SPS construction), a balance must be struck between the need to postpone investment as long as possible and the need to minimize the capital cost of the equipment to produce the inventory on time. The curves show the discounted unit cost of inventory of components, taking into account production costs and capital equipment costs, in arbitrary units (because actual costs of course depend on the component under consideration). No costs are included for maintaining inventory (warehousing, etc.), because these are also component-specific.

In constructing these particular curves, it was assumed that the ratio of the unit production cost to the capital equipment cost per unit production rate was two years.

DISCOUNTED UNIT COST OF INVENTORY



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PROJECTED SOLAR CELL ARRAY PRODUCTION (1986)

	Annual Production (MWp)
U.S. Market (present applications)	52
World Market (present applications)	140
World Market (potential terrestrial applications)	4000
2.5 GW SPS Prototype (7 year inventory)	360
SPS Build-Up Demand (late '90s)	20000

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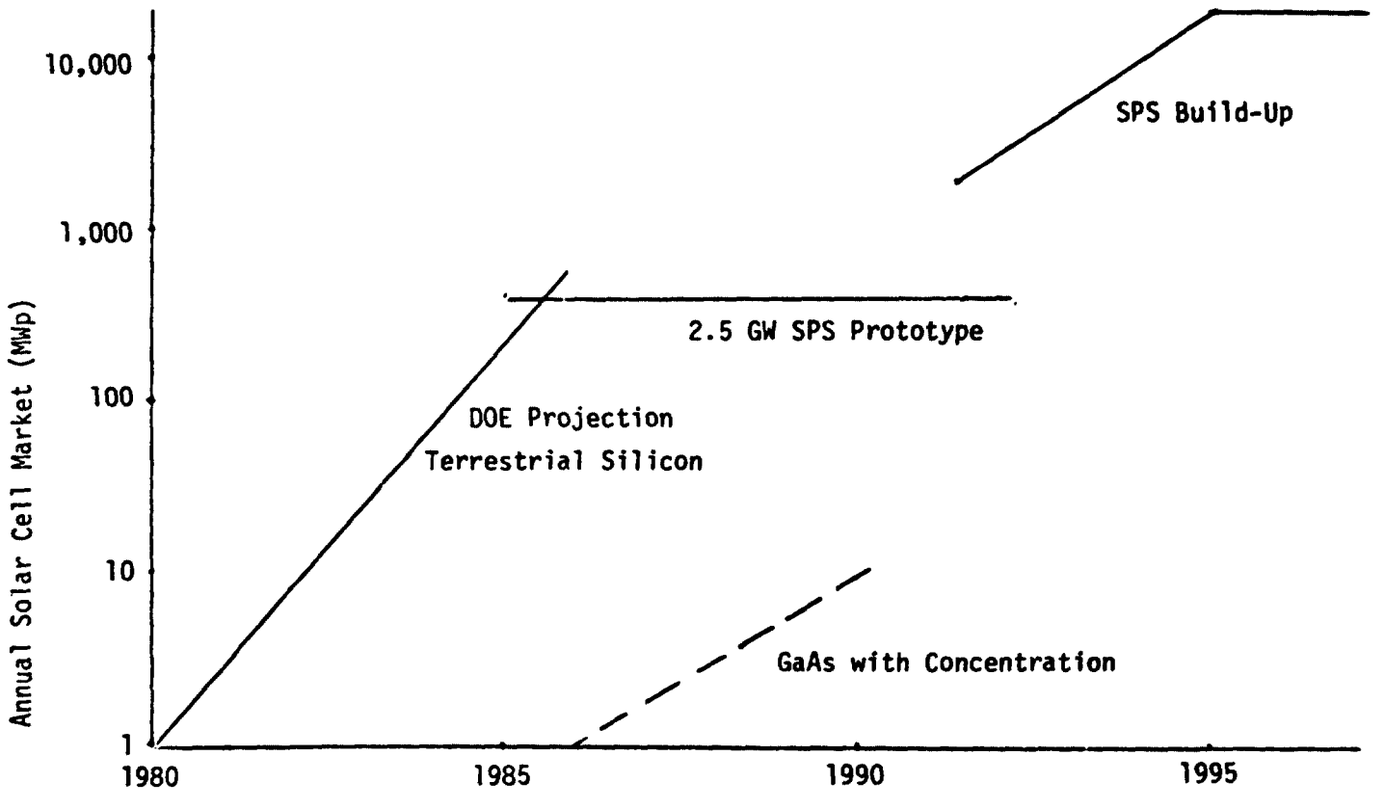
TERRESTRIAL AND SPS PHOTOVOLTAIC MARKET GROWTH SCENARIOS



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PHOTOVOLTAIC CELL PRODUCTION: CONCLUSION

- 2.5 GW SPS PROTOTYPE SHOULD PLAN USING SINGLE-CRYSTAL SILICON CELLS
- WITH OPTIMUM PRODUCTION RATE FOR INVENTORY, 2.5 GW PROTOTYPE IS WITHIN PROBABLE PHOTOVOLTAIC (SILICON) PRODUCTION CAPACITY IN MID-EIGHTIES
- SPS BUILD-UP WILL REQUIRE MAJOR INCREASE IN PHOTOVOLTAIC PRODUCTION -- IMPACT EVALUATION DIFFICULT WITHOUT SPECIFICATION OF CELL TYPE AND STUDY OF PRODUCTION ENGINEERING

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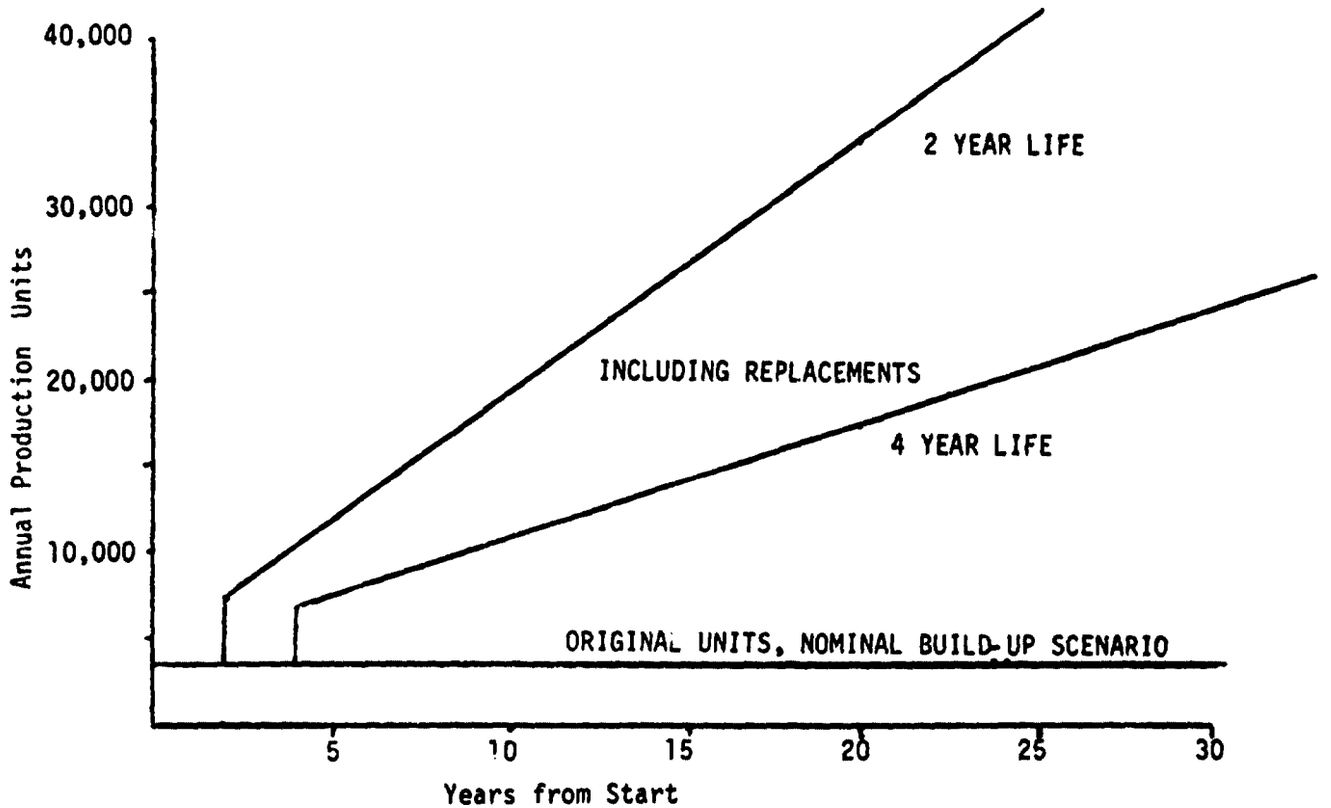
PRODUCTION REQUIREMENTS, ARGON ION THRUSTERS



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ION THRUSTER PRODUCTION: CONCLUSIONS

- MAXIMIZE THRUSTER LIFETIME TO MINIMIZE PRODUCTION COST
- ANNUAL PRODUCTION TO SUPPORT BUILD-UP IS 3500 to 40,000 UNITS, DEPENDING ON OPERATING LIFE
- THRUSTER PRODUCTION IS MODEST ENTERPRISE -- COMPARE WITH TYPICAL AUTOMOBILE PLANT, PRODUCING 300,000 UNITS/YEAR
- ARGON REQUIRED FOR BUILD-UP: 24,800 to 28,400 TONS/YEAR
  ARGON AS BY-PRODUCT OF LOX FOR HLLV: 163,000 TONS/YEAR
  U.S. ARGON PRODUCTION (1975): 230,000 TONS

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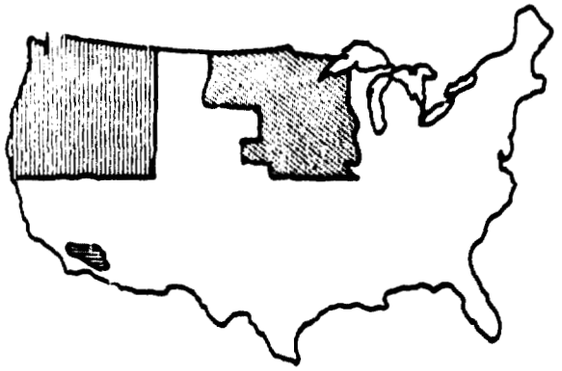
Siting Groundrules

- INVESTIGATION LIMITED TO THREE UTILITY REGIONS:
  - BONNEVILLE POWER ADMINISTRATION (BPA) (PACIFIC NORTHWEST)
  - MID-CONTINENT AREA POWER POOL (MAPP) (NORTH CENTRAL USA)
  - SOUTHERN CALIFORNIA EDISON



SITING GROUND RULES CONTINUED

Additional ground rules employed in the siting investigation are tabulated on the facing page. Most of these can be regarded as candidate site selection criteria.

Siting Ground Rules, Continued

- TWO "BEAM + BUFFER" REGION WIDTHS (EAST-WEST DIMENSION)

  13.18 km (CORRESPONDS TO 5000 MW OUTPUT)
  9.32 km (CORRESPONDS TO 2500 MW OUTPUT)

- SPS ON THE LONGITUDE OF THE SITE

- NORTH-SOUTH DIMENSION A FUNCTION OF LATITUDE

  EXAMPLES: 48° LATITUDE, 23.06 km
  35° LATITUDE, 17.37 km

- NO ENCROACHMENT UPON:

  - GAME PRESERVES
  - BIRD REFUGES
  - NATIONAL MONUMENTS
  - NATIONAL AND STATE PARKS
  - INDIAN RESERVATIONS

- MAXIMUM & MINIMUM ELEVATIONS IN SITE TO BE WITHIN 1000 FEET OF EACH OTHER

- MINIMUM DISPLACEMENT OF PERSONS AND PROPERTY

- NATIONAL FOREST & EXISTING FARMLAND USE O.K.

SITING APPROACH

The basic siting approach employs map searches with the steps as indicated on the facing page.

