BOEING

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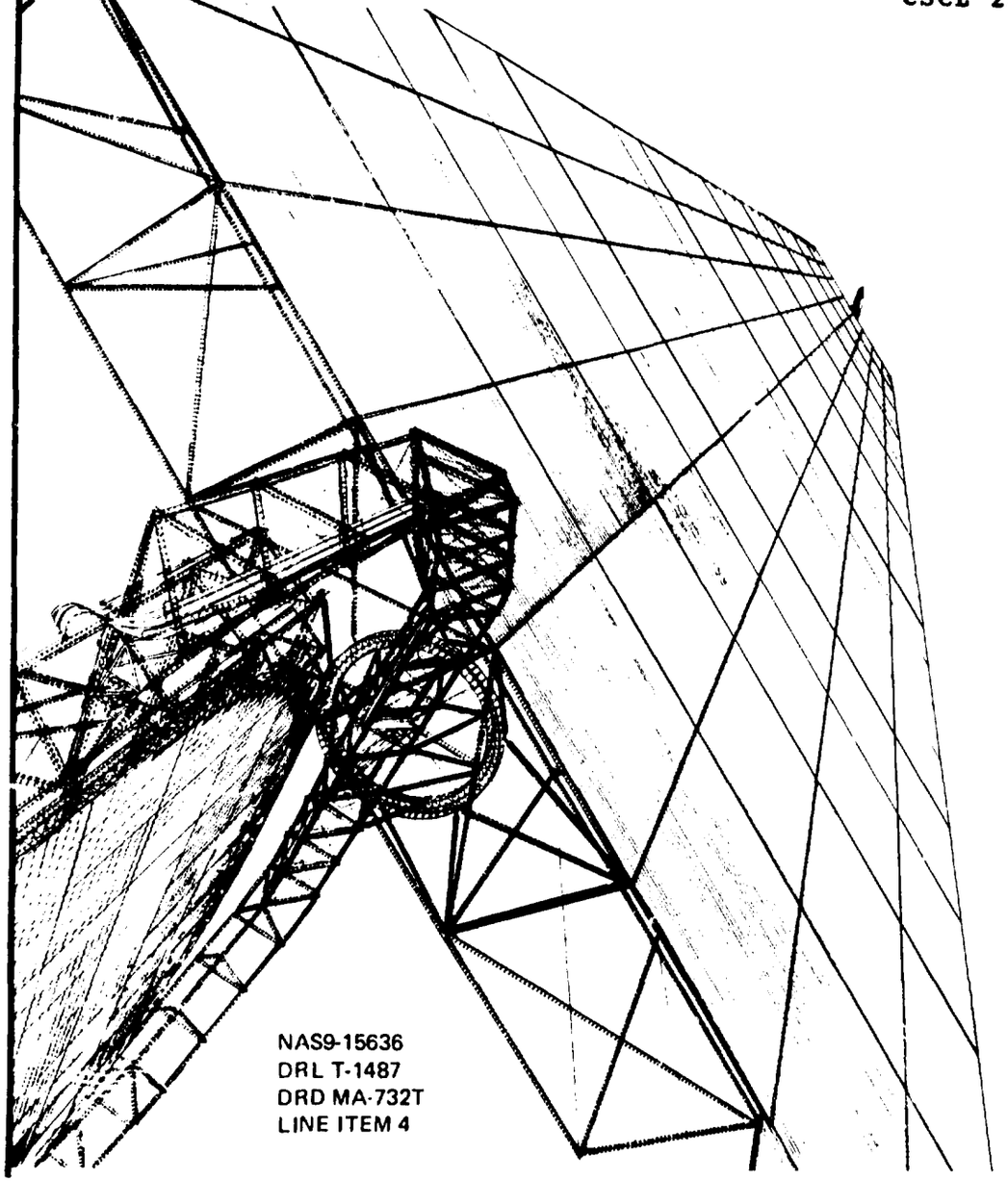

Part I,

Midterm Briefing

D180-24872-1

NASA CR-
160369

Solar Power Satellite System Definition Study

BOEING

GENERAL ELECTRIC

GRUMMAN

Arthur D Little, Inc

TRW

NAS9-15636
DRL T-1487
DRD MA-732T
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Solar Power Satellite
System Definition Study

Part I
MIDTERM BRIEFING
D180-24872-1
October 19, 1978

Approved By:

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Solar Power Satellite Systems Definition Study
Phase I Midterm Briefing
Agenda

SPS-2289

	SUBJECT	BRIEFER	TIME (MIN)
	EXECUTIVE SUMMARY	G. WOODCOCK	:30
(TASK 1)	BASELINE SYSTEMS		
	• STRUCTURE UPDATE	G. WOODCOCK	:10
	• SOLAR CELL ANNEALING	G. WOODCOCK	:10
	• MICROWAVE POWER TRANSMISSION	E. NALOS	:50
	• INDEPENDENT ELECTRIC OTV	E. DAVIS	:50
	• SPS SIZE OPTIONS	G. WOODCOCK	:10
(TASK 4)	LAUNCH AND RECOVERY OPERATIONS	G. WOODCOCK	:20
	LUNCH		
(TASK 2)	SPACE CONSTRUCTION	K. MILLER/R. McCAFFREY	:60
(TASK 1)	ALUMINUM SATELLITE STRUCTURE	R. McCAFFREY	:15
(TASK 2)	RECTENNA CONSTRUCTION	R. ANDRYCZYK	:30
(TASK 1)	RECTENNA POWER PROCESSING	R. ANDRYCZYK	:15
(TASK 5)	MISSION/SYSTEM CONTROL	R. CRISMAN	:20
(TASK 6)	RECTENNA SITING	G. WOODCOCK	:15
(TASK 7)	TECHNOLOGY ADV. PLANNING	G. WOODCOCK	:20

Executive Summary

STUDY CONTRACT TEAM ORGANIZATION

The Study Contract Team includes Boeing as prime contractor and General Electric, Grumman, Arthur D. Little, and TRW as subcontractors. Principal task areas for the subcontractors are shown and the study team leaders for each contractor are indicated.

Study Contract Team Organization (Phase I Tasks Shown)

BOEING
G. R. WOODCOCK

GENERAL ELECTRIC
R. ANDRYCZYK

- PHASE CONTROL INSTALLATION
- RECTENNA CONSTRUCTION & MAINTENANCE
- RECTENNA-GRID POWER PROCESSING

GRUMMAN
R. McCAFFREY

- SPACE CONSTRUCTION OPTIONS
- ALUMINUM STRUCTURE

A. D. LITTLE
P. CHAPMAN

- EFFECTS OF POWER BEAM ON SPACECRAFT
- INDUSTRIAL COMPLEX

TRW
R. CRISMAN

- MISSION CONTROL CONCEPTS
- SPS AVIONICS & DATA SYSTEM

SPS SYSTEM DEFINITION STUDY OBJECTIVES

The study objectives tabulated on the facing page were taken from the contract statement of work. These objectives include both the phase I and phase II activities.

SPS System Definition Study Objectives

- VERIFY, MAINTAIN, AND UPDATE THE PRESENTLY-DEFINED ELEMENTS OF THE SYSTEM
- COMPLETE THE DEFINITION OF THE TOTAL SYSTEM
- PREPARE A SERIES OF PLANS REQUIRED FOR TECHNOLOGY ADVANCEMENT AND SPS PROGRAM IMPLEMENTATION

STUDY TASKS

The statement of work includes eight major tasks as itemized on the facing page. These tasks are applicable to both phase I and phase II. The phase I effort emphasizes examination of alternatives to the present baseline whereas the phase II effort emphasizes definition of the end to end operational system.

Study Tasks

- CRITIQUE, MODIFY, MAINTAIN BASELINE SYSTEMS
- REFINE CONSTRUCTION AND MAINTENANCE APPROACHES
- DEFINE INDUSTRIAL AND TRANSPORTATION COMPLEXES
- CONDUCT LAUNCH SITE ANALYSIS
- DEFINE AND ANALYZE OPERATIONAL ACTIVITY
- ANALYZE SPS-GRID INTEGRATION
- PREPARE TECHNOLOGY ADVANCEMENT PLANS
- PERFORM COST AND SCHEDULE ANALYSES

BASELINE SYSTEM SUBTASKS

Many of the important alternative examination activities are itemized in the list of subtasks of the first major study task on the facing page. Progress in all of these activities is discussed in this briefing except for SPS avionics and data systems, and failure and diagnostics analyses. Discussion of the critique of baselines is discussed only by implication in that many of the discussions represent responses to the critique activity. The critiques were presented in monthly progress reports provided earlier and in the orientation briefing.

Baseline System Subtasks

- CRITIQUE BASELINES
- STRUCTURE OPTIONS—ALUMINUM VS GRAPHITE
- SOLAR CELL ANNEALING
- INDEPENDENT ELECTRIC OTV
- SPS SIZE EFFECTS
- SOLID STATE TRANSMITTER
- LONG-LIFE POWER PROCESSOR
- PHASE CONTROL INSTALLATION
- SPS AVIONICS AND DATA SYSTEMS
- UPDATE TRANSMITTER ARRAY ANALYSIS PROGRAM
- FAILURE AND DIAGNOSTICS ANALYSES
- RECTENNA/GRID POWER PROCESSING

ANTICIPATED BASELINE CHANGES

As a resul' of the critique activities, and analyses responsive to these critiques, it is reasonably clear that changes to the SPS and antenna structure are in order as well as changes to the bussing, rotary joint and power processing configuration. It is also expected that a change to the baseline space construction concept will be proposed although analyses of the options are not yet complete. Study of low earth orbit versus geosynchronous orbit construction with the electric orbit transfer vehicle option have not yet progressed sufficiently far to make a judgment as to whether a baseline change will be recommended. The next several charts of the Executive Summary will highlight the results of the study to this date.

Anticipated Baseline Changes

- SPS AND ANTENNA STRUCTURE
- BUSSING, ROTARY JOINT, AND POWER PROCESSING CONFIGURATION

SPS STRUCTURE

A pentahedral truss configuration has been identified as a likely improvement for both the solar array support structure and the antenna structure. The present baseline for the solar array support structure is a hexahedral truss. The pentahedral truss provides improvements in efficiency and maintains the configuration of square solar array suspension base. The present antenna baseline is an A-frame structure that provides for support of square subarrays, but has poor structural efficiency. The pentahedral truss closely approaches the structural efficiency of the earlier tetrahedral truss baseline without the complexity of hexagonal or triangular configurations; the capability to support square subarrays is maintained as for the A-frame.

We have elected not to recommend these changes at the present time because such changes would introduce significant perturbation to the evaluation of construction options, and to the comparison of aluminum solar array support structure with the baseline graphite solar array support structure. Further, since there is a relationship between the space construction approach and the structure to be fabricated, it is deemed desirable to have the result of the construction options evaluation in hand before a final decision is made regarding structural configurations.

The SPS structure concept has gone through several changes in the past three years. It is only reasonable to expect that this pattern of evolution will continue in the future.

SPS Structure

- PENTAHEDRAL TRUSS IDENTIFIED AS IMPROVEMENT
- DO NOT RECOMMEND CHANGE UNTIL PHASE II;
  CHANGE NOW WOULD IMPACT CONSTRUCTION OPTIONS EVALUATION
- STRUCTURAL DESIGN WILL CONTINUE TO EVOLVE

SOLID STATE POWER AMPLIFIER

Principal findings to date, and principal issues identified are summarized on the facing page. The solid state power amplifier configuration for a microwave power transmission transmitter seems well suited to low power SPS's. We found the potential for accomplishing definition of a suitable solid state system to be considerably more encouraging than we had expected. Certain key issues remain.

Probably primary is the concern for elimination of power processing. Solid state devices suitable for microwave power amplification operates at voltages on the order of 25 volts. Distribution voltages suitable for SPS application range from 20,000 to 40,000 volts. If it were necessary to process all this power down to a voltage of 25 volts, the cost and efficiency of power processing combined with the I^2R losses and conductor mass for such operations would be prohibitive. Therefore, an approach to elimination of power processing is mandatory. Two approaches have been identified that may prove workable. One is being explored by Rockwell based on earlier suggestions by Aerospace Corporation. This is the idea of distributing the microwave power conversion over the solar array and using a microwave waveguide system for power distribution. In this way, the need for electrical power distribution is eliminated and the solar array can supply power to local microwave generators at low voltage. This option raises serious concerns regarding the degree to which phase control precision can be maintained. The second approach is to employ a series-parallel connection of the microwave power amplifiers (as regards DC power supply) similar to that used for solar cells in generation of the DC power. Aggregate sets of microwave power generators can then be supplied at comparatively high distribution voltages. This option raises concerns regarding stability, matching, and balance of the power supply and control network.

Secondly, experimental verification of acceptable efficiencies for integrated assemblies of amplifier devices, coupling circuits, and RF radiators is needed.

Finally, there is the issue of device cost. Gallium arsenide FET's today cost on the order of $100 per watt. This is obviously prohibitive. A production rate curve extrapolation to quantities appropriate to SPS leads to cost predictions in the acceptable range. These, however, will require further confirmation through experience in larger scale production.

Solid State Power Amplifier

FINDINGS

- IDENTIFIED A PRACTICAL ELEMENT/SUBARRAY DESIGN APPROACH
- SOLID STATE TRANSMITTER IS A MASS/AREA SYSTEM RATHER THAN A MASS/POWER SYSTEM
- GaAs FET'S HAVE ADEQUATE PERFORMANCE—80% EFFICIENCY IS A REASONABLE EXPECTATION
- EFFICIENCY AND THERMAL CAPABILITY YIELD A MAXIMUM TRANSMITTER RATING OF ROUGHLY 2.5 GW GROUND OUTPUT AT 1.4 km DIA.
- EXPECT SIGNIFICANT RELIABILITY ADVANTAGE

ISSUES

- ELIMINATION OF POWER PROCESSING
- EXPERIMENTAL MEASUREMENT OF INTEGRATED DEVICE/CIRCUIT/RADIATOR PERFORMANCE: EFFICIENCY, GAIN, NOISE, HARMONICS
- DEVICE COST (NOW ≈ $100/WATT IN LOTS OF 100)

LONG LIFE POWER PROCESSOR ANALYSIS

The power processor design resulting from previous study was judged to be inadequate with regards to life. Further analysis has identified the three options indicated on the facing page. Based on mass considerations, option three is recommended for incorporation into the baseline.

Long-Life Power Processor Analysis

- **PROBLEM**

  POWER TRANSFORMER LIFE IS INVERSELY PROPORTIONAL TO THE OPERATING FREQUENCY. PART II MASS OPTIMIZED SWITCHING FREQUENCY WAS 20 KHZ.

- **RESULTS OF ANALYSIS**
  - OPTION 1: REDUCE SWITCHING FREQUENCY
    MASS PENALTY = +59% @ 1 KHZ
  - OPTION 2: DERATE DIELECTRIC MATERIAL
    MASS PENALTY = +17% @ 20KHZ
  - OPTION 3: USE LIQUID (FREON) COOLED TRANSFORMER*
    MASS PENALTY = −63% @ 10 KHZ

*PROTOTYPE TRANSFORMER BUILT FOR USAF AERO PROPULSION LAB

INDEPENDENT ELECTRIC ORBIT TRANSFER VEHICLE

Analysis of the potential transportation cost for a space transportation system incorporating an independent electric orbit transfer vehicle with construction of SPS's at geosynchronous orbit has indicated more favorable cost characteristics than expected. Although the independent electric OTV requires solar arrays and support systems to be dedicated to the transportation purpose rather than simply temporarily used for that purpose (as in the case of self-power) there is a compensating effect not identified in earlier studies. That is, that the size of the independent electric OTV is such that inertia balance is not important and gravity gradient losses are minimal. By comparison these losses are more significant for the larger self-power configurations. On balance the preliminary costs are comparable. These preliminary estimates have not yet been subjected to detailed cost estimating for the independent electric OTV.

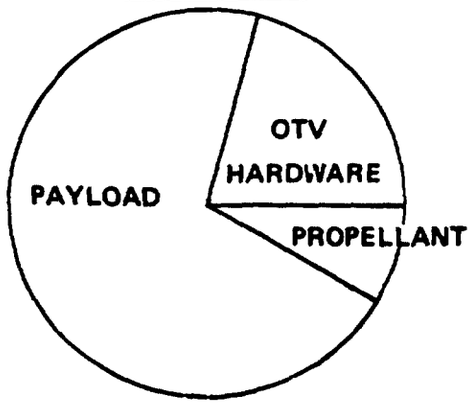
Cost-optimized performance data are indicated. The optimization is not sensitive as indicated by the two pie charts showing that OTV hardware and hardware cost are not a particularly large contribution to total mass or cost.

Thruster beam current per unit area was identified as a potential difference between Boeing and Rockwell study results. Our continuing analyses of thruster performance have indicated the beam current values that we have used are generally within the expected range. Further the thruster beam current does not seem to be a high leverage parameter. Thruster mass is less than 10% of the OTV hardware mass even with this possibly conservative current estimate. Differences in optimization results between our system and the Rockwell system appear to arise from Rockwell's mass optimization versus our cost optimization. Finally, it is observed that because of the relatively large radiation doses received during low thrust transfers through the Van Allen belts, repetitive annealing of solar cells is critical for the silicon independent electric OTV.

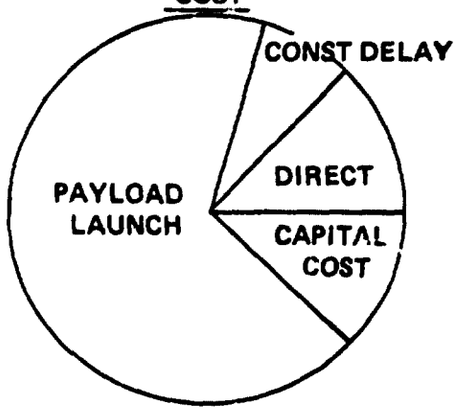
Independent Electric OTV

- PRELIMINARY COSTS COMPARABLE TO SELF-POWER; SEVERAL UNCERTAINTIES REMAIN
- COST-OPTIMIZED I_{SP} 8000 SEC, TRIP TIME 180 DAYS
- OPTIMIZATION IS NOT SENSITIVE
- INERTIA BALANCING NOT IMPORTANT
- THRUSTER BEAM CURRENT CONFIRMED AT ≈ 100 AMPS/120 CM; NOT A HIGH-LEVERAGE PARAMETER
- REPETITIVE ANNEALING CRITICAL FOR SILICON IEOTV

START MASS



COST



SPACE CONSTRUCTION

In response to the statement of work, four alternatives to the earlier baseline have been identified and are being analyzed. Of these, the single-deck and end-builder options appear most promising. Both offer significant advantages over the earlier C-clamp baseline and when a selection is made the construction base mass and cost will be reduced compared to the earlier baseline.

Space Construction

- FOUR ALTERNATIVES TO THE "C-CLAMP" IDENTIFIED AND UNDER ANALYSIS
  - SINGLE-DECK
  - END-BUILDER

    } MOST PROMISING
  - INTERNAL
  - BOOTSTRAP

- SELECTION WILL REDUCE CONSTRUCTION BASE MASS AND COST RELATIVE TO EARLIER "C-CLAMP" BASELINE

LAUNCH SITE SELECTION

The launch site analysis task was motivated by the premise that selection of a low-latitude site would offer significant cost advantages with respect to operations from the Kennedy Space Center, where earth-to-low-orbit space transportation arrives at a 30° inclination orbit. With a 30° inclination orbit for staging or construction operations, a 30° plane change is required to reach a geosynchronous equatorial orbit. It was presumed that this plane change would incur significant performance penalties relative to a zero-degree or low-inclination low earth orbit. However, with electric propulsion this performance difference in terms of cost is minimal. Therefore, the principal motivation for leaving KSC for a remote site will stem from the eventuality of SPS operations outgrowing KSC. Our estimates to date indicate that KSC can handle approximately 10 gigawatts per year of SPS construction.

Remote site options include land-based sites such as the mouth of the Amazon in Brazil and ocean-based sites employing large floating structures such as the western Pacific low latitude sites identified by Jim Akkerman in studies at the Johnson Space Center. Large uncertainties presently exist as to the cost of large floating structures. The two orders of magnitude range is indicated on the facing page.

Launch Site Selection

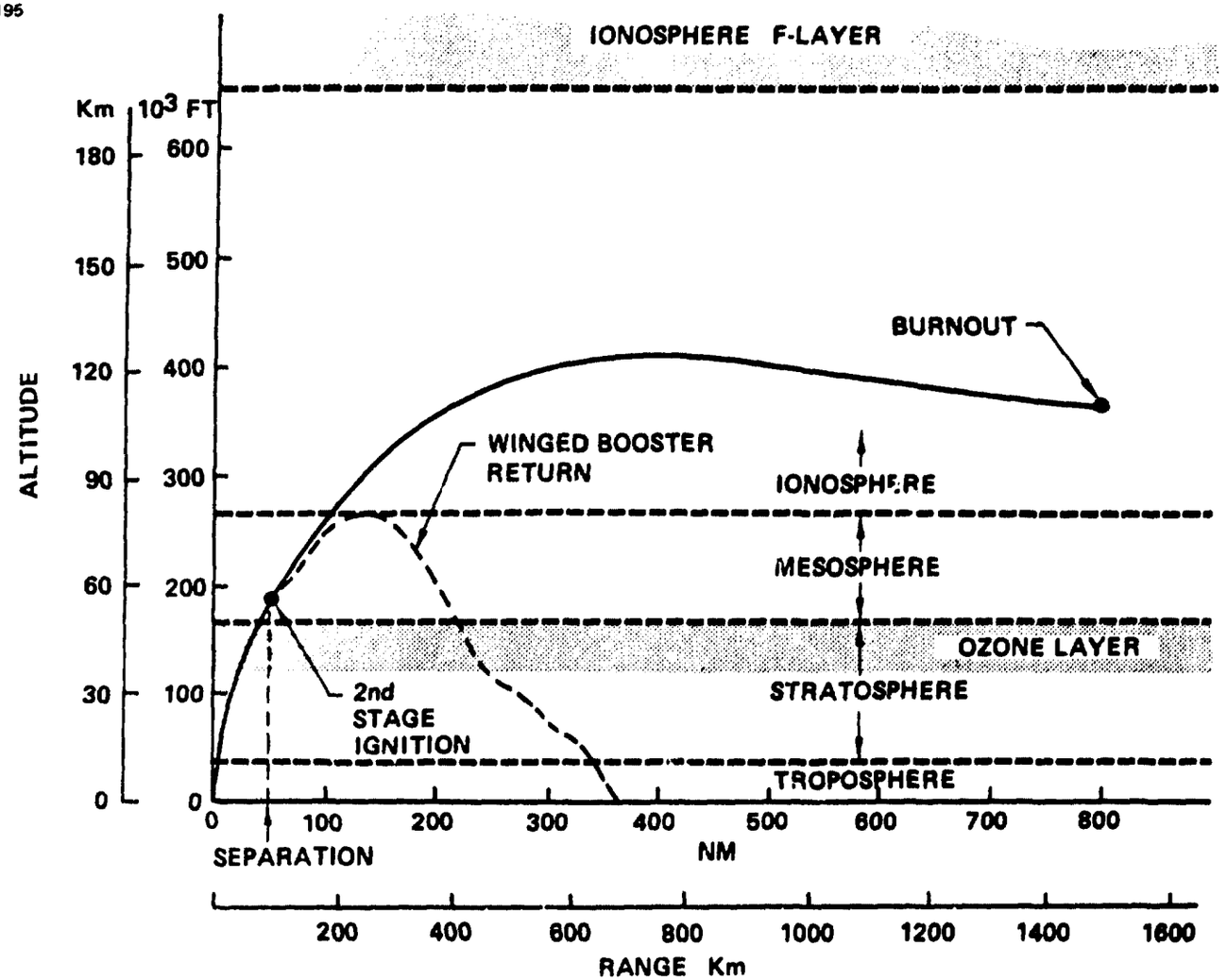
- PERFORMANCE ADVANTAGE FOR LOW LATITUDE IS SMALL (<10%) FOR ELECTRIC PROPULSION
- PRINCIPAL MOTIVATION FOR REMOTE SITE WILL OCCUR IF SPS OPERATIONS OUTGROW KSC
- KSC APPEARS SUITED FOR ABOUT 10GW/YEAR
- OCEAN SITE POTENTIALLY ATTRACTIVE DEPENDING ON COST OF LARGE FLOATING STRUCTURES
  - AIRCRAFT CARRIERS ~ $50 000/M^2
  - DRYDOCKS & BARGES ~ $5 000/M^2
  - CONCRETE FLOATS < $500/M^2 (HOUSEBOATS)

REFERENCE HLLV LAUNCH TRAJECTORY

One of the environmental issues raised with respect to SPS operations is the possibility of influences on the upper atmosphere from launch operations. This figure shows the relationship of the current baseline trajectory to the key regions of the upper atmosphere.

Reference HLLV Launch Trajectory

SPS-2195



ROCKET PLUME EFFECTS

CONCLUSIONS

One of the tasks assigned to Boeing was the investigation of trajectory modifications that could reduce potential effects on the upper atmosphere. An earlier Los Alamos Scientific Laboratory (LASL) study had assumed that the HLLV's would fly directly into the ionosphere F-layer (they won't, see previous chart) and predicted nearly complete depletion of the F-layer. Under IR&D, Boeing performed a preliminary analysis of upper atmosphere effects to try to develop recommendations for trajectory shaping. Conclusions from that effort are reported on the facing page. A complete report of that effort is being prepared for release under separate cover.

Rocket Plume Effects Conclusions

- IONOSPHERE PROBLEM IS ≈ FACTOR OF 5 LESS THAN LASL PAPER, STILL A PROBLEM

- OZONE LAYER DOESN'T APPEAR TO BE A PROBLEM

- IONOSPHERE PROBLEM IS MAINLY UPWARD MOLECULAR DIFFUSION OF H_2
  - INCREASE MIXTURE RATIO?
  - TRY TO KEEP TRAJECTORY BELOW 100 km

- CONTINUED ANALYSIS OF PLUME EFFECTS SHOULD TREAT *ALL UPPER ATMOSPHERE AS AN INTEGRATED ENTITY*

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

TECHNOLOGY ADVANCEMENT PLANNING

Substantial emphasis has been placed on technology advancement planning in phase I of the present study. A detailed plan has been developed covering the ten areas indicated on the facing page. This detailed plan in most cases includes multiple paths such as indicated. The plan is being developed with the aid of automated network, scheduling, cost, and resource analysis. The overall plan is presently being reviewed with JSC and a series of updates is contemplated. Present indications are that all high priority technology advancement objectives can be achieved by 1985 with an average funding level of $25 million per year beginning in fiscal 1981.

Technology Advancement Planning

DETAILED PLAN COVERS TEN AREAS

- PHOTOVOLTAICS
- THERMAL SYSTEMS
- POWER TRANSMISSION
- SPACE STRUCTURES
- MATERIALS & PROCESSES
- FLIGHT CONTROLS
- SPACE CONSTRUCTION
- SPACE TRANSPORTATION
- POWER DISTRIBUTION
- SPACE ENVIRONMENT EFFECTS

MULTIPLE PATHS IN MOST AREAS, e.g.,

SILICON
GALLIUM ARSENIDE → SELECT
OTHER

BASELINE TREND

No dramatic changes in the baseline mass or cost are presently anticipated. A number of small changes have been identified. These will lead to increases in structure mass and cost and a very slight increase in solar array unit mass and cost. Improvements in the RF link efficiency resulting from adoption of the LinCom baseline of phase control distribution to the klystron amplifier level will improve slightly the RF link efficiency and thus reduce actual solar array area. Other changes identified also indicate slight reductions in mass and cost. The net effect is expected to be an overall slight reduction. Finally, the investigations of solid state systems and lower power SPS's indicate that a baseline option of a 2,500 megawatt solid state power transmitter SPS should be considered.

Baseline Trends

	MASS	COST
STRUCTURE	+	+
SOLAR ARRAY	+	+
POWER DISTRIBUTION & PROCESSING	–	–
RF LINK EFFICIENCY	–	–
RECTENNA	0	–
SPACE TRANSPORTATION	–	–
SPACE CONSTRUCTION	–	–

- NET EFFECT IS EXPECTATION OF SLIGHT REDUCTION IN MASS AND COST
- BASELINE OPTION OF 2500 Mw, SOLID STATE MPTS SHOULD BE CONSIDERED

Structure Update

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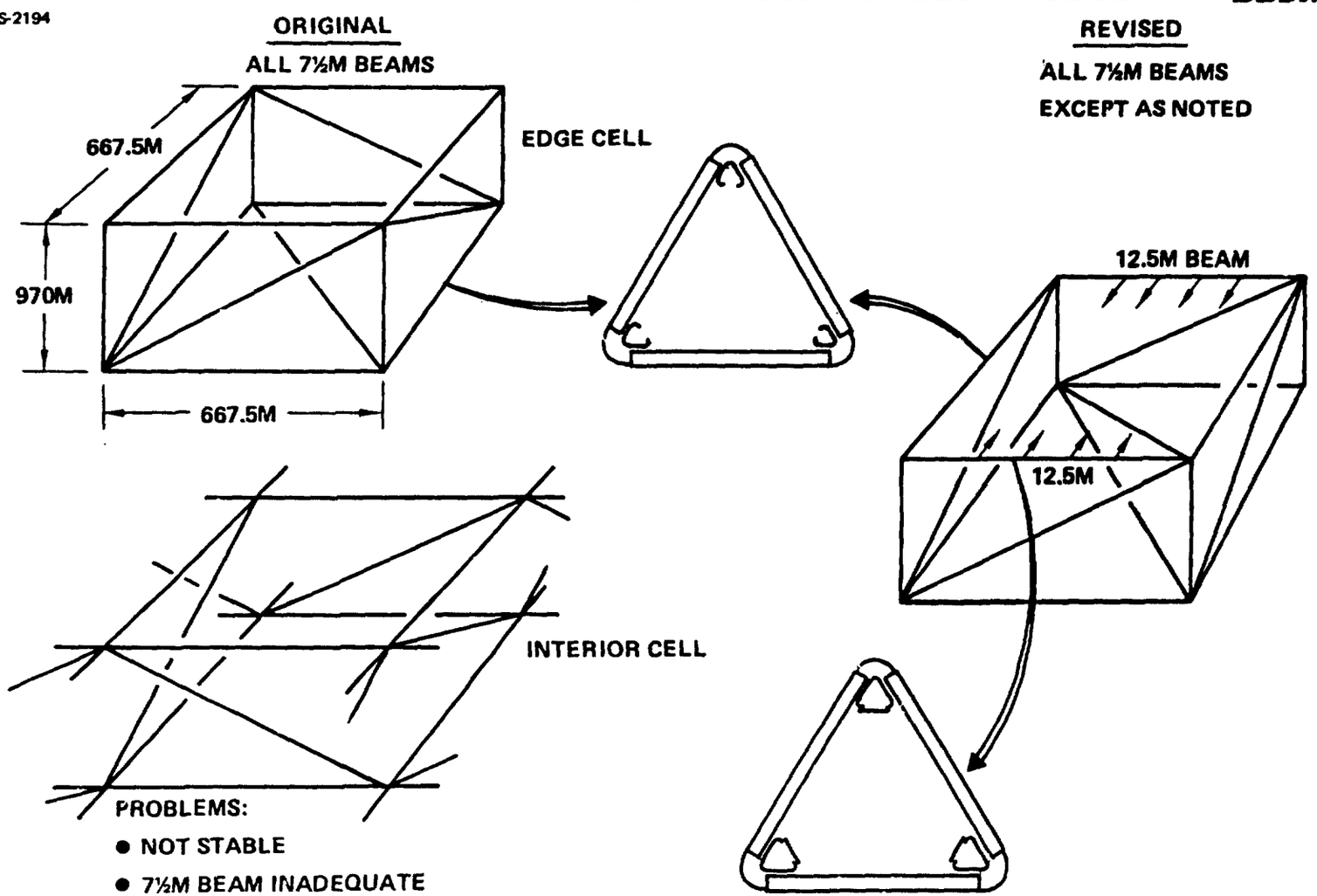
SOLAR ARRAY SUPPORT STRUCTURE EVOLUTION

Illustrated here are the original and revised baseline hexahedral solar array support structure concepts. In the original system the edge cells of each of the eight modules making up the entire SPS used the configuration illustrated. The interior cells employed an absolute minimum of structure. Further analysis indicated that the edge cells were not stable with the result that the entire system was not stable. Further, the 7½ meter beams were not adequate for solar blanket tension when the solar blanket tension was changed to uniaxial. As a result, the system was revised to the configuration indicated with 12½ meter beams for solar blanket tension support and all cells incorporating the structural concept shown. The lower-deck-to-upper-deck diagonal provides structural stability.

Solar Array Support Structure Evolution

SPS-2194



PROBLEMS:

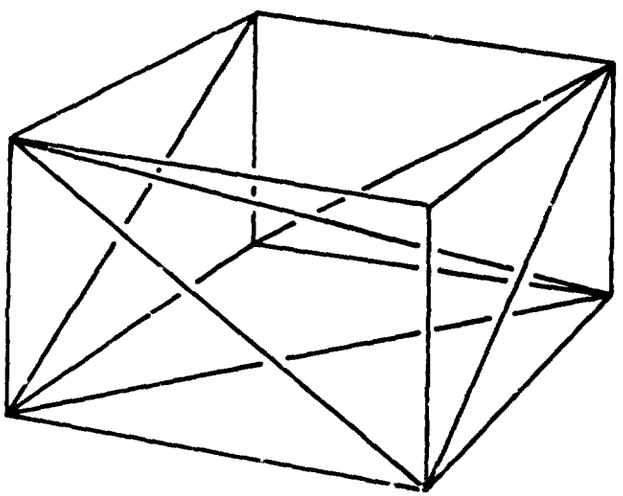
- NOT STABLE
- 7½M BEAM INADEQUATE FOR SOLAR BLANKET TENSION

BAY CONFIGURATION SOLAR COLLECTOR PRIMARY STRUCTURE

As the baseline system has become more complicated the motivation to change to a new structural approach has increased. This figure illustrates the relative simplicity of the pentahedral truss structure compared to the current hexahedral baseline.

Bay Configuration: Solar Collector Primary Structure

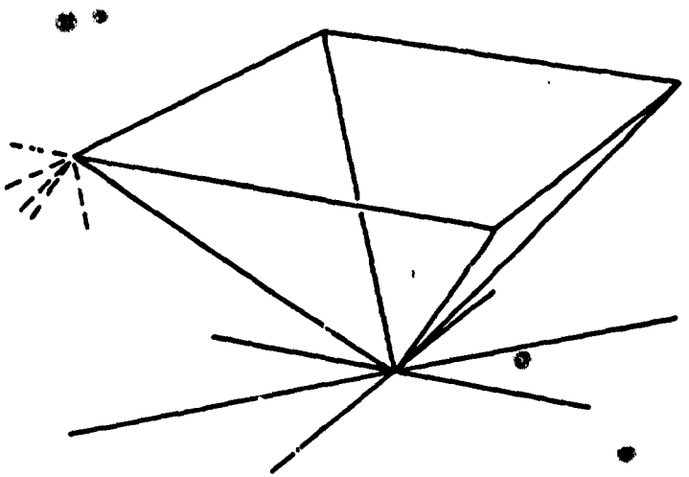
HEXAHEDRAL BRACING
(BASELINE)



PER MODULE: SECONDARY STRUCTURE

JOINTS	90
JOINT CONFIG.	18
MEMBERS	216

PENTAHEDRAL BRACING



PER MODULE: SECONDARY STRUCTURE

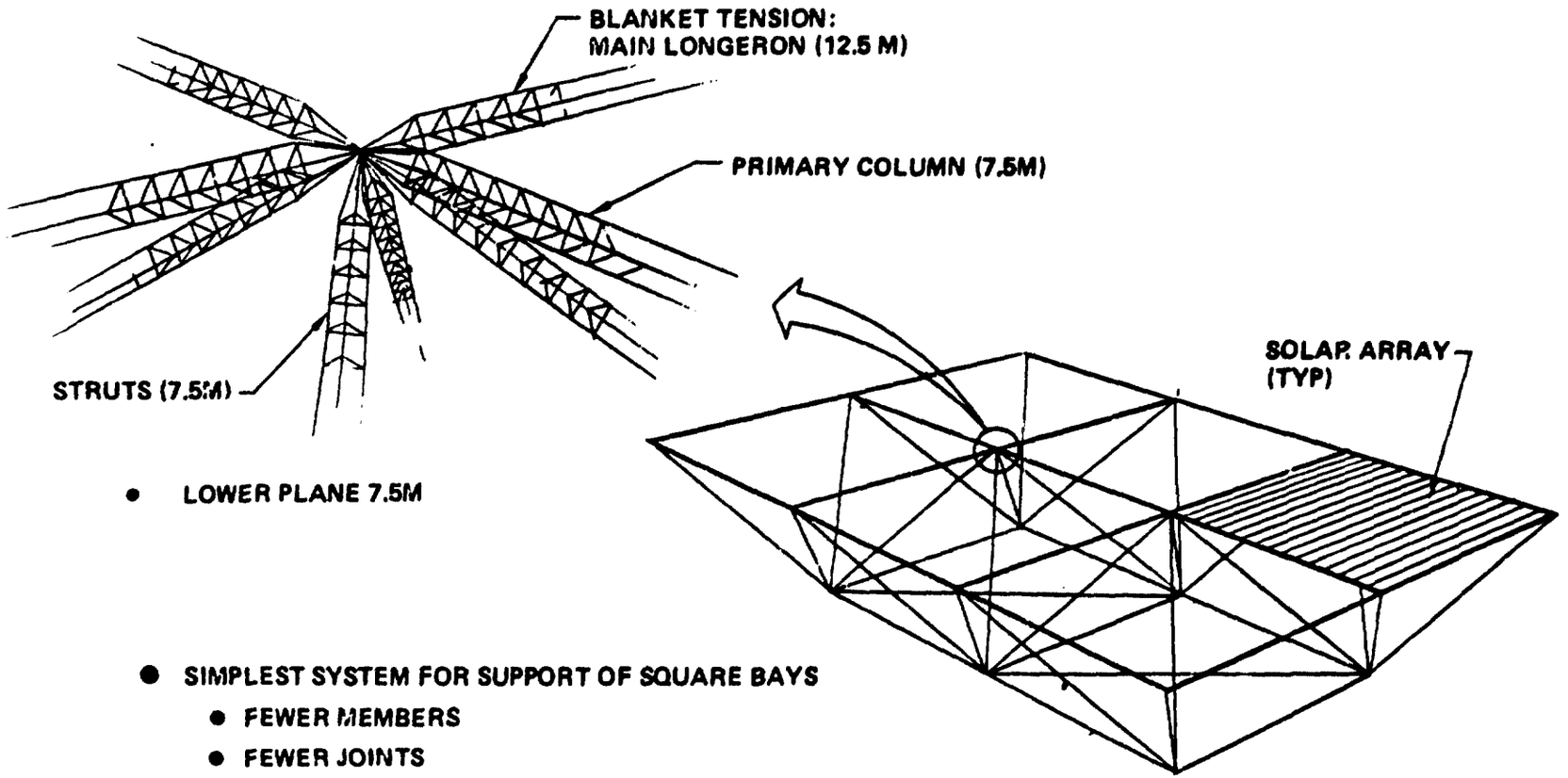
JOINTS	79
JOINT CONFIG.	8
MEMBERS	205

PENTAHEDRAL TRUSS PRIMARY STRUCTURE OPTION

Illustrated here is the pentahedral truss concept for solar array support. We anticipate that this structural approach will be recommended as a baseline change at the completion of the current phase of study.

Pentahedral Truss
Primary Structure Option

SPS-2258



- LOWER PLANE 7.5M

- SIMPLEST SYSTEM FOR SUPPORT OF SQUARE BAYS
  - FEWER MEMBERS
  - FEWER JOINTS
  - LIGHTER
  - BETTER ACCESS FOR SERVICING

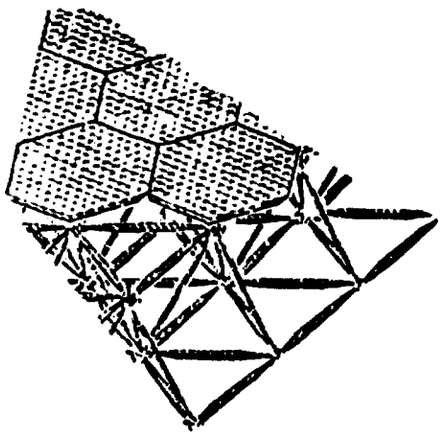
ANTENNA STRUCTURE OPTIONS

Early investigations of the SPS microwave power transmission systems antenna structure developed the tetrahedral truss primary and secondary structure concept. This system represents a maximum of structural efficiency for such an antenna. However, it constrains the subarrays to a non-square system and presented certain difficulties with respect to maintenance access.

The center illustration in the facing page represents the antenna structure as visualized by the maintenance engineer. It provides easy access to subarray repair or replacement and allows square subarrays but structurally is not very efficient and employs tension members. The use of tension members results in dubious dynamic qualities for the structure. Further, the secondary structure is required to provide stability of the primary structure. Analysis of this combination indicated a relatively poor stiffness efficiency.

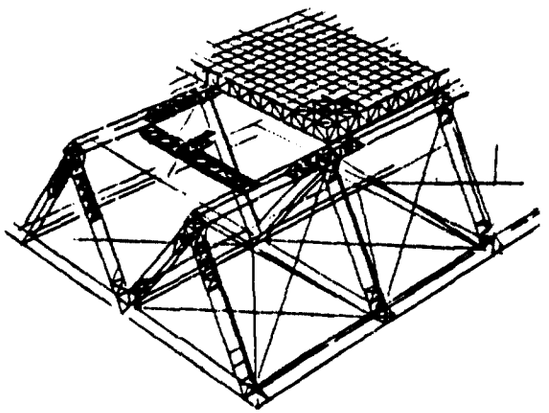
Here again, the pentahedral truss appears to offer a way out. It maintains good access with good efficiency, eliminates tension members and allows square subarrays. A potential interference problem has been identified with respect to the operation of the maintenance gantry and the existence of cross beam members for the primary pentahedral truss structure. This is better illustrated on the next figure.