Siting Approach

- MAP SEARCH WITH:

  AERONAUTICAL CHARTS
  CONTOUR PLOTS
  ROAD MAPS

- POPULATION COUNTS FROM "ATLAS OF THE UNITED STATES"

- APPROACH:

  1. IDENTIFICATION OF PROMISING AREAS
  2. CHECK FOR AGREEMENT WITH GROUND RULES
  3. CHECK FOR FIT OF 5000 MW RECTENNA
  4. IF FIT O.K., 5000 MW ASSIGNED
  5. IF 5000 MW DID NOT FIT, 2500 MW WAS TRIED

RECTENNA SITING POTENTIAL SITES IDENTIFIED

Preliminary studies of rectenna siting have indicated that the number of potential sites is considerably greater than presently-estimated requirements. Specific sites were identified in the three areas indicated with total numbers of sites as summarized.

Rectenna Siting
Potential Sites Identified

UTILITY REGION	5000 MW SITES [1]	2500 MW SITES
BONNEVILLE POWER ADMINISTRATION	25	27
MID-CONTINENT AREA POWER POOL	51	34
SOUTHERN CALIFORNIA EDISON	8	9
TOTALS	84	70

[1] ALSO SUITABLE FOR 2500 MW

RECTENNA SIZE EFFECTS

It was found beneficial to have available in the inventory two sizes of receiving antenna. The two sizes utilized correspond to the two power transmission link capacities discussed earlier in this briefing under Alternative Sizes for SPS. If both 2500 and 5000 megawatts receiving sites could be employed, the total amount of power that could be sited was much greater than that for either size of receiving antenna alone.

Rectenna Size Effects

- IF ONLY 2500 MW RECTENNAS WERE SITED, 385 GW OF CAPACITY COULD BE INSTALLED
- IF ONLY 5000 MW RECTENNAS WERE SITED, 420 GW OF CAPACITY COULD BE INSTALLED (9% MORE THAN WITH 2500 MW ALONE)
- IF BOTH 2500 MW AND 5000 MW RECTENNAS ARE AVAILABLE, 595 GW COULD BE SITED (42% MORE THAN WITH 5000 MW ALONE)

CAPACITY VS. REQUIREMENTS

As noted, the preliminary siting investigation had no difficulty in finding sites equal to the power generation needs for these utilities regions at about the turn of the century.

Capacity Versus Requirements

- THIS PRELIMINARY ANALYSIS INDICATES THAT *POTENTIAL* SITES EXIST FOR AT LEAST FOUR TIMES THE 2000 A.D. REQUIREMENTS.

- SITING IN THE ENERGY INTENSIVE NORTHEAST WAS NOT INVESTIGATED, BUT DEMANDS FOR THAT AREA MIGHT BE MET BY MODEST INTERTIES FROM RECTENNAS IN THE NORTH CENTRAL U.S.

RECTENNA SITING - CLOSE UP LOOK

A number of sites in each utility region was selected at random for closer investigation of slope and other features which might presumably cause rejection. In general, most of the sites were quite flat. That is, the average slopes were less than 5 parts in 100; however, most of sites had small regions of local slope which might be considered to be excessive (slopes of 30 degrees or more).

Rectenna Siting—Close-Up Look

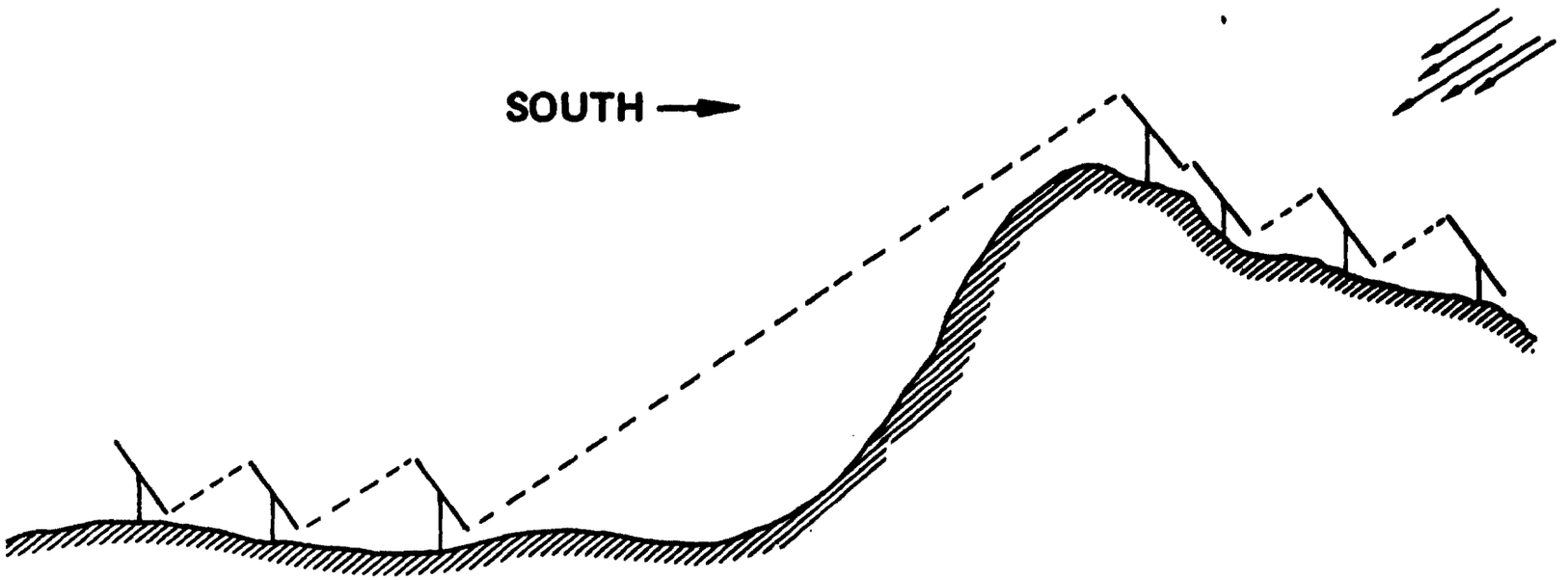
Localized Slope

- Previous data used only total site slope as a basis for rejection.
- Several sites were selected at random for additional analysis.
- Typical result:
  - Majority of site is "flat" (slope less than 5 in 100).
  - 1% to 5% of site has slopes up to 60 in 100.

EVEN EXTREME SLOPES DO NOT BLOCK THE BEAM

As shown here, the microwave beam from space ultimately falls on some ground area. It is possible in this concept to locate rectenna panels so as to receive all of the beam area even in regions of very extreme slope. Consequently, it appears that rejection of cites on the basis of slope must be decided individually with, economics as the criterion.

Even Extreme Slopes Do Not Block the Beam



- Rejection on basis of slope will be a function of construction economics.

RECTENNA ARTIST CONCEPT

The concept shows here a mountain area and a "gulch" which were not suitable for rectenna construction; the rectenna has, in essence, been built around them. Also visible is a buffer region around the rectenna between it and the exclusion fence.

ORIGINAL PAGE IS
OF POOR QUALITY

OPTIONS

In investigation of individual sites it might be decided to merely reject any site with localized slope. Alternatively, large scale landscaping would be used. Also it might be desirable, in some cases, to allow holes in the rectenna. That is, in the area of either excessive slope, or some other terrain features, to merely not construct panels in that area, and allow the microwave beam to fall (wasted) directly on the natural or somewhat modified terrain.

Options

1. Reject any site with localized excessive slope
2. Large-scale landscaping
3. "Holes" in rectenna
4. Build on all slopes

SITING CONCLUSIONS

This siting effort indicated that, in the three utility areas investigated,"potential" sites exist to more than fill the requirements for electrical power for those regions in the year 2000. Due to the potential of excess sites, it might be possible to feed energy to the northeast from rectenna sites in the north central area, using modest interties. The benefits of having two rectenna and SPS sizes (in this case 5,000 and 2500 megawatts) were obvious. Far more "energy from space" can be sited by having two sizes rather than with either size alone. Further, the siting of SPS rectennas will obviously require individual site investigation. Each site selected will be a compromise. That is no site can be expected to be perfectly flat, with the most desired terrain, type of soil, drainage, etc. No site will be immediately adjacent to the required energy use point. Thus, each siting will be a engineering and economic compromise.

Siting Conclusions

- ADEQUATE SITES APPEAR TO EXIST IN THE AREAS INVESTIGATED (ALTHOUGH MORE DETAILED ANALYSIS CAN BE EXPECTED TO RULE OUT MANY SITES, AS WOULD LICENSING PROBLEMS)
- MODEST INTERTIES FROM THE NORTH CENTRAL AREA MIGHT EASE NORTHEAST SITING PROBLEMS
- WITH TWO RECTENNA (& SPS) SIZES AVAILABLE, 5000 & 2500 MW, MUCH MORE CAPACITY CAN BE SITED THAN WITH EITHER SIZE ALONE
- SITING WILL REQUIRE INDIVIDUAL INVESTIGATION OF EACH POTENTIAL SITE; EACH WILL BE A COMPROMISE.

RECOMMENDATIONS

The siting data developed in this study should be correlated with that produced in the exclusion area study of SPS rectennas accomplished at Rice University. If possible, this effort should be extended to cover not only to the three contributing utility regions but the entire United States. As stated in the groundrules section of the previous chart, sites were not rejected which involve either national forests or farms currently in use. The impact of changing this ground rule to preclude use of national forests or land currently in use for farming should be investigated. Tests should be conducted on rectenna panels to determine the effect of percipitation particularly as regards to water sheet build-up during heavy rain.

Recommendations

1) INTEGRATE EXCLUSION AREA RESULTS FROM RICE UNIVERSITY.

2) EXTEND EFFORT TO ENTIRE U.S.

3) INVESTIGATE IMPACT OF NATIONAL FOREST AND FARM USE.

4) CONDUCT TESTS TO DETERMINE EFFECTS OF PRECIPITATION ON RECTENNAS.

5) NUCLEAR INDUSTRY EXPERIENCE IS TYPICALLY 12 YEARS FROM SITE SELECTION/LICENSING TO UNIT COMPLETION. IF SPS IS TO GO ON-LINE IN THE LATE 1990's, SITE SELECTION SHOULD RECEIVE EMPHASIS SOON.