Antenna Structure Options



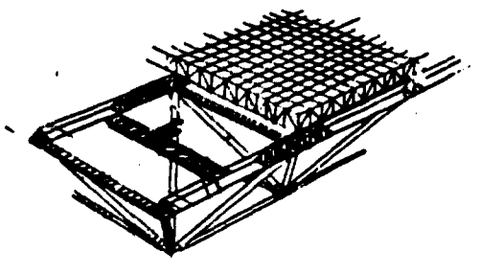
TETRAHEDRAL TRUSS

- MAXIMUM EFFICIENCY
- NO TENSION MEMBERS
- NON-SQUARE SUBARRAYS
- MAINTENANCE ACCESS DIFFICULT



A-FRAME

- GOOD ACCESS
- SQUARE SUBARRAYS
- POOR EFFICIENCY
- USES TENSION MEMBERS
- SECONDARY STRUCTURE IS PART OF PRIMARY STRUCTURE



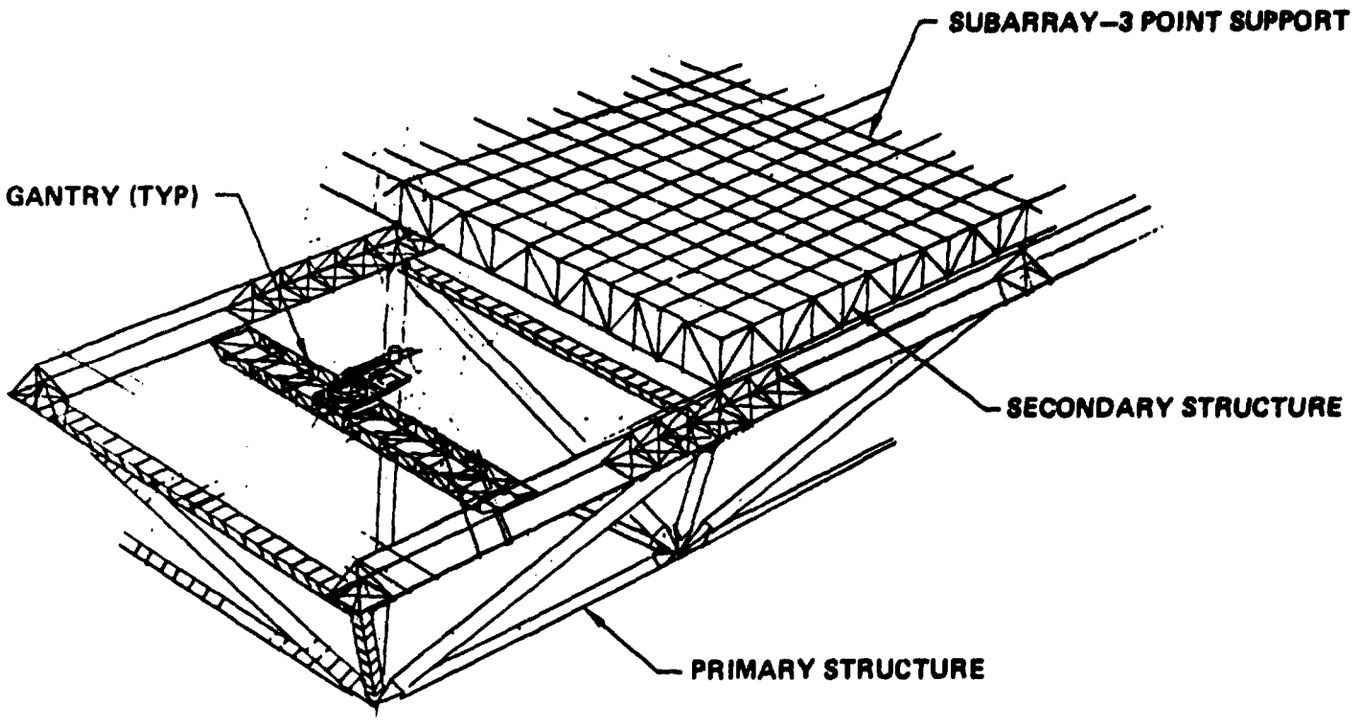
PENTAHEDRAL TRUSS

- GOOD ACCESS
- GOOD EFFICIENCY
- NO TENSION MEMBERS
- SQUARE SUBARRAYS

PENTAHEDRAL MPTS STRUCTURE

The pentahedral structure is shown in more detail here. Simplification of the secondary structure appears in order. The upper cross-braces in the primary structure create an interference with operation of the maintenance gantry. Further investigation is expected to find a way to eliminate this interference.

Pentahedral MPTS Structure



- CROSSBEAMS ON FACE OF PENTAHEDRAL STRUCTURE ELIMINATE USE OF SECONDARY STRUCTURE AS PRIMARY LOAD PATH.

SPS STRUCTURE

The facing page adopted from the Executive Summary summarizes the results of structure options investigations to date.

SPS Structure

- PENTAHEDRAL TRUSS IDENTIFIED AS IMPROVEMENT
- DO NOT RECOMMEND CHANGE UNTIL PHASE II;
  CHANGE NOW WOULD IMPACT CONSTRUCTION OPTIONS EVALUATION
- STRUCTURAL DESIGN WILL CONTINUE TO EVOLVE

Laser Annealing

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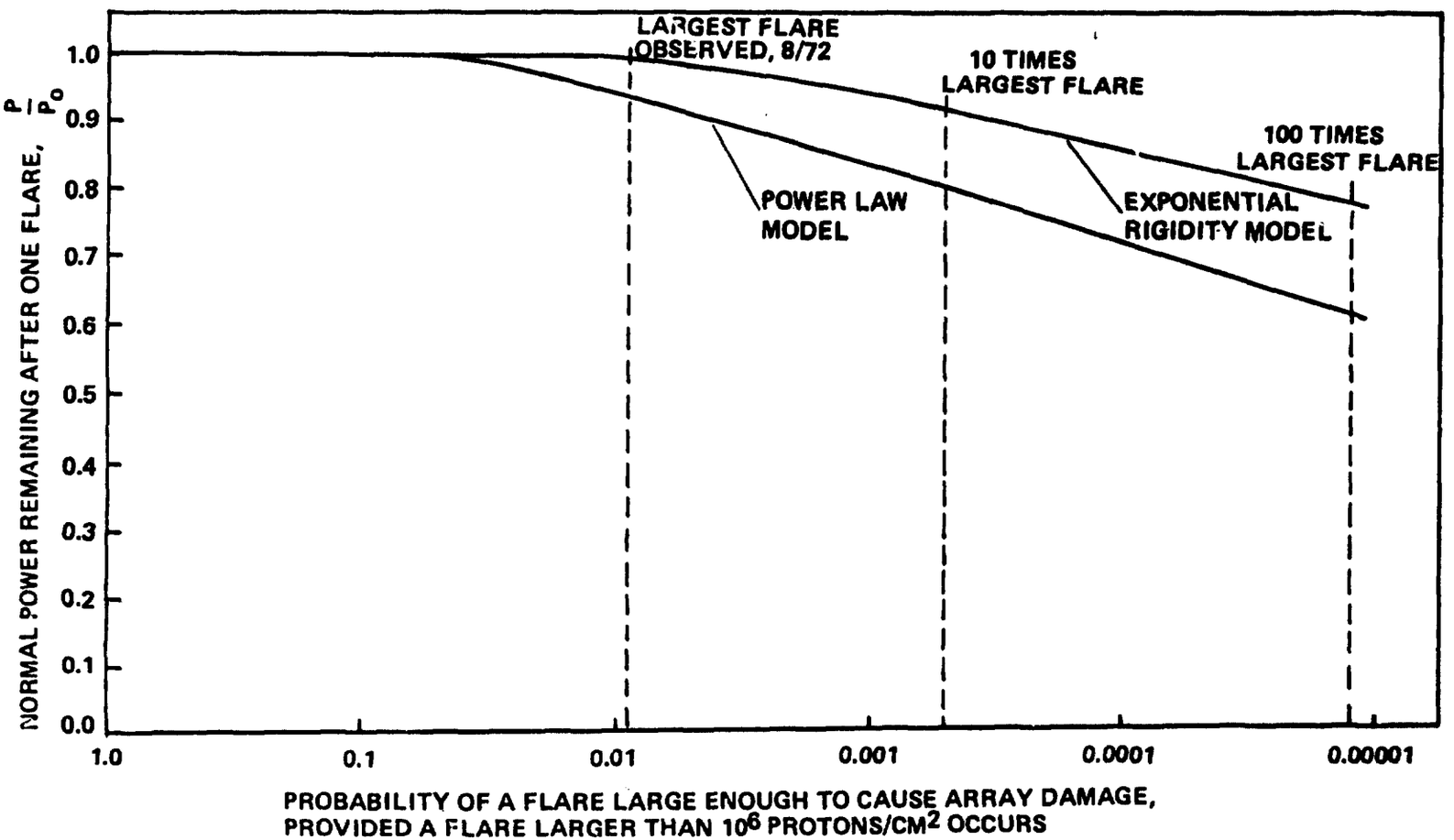
LARGE FLARE EFFECT ON ARRAY PERFORMANCE

Results of a statistical analysis of solar flare size are shown. The flare size probability distribution was assumed to follow a log-normal curve. The available statistical sample is too small to develop detailed conclusions as to flare size. It seems unlikely that a log-normal distribution would hold for very large flares since this distribution places no upper limits on flare size.

The two curves shown represent power law and exponential rigidity models for the proton spectrum. Available data fit either law about equally, yet these spectral distributions predict large differences in proton fluxes in the energy range from 2 MEV to 10 MEV. This energy range is of principal concern for thin solar cells with thin covers, but available data do not extend into this region.

Degradation more than 10% from a single large flare is deemed to be highly unlikely. Much improvement in the confidence in this result can be expected due to continued accumulation of statistical data from the current solar cycle and with direct observation of proton fluxes in the 2 MEV to 10 MEV range.

Large Flare Effect on Array Performance

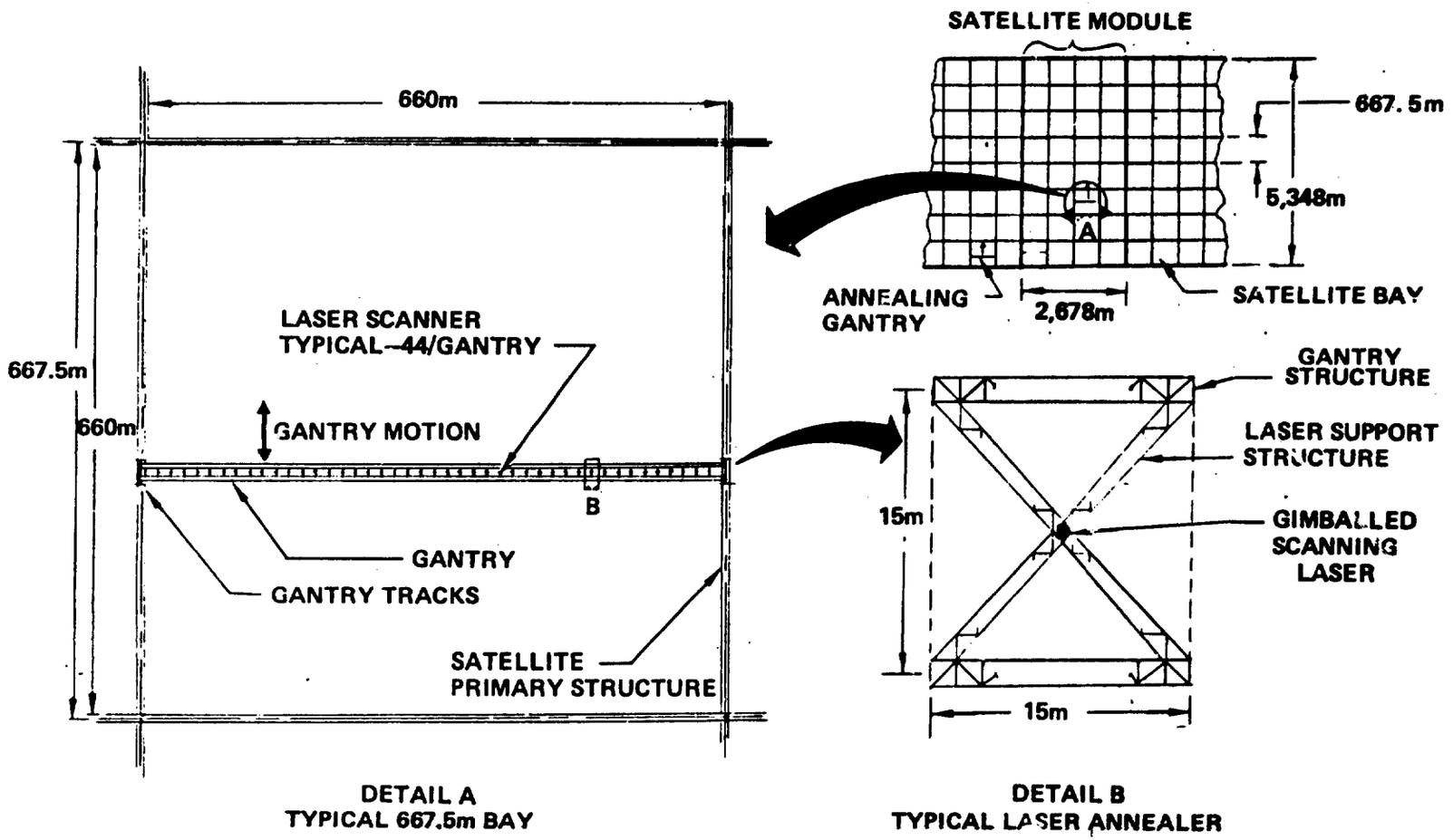


LASER ANNEALING CONCEPT

The concept of how the actual annealing process would be accomplished is shown. Each laser gimbal would actually have 64-500 watt CO_2 lase installed. The laser beams would be optically tailored to provide the desired illumination pattern and energy density.

The gimbals would be mounted on an overhead gantry that would span the entire bay width, one bay of solar array would be annealed in fifteen meter increments. It should be noted that the solar array strings that are undergoing an ealing are nonoperational.

Laser Annealing Concept



DETAIL A
TYPICAL 667.5m BAY

DETAIL B
TYPICAL LASER ANNEALER

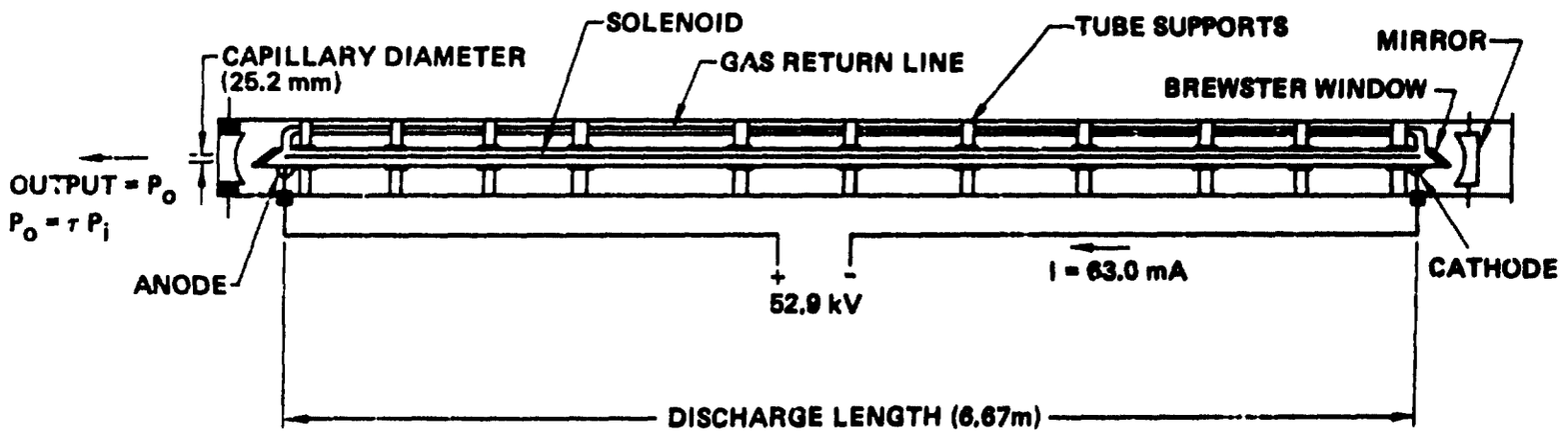
CO_2 LASER DESCRIPTION

This figure shows the basic essentials for a 500 watt CO_2 laser operation. The small diameter of the beam can be optically tailored to provide the desired illumination pattern on the solar blanket.

This device would be a flow type laser in that the CO_2 gas is moved through the tube to allow recombination and cooling. This figure shows a simple return line but in practice, with several lasers operating in parallel, a centralized accumulator and thermal control system may be desirable.

Commercial CO_2 lasers have been built that are much larger than that shown here. The application of this device to SPS requirements and improved reliability are the major areas that need further development.

CO_2 Laser Description



GAS PRESSURE:	1.98 torr
EFFICIENCY:	15%
POWER OUTPUT:	500W

LASER ANNEALING SUMMARY

The main points of the investigation are indicated. Recent examination of the Spire test results, coupled with analytical estimates of the quantity of energy required to accomplish heating to annealing temperatures, suggests that current estimates of laser energy required may be up to 10 times too high. The Spire tests had the solar cells mounted on heatsinks, thus requiring far more energy to reach annealing temperatures than would be required in the essentially adiabatic case that will hold in space.

Laser Annealing

- SINGLE LARGE FLARES NOT EXPECTED TO CAUSE SIGNIFICANT DEGRADATION

- CURRENT ESTIMATES OF LASER ENERGY REQUIRED MAY BE UP TO 10X TOO HIGH; THEY ARE BASED ON SPIRE TESTS WHICH HAD CELLS MOUNTED TO HEAT SINKS.

MPTS Midterm Review

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MPTS MIDTERM REVIEW

The following section describes Boeing work to date on solid state microwave power transmitting antenna concepts. Certain sections of this work were conducted on internal Boeing IR&D funding, as indicated, to extend the investigation beyond the present scope of the study. The following contributors participated in this portion of the study.

MPTS System	Ervin J. Nalos
Phase Control:	
Walt W. Lund	The Boeing Co.
Peter Foldes	General Electric Co.
Solid State Design:	
G. Fitzsimmons	The Boeing Co.
Ray Sperber	The Boeing Co.
Fiber Optic Feasibility	
Glen Miller	The Boeing Co.
MPTS Computer Program	
Scott Rathjen	The Boeing Co.

NASA-JSC
Oct. 19, 1978

MPTS Midterm Review

- SPS PHASE CONTROL IMPLEMENTATION
  - COMMENTS ON LINCOM SYSTEM
  - INITIAL REDUNDANCY CALCULATIONS
  - FIBER OPTIC FEASIBILITY ASSESSMENT
- SOLID STATE DESIGN FOR SPS
  - DEVICE PARAMETERS ASSESSMENT
  - POTENTIAL CIRCUIT FOR SPS INTEGRATION
    COMMENTS ON NOISE BEHAVIOR
- MPTS COMPUTER PROGRAM
  - COMPUTER MODEL STATUS
  - PLAN FOR NEXT PERIOD

OCTOBER 19, 1978

SPS PHASE CONTROL

This chart describes the tasks undertaken in the review and implementation of the Lincom System and some suggested follow-on tasks for Phase II of the System Evaluation Study.

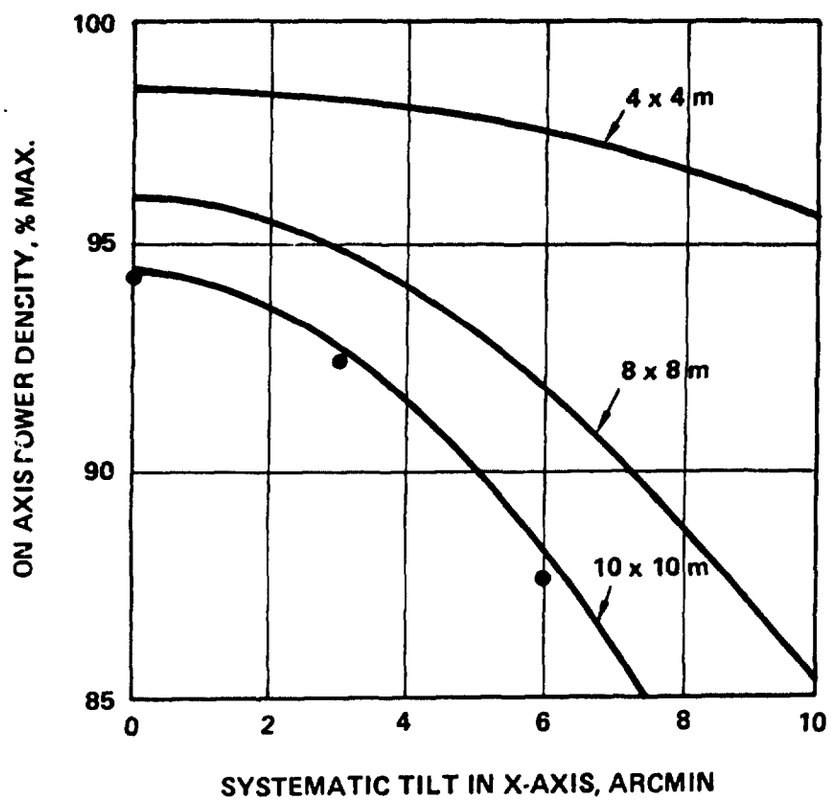
SPS Phase Control

- LINCOM SYSTEM IMPLEMENTATION
  - ANALYTICAL VERIFICATION
  - DISTRIBUTION TREE OPTIONS
  - KEY TRADE STUDIES
  - DESIGN REFINEMENTS
- FOLLOW–ON TASKS
  - SIMULATION/ANALYSIS
  - EXPERIMENTAL

COMPARISON OF ARRAY PERFORMANCE DEGRADATION WITH TILT

Calculations by Lincom show that going to smaller subarraydesensitizesthe transmitting antenna performance degradation due to systematic tilt. Selected results from recent Boeing computer runs are in good agreement with Lincom data and indicate that if greater tilts are to be experienced than presently allocated, a review of the baseline 10 meter subarray size is warranted.