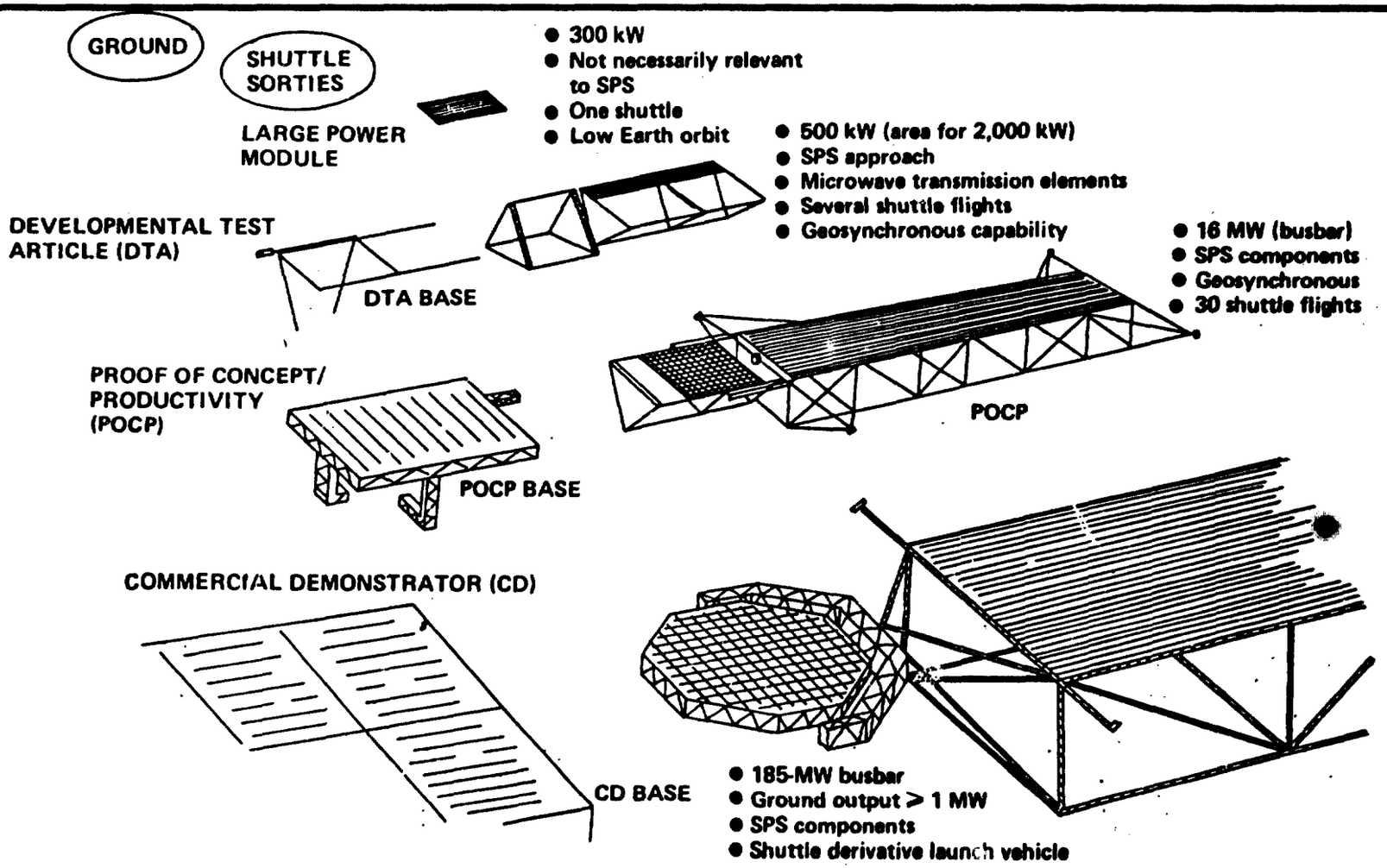
POTENTIAL SPS PERCURSORY ELEMENTS

This chart illustrates a potential sequence of developmental efforts ranging from ground test (ground exploratory research program) to a very large commercial demonstrator which would be built before an operational solar power satellite. Also shown are shuttle sortie flights such as those discussed on the previous chart, a large power module (which might not be directly relevant to solar power satellites), a small developmental test article and its construction platform or base, and a proof-of-concept/productivity satellite and its construction base. The commercial demonstrator is sufficiently large to have a ground output of at least 1 megawatt. If all of the elements shown here were to take place prior to a full-size SPS, the date of significant solar power satellite energy availability might be as far off as the year 2020 or 2030. That is it would be advantageous not to have to construct each of the precursory units shown.

BOEING SPS

Potential SPS Precursory Elements

78-292



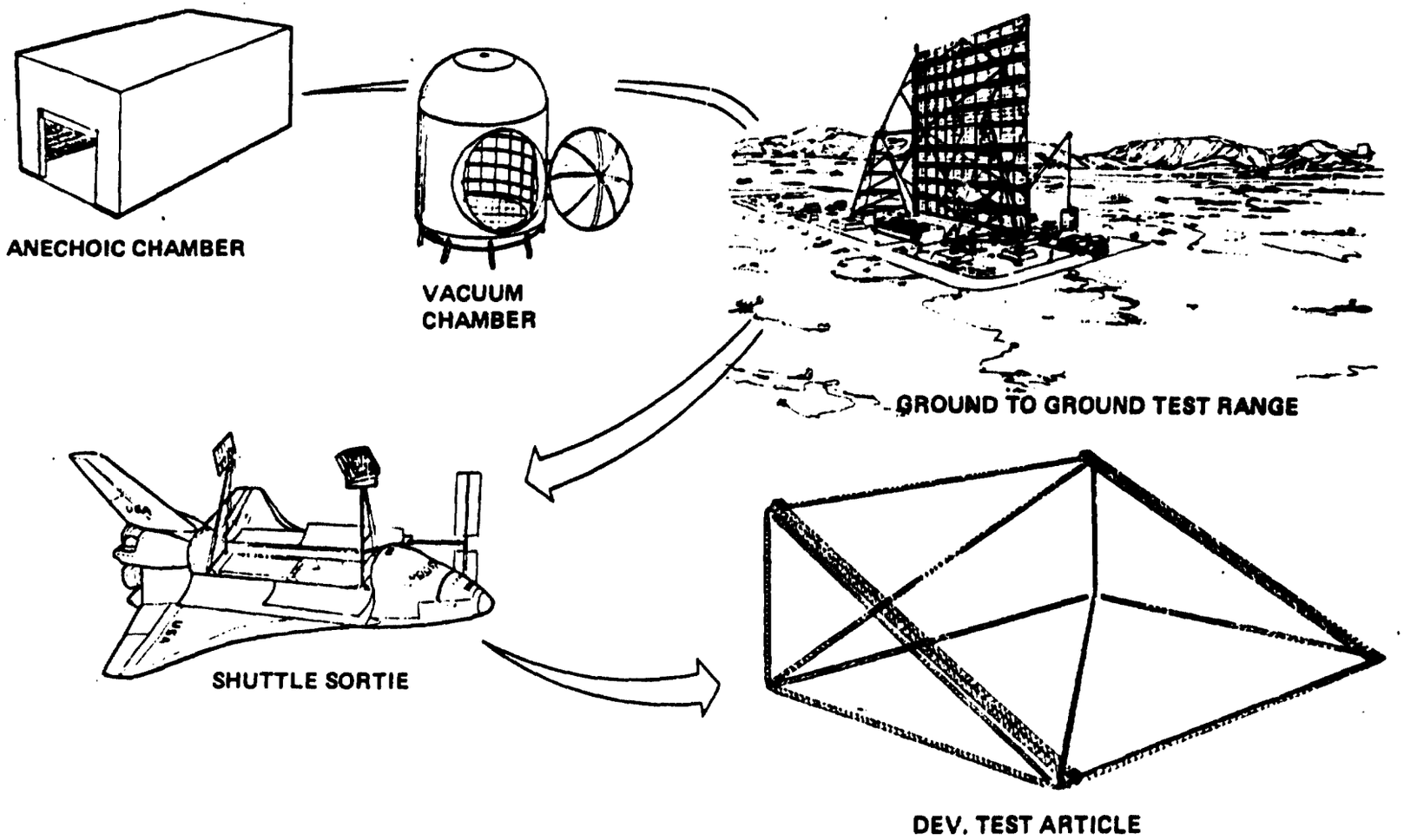
3.0 METER SUBARRAY

This chart shows a path for the developmental test effort related to a shuttle size microwave power transmitter subarray. By selecting a size of 3.0 meters per side, the subarray will fit the shuttle bayload bay in a position normal to the acceleration vector. The subarray would be tested in a microwave anechoic chamber and a vacuum chamber, where phenomena such as multipactor, heat rejection, etc. could be investigated. It would be used in a microwave power transmission ground-to-ground test range, shown here as 30 meters on a side (hence with 100 subarrays) under the control of a pilot transmitter located on a rectenna panel oriented normal to the beam some distance away. The subarray would fly on a high power element sortie test flight which could include test of electric thruster panels requiring approximately the same power level as the subarray. Finally, the subarray would be the transmitting element of a solar power satellite developmental test article. In the DTA shown, four subarrays are located at the corners of the array, mounted upon extendable/deployable secondary structure, which is in turn mounted upon a primary structure.

BOEING SPS

3.0 Meter Subarray

78



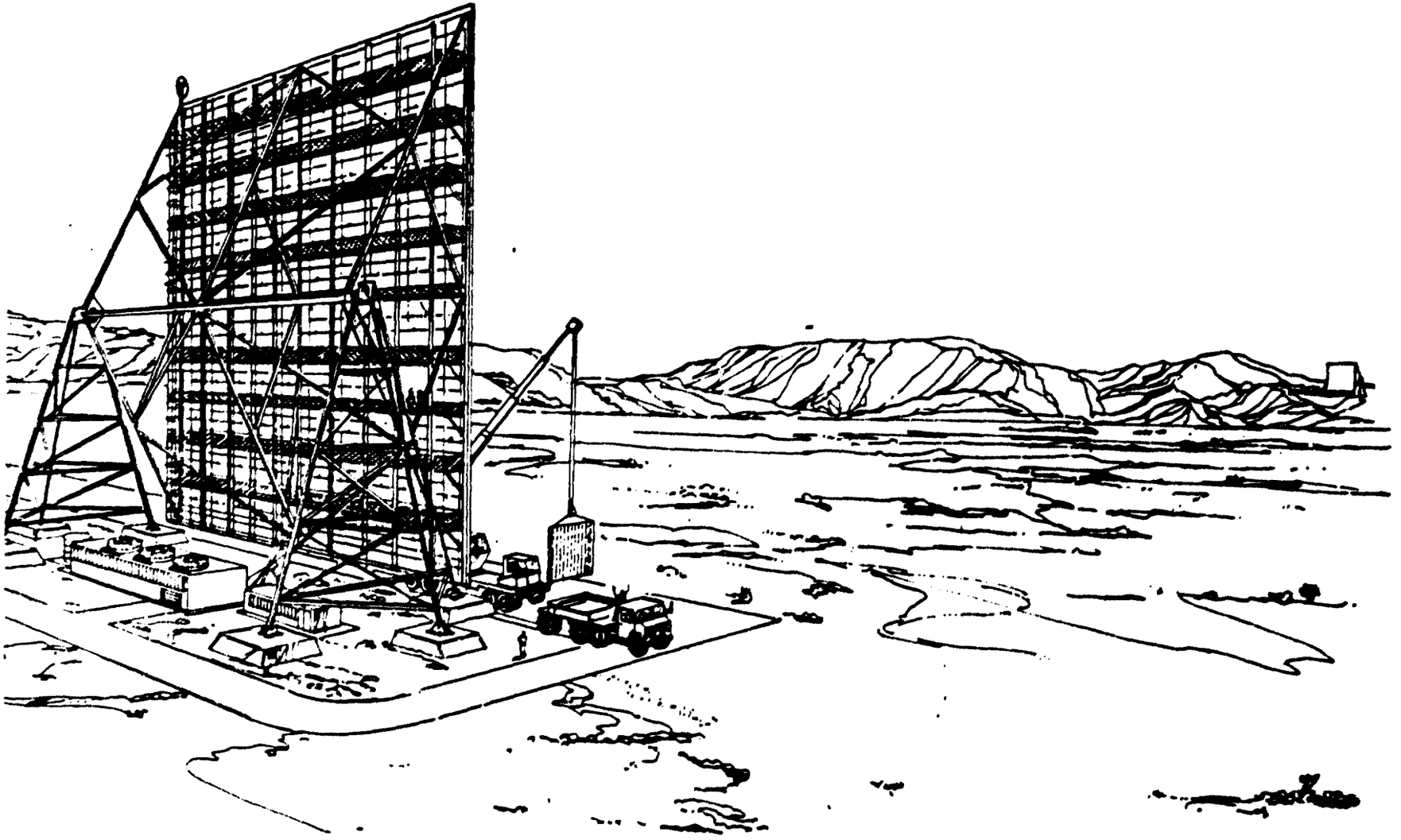
GROUND-TO-GROUND MICROWAVE RANGE

Shown here is installation of a 3.0 meter subarray into the transmitting group of the microwave ground-to-ground test range. The structure of the microwave test range transmitter supports the subarray elements and allows for tilt. In test, a tilt angle might be used such that the difference in distance from the subarray which is closest to the rectenna panel and that which is furtherst from the rectenna panel would be the same as that anticipated in a full scale solar power satellite. That is, the angle would be much larger than the angle in a full size satellite but the distance difference would be the same. Trunnions are provided for this tilt. The framework includes power distribution, phase control distribution, etc. The run of coaxial cable or optical fiber between subarrays and to the central reference subarray, might use coils so as to equal the total distance involved in phase distribution aboard the full size satellite.

BOEING SPS

Ground-To-Ground Microwave Range

78-379



DEVELOPMENTAL SORTIES

The large aperture test satellite, launched by a IUS, serves to address the major questions of the "will SPS work?" type. That is, questions related to microwave transmission, susceptability of the SPS to the geosynchronous environment, and suitability of selected materials. The second category of developmental sortie flights of the space shuttle would be those to ensure that a precursory major flight project succeeds. Finally, during actual design of the solar power satellite and its construction base, qualification flights for specific SPS components will take place. These might involve, for large components, the heavy lift launch vehicle.

BOEING SPS

Developmental Sorties

78-349

A. PROOF OF SPS CONCEPTS (ABOUT 1983)
(MICROWAVE TRANSMISSION, ENVIRONMENTAL SUSCEPTIBILITY, MATERIALS SUITABILITY)

1. "LARGE APERTURE SATELLITE" (REQUIRES IUS)
(SINGLE FLIGHT)

B. ASSURE SUCCESS OF "MAJOR FLIGHT PROJECT(S)"
(ABOUT 1984)

1. STRUCTURAL BEAM "MACHINE"
2. ORBITAL WORK STATION
3. HIGH POWER ELEMENTS

C. QUALIFICATION OF SPECIFIC SPS COMPONENTS
(ABOUT 1990)
(PERHAPS EIGHT FLIGHTS)

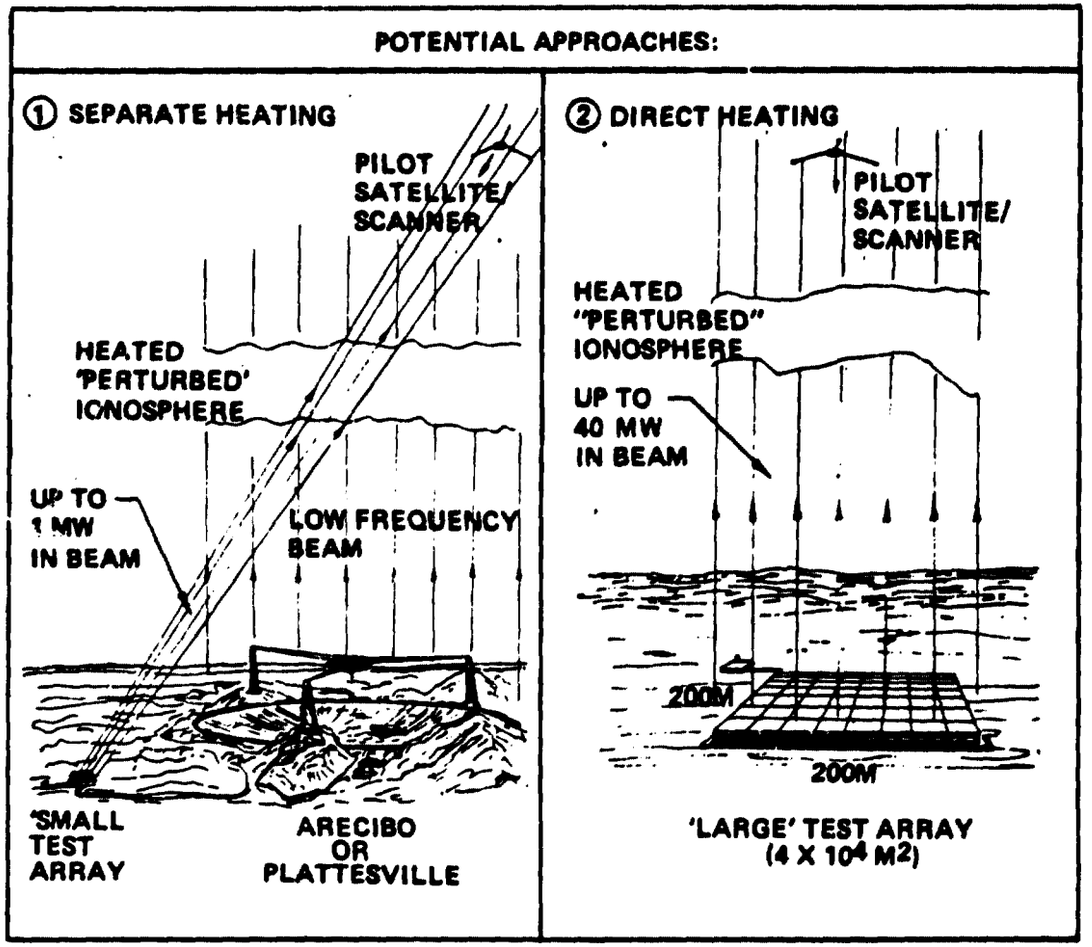
GROUND-TO-SPACE MPTS TEST SYSTEM

This chart shows two potential methods of utilization for the large aperture test satellite. On the left a test array such as the 30 meter square array of 100 subarrays, shown previously, transmits to space under control of the 9.0 meter dish of the large aperture test satellite. That is, the large dish on the satellite provides the pilot beam for phase control of the test array. The test array was provided with trunnions to permit tilt to the required near-vertical orientation. Operation could be accomplished through ionospheric strata heated by a transmitter such as that Arecibo. If frequency scaling was employed, and the power level at that transmitter was increased, another possible utilization is to act as a pilot transmitter for a large array of SPS similar transmitter elements placed horizontally on the ground (as shown on the right). Here the test array is sufficiently large to directly heat the ionisphere without frequency scalling.

BOEING SPS

Ground-To-Space MPTS Test System

78-378



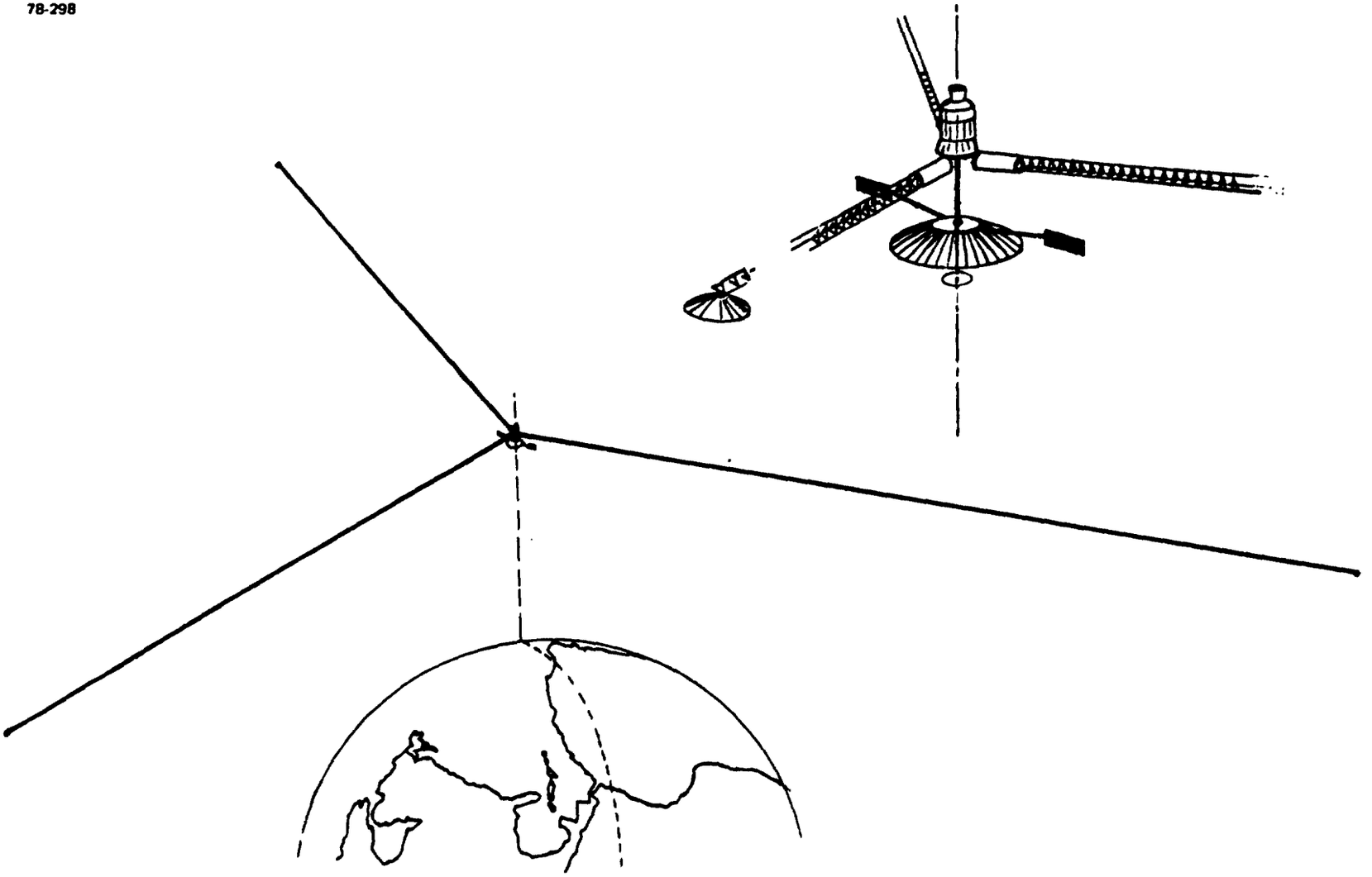
LARGE APERTURE SATELLITE

To position the four transmit/receive elements indicated on the previous chart a geosynchronous satellite employing large extendable booms is shown. The number of booms is somewhat arbitrary. Two or four might be preferred. The transmit/receive dishes at the ends of the arms are baselined as being 2.0 meters in diameter. A 2.0 meter diameter transmit/receipt element is also located in the center of the satellite just below a 9.0 meter diameter antenna. This larger antenna would be used for pilot control of a ground transmitter subarray group. The large aperture satellite would be launched to geosynchronous orbit by a shuttle and inertial upper stage. After arrival in geosynchronous orbit the cannisters for the extendable booms would be swung out and then the booms extended to locate the transmit/receive elements. The satellite would include solar power supply, attitude and stationkeeping control systems, command and control systems, etc. It would be advantageous to have a design lifetime of several years for this satellite. The transmitter tubes used for the 2.0 meter dishes might be 10 to 20 watts traveling wave tube of the type currently flying in many satellites and space probes.