Comparison of Array Performance Degradation with Tilt



LEGEND

LINCOM RESULTS

3 arcmin SYSTEMATIC Y TILT
3 arcmin RANDOM TILT (1 σ)
Surface ϵ = .01λ (48 mils)

● BOEING "TILTMAIN" RESULTS

① 3 arcmin SYSTEMATIC TILT
$3\sqrt{2}$ arcmin RANDOM TILT

② $3\sqrt{2}$ arcmin SYSTEMATIC TILT
$3\sqrt{2}$ arcmin RANDOM TILT

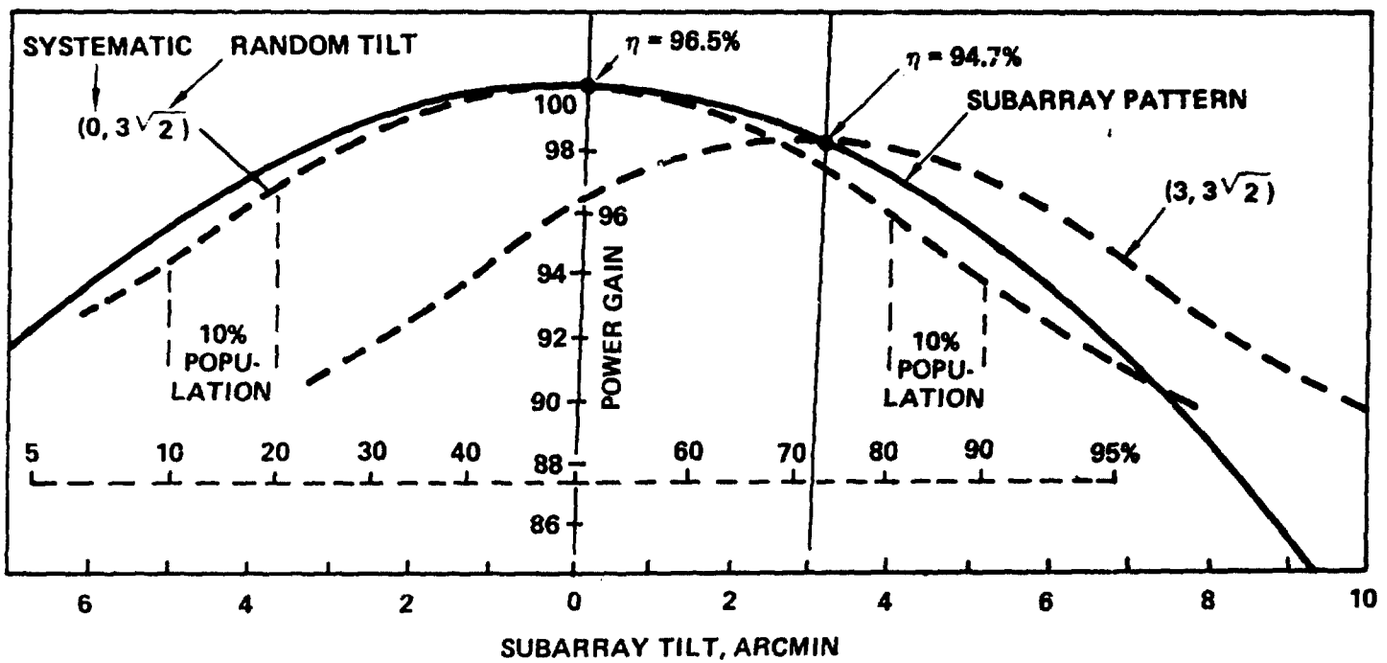
③ $3\sqrt{5}$ arcmin SYSTEMATIC TILT
$3\sqrt{2}$ arcmin RANDOM TILT

Surface ϵ = .01λ corresponds to 1/2% power loss

EFFECT OF SYSTEMATIC AND RANDOM SUBARRAY TILT

Further runs on the Tiltmain program confirmed by graphical integration of superposed random tilts on various values of systematic tilt indicate that random tilts can have greater effects than previously realized. For instance, for 3 arc min of systematic tilt the efficiency is reduced from 98.5% for zero random tilt to 94.7% with $3\sqrt{2}$ arc min of random tilt. The choice of $3\sqrt{2}$ of random tilt (1 dimensional at 45° on the "Tiltmain" program) corresponds to a choice of 3 arc min of 2 dimensional tilt on the Lincom program.

Effect of Systematic and Random Subarray Tilt

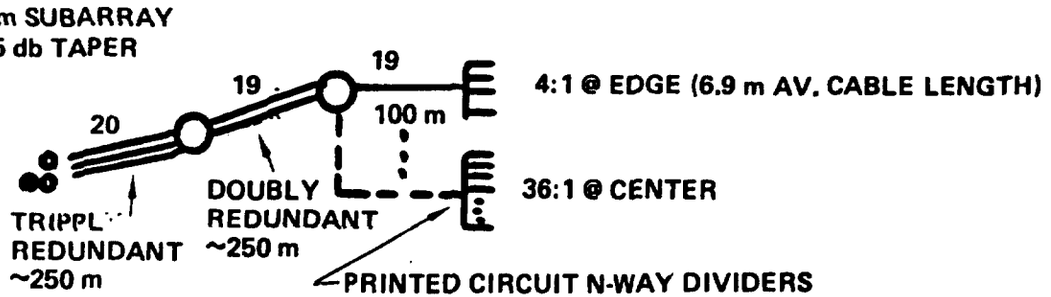


POTENTIAL PHASE DISTRIBUTION TREE LAYOUTS

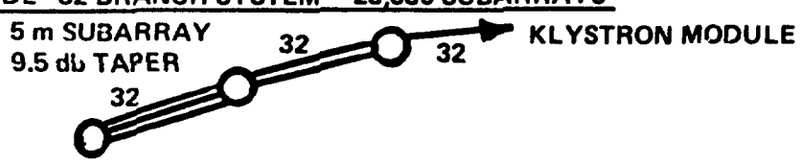
Four different distribution trees are outlined, each indicative of different level of phase control and degree of power splittings. The baseline system of Lincom with 9 nodes (d) is based on a maximum of 4:1 power split whereas the 4 node system (a) elaborated by GE is based on a 20x19x19 distribution to the subarray level and a variable power splitting to the klystron level (4th node) using 4:1 power splitters at the edge and 36:1 power splitters at the array center.

Potential Phase Distribution Tree Layouts

- 4-NODE SYSTEM – 7,220 SUBARRAYS, 100,000 KLYSTRON MODULES

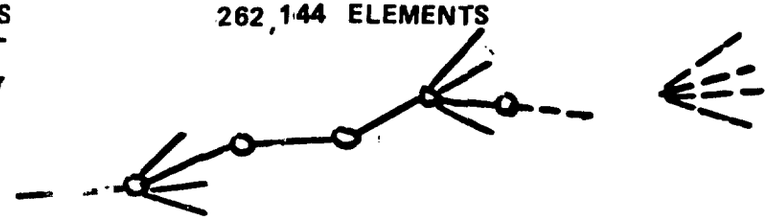


- 3-NODE–32 BRANCH SYSTEM – 28,880 SUBARRAYS

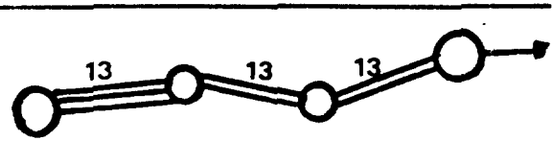


- 9 NODE – 4 BRANCH SYSTEM

262,144 ELEMENTS



- 4-NODE–13 BRANCH SYSTEM – 28,880 SUBARRAYS



ESTIMATE OF REQUIRED CABLE LENGTH

The approximate calculation of cable length and weight indicates that cable length optimization may not be a really significant parameter since cable weight will likely be less than 1% of the array waveguide weight. The reliability analysis initiated in the GE midterm documentation will be carried further, as will the development of a maintenance concept.

Estimate of Required Cable Length

- ALL CABLE LENGTHS EQUAL

1ST LAYER	20 CABLES @ 250 m	TRIPLY REDUNDANT	15 km (1/4" DIA)
2ND LAYER	380 CABLES @ 250 m	DOUBLY REDUNDANT	190 km (1/4" DIA)
3RD LAYER	7220 CABLES @ 100 m	NON-REDUNDANT	722 km (1/8" DIA)
4TH LAYER	100,784 CABLES @ 6.9 m	NON-REDUNDANT	702 km (1/8" DIA)
			1629 km

- NON-EQUAL CABLE LENGTHS

SAVING ~ FACTOR OF 2 ~ 850 km

APPROX. CABLE WEIGHT ≅ 1% OF WAVEGUIDE WEIGHT
~ 9000 km OF W/G vs. 850 km OF CABLE

GENERAL ELECTRIC

FOUR-NODE
PHASE CONTROL SYSTEM LAYOUT ASSUMPTIONS

space division

- 7220 SUBARRAY, 10.4 M X 10.4 M EACH
- 10 LEVEL POWER DISTRIBUTION APPROXIMATING GAUSSIAN FUNCTION WITH -9.54 DB TAPER
- SEPARATE PHASE DISTRIBUTION AND CONJUGATION CIRCUITS
- ELECTRONIC CIRCUITS AS PER LINCOM REPORT
- PHASE DISTRIBUTION TREE EMPLOYS THREE LAYERS TO SUBARRAY OR FOUR LAYERS TO KLYSTRON LEVEL
- FOURTH LAYER IS ADD ON (IF NECESSARY)
- FIRST LAYER IS TRIPLE REDUNDANT, SECOND LAYER IS DOUBLE REDUNDANT IN PHASE DISTRIBUTION TREE

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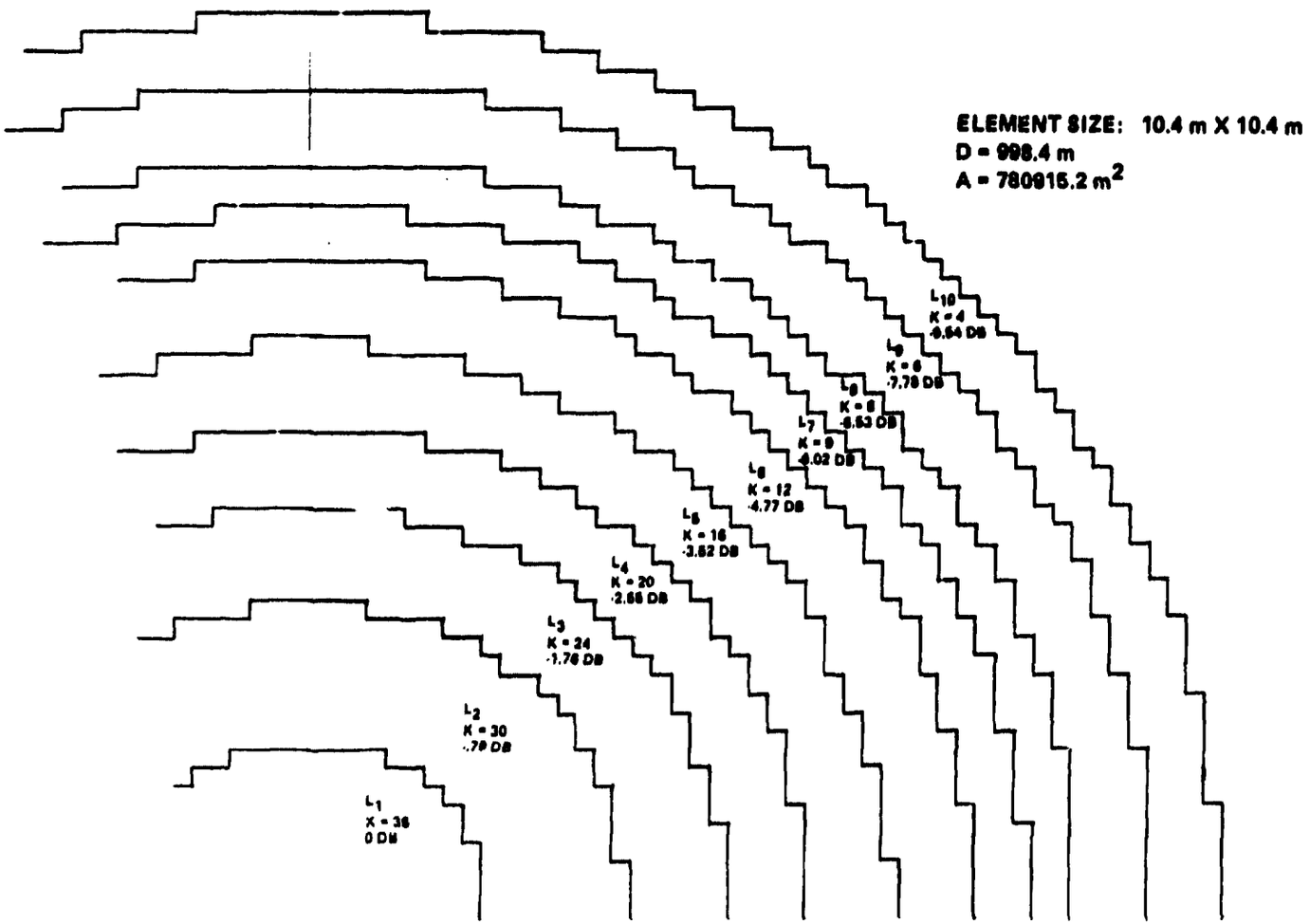
GENERAL ELECTRIC

DIVISION OF 7220 ELEMENT SPACEANTENNA INTO 10 POWER LEVEL RINGS

space division



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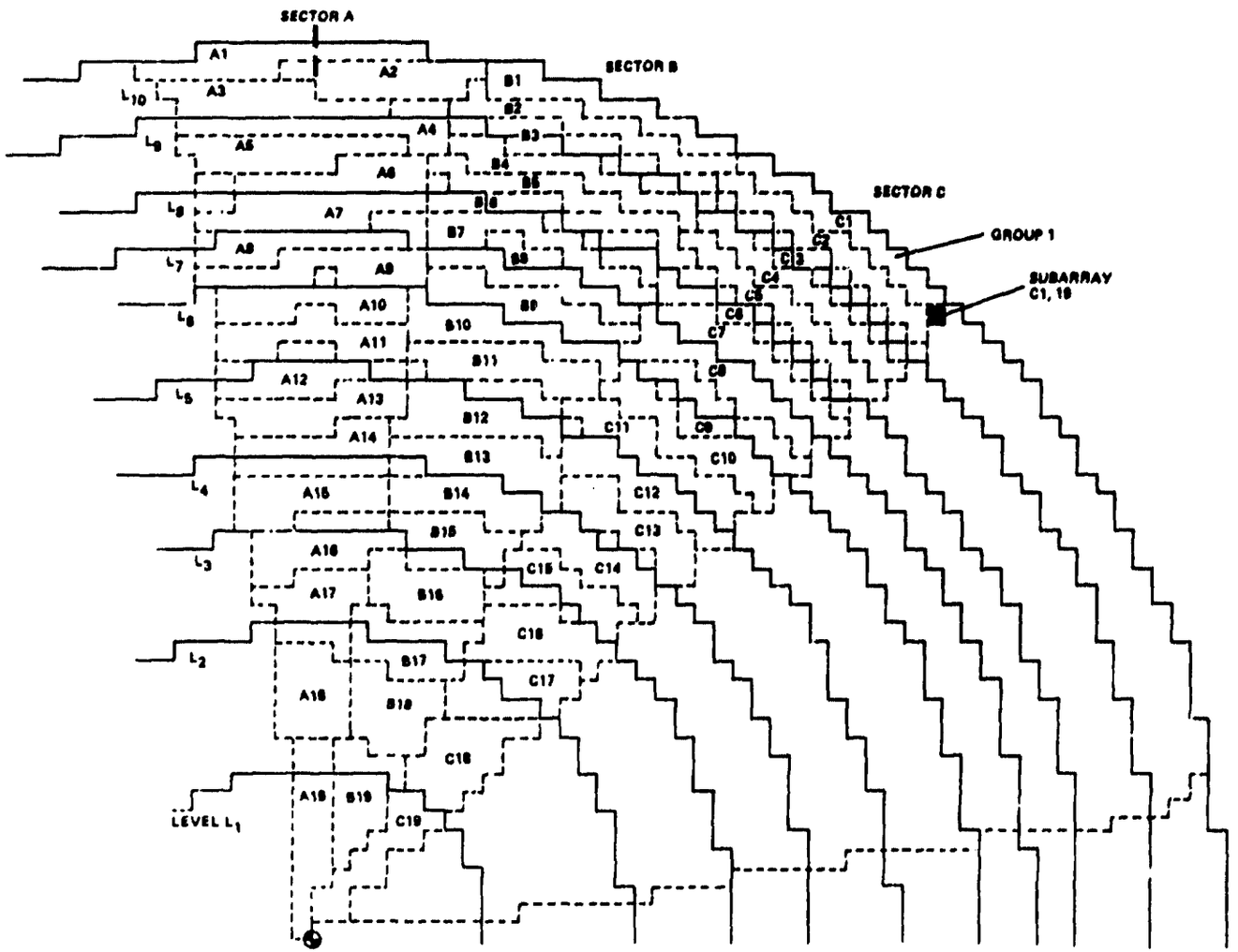
LAYOUT OF PHASE DISTRIBUTION SECTORS AND GROUPS

THE SPACE ANTENNA IS DIVIDED INTO 20 SECTORS AND EACH SECTOR INTO 19 GROUPS OF SUBARRAYS. EACH GROUP CONTAINS 19 SUBARRAYS. IN FINE DETAIL THREE DIFFERENT SECTOR LAYOUT IS NECESSARY FOR THIS SCHEME, WHICH THEN ARE PERIODICALLY REPEATED IN THE AZIMUTH DIRECTION.

GENERAL ELECTRIC

LAYOUT OF PHASING SECTORS AND GROUPS

space division



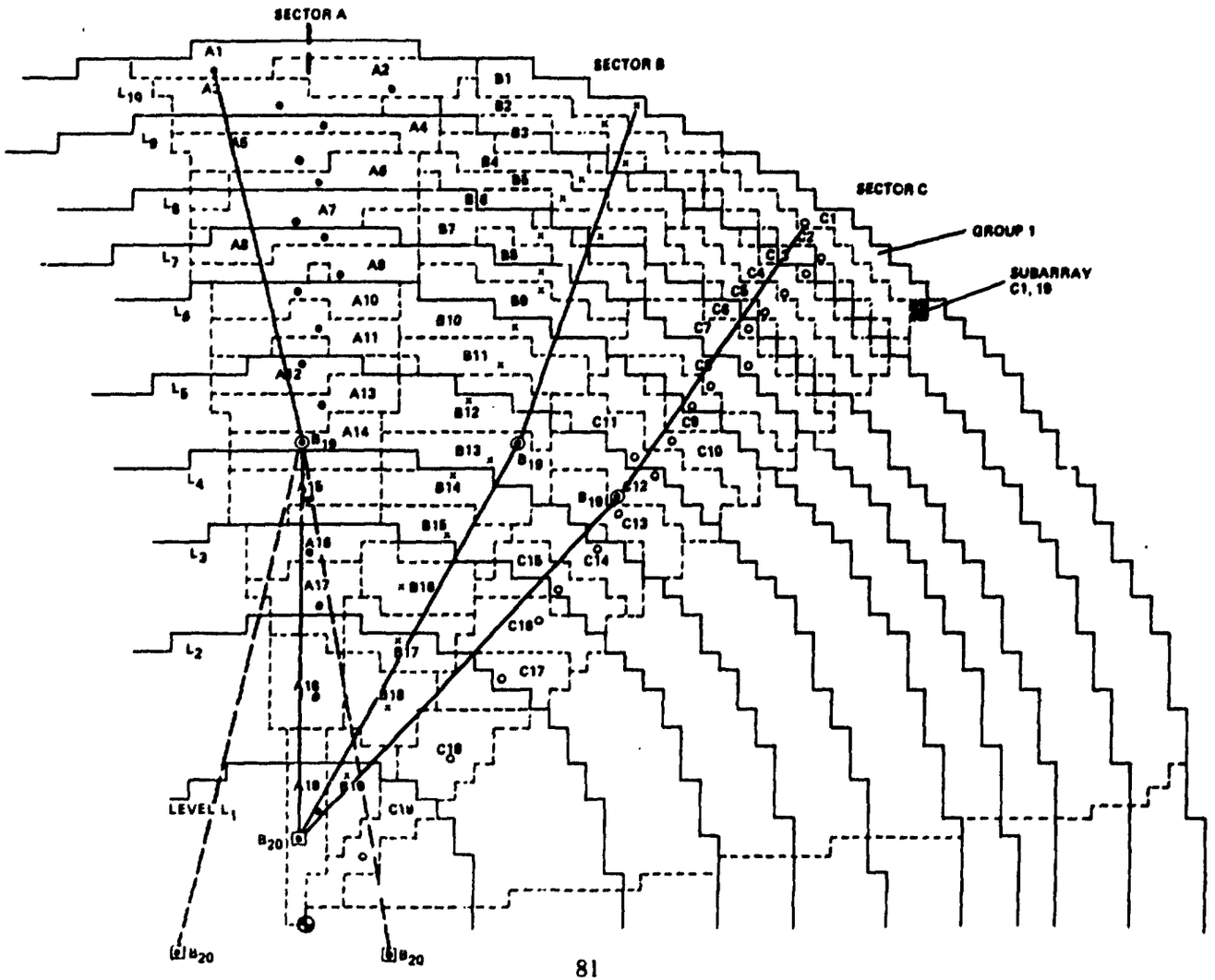
LOCATION OF REFERENCE PHASE REPEATER STATIONS AT SECTOR AND GROUP CENTERS

THE REFERENCE PHASE DISTRIBUTION NETWORK HAS THREE INDEPENDENT CENTERS LOCATED ON A 70 M RADIUS, 120° AZIMUTH ANGLE FROM EACH OTHER. THESE PROVIDE TRIPLE REDUNDANCY. THE FIRST LAYER OF THE PHASE DISTRIBUTION TREE GOES FROM THESE CENTERS TO SECTOR CENTERS. THE SECOND LAYER GOES FROM SECTOR CENTERS TO GROUP CENTERS. THE THIRD LAYER (NOT SHOWN) GOES FROM GROUP CENTERS TO SUBARRAY CENTERS. THE FOURTH LAYER (NOT SHOWN) GOES FROM SUBARRAY CENTERS TO KLYSTRONS, WHEN THIS LAYER IS IMPLEMENTED.