BOEING SPS

Large Aperture Satellite

78-298



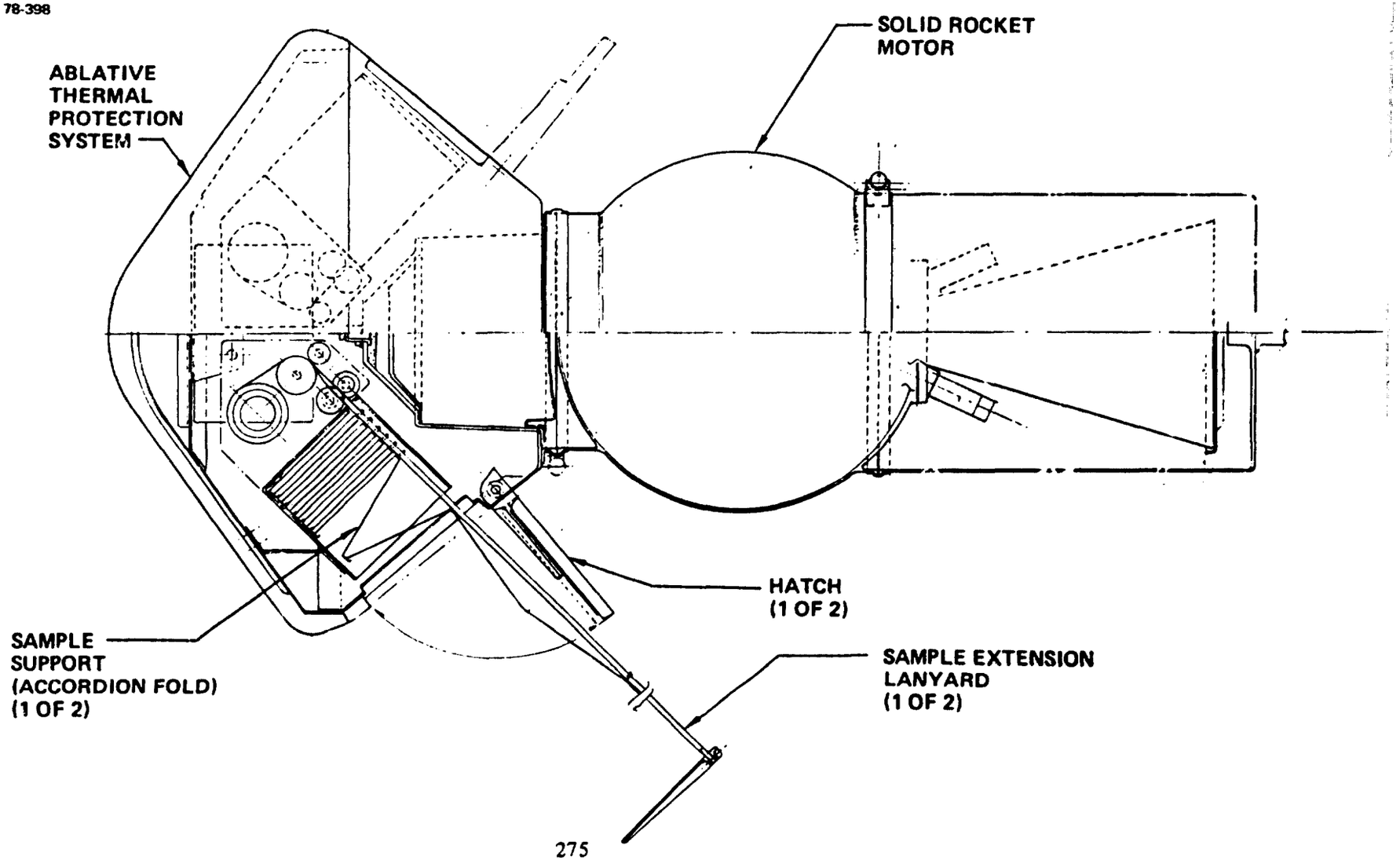
SAMPLE EXPOSE/RETURN SYSTEM

The large aperture test satellite could potentially provide years of stable orientation in geosynchronous orbit. In the concept shown here, samples of potential SPS components would be extended and deployed aboard that satellite by an accordian pull-out and lanyard system. These samples might include solar cells of various types, potential structural elements and materials such as composites, metals, plastics, etc. After the desired exposure period the samples would be drawn within the reentry body and hatches closed. The entire system, including the solid rocket return motor, would be spun up upon a turntable; after reaching the required spin rate, springs would be used to kick the system free of the large aperture transmission satellite and achieve a save separation before firing the solid rocket moter. Approximately 5½ hours later the reentry body would enter the earths' atmosphere. Here it would be recovered using proven space recovery techniques. The SPS candidate material samples could then be tested to determine the resultant degradation due to their exposure. During the exposure period in space, analyses should have been carried out to predict degradation mechanisms, ground test including radiation exposure should have taken place, so that the space operation provides a correlation and calibration of the ground test program.

BOEING SPS

Sample Expose/Return System

78-398



CHARGING TEST PROVISIONS: CONCEPT

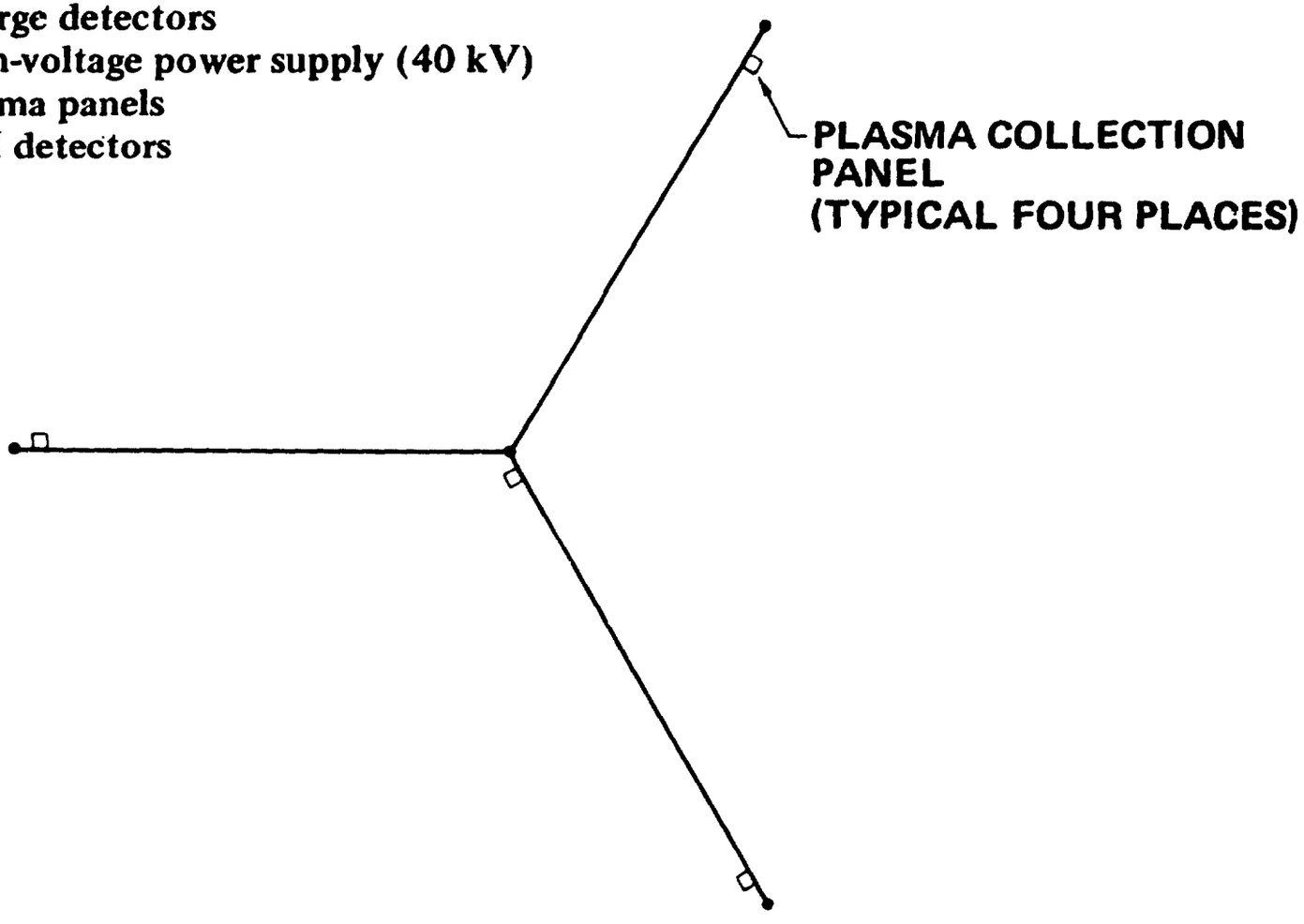
Charging of spacecraft elements to high voltages during operation in geosynchronous orbit has been observed. Actual failures of some components have been observed. The solar power satellite with its large dimensions and high voltage power tranmission systems may have additional problems resulting from the energetic plasma occurring during geomagnetic substorms. To investigate this phenomena a test satellite of large dimensions should be provided in geosynchronous orbit. The large aperture test satellite could serve this purpose since its extendable booms might be up to three hundred meters or more in length. By providing a high voltage power supply, for example at forty thousand volts, and distributing this charge to the test panels located at the end of the arms, plasma interaction phenomena could be observed. Test instrumentation would be used to search out currents induced by the external plasma, arc discharges (potentially a source of electromagnetic interference), etc.

BOEING SPS

78-302

Charging Test Provisions: Concept

- Charge detectors
- High-voltage power supply (40 kV)
- Plasma panels
- EMI detectors



DEVELOPMENT ISSUE ASSIGNMENT

These issues were drawn from analyses of specialists who have been involved with construction concepts for solar power satellites. They identify these as primary issues. The issues have been assigned to either analysis ground test, shuttle sortie flights, or to (in most cases) a major flight project, such as the developmental test article.

BOEING SPS

Development Issue Assignment

78-344

(Construction)

ISSUE	ANALYSIS/GND. TEST	SHUTTLE SORTIE	MAJOR FLT. PROJECT
1. BEAM MACHINE RATE, RELIABILITY	ONE G UNITS	SHUTTLE SORTIE	INTEGRATION WITH "BASE"
2. JOINTS, BEAM HANDLING	NEUTRAL BOYANT	WORK STATION SORTIE	INTEGRATED OPS.
3. SOLAR ARRAY DEPLOYMENT		COMBINE WITH BEAM SORTIE (SMALL SCALE)	INTEGRATION WITH "BASE"
4. BUSBAR INSTALLATION			DEPLOY BUSBAR (DUMMY)
5. MODULE INDEXING			DEMONSTRATE
6. ANTENNA SECONDARY STRUCTURE			DEPLOYMENT, MOUNTING
7. SUBARRAY INSTALLATION			MOUNT ON SECONDARY STRUCTURE

(Maintenance)

KLYSTRON CHANGEOUT	NEUTRAL BOUYANT	POSSIBLE CHANGEOUT ON SORTIE	"ADVANCED" DTA COULD INCLUDE GANTRY

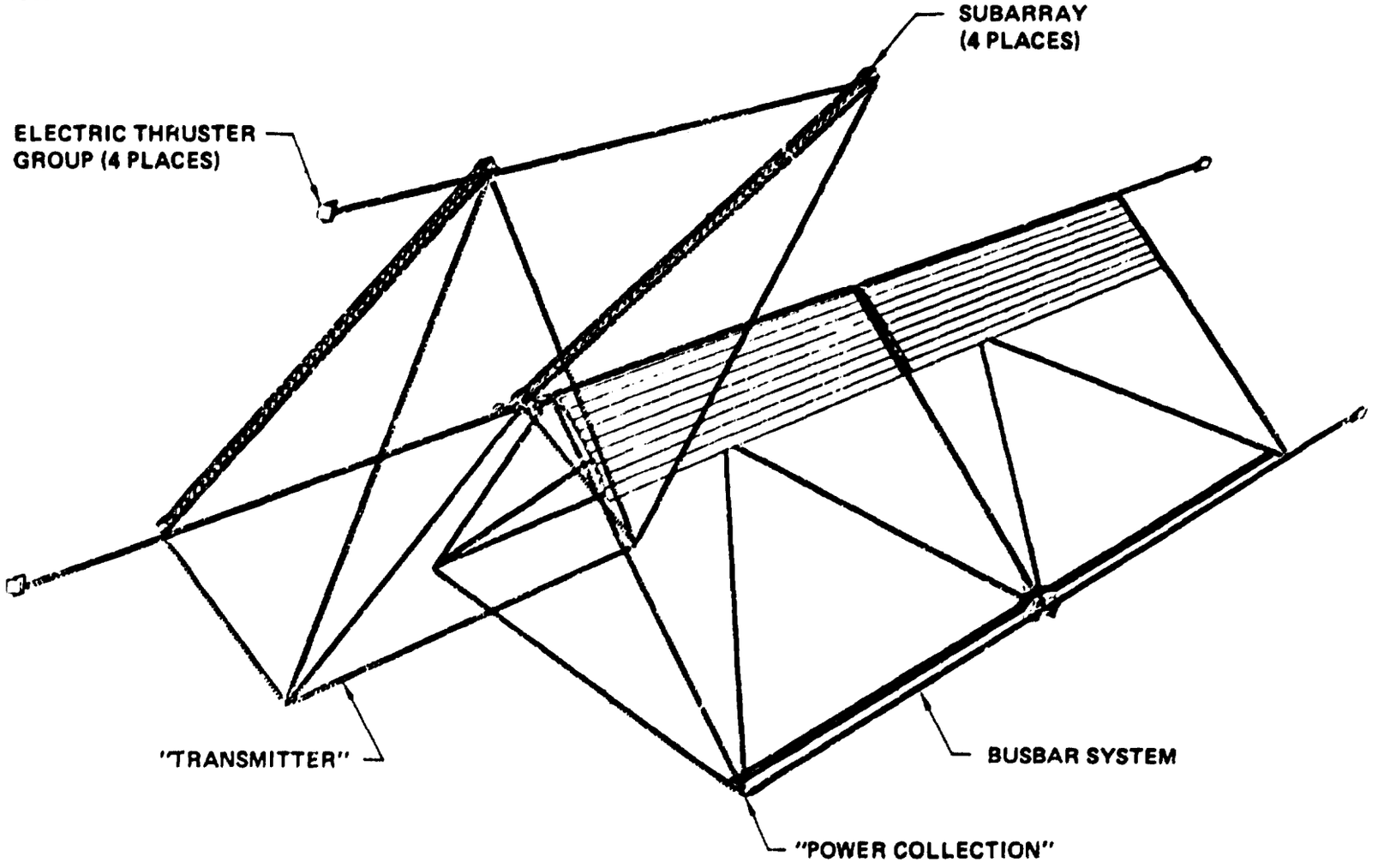
DTA GENERAL ARRANGEMENT

The developmental test article configuration shown here incorporates two power collection modules and one power transmission module. This system would be constructed in low Earth orbit on a platform or base and then moved to geosynchronous orbit by means of electric thrusters located at the four corners. During this transfer the transmitter would be rotated on its turntable so as to be in alignment with the two power collection bays. The transmitter incorporates four sub arrays (of the type shown in previous charts as being used for ground and shuttle sortie tests) at its corners. Solar blanket area is provided to energize these transmitters and to allow for degradation on the way to geosynchronous orbit. The power busbars and other parts of the full size system concept are also incorporated so as to thoroughly investigate the construction issues shown on the previous chart.