GENERAL ELECTRIC

LOCATION OF REFERENCED PHASE REPEATER STATIONS OF SECTORS AND GROUPS

space division



QUANTITIES OF SUBARRAYS IN VARIOUS LEVELS, SECTORS AND GROUPS

THE OVERALL SPACE ANTENNA IS DIVIDED INTO POWER DISTRIBUTION LEVELS (FROM ONE TO TEN) AND MULTIPLE PHASE DISTRIBUTION LAYERS. THE FIRST PHASE DISTRIBUTION LAYER CONTAINS TWENTY SECTORS (A, B, C, C, B, A, B ... B). READ HORIZONTALLY THE LEVEL AND SECTOR DESIGNATION AND VERTICALLY THE GROUP DESIGNATIONS ON THE CHART.

GENERAL ELECTRIC

QUANTITIES OF SUBARRAYS IN VARIOUS LEVELS, SECTORS AND GROUPS

space division

LEVEL, SECTOR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1A																			15
1B																			12
1C																		19	19
2A																	5	19	4
2B																	10	19	7
2C																9	19	19	
3A																14	14		
3B															5	9	19		
3C															6	10	19		
4A														8	19	5			
4B														19	14				
4C														17	13				
5A													11	19					
5B													-	19					
5C													2	19					
6A												3	19						
6B												7	19						
6C												1	19						
7A											19	19							
7B										1	19								
7C										19	19								
8A									14	19									
8B									14	19									
8C								5	19										
9A						2	19	14											
9B						4	19												
9C						7	19												
10A					16	17													
10B				19	15														
10C			2	19	12														
	19	19	8																
	19	19	11																

GROUP ↓

→ 6B

SUMMARY OF SUBARRAY QUANTITIES IN VARIOUS PHASING SECTORS AND GROUPS

THE TABLE SHOWS THE NUMBER OF SUBARRAYS IN A GIVEN LEVEL, SECTOR AND GROUP AND ALSO THE NUMBER OF SUBARRAYS IN A GIVEN T_{ij} GROUP, FINALLY THE OVERALL TOTAL OF SUBARRAYS, T AT A GIVEN POWER LEVEL.

SUMMARY OF SUBARRAY QUANTITIES IN VARIOUS PHASING SECTORS AND GROUPS

LEVEL	QTY	
1	$A_{19} = 60$ $B_{19} = 96$ $C_{19} = 152$	$T_{19} = 308$ $T = 308$
2	$A_{19} = 16$, $A_{18} = 76$, $A_{17} = 20$ $B_{19} = 56$, $B_{18} = 152$, $B_{17} = 80$ $C_{18} = 152$, $C_{17} = 72$	$T_{19} = 72$, $T_{18} = 380$, $T_{17} = 172$ $T = 624$
3	$A_{17} = 56$, $A_{16} = 56$ $B_{17} = 72$, $B_{16} = 153$, $B_{15} = 40$ $C_{17} = 80$, $C_{19} = 152$, $C_{15} = 48$	$T_{17} = 208$, $T_{16} = 360$, $T_{15} = 88$ $T = 656$
4	$A_{16} = 20$, $A_{15} = 76$, $A_{14} = 32$ $B_{15} = 112$, $B_{14} = 152$ $C_{15} = 104$, $C_{17} = 136$	$T_{16} = 20$, $T_{15} = 292$, $T_{14} = 320$ $T = 632$
5	$A_{14} = 44$, $A_{13} = 76$, $A_{12} = 64$ $B_{13} = 152$, $B_{12} = 96$ $C_{14} = 16$, $C_{13} = 152$, $C_{12} = 144$	$T_{14} = 60$, $T_{13} = 380$, $T_{12} = 304$ $T = 744$
6	$A_{12} = 12$, $A_{11} = 76$, $A_{10} = 72$ $B_{12} = 56$, $B_{11} = 152$, $B_{10} = 152$ $C_{12} = 8$, $C_{11} = 152$, $C_{10} = 152$, $C_9 = 40$	$T_{12} = 76$, $T_{11} = 380$, $T_{10} = 376$, $T_9 = 40$ $T = 872$
7	$A_{10} = 4$, $A_9 = 76$, $A_8 = 56$ $B_9 = 152$, $B_8 = 112$ $C_9 = 112$, $C_8 = 152$	$T_{10} = 4$, $T_9 = 340$, $T_8 = 320$ $T = 664$
8	$A_8 = 20$, $A_7 = 76$, $A_6 = 8$ $B_8 = 40$, $B_7 = 152$, $B_6 = 32$ $C_7 = 152$, $C_6 = 56$	$T_8 = 60$, $T_7 = 380$, $T_6 = 96$ $T = 536$
9	$A_6 = 68$, $A_5 = 76$, $A_4 = 64$ $B_6 = 120$, $B_5 = 152$, $B_4 = 152$, $B_3 = 16$ $C_6 = 96$, $C_5 = 152$, $C_4 = 152$, $C_3 = 64$	$T_6 = 284$, $T_5 = 380$, $T_4 = 368$, $T_3 = 80$ $T = 112$
10	$A_4 = 12$, $A_3 = 76$, $A_2 = 76$, $A_1 = 76$ $B_3 = 136$, $B_2 = 152$, $B_1 = 152$ $C_3 = 88$, $C_2 = 152$, $C_1 = 152$	$T_4 = 12$, $T_3 = 300$, $T_2 = 380$, $T_1 = 380$ $T = 1072$

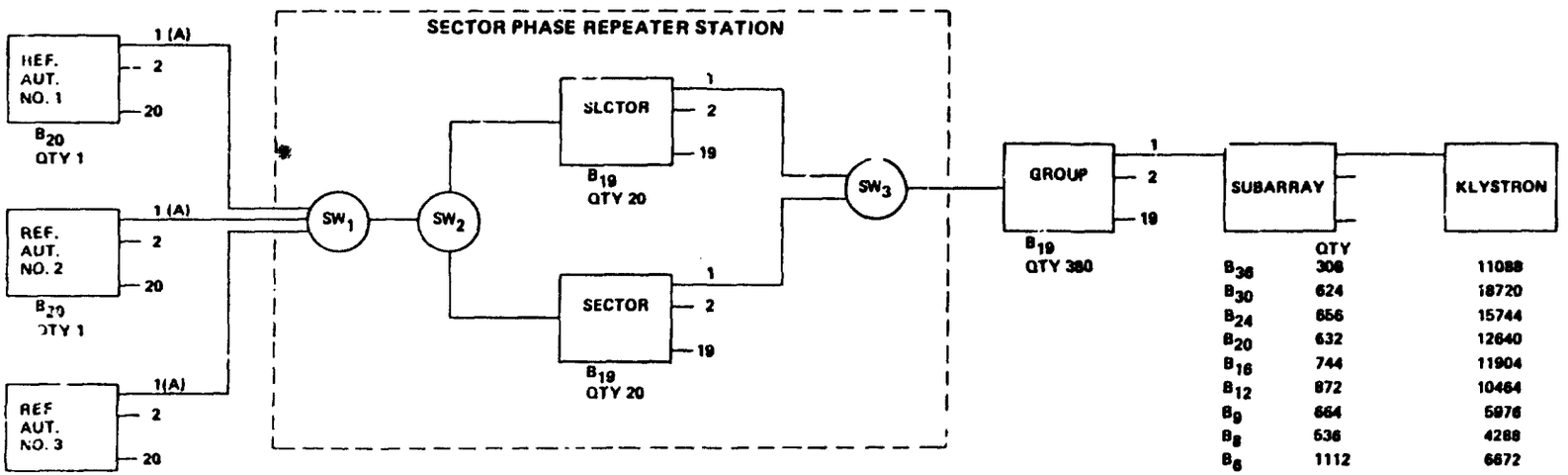
REDUNDANCY CONCEPT OF PHASE DISTRIBUTION NETWORK

THE EXHIBITED REDUNDANCY CONCEPT EMPLOYS TRIPLE REDUNDANCY AT THE FIRST AND DOUBLE REDUNDANCY AT THE SECOND LAYER. EXCEPT SECOND LAYER CABLES THEMSELF ARE NOT REDUNDANT.

GENERAL ELECTRIC

REDUNDENCY CONCEPT OF PHASE DISTRIBUTION NETWORK

space division



	QTY	
B_{36}	308	11088
B_{30}	624	18720
B_{24}	656	15744
B_{20}	632	12640
B_{16}	744	11904
B_{12}	872	10464
B_9	664	5976
B_8	536	4288
B_6	1112	6672
B_4	1072	4288
	7220	101784

LIST OF PHASE CIRCUIT DIVIDERS TO SUBARRAY LEVEL

IN THE PHASE DISTRIBUTION TREE WITH REDUNDANCY, 423 DIVIDERS (TWO TYPES) OR 7643 DIVIDERS (ELEVEN TYPES) ARE NEEDED TO SUBARRAY OR KLYSTRON LEVELS RESPECTIVELY.

GENERAL ELECTRIC

LIST OF PHASE DIVIDERS TO SUBARRAY LEVEL

space division

BASIC SYSTEM

	QTY	TOTAL	
B_{20}	1		
B_{19}	400		

REDUNDANT SYSTEM

B_{20}	2		
B_{19}	20		

TOTAL SYSTEM

B_{20}	3		2 TYPES
B_{19}	420		
		423	

ADD ON TO KLYSTRON LEVEL
(NO REDUNDANCY)

		TOTAL	
B_{36}	308	308	11 TYPES
B_{30}	624	624	
B_{24}	656	656	
B_{20}	632	635	
B_{16}	744	B_{19} = 420	
		744	
B_{12}	872	872	
B_9	664	664	
B_8	536	536	
B_6	1112	1112	
B_4	1072	1072	
		7643	

LIST OF PHASE DISTRIBUTION CABLES

THE QUANTITIES AND LENGTHS OF PHASE DISTRIBUTION CABLES ARE SHOWN WHEN

A. ALL PATH LENGTHS FROM INPUT TO OUTPUT TERMINALS ARE EQUAL

B. CABLE LENGTHS ARE MINIMIZED

GENERAL ELECTRIC

LIST OF PHASE DISTRIBUTION CABLES

space division

LAYER	NO. OF CABLES	AV. LENGTH KM	TOTAL LENGTH KM	REMARKS
EQUAL CABLE LENGTH SYSTEM				
1	60	0.25	15	(TRIPLE REDUNDANT CABLES)
2	380	0.25	95	(NO REDUNDANCY IN CABLES)
3	7220	0.10	722	(NO REDUNDANCY IN CABLES)
TOTAL TO SUBARRAY			832	(927 KM IF SECOND LAYER IS ALSO REDUNDANT)
4	101784	0.0069	702.3	
TOTAL TO TRANSMITTERS			1534.3	(1629.3 KM IF SECOND LAYER IS ALSO REDUNDANT)
UNEQUAL CABLE LENGTH SYSTEM				
1	60	0.25	15	
2	380	0.125	47.5	
3	7220	0.06	433.2	
TOTAL TO SUBARRAY			495.7	(543.2 KM IF SECOND LAYER IS ALSO REDUNDANT)
4	101784	0.0028	285	
TOTAL TO TRANSMITTERS			780.7	(828.2 KM IF SECOND LAYER IS ALSO REDUNDANT)

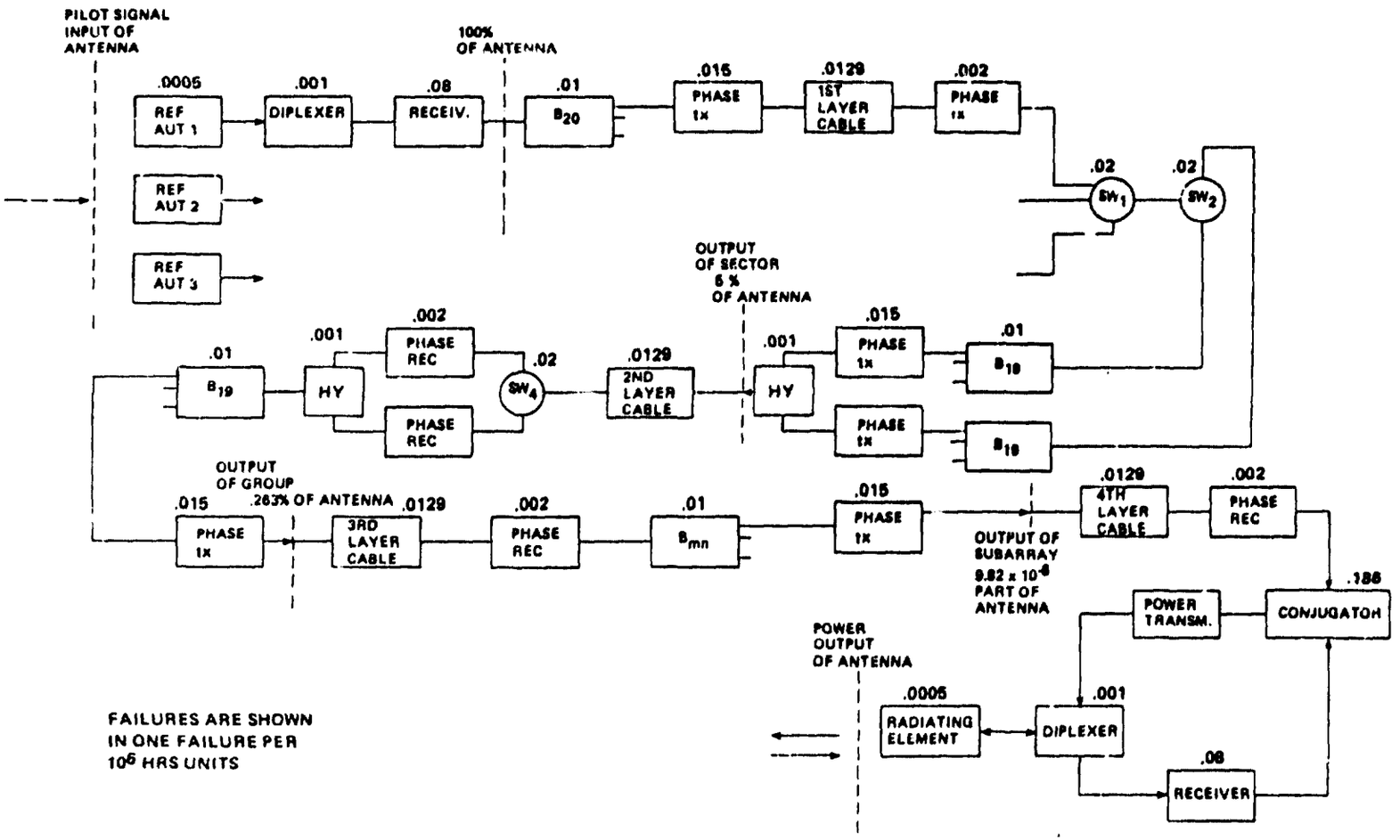
BLOCK DIAGRAM FOR RELIABILITY CALCULATIONS

DIAGRAM SHOWS ALL THE APPLICABLE PARALLEL AND SERIES CONNECTED ELEMENTS IN A TYPICAL PATH OF THE PHASE CONTROL NETWORK.

GENERAL ELECTRIC

BLOCK DIAGRAM FOR RELIABILITY CALCULATIONS

space division



LIST OF COMPONENTS IN PHASE CONTROL CIRCUIT

TABLE SHOWS THE COMPONENTS REQUIRED IN THE PHASE CONTROL CIRCUIT WHEN THE PHASE DISTRIBUTION IS TO SUBARRAY OR TO KLYSTRON LEVEL. THE PHASE CONTROL CIRCUIT TO THE KLYSTRON LEVEL REQUIRES ABOUT ONE ORDER OF MAGNITUDE MORE COMPONENTS.

GENERAL ELECTRIC

LIST OF COMPONENTS IN PHASE CONTROL CIRCUIT

space division

COMPONENT	TO SUBARRAY LEVEL QTY		TO KLYSTRON LEVEL QTY		DIFFERENTIAL
DIPLEXER	7220		101784		94564
RECEIVER	7220		101784		94564
B_{36}	-		308		
B_{30}	-		624		
B_{24}	-		656		
B_{20}	3		635		
B_{19}	420	423	420	7643	7220
B_{16}	-		744		
B_{12}	-		872		
B_9	-		664		
B_8	-		536		
B_6	-		1112		
B_4	-		1072		
PHASE TRANSMITTER	8420		110204		101784
FIRST LAYER CABLE (250 M)	60 (15 KM)	832 KM	60 (15 KM)	1629 KM	794
SECOND LAYER CABLE (250 M)	380 (95 KM)		380 (95 KM)		
THIRD LAYER CABLE (10 M)	7220 (722 KM)		7220 (722 KM)		
FOURTH LAYER CABLE (7 M)	-		101784 (702 KM)		
PHASE RECEIVER	8420		110204		101784
SW_1	20		20		
SW_2	20		20		
SW_3	380	1180	380	1180	-
SW_4	380		380		
SW_5	380		380		
CONJUGATOR	7220		101784		94565
POWER TRANSMITTER	101784		101784		-
SUBARRAY	7220 (9202 KM)		101784 (9202 KM)		-

SUMMARY OF PRELIMINARY AVAILABILITY CALCULATIONS

AVAILABILITIES AND TOTAL LOST ENERGY IS CALCULATED FOR THE SELECTED REDUNDANCY SCHEME, INDIVIDUAL FAILURE RATES OF COMPONENTS AND ASSUMED MEAN TIME TO REPAIR VALUES. TOTAL AVERAGE POWER REDUCTION DUE TO IMPERFECTNESS OF PHASE CONTROL SYSTEM IS APPROXIMATELY .24%.