BOEING SPS

DTA General Arrangement

78-331



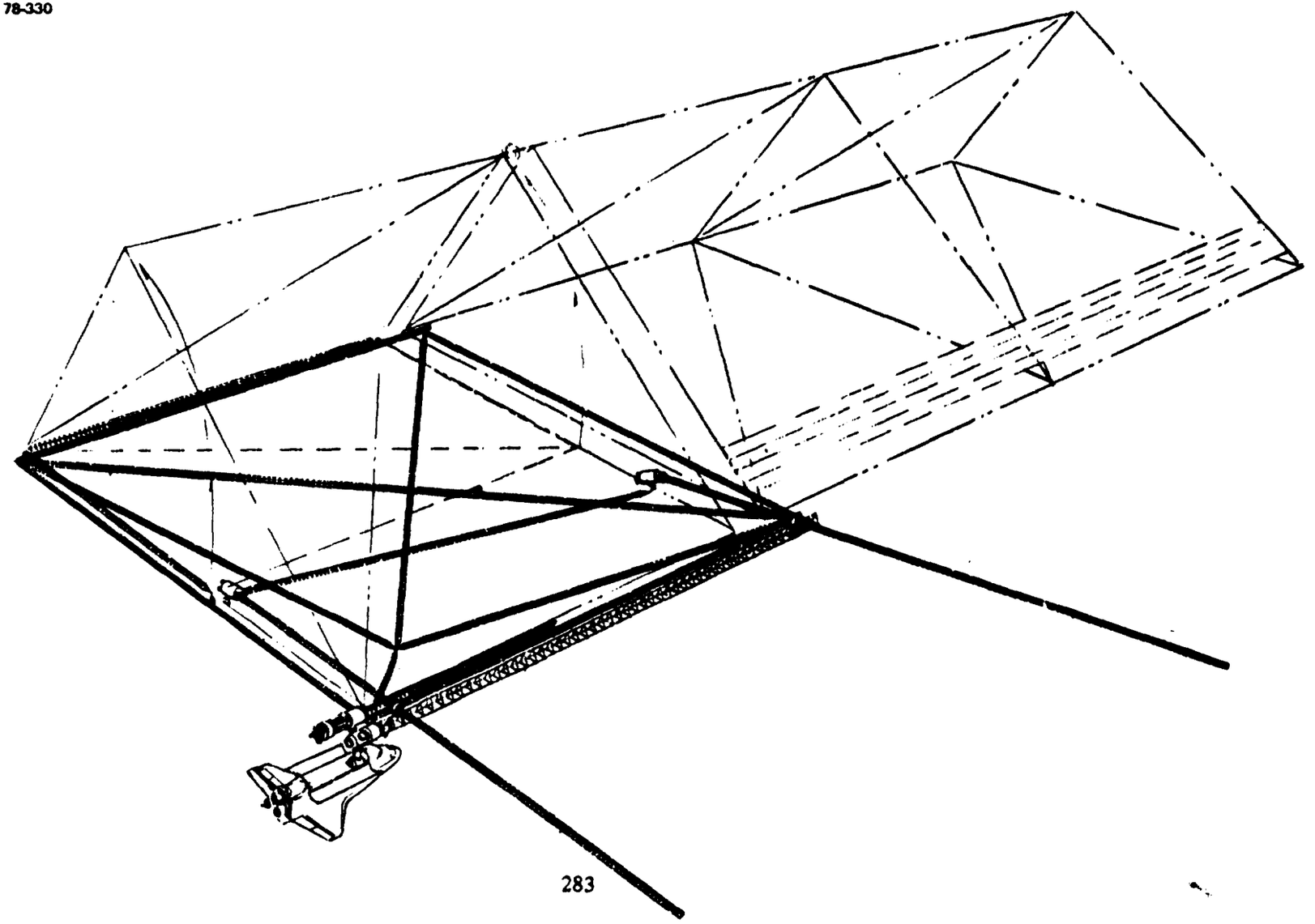
RELATION OF DTA TO ITS CONSTRUCTION PLATFORM

Shown in heavy lines is a pentrahedral construction platform for the developmental test article. It would be built by deployment and construction of materials brought to low Earth orbit by two shuttle flights. It incorporates two cranes and turrets with mobile work stations at their ends, a beam builder machine and other construction elements to allow a developmental test articles module to be built aboard the platform and then "indexed" or shifted to the side to allow construction of the next module.

BOEING SPS

Relationship Of DTA To Its Assembly Platform

78-330



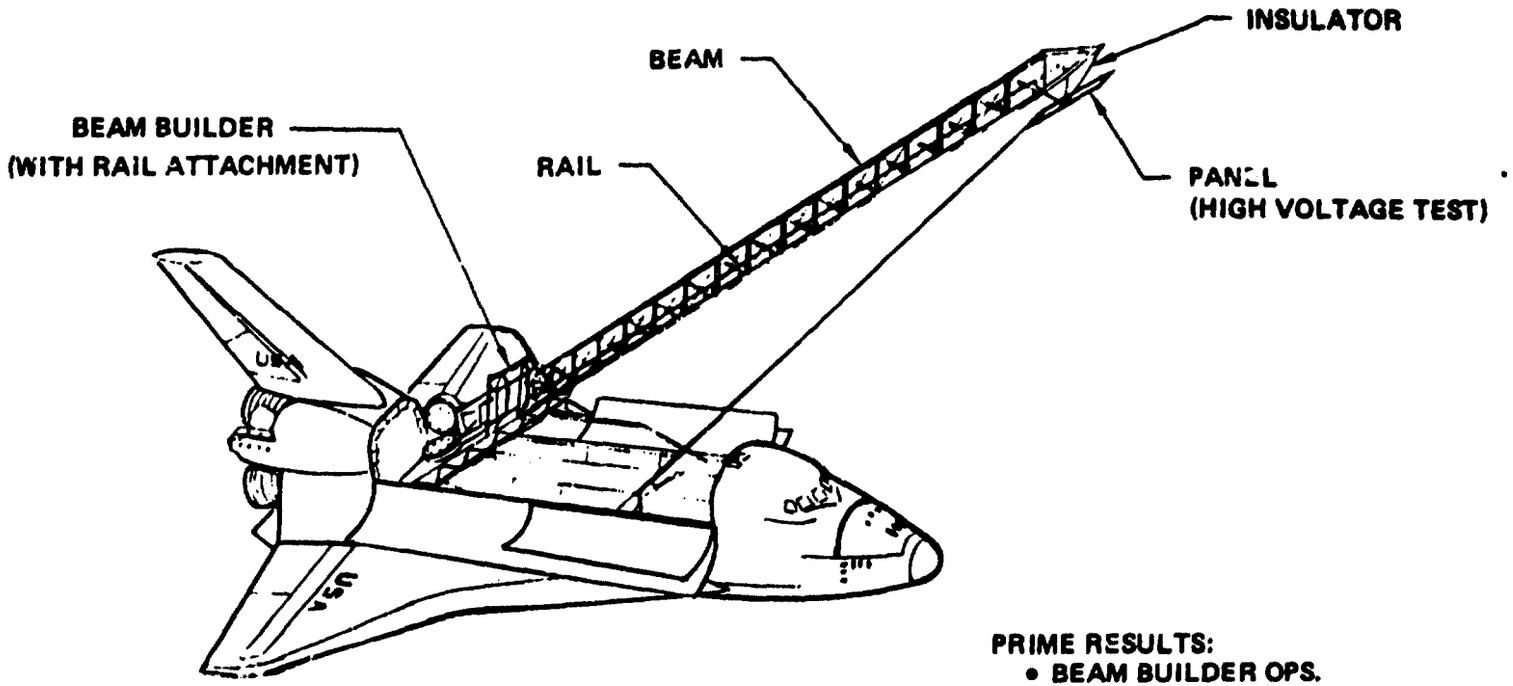
BEAM BUILDER SORTIE

This is the first of three shuttle sortie flights which preceed the developmental test article. The beam builder shown extended from the payload bay incorporates not only provisions for the construction of the triangular beam but also for the attachment of rails which, on the developmental test article construction platform, allow modules of the DTA, after construction, to be moved to the side of the construction platform.

BOEING SPS

Beam Builder Sortie

78-382



PRIME RESULTS:
- BEAM BUILDER OPS.
- RAIL ATTACHMENT
- TIMELINES

ADDITIONAL RESULTS:
- LARGE OBJECT CHARGING IN EARTH'S MAGNETIC FIELD
- BEAM DYNAMICS
- END FITTING INSTALLATION

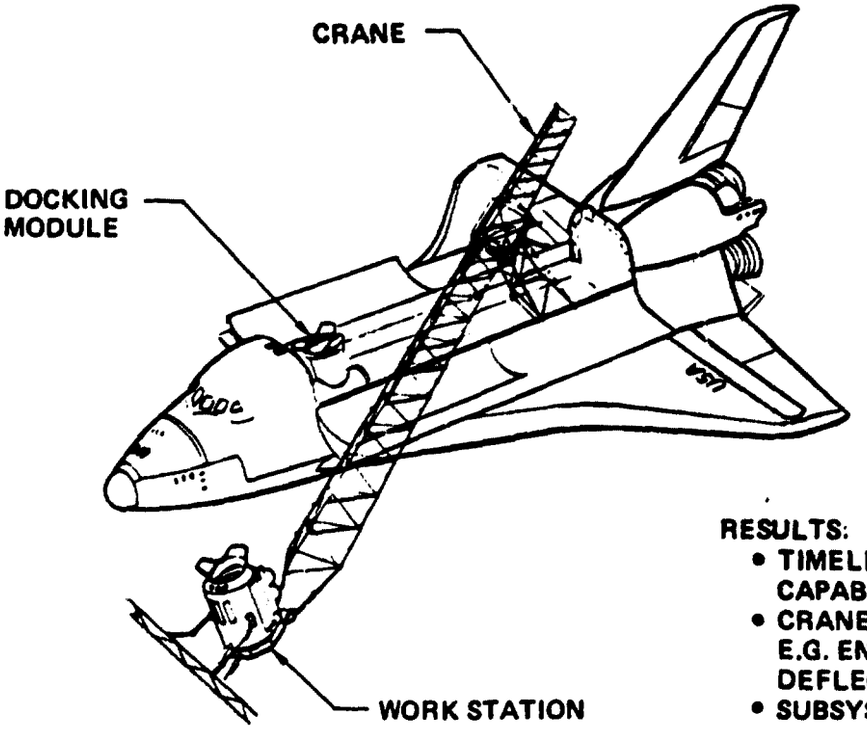
WORK STATION/CRANE SORTIES

The second shuttle sortie flight which preceeds the developmental test article will test the crane turret and a mobile work station with 1 or 2 crewmen. The work station would be varified by this test flight. That is timelines, manipulator capability, etc. would be investigated.