GENERAL ELECTRIC

SUMMARY OF PRELIMINARY AVAILABILITY CALCULATIONS

space division

	PROBABILITY THAT ALL IS AVAILABLE	EQUIVALENT LOST ENERGY GW HR. IN 30 YEARS	TOTAL LOST REVENUE M$
OVERALL ANTENNA (NO REPAIR)	0.999990 PER 30 YEARS	0.035429	.001
SECTOR (2160 HR. MTTR)	0.992722 PER YEAR	150.654	3.54
GROUP (4383 HR. MTTR)	0.84412 PER 6 MONTH	339.65	16.17
SUBARRAY (8766 HR. MTTR)	0.296275 PER 1 MONTH	770.61	23.118
KLYSTRON INPUT (8766 HRS. MTTR)	0.195510 PER DAY	1897.98	56.939

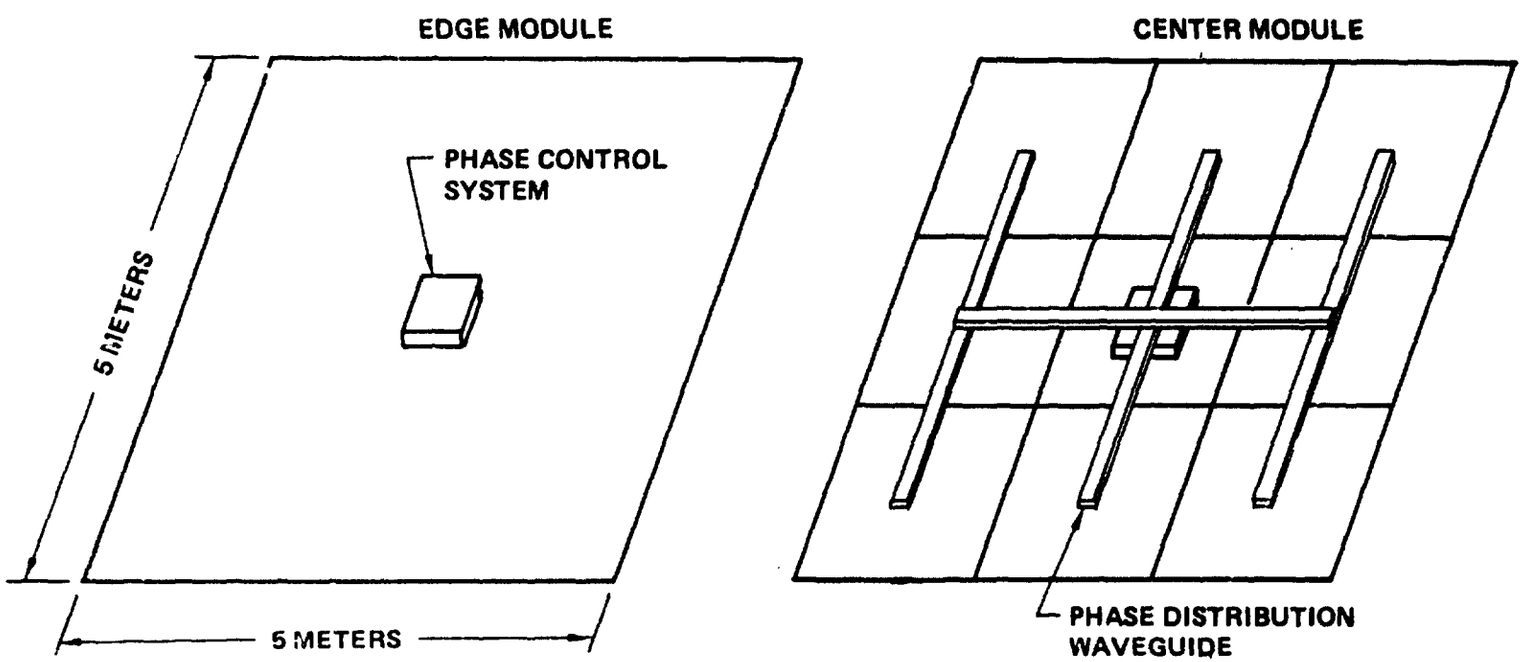
TOTAL EQUIVALENT POWER LOSS DUE TO PHASE CONTROL SYSTEM 0.2402%

RESULTANT AVAILABILITY FOR 30 YEAR PERIOD 0.997597

SUBARRAY SIZE CONSIDERATIONS

A critical review of the phase control baseline system needs to encompass a review of the viability of phase control to the klystron level in terms of trading complexity for performance improvement. One possible approach is to consider an increased number of subarrays (perhaps by a factor of 4) and providing phase control only to the subarray level. A rationale for a 5 meter subarray is suggested on the attached chart. Since passive elements will have to provide phase integrity within the allowable errors at the edge of the array (4 klystrons per 10mx10m subarray, i.e., 5mx5m size per klystron), the same cell size forretrodirective phase control could be used at the center, possibly using a thermally compensated waveguide for phase distribution to the 9 individual klystrons at this level. If compatible with overall array performance (to be checked when "Modmain" program is running) this would result in 4:1 reduction in phase distribution complexity.

Phase Control Distribution Level

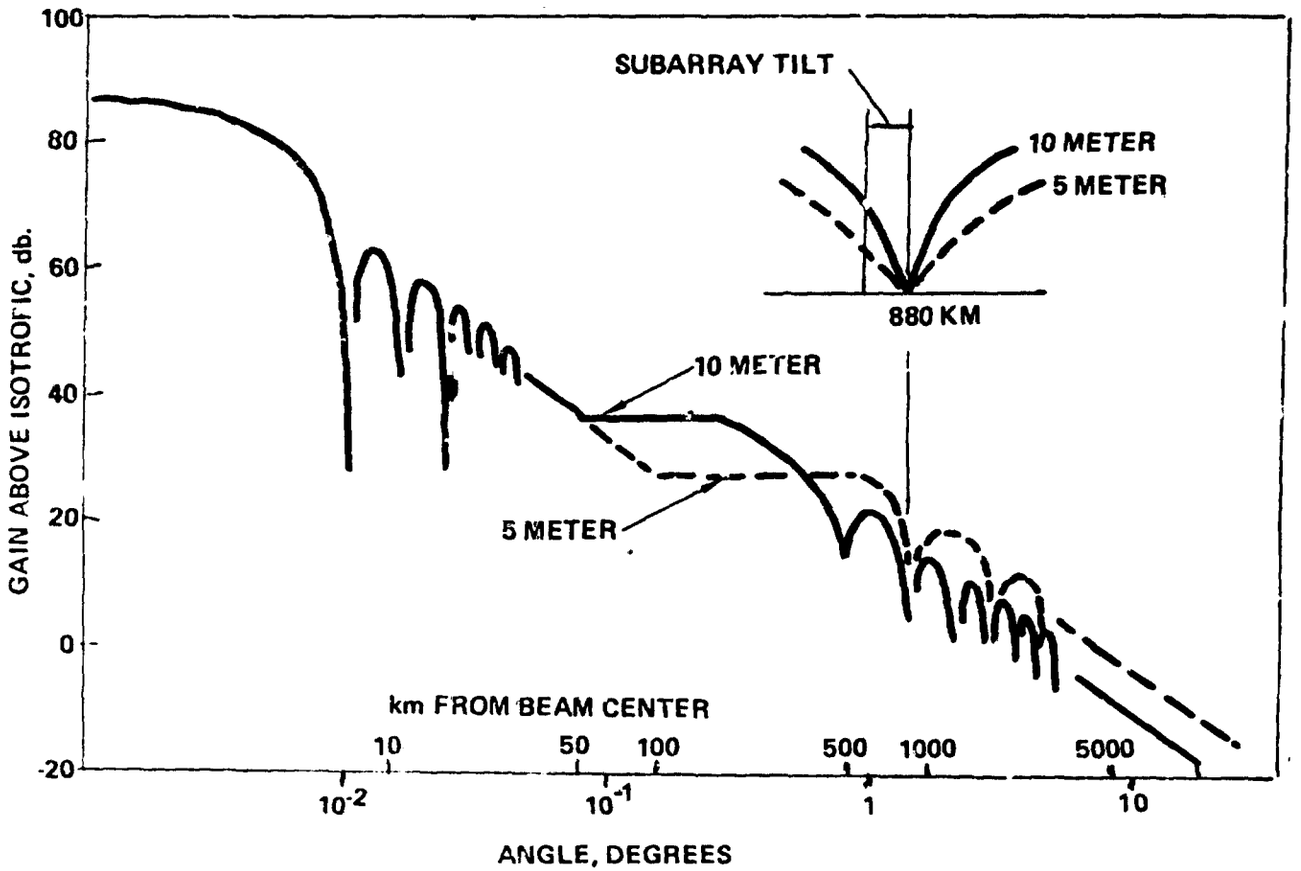


EFFECT OF SUBARRAY SIZE ON GRATING LOBES

An added benefit of reduced subarray size would be reduction in the number and magnitude of grating lobes, as indicated. The grating lobe level would be reduced by 20 log D_2/D_1, which is 6 dB.

Effect of Subarray Size on Grating Lobes

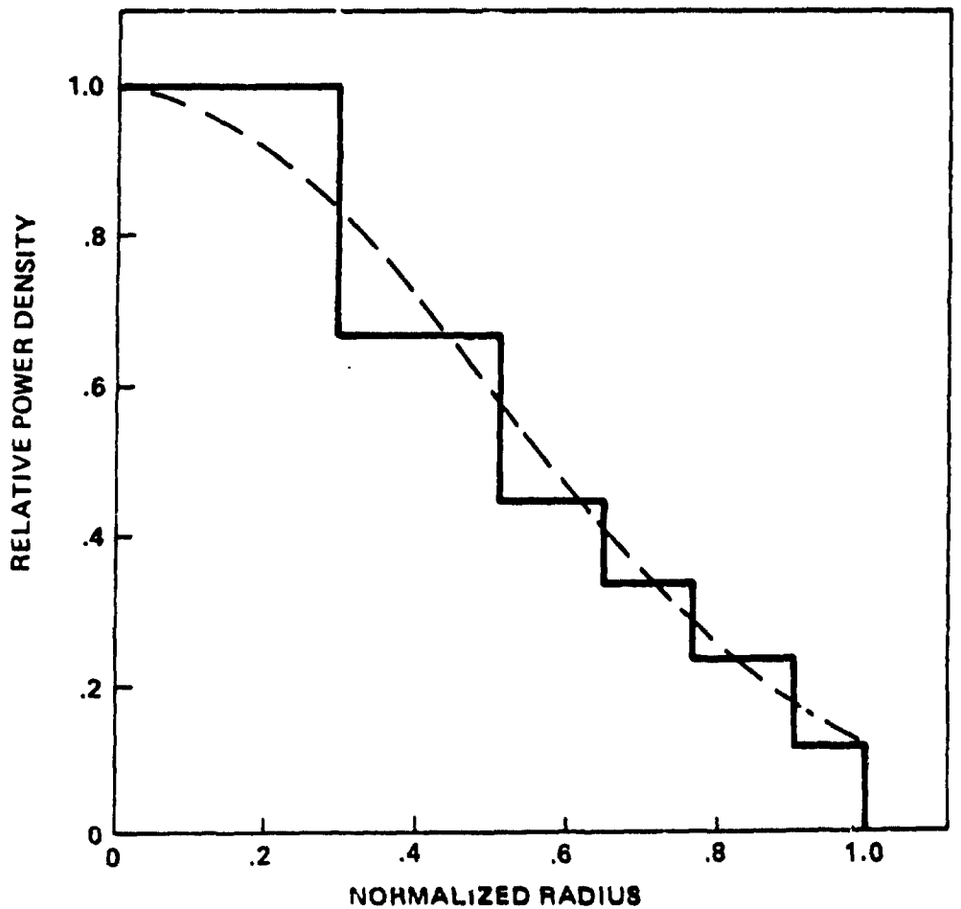
SPS 2327



SIX STEP TAPER IMPLEMENTATION OF 3 NODE PHASE DISTRIBUTION SYSTEM

An initial assessment of the 5 meter subarray option indicates that subject to the previous sticklength and waveguide dimensional constraints, a six step taper would have to be used. The attached chart, using the array computer model indicates that such a taper would result in insignificant deviation in efficiency and sidelobe level from the baseline values.

Six Step Taper Implementation of 3 Node Phase Distribution System



TAPER	SIX STEP	TEN STEP
η	96.2	96.7%
1ST SIDE LOBE	-24.5	-24.9 db

LOST ELEMENTS AS A FUNCTION OF THE NUMBER OF DISTRIBUTION LEVELS

Initial redundancy calculations for a "K" level, "N" branch distribution system indicate that the expected number of failures is

$$N^K \left\{ 1 - (1-Po)^K \right\} \cong KN^K po$$

Where po is the prohibits of failure of a single path. Since N^K is chosen to be equal for all cases (~28,800 for the 5m subarray case), the fraction of elements lost ≅ Kpo to first order. In a "K" level system, if n levels are redundant, the expected elements lost are reduced from Kpo to (K-n)po, independently of where the redundancy is implemented, or the degree of it (to first order). Thus a 9 node system would have to incorporate redundancy at five levels to be equivalent to a 4 node system from this point of view.

Lost Elements as a Function of the Number of Distribution Levels

NUMBER OF LEVELS (K)	BRANCHES PER NODE (N)	SUM OF RELATIVE PHASE ERRORS	EXPECTED FRACTION OF ELEMENTS LOST DUE TO LINK FAILURES
1	28,880	1	P_0
2	170	1.41	$2P_0$
3	32	1.73	$3P_0$
4	13	2	$4P_0$
5	8	2.23	$5P_0$

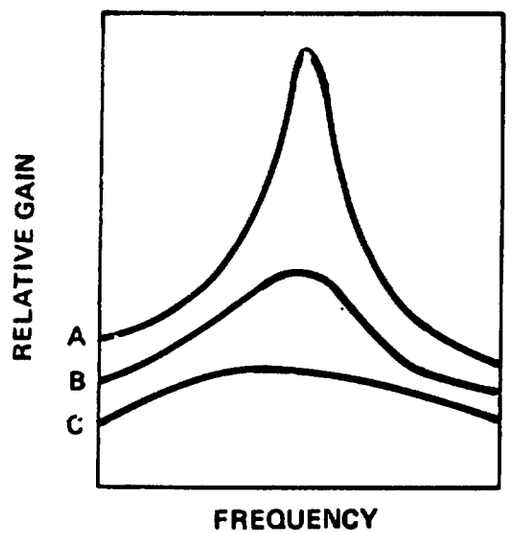
$$\text{EXPECTED NO. OF FAILURES} = N^K[1-(1-P_0)^K] \cong KN^KP_0$$

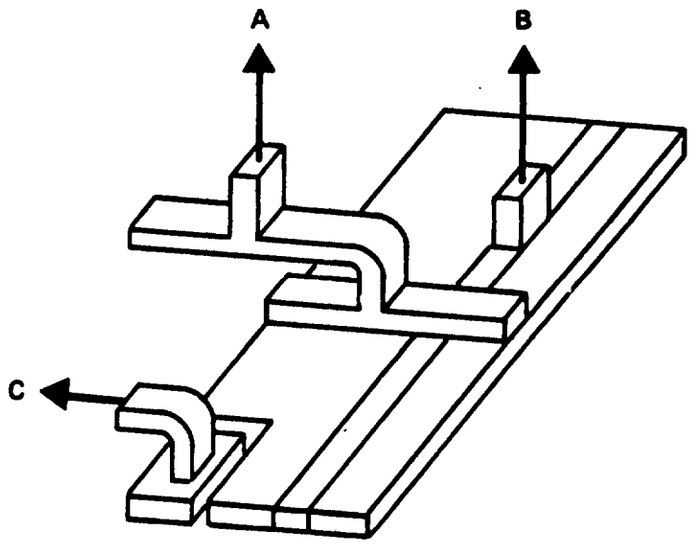
ANTENNA BANDWIDTH TRADE STUDIES

The antenna bandwidth will have to be assessed from the viewpoint of compatibility with the baseline phase control concept. Depending on the offset due to the spread spectrum modulation of the pilot uplink, the feasibility of sharing the transmitting and receiving aperture will have to be determined. The antenna, being composed of standing wave resonant sticks is inherently narrowband, and it may be necessary to use only portions of the transmitting aperture for receiving the pilot signal to increase the available bandwidth.

Experimental measurements are suggested to obtain specific bandwidth values, as well as suitable diplexer measurements to verify feasibility of adequate isolation of the pilot beam.

Antenna Bandwidth Trade Studies





A – HALF MODULE DIPLEX
B – SINGLE STICK DIPLEX
C – SEPARATE ANTENNA

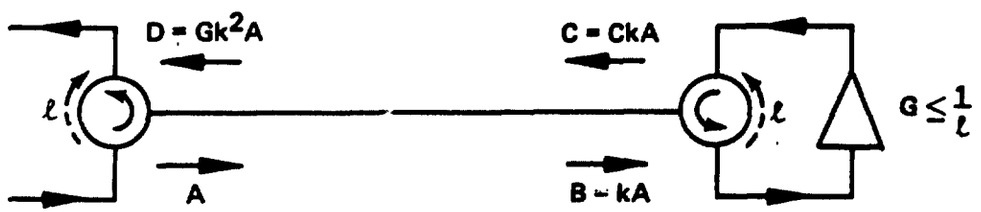
APPROACH TO LINE ATTENUATION IN PHASE DISTRIBUTION SYSTEM

The implementation of the Lincom system will require compensation of cable loss between different nodes. The limits of gain compensation due to diplexer leakage are indicated in the chart. For a signal to error ratio of 20 dB, with 40 dB of diplexer isolation,

$$0 - 2K + 40 = 20 - 40 \text{ dB, i.e. } K = 30 \text{ dB}$$

Thus, for example, the maximum cable length of RG8 cable which can be compensated @500 MHz is 150 meters.

Approach to Line Attenuation In Phase Distribution System



K = LINE ATTENUATION
= DEVICE ISOLATION

FOR -40 DB ISOLATION, S/E, K = -30 DB, I.E., MAX. LINE LENGTH OF RG8 CABLE IS 150 METERS @ 500 MHZ AND 60 METERS @ 2.5 GHZ.

SPS Phase Control Technology Recommendations

SIMULATION/ANALYSIS

- DEVELOP COMPUTER MODEL OF LINCOM SIGNALING FORMAT
  - MODEL UP–DOWN LINK ISOLATION FOR DIFFERENT SPREAD SPECTRUM CHIP RATES
- COMPARE PHASE ERROR BUILDUP IN SINGLE AND MULTIPLE FREQUENCY SYSTEM
- COMPLETE DISTRIBUTION TREE REDUNDANCY/OPTIMIZATION STUDIES IN PROGRESS

EXPERIMENTAL

- CONSTRUCT MSRTS TO VALIDATE PERFORMANCE OVER 300 METER CABLE
- CONSTRUCT ANTENNA FEED AND WAVEGUIDE STICKS TO MEASURE AVAILABLE BANDWIDTH
- EVALUATE PHASE PERFORMANCE OF SCALED KLYSTRON UNDER VARIOUS POWER SUPPLY CONDITIONS
- INVESTIGATE FILTERING CAPABILITY OF PRACTICAL DIPLEXERS
- TEST DIPLEXER–AMPLIFIER COMBINATION TO COMPENSATE FOR CABLE LOSS
- BUILD AND TEST FOUR MODULES TO ASSESS PERFORMANCE OF BACKUP MULTIPLE FREQUENCY SYSTEM
- CONDUCT SCALED TESTS ON RANGE FOR PATTERN VERIFICATION

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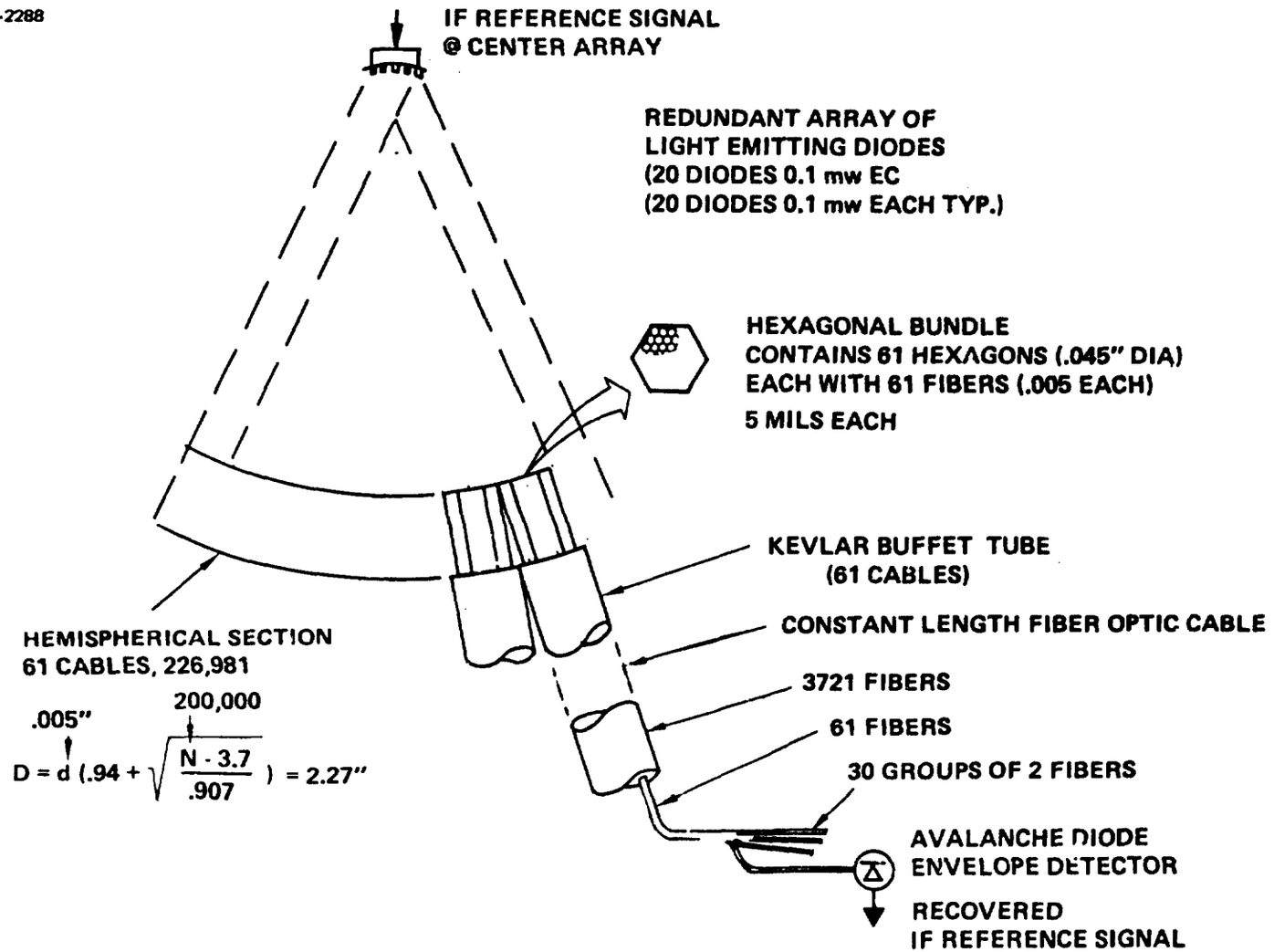
FIBER OPTIC PHASE CONTROL FEASIBILITY

The results of a preliminary assessment indicate that noncoherent fiber optic techniques using low cost LED arrays and state of the art multimode fiber technology may have direct applicability to SPS phase control, either as two-way optical cables to distribute the phase reference in the baseline implementation or as a potentially new phase distribution scheme. The initial issues are maximum modulation rates compatible with the specified phase error budget (5° @ 150 MHz is not adequate when multiplied up to 2.45 GHz) and fiber material selection compatible with radiation and temperature requirements. The attached chart indicates a feasible F-O cable configuration in a roughly 2.5" spherical section capable of accommodating 200,000 individual jacketed fibers.

The material generated in this portion of the briefing was evolved as part of the Boeing IR&D effort in support of SPS technolcgy.

Fiber Optic Distribution System Concept

SPS-2288



Candidate Fiber Optic Materials

- FUSED SILICA CORE, SILICONE CLAD (VALTEC)
  - LOW TEMPERATURE - - - ATTENUATION INCREASES FROM 3.5 DB/KM @ +85°C TO 14 DB/KM @ -40°C
  - HIGH TEMPERATURE - - - OK TO +150°C
  - RADIATION RESISTANCE - - - GOOD
- FUSED SILICA CORE, POLYMER CLAD (DU PONT)
  - LOW TEMPERATURE - - - OK TO 0°C, POSSIBLY TO -50°C
  - HIGH TEMPERATURE - - - CLADDING MELTS AT ~ +80°C
  - RADIATION RESISTANCE - - - REPORTED BEST
- ALL GLASS, GRADED INDEX (CORNING)
  - LOW TEMPERATURE - - - OK TO -50°C, LESS THAN 1DB/KM CHANGE -30° TO + 60°C
  - HIGH TEMPERATURE - - - BELIEVED OK TO +150°C
  - RADIATION RESISTANCE - - - POOR
- ALL GLASS, STEP INDEX (GALILEO)
  - LOW TEMPERATURE - - - 2 TO 3 DB INCREASED ATTENUATION AT -55°C SHRINKING BUFFER CAUSES MICROBENDS
  - HIGH TEMPERATURE - - - BELIEVED OK TO +150°C
  - RADIATION RESISTANCE - - - POOR, BUT IMPROVING

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COMPARISON OF COAXIAL AND FIBER OPTIC SYSTEM

A comparison of expected phase changes with temperature for a coaxial cable and a fiber optic cable @ IF frequency indicates that there is a nearly 20 times smaller phase change for the fiber optic cable. As an example, for a 100°C change in temperature, over a 30 meter length, the phase change in a F-O cable would be just under 5° when multiplied up from 150 MHz to 2.45 GHz. This does not include the compensating effects of the change of refractive index with temperature which would reduce this value, or the possibility of using an injection laser with a single mode fiber which would have much lower dispersion. Since the last level of distribution to the klystron modules themselves would, on the average, require cables below 30 meter long, the total phase error budget of 10° (RSS value) might well accommodate such an error, resulting in a large simplification of the phase control distribution circuitry.

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Comparison of Coaxial and Fiber Optic System

SPS-2276

	COAXIAL CABLE		OPTICAL FIBER
	RG-58 SOLID DIEL.	LDF-50 FOAM DIEL. (1/2 DIA)	~5 MIL DIA (65 μm ACTIVE CORE)
ATTENUATION db/km (100 MHz)	180 db	35	5
MASS kg/km	43	160	.5
COST $/km	2,000	4,200	1500 (1978)
PHASE DELAY @ IF	120°/METER (ϵ=1.0, λd=3m)		180°/METER (ϵ=1.5 γ=2m) FIBER=1.3m
LINEAR EXPANSION	16.5×10^{-6} per °C (COPPER)		5.5×10^{-7} (QUARTZ)
PHASE CHANGE FOR ΔT=150°C L=300m	89.1°		4.46°

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Fiber Optic Phase Distribution Assessment

- POTENTIAL ADVANTAGES
  - LOWER ATTENUATION, LIGHTER, LOWER COST, LOWER PHASE DELAY
  - EASY IMPLEMENTATION OF REDUNDANCY
  - NO ELECTROMAGNETIC SHIELDING NEEDED
  - NO REVERSE COUPLING
  - ONE FAILURE MODE ONLY – CANNOT SHORT CIRCUIT

- POTENTIAL PROBLEM AREAS
  - COMBINED TEMPERATURE & RADIATION HARDNESS MAY REQUIRE SPECIAL FIBER
  - COMBINED PHASE DELAY, ATTENUATION, BANDWIDTH AND NUMERICAL APERTURE OVER DESIRED TEMPERATURE RANGE NOT FULLY UNDERSTOOD.

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Fiber Optics Verification Program

- SELECT CANDIDATE COMPONENTS
- DESIGN AND FABRICATE 100 MHZ FIBER OPTIC TRANSMITTER WITH EMITTER ARRAY
- DESIGN AND FABRICATE TWO OR MORE 100 MHZ FIBER OPTIC RECEIVERS
- SIMULATE TRANSMITTER/FIBER COUPLING CONDITIONS
- ASSEMBLE TWO OR MORE 0.5 KM LINKS WITH ONE OR MORE FIBER TYPES
- EVALUATE PERFORMANCE OVER FULL TEMPERATURE RANGE

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MPTS Midterm Review

- SPS PHASE CONTROL IMPLEMENTATION
  - COMMENTS ON LINCOM SYSTEM
  - INITIAL REDUNDANCY CALCULATIONS
  - FIBER OPTIC FEASIBILITY ASSESSMENT

- SOLID STATE DESIGN FOR SPS
  - DEVICE PARAMETERS ASSESSMENT
  - POTENTIAL CIRCUIT FOR SPS INTEGRATION
    COMMENTS ON NOISE BEHAVIOR

- MPTS COMPUTER PROGRAM
  - COMPUTER MODEL STATUS
  - PLAN FOR NEXT PERIOD

OCTOBER 19, 1978

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FIELD EFFECT TRANSISTOR MATERIALS

Materials parameters determine field effect transistor performance for a given geometry. For the devices desired for SPS, silicon has marginal high-frequency capability. The state of the art is the considerably faster gallium arsenide, which has been baselined. There may however be better materials developed in the future which allow better performance, such as indium phosphide.

As data develops on relative radiation degradation and relative reliabilities of similar devices made of these different materials it will be incorporated into updating the study results.

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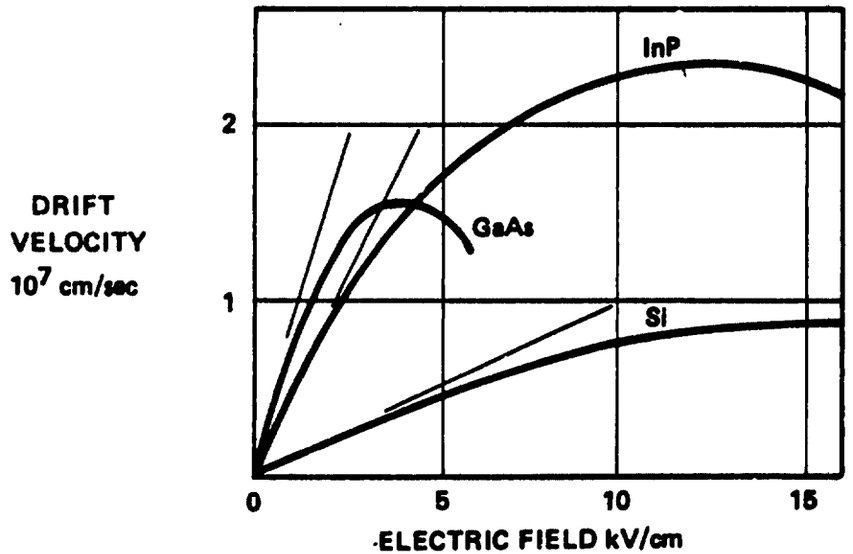
Field Effect Transistor Materials

SPS-2263



	MAX. DRIFT VELOCITY ($\times 10^7$ cm/sec)	MOBILITY (cm^2/v-sec)	G_r	ON RESISTANCE	f MAX. (GH_z)
Si	0.8	1350	11.7	1	40
GaAs	1.6	8500	12.5	1/6	80
InP	2.5	5500		1/4	120 (SILICON BIPOLAR ~ 20)

MICROWAVE TRANSISTOR POWER ADDED EFFICIENCY

Potential improvements large enough to ensure viability for SPS in power efficiency exist for solid state devices by operating them as switching mode amplifiers. Due to these considerations, an efficiency of 80% is projected for GaAs MESFET's within the SPS time-frame.

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Microwave Transistor Power Added Efficiency

CLASS	A	B	C	D (SWITCHING MODE)
THEORETICAL COLLECTOR EFFICIENCY (η_c)	50%	78.5%	85%	>90%
TYPICAL RANGE OF PRACTICAL COLLECTOR EFFICIENCY (η_c)	20-30%	60-70%	65-85%	>90%
GaAs MESFET AMPLIFIER (ABOVE 2 GHz) POWER ADDED EFFICIENCY	to 44%	to 68%		
SILICON BIPOLAR AMPLIFIER (ABOVE 1 GHz) POWER ADDED EFFICIENCY			to 50%	

$$\eta(\text{POWER ADDED}) = \eta_c(1 - 1/g)$$

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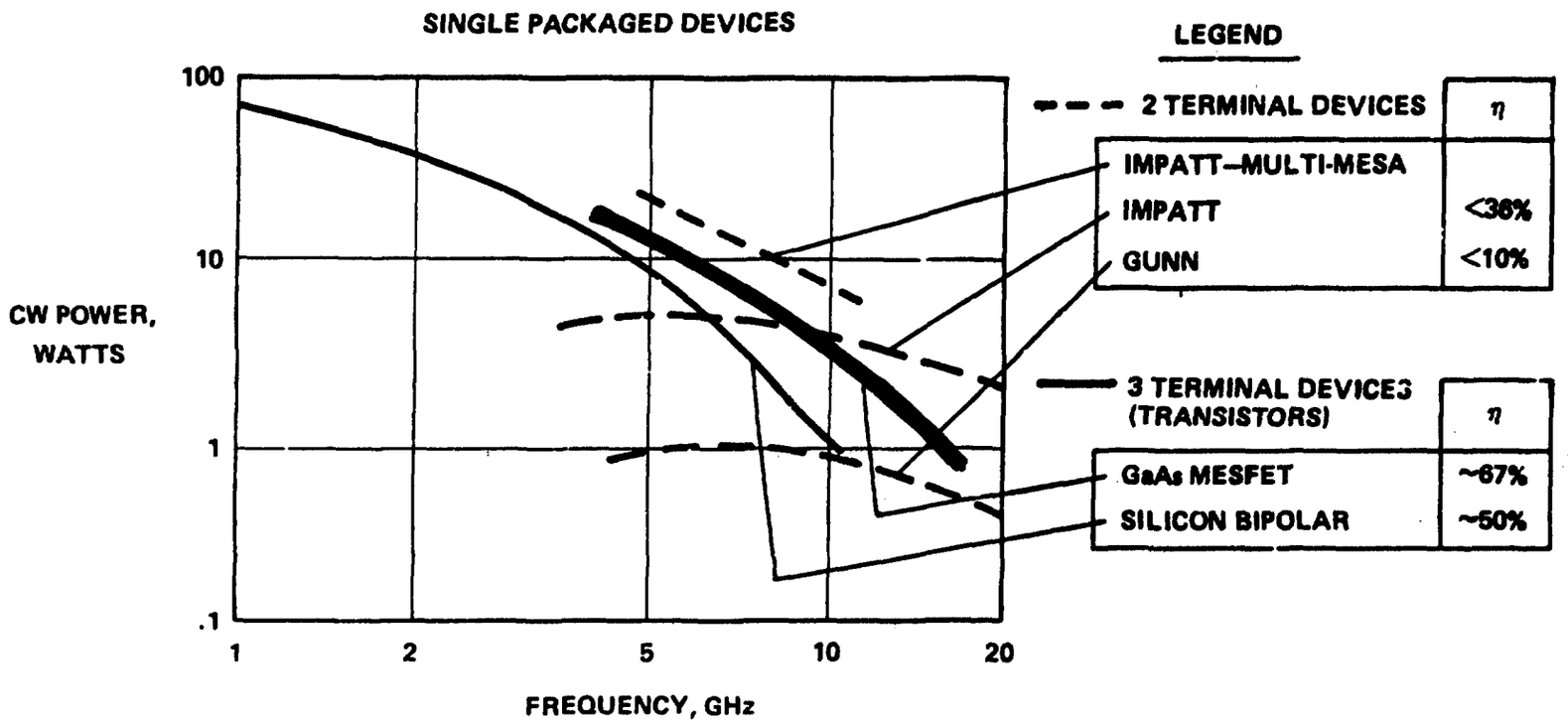
SOLID STATE C.W. POWER STATUS - 1978

While two-terminal microwave amplification devices have equivalent or greater power handling capability compared to 3- terminal devices they lack sufficient efficiency for SPS viability. Of the 3- terminal devices GaAs MESFET's were chosen as the most attractive solid state power amplifier devices.

Solid State CW Power Status—1978



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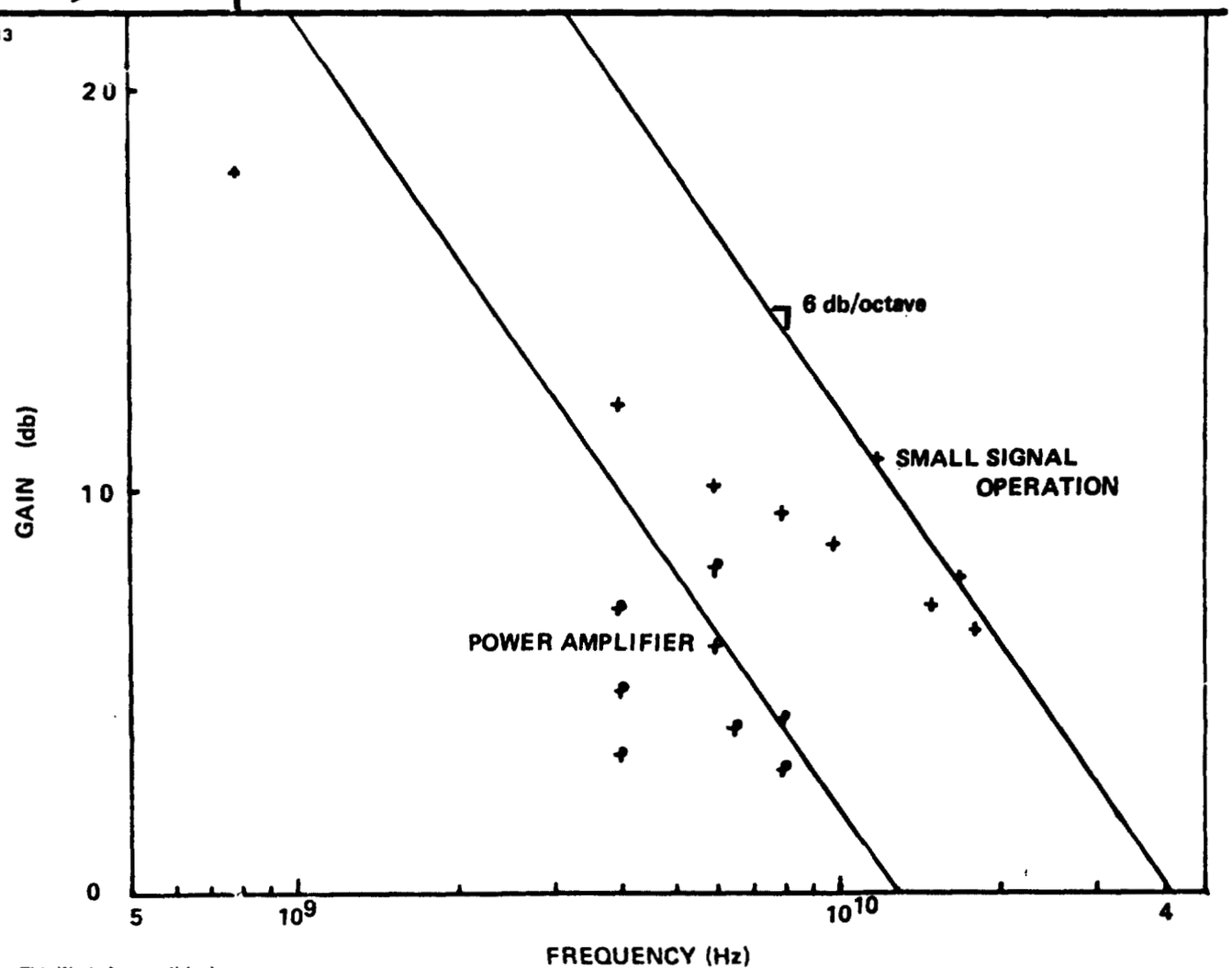
GAIN VS FREQUENCY FOR GaAs FETS

The difference between small-signal and large-signal gains is significant. GaAs FETS still have sufficient gain for use in high-efficiency SPS power amplifiers. It was this consideration and the reliability aspects that resulted in our selection of the use of FETS instead of bipolar transistors in the concept. This data is subsequently used in the design of the 3 stage amplifier proposed for the SPS module.

Gain vs Frequency for GaAs Fets

SPS-2313



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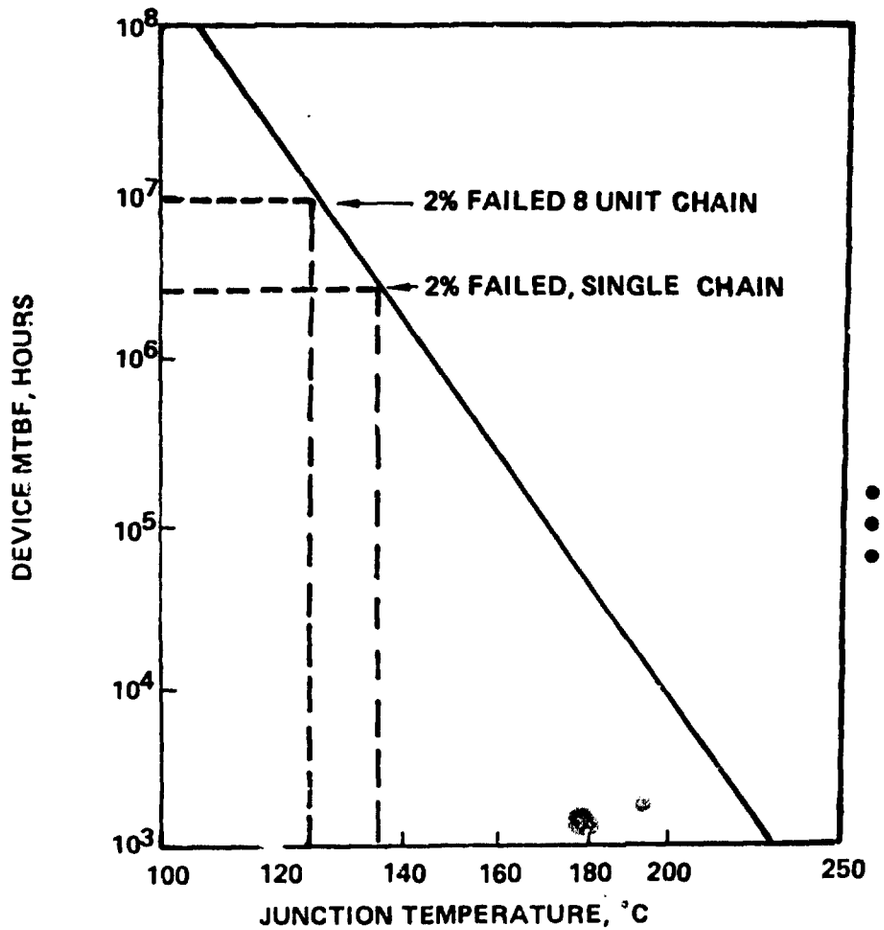
SOLID STATE DEVICE LIFETIMES

The failure statistics indicated in the attached chart show that at a channel temperature of 135°C, 98% of the devices will still be operating after 30 years. This suggests that a no-maintenance mode of operation may not be unfeasible. Even if a single FET failure in a power module consisting of 8 output FET's (say 4 watts each) constituted a total loss of the entire module (no graceful degradation), the operation of such modules @ 125°C would result in 2% loss after 30 years, compatible with SPS failure rate budget.