BOEING SPS

Work Station/Crane Sortie

78-391



RESULTS:
- TIMELINES/CREW CAPABILITY
- CRANE DYNAMICS E.G. END FORCE VS. DEFLECTION
- SUBSYSTEM PERFORMANCE

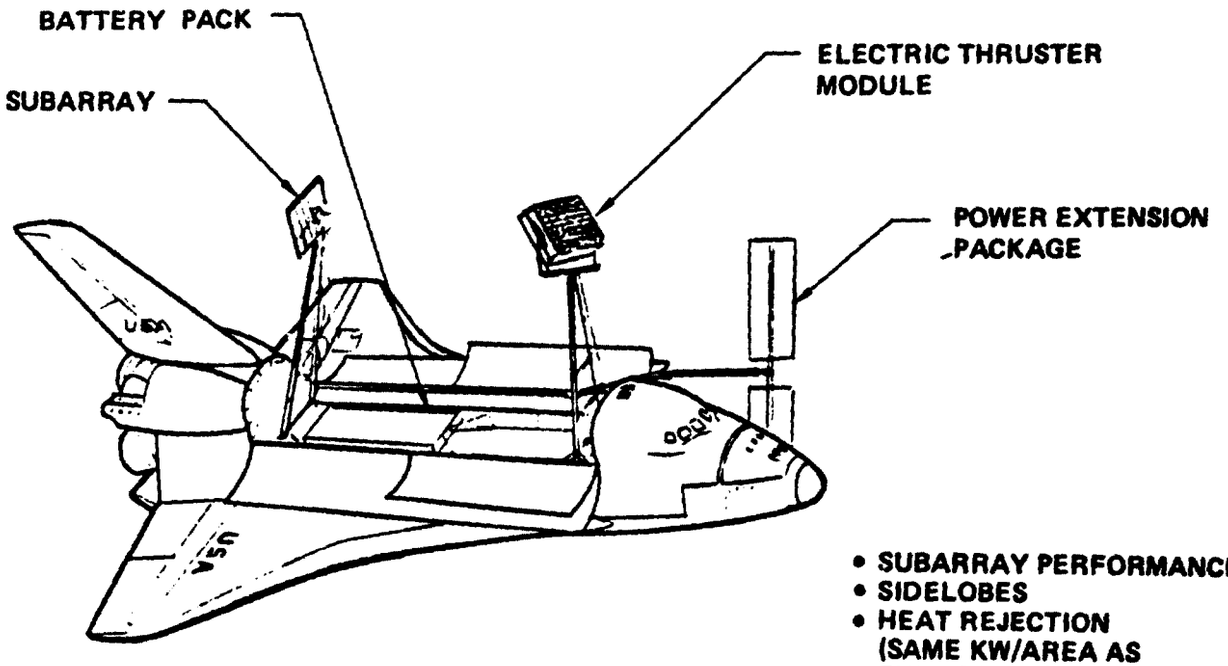
HIGH POWER ELEMENT SORTIE

On this flight either a 3.0 meter microwave transmitter subarray or an electric thruster module used to elevate the developmental test article to geosynchronous orbit would be tested. Power capability and physical arrangement of the system would allow either of these to be tested, but not simultaneously. An alternative to the use of a power extension package and battery pack, as shown, would be the use of an Orbital Service Module.

BOEING SPS

High Power Element Sortie

78-381



- SUBARRAY PERFORMANCE
- SIDELOBES
- HEAT REJECTION (SAME KW/AREA AS FULL SCALE)
  - –START-UP
- TUBE START-UP PLUME FORM
- FROM THRUSTERS

- (SUBARRAY AND THRUSTER MODULE ARE NOT SIMULTANEOUSLY ERECTED, AS SHOWN)
- ALTERNATIVE APPROACH: POWER WITH OSM.

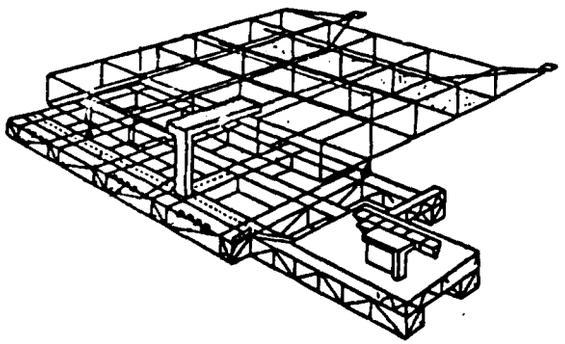
MAJOR FLIGHT PROJECTS PROOF OF CONCEPT/PRODUCTIVITY UNIT

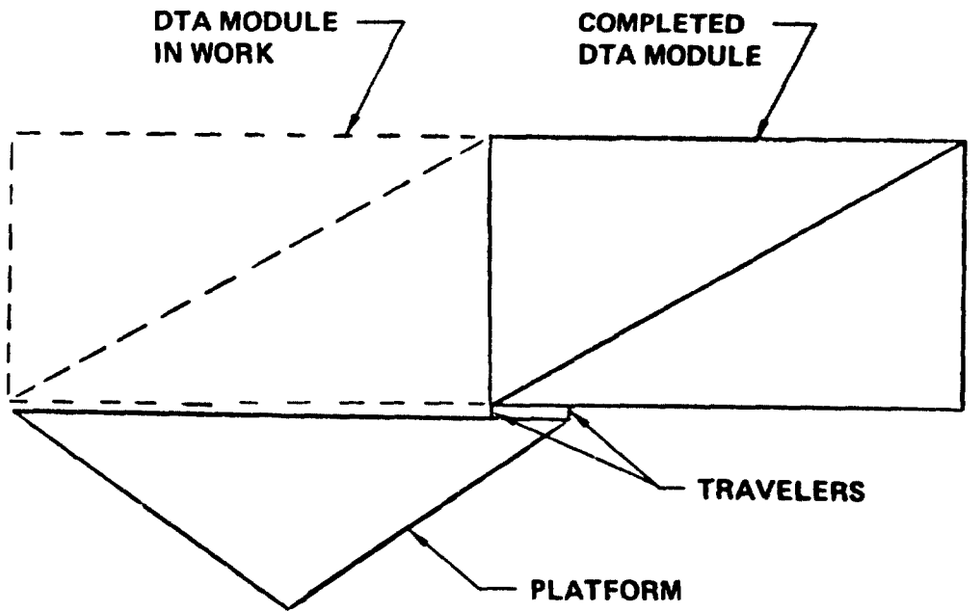
The unit shown here is essentially an enlargement of the developmental test article concept. It permits power generation bays of the "cubical" form intended for SPS to be used. It is also sufficiently large to allow a larger number of transmitter subarrays and provision of a maintenance gantry to investigate klystron changeout capability. An annealing gantry is also provided for developmental test efforts in this area. Again, outriggers and thruster units are provided to elevate this unit to geosynchronous orbit. This unit is then essentially a growth version of the developmental test article concept.

BOEING SPS

Module Indexing

78-386



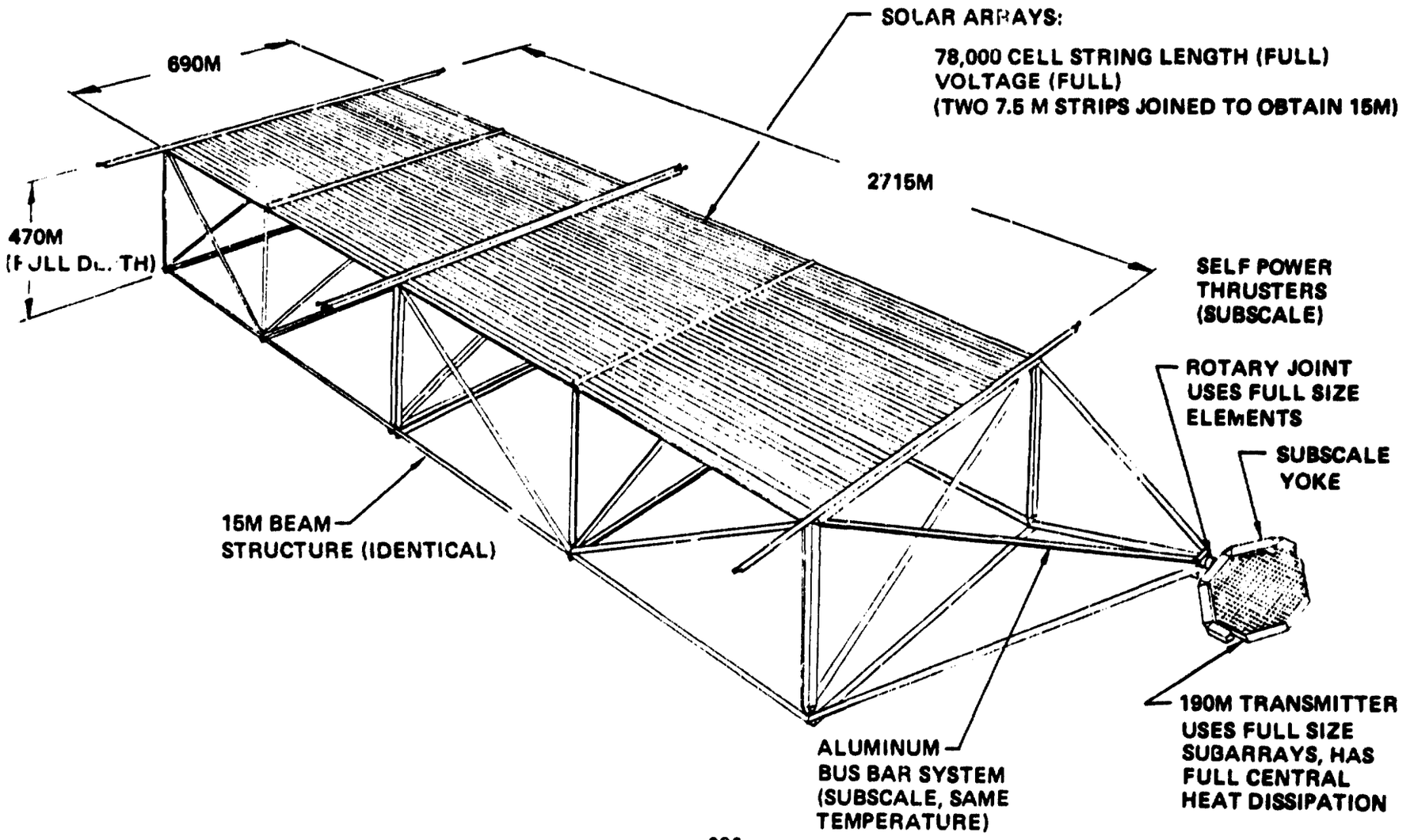


COMMERCIAL DEMONSTRATOR

This system was covered in part III of the previous JSC study. The power output level from the microwave transmitter was 185 megawatts. If approximately 10% of the project budget was involved with ground reception (rectenna) about 1 megawatt of useful power would be produced. The system is also sufficiently large to use full size SPS power generation bays, full length solar cell strings, etc.; it can be made, essentially, of full scale SPS components.

Commercial Demonstrator

SPS-1812



PRECURSORY SPS COST ESTIMATE

As shown here, the estimated cost for accomplishment of a commercial demonstrator, sized to be 1.56 percent of a full 10,000 megawatt SPS, was approximately $16.5B.

Precursor SPS Cost Estimate ("1.56%")

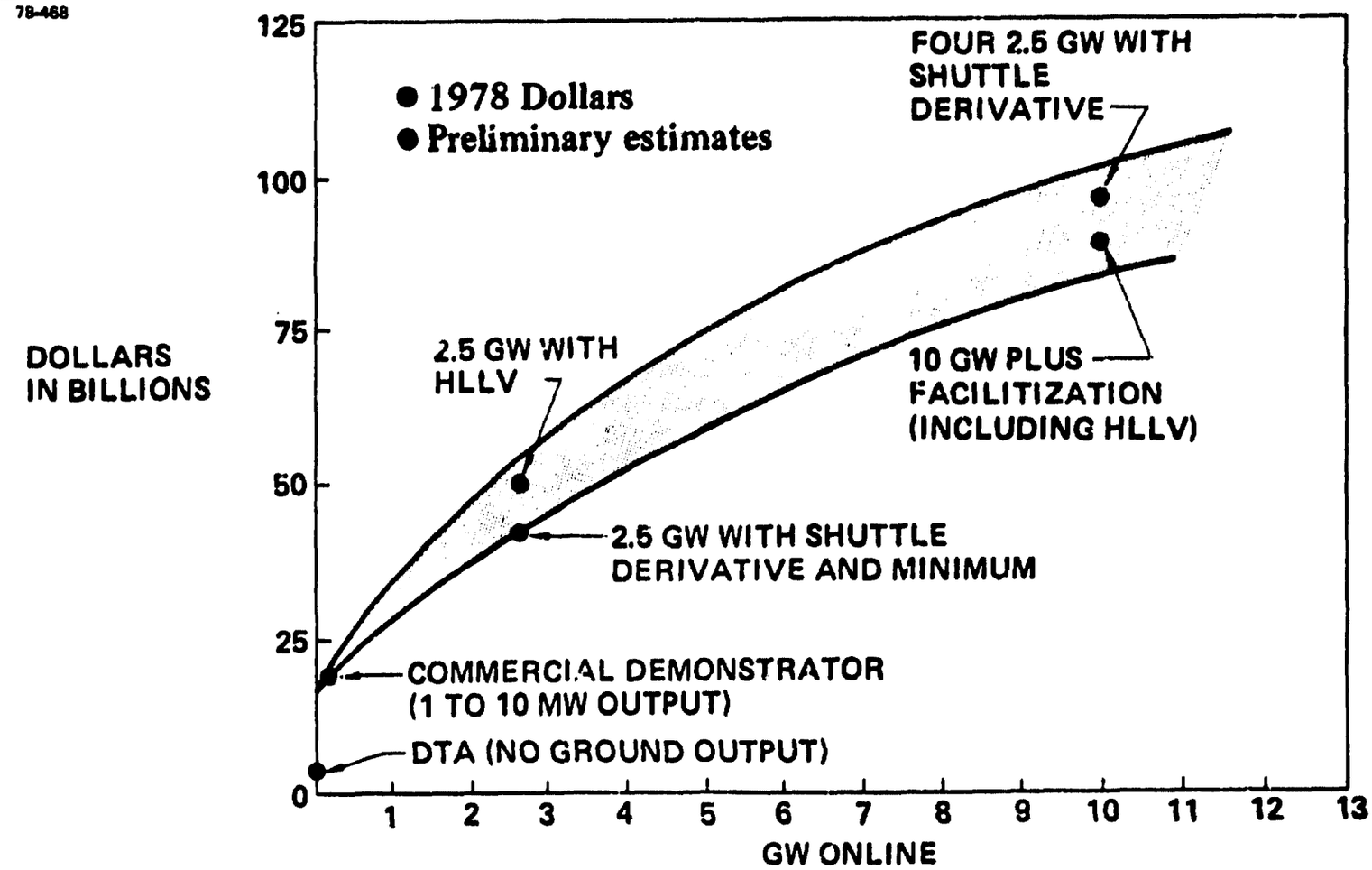
ELEMENT		$B (1977)	APPROXIMATE CONTRIBUTION TO SPS DDT&E $B (1977)
CONSTRUCTION BASE (WITH $3.0B DDT&E)		5.30	3.1
SPS DDT&E:	POWER GENERATION	0.96	0.8
	POWER TRANSMISSION	0.59	0.4
	POWER RECEPTION	0.12	0.1
SPS HARDWARE·	POWER GENERATION	0.35	
	POWER TRANSMISSION	0.25	
	STRUCTURE, MISCELLANEOUS	0.20	
SELF POWER TRANSFER (WITH DDT&E)		0.85	0.6
GSO SUPPORT STATION (WITH DDT&E)		1.20	0.4
LEO TRANSPORT (FLYBACK BOOSTER/ET/8M SHROUD/SSME CAPSULE)			
	¼ OF DDT&E	1.00	0.2
	47 FLIGHTS (9 SUPPORT GSO STATION)	0.66	
	FLEET (½ BOOSTER, ½ SSME CAPSULE)	0.80	
FACILITIES (¼ PAD, PAYLOAD HANDLING, ETC.)		0.40	
CHEMICAL OTV (40 MT CLASS, ¼ DDT&E)		0.40	0.3
CREW ROTATION (75 PERSON CARRIER)			
	DDT&E	0.15	0.15
	25 SHUTTLE LAUNCHES (OVER 3 YEARS)	0.50	
RECTENNA (ONE MEGAWATT OUT)		0.70	
SUBTOTAL		14.43	6.05
WITH 15% FOR OPERATIONS, MICSCELLANEOUS		16.57	

SPS OUTPUT VERSUS INVESTMENT

This chart is a somewhat approximate estimate of SPS and SPS percursory costs vs. power output. It shows a basic phenomena involved with microwave power transmission: essentially no useful ground power output is obtained until relatively large expenditures have taken place. The commercial demonstrator, which might have 1 to 10 megawatts of ground output, is estimated to require approximately 17 billion dollars for its accomplishment. A 2500 megawatt SPS constructed in space with shuttle derivative launch vehicles and minimum facilitization (for construction of solar cells, etc.) is estimated to cost 43 billion dollars. If a heavy lift launch vehicle is used instead, it saves some money for space transportation but requires that the heavy lift launch vehicle development cost, fleet costs, launch pads costs, etc. be expended, raising the total approximate cost to just over 50 billion dollars. A 10,000 megawatt SPS plus facilitization to produce a similar unit every year (including the heavy lift launch vehicle) has been estimated at somewhat over $90B (for 1978 dollars). If four 2500 megawatt units were built with shuttle derivatives, the expenditure would be greater, due to higher transportation cost, even though no costs for the heavy lift launch vehicle are included.

BOEING SPS

SPS Output Versus Investment



DEVELOPMENT PROGRAM PROVIDES DECISION BASIS

A schedule by which the previous developmental flight project elements could lead to a potential decision either to preceed with a large (2000 to 10,000 megawatt) SPS or to a smaller "commercial demonstrator" is shown.

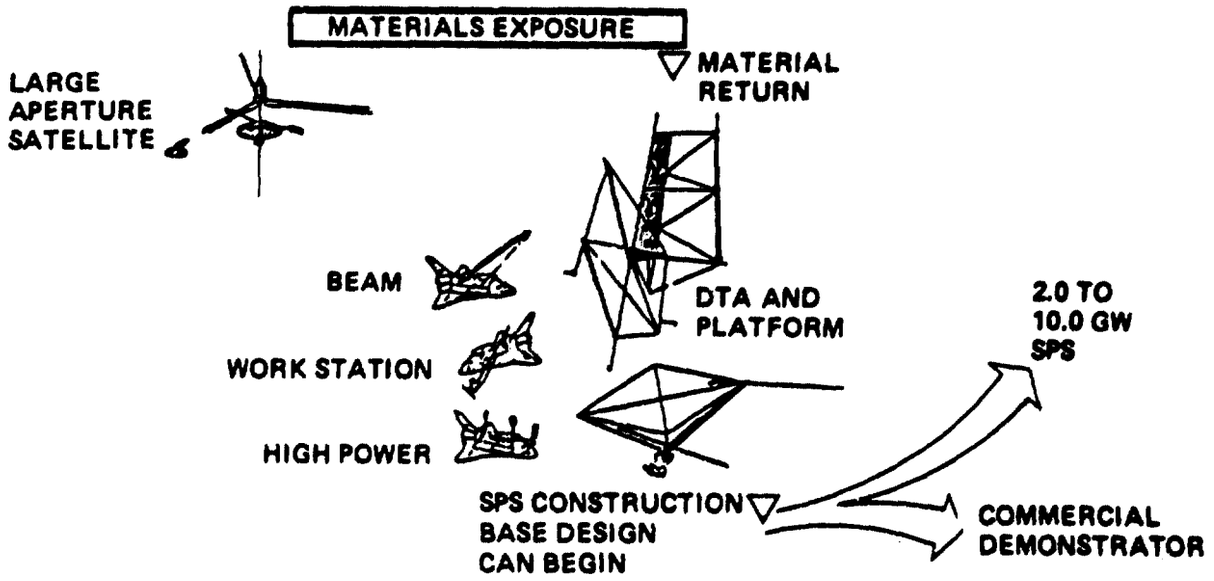
BOEING SPS

Development Program Provides Decision Basis

78-467

FY 79	FY 80	FY 81	FY 82	FY 83	FY 84	FY 85	FY 86	FY 87	FY 88
CY 79	CY 80	CY 81	CY 82	CY 83	CY 84	CY 85	CY 86	CY 87	

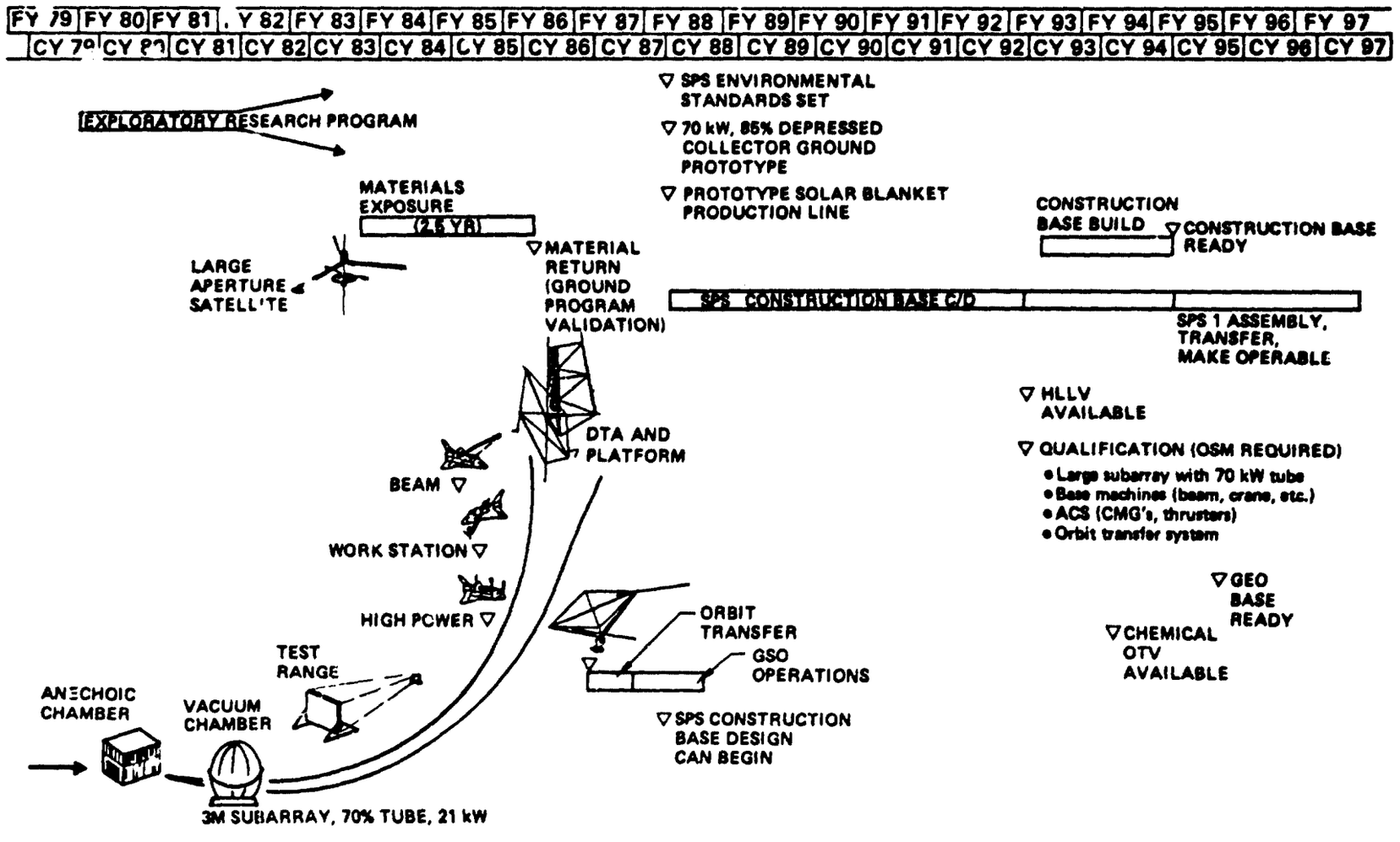
EXPLORATORY RESEARCH PROGRAM



OVERALL DEVELOPMENT PROGRAM

This charts expands on the overall developmental test program presented here. Again, it leads to a potential decision point whereafter construction base and solar power satellite phase C/D might begin. Essential for this decision point are accomplishment of the large aperture test satellite, shuttle sortie flights, developmental test article, etc. In addition, SPS environmental standards must be set. It is also recommended that a high efficiency, 70 kilowatt (full size) klystron have been successfully tested on the ground, and that a prototype of the production line intended to produce high volume, low cost cells should have been demonstrated. Near the end of the SPS and construction base phase C/D, qualification flight of actual SPS and construction base parts should take place. Two years are allowed for build up of the construction base before construction of SPS #1, transfer to geosynchronous orbit, a make-operable period, etc. Again, at the decision point shown it might be decided to proceed instead with a large commercial demonstrator or some other SPS percursor unit. However, it is felt that at the decision point the internal SPS technologist would feel that preceeding with a full size unit could take place with confidence.

BOEING SPS

Overall Development Program

78-469