Solid State Device Lifetime



- GaAs FET
- 30 YEAR MAINTENANCE
- LOG NORMAL FAILURE DISTRIBUTION
  $\sigma = 1$

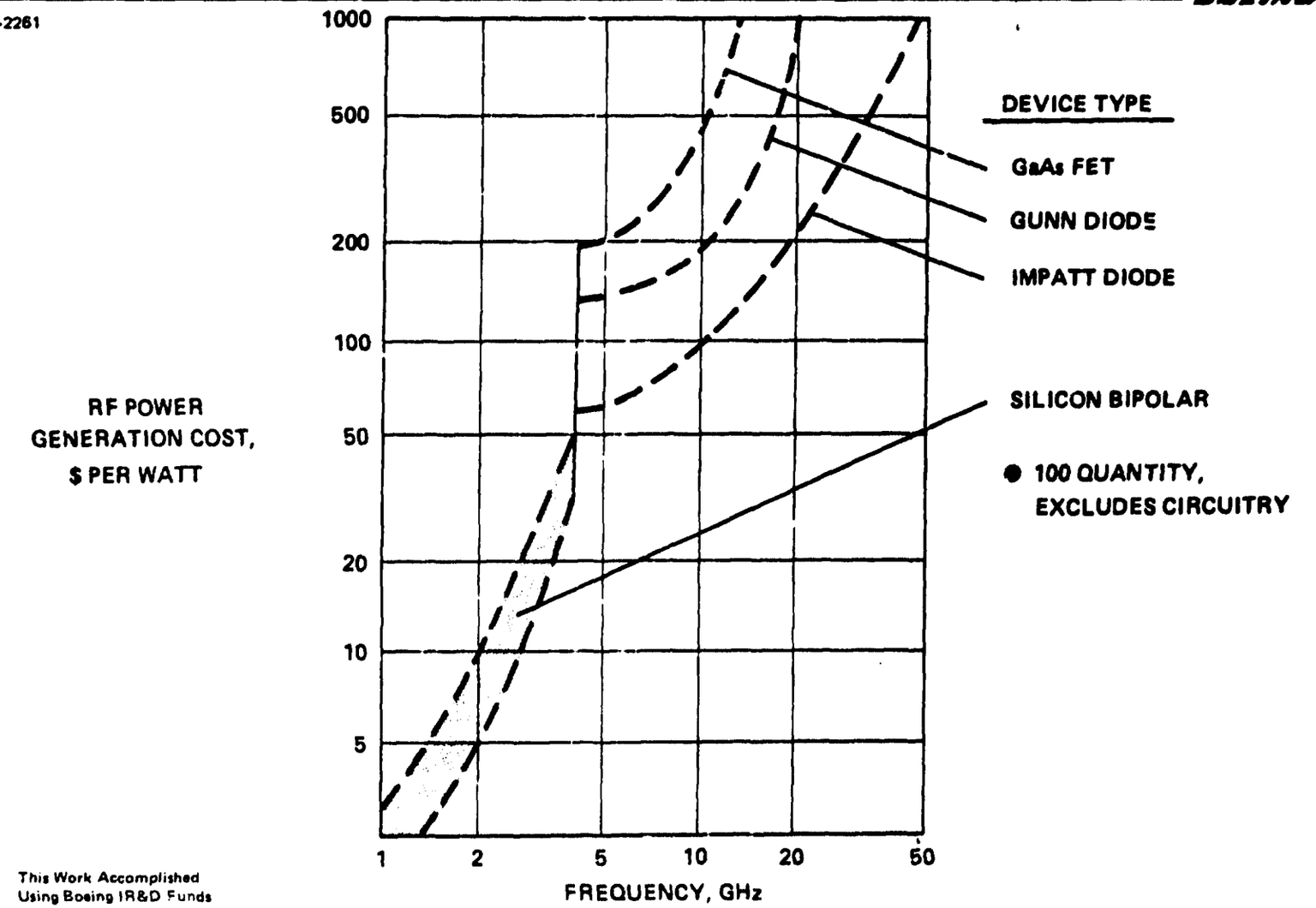
1978 RELIAB. PHYSICS SYMP.

DEVICE COST TRENDS - 1978

At present RF power from solid state devices is quite expensive, in excess of $100 per watt at the SPS frequency. However, no large unit production has been experienced to date.

Device Cost Trends–1978

SPS-2261



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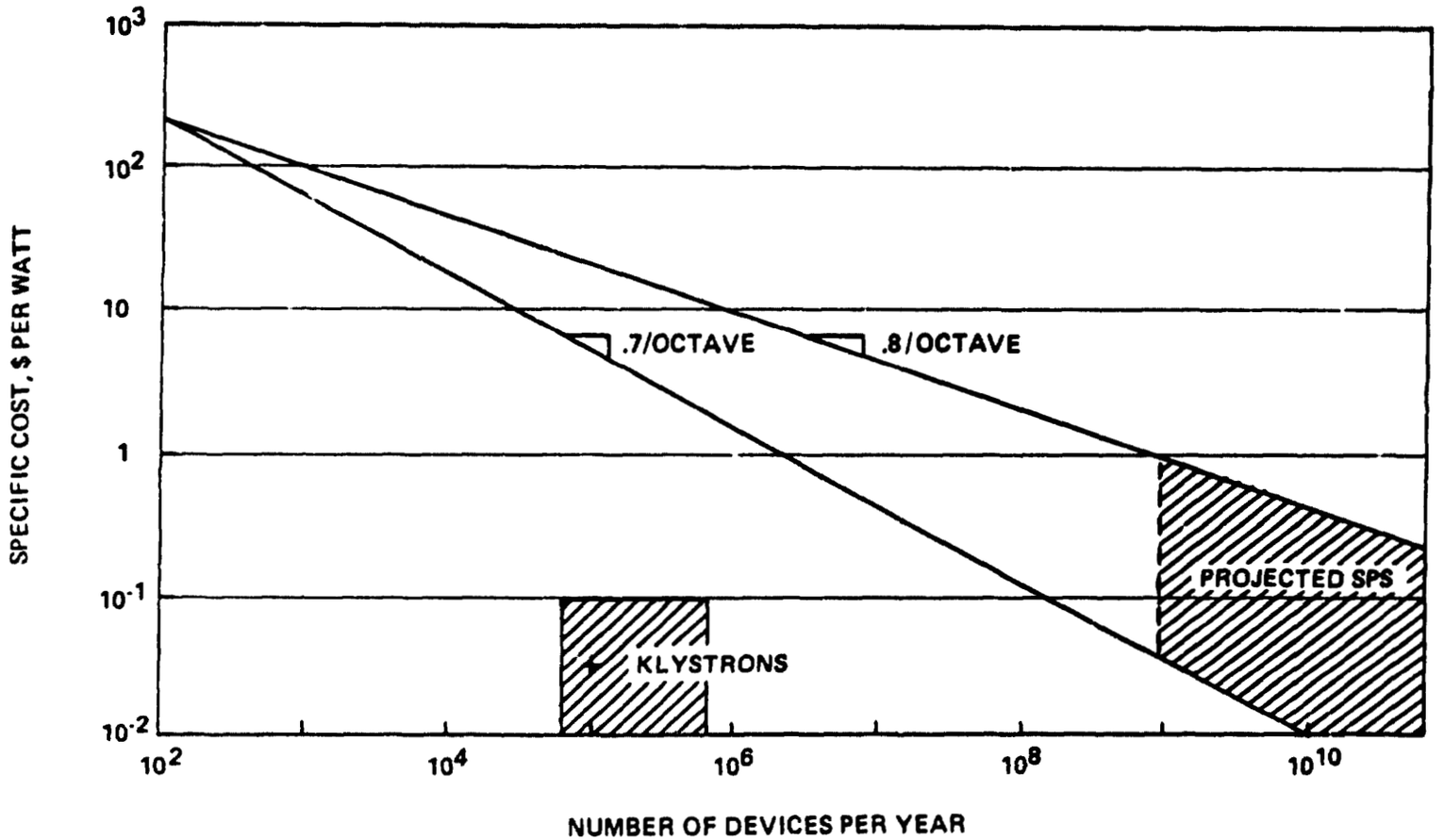
SOLID STATE DEVICE MATURE INDUSTRY COSTING

With a 70% learning curve (i.e. units produced at the rate of 2n per year cost 70% as much as units produced at the rate of n per year), cost per unit power for GaAs FETS is about the same as the projected cost per unit power for klystrons.

Solid State Device Mature Industry Costing

SPS-2326



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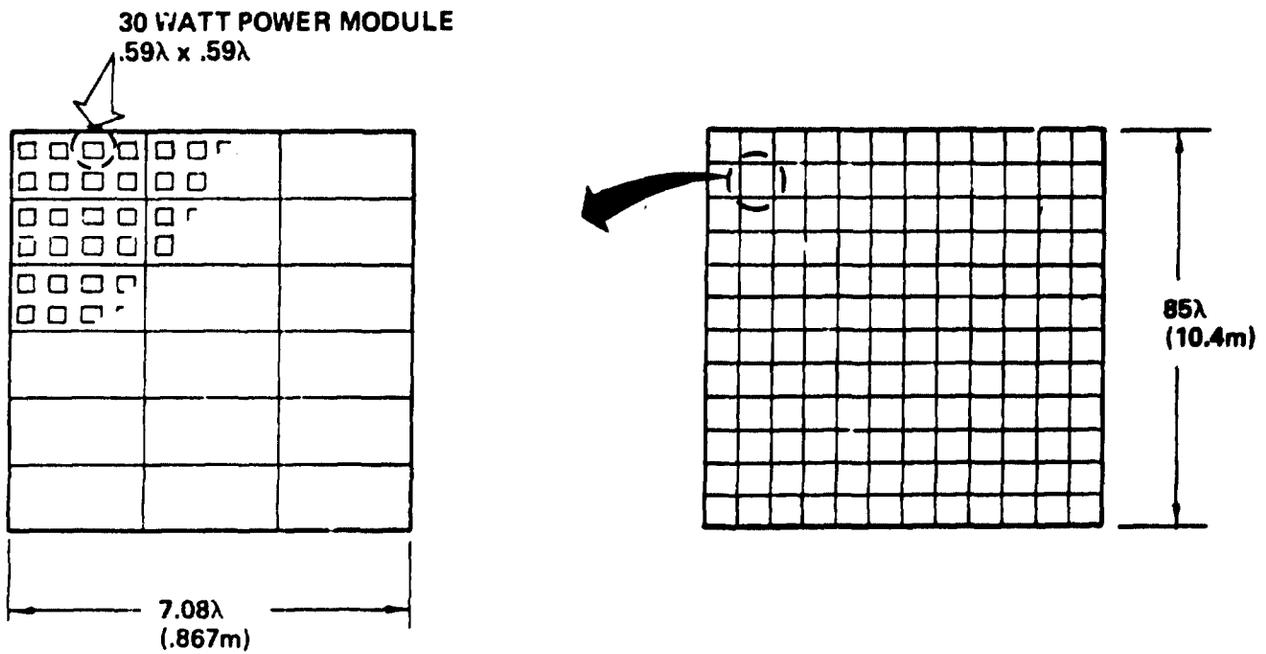
POTENTIAL SOLID STATE SUBARRAY LAYOUT

For our initial solid state microwave power transmitter design, individual 30 watt power modules will be fabricated in panels of 8 modules dropping 30 volts each due to an internal series connection. The panels are combined into panel groups consisting of 3 parallel strings of 6 panels in series. The panel groups are arranged in a 12 x 12 series - parallel matrix to make up a subarray of standard size.

Further investigation is needed into the failure made of such a chain to determine whether an acceptable reliability can be obtained.

Potential Solid State Subarray Layout



- 1 PANEL GROUP = 144 MODULES = 4.32 kw
- 3 STRINGS OF 6 PANELS IN SERIES
- 180^{V} PER PANEL GROUP @ 15^{V} PER DEVICE
- 1 SUBARRAY = 144 PANEL GROUPS = 622 kw
- 12 STRINGS OF 12 PANEL GROUPS = 2.16 kv

SOLID STATE SPS DESIGN PARAMETERS

The proposed power module size has been subjected to an initial thermal assessment. An assumed internal drop of 25°-35°C between the FET channel and the heat sink has been allocated and a two sided radiator capability has been assumed. Design charts relating the rf efficiency, thermal capability and SPS design constraints have been developed (to be published in Microwave System News Nov 1978) which allow the determination of the dc power output and array size. For the power module rf level and size selected, the center of the array operates at the thermal limit of 5.75 kw/m^2 (cf 22 kw/m^2 for the klystron design). The power output is thus roughly a half (2.5 GW) and the space array area is roughly twice (1.5 km dia.), resulting in 1/4 the power density due to the fact that solid state sources cannot operate at the temperature of the klystron (300°-500°C). Alternate array layouts are feasible which overcome this problem but the associated beam shaping constraints have not been solved.

Solid State SPS Design Parameters

- HEAT DISSIPATION CAPABILITY FOR LONG LIFE T_j=125°C -ΔT=25°C i.e., T=100°C WITH 2-SIDED RADIATOR, 90% FIN EFFICIENCY, ϵ=.8 α_s=.3, SUN NORMAL TO RADIATOR PLANE IS Q/A=1.25 kw/m^2

- FOR A POWER ADDED EFFICIENCY OF 82%, THIS CORRESPONDS TO AN RF POWER DENSITY OF 5.75 kw/m^2, i.e., COMPATIBLE WITH THE 30-WATT PER MODULE DESIGN. FOR A 75% EFFICIENCY, THIS IS 3.75 kw/m^2 OR 19.5 WATTS PER MODULE.

- THE RESULTING SPS PARAMETER WITH THE BASELINE CHAIN EFFICIENCY ESTIMATES ARE

  2.5 GIGAWATT, 1.4 km (η=82%)
  2.0 GIGAWATT, 1.55 km (η=75%)

  WITH 10db GAUSSIAN TAPER AND 23 mw/cm^2 IONOSPHERIC DENSITY

IMPACT OF PHASE LOCKING ON PHASE NOISE

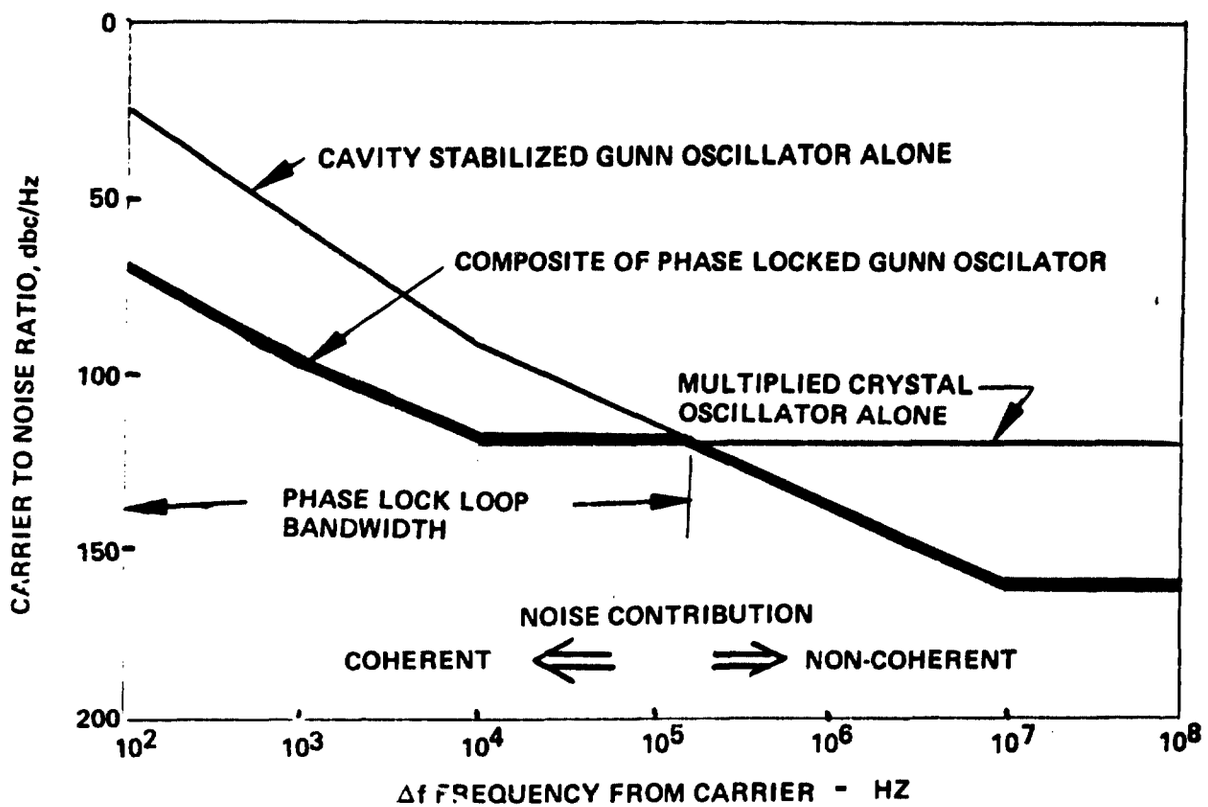
Phase locking can reduce phase noise greatly and allow devices with lower noise floor but higher phase noise to be used. For noise power levels outside the rectenna site the noncoherent distributions are of main importance and the noise level floor outside the passband of the phase lock loop is of importance.

An initial assessment of the noise properties of S.S. sources indicate that as in the case of the klystron, the out of band near-carrier component noise floor of -160 dbc/Hz can be expected.

Impact of Phase Locking On Phase Noise

SPS-2347

(X-BAND, SINGLE SIDEBAND)



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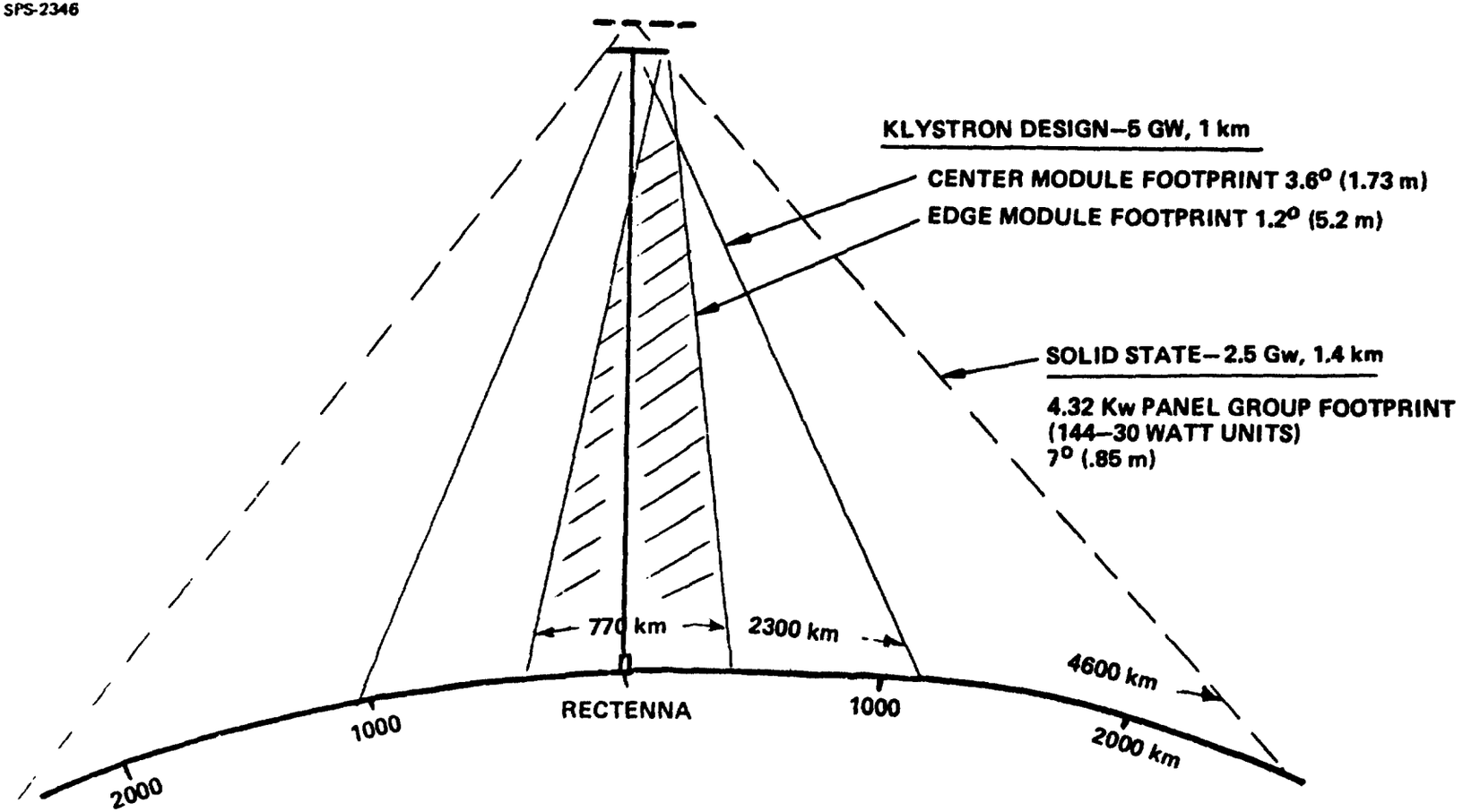
NON-COHERENT NOISE POWER DISTRIBUTION

The footprints of the noise contributions for different levels of phase control are indicated. Due to the smaller lowest order phase controlled area unit of a solid state SPS, its incoherent noise will have a wider footprint. There is no other internal transmitter effect at work except the filtering action of the klystron cavities (estimated by NASA-JSC at 24 dB/octave), which should be built-in at a low level of the S.S. amplifier. The coherent, close in to carrier, contributions are expected to result in negligible offset from nominal beam center. For a frequency deviation of 5 MHz (phase lock loop bandwidth, say), $df/f = d\lambda/\lambda = d\theta/\theta = 5/2500 = 1/500$. The expected offset would then be, for a 10 km rectenna ($R\theta$)

$$Rd\theta = \frac{(10{,}000)}{500} = 20 \text{ meters.}$$

Non-Coherent Noise Power Distribution

SPS-2346



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COMPARATIVE CALCULATION OF GROUND NOISE

Preliminary calculations of the noncoherent noise spectral density indicate that the solid state SPS should have significantly less ground noise than the baseline SPS with a 70 Kw klystron. Nevertheless, this is not due to the fact that klystrons are "noisier" rather that there is less total power radiated (~factor of 2) over a larger area. Further refinements of these calculations are needed, both close to the carrier and out of band, where filtering action of external circuits can be utilized.

Comparative Calculation of Ground Noise

SOLID STATE

$P_N = 3.5 \times 10^9 \times 10^{-16} = 3.5 \times 10^{-7}$ W/Hz

$G_N = 4\Pi AN/\lambda^2 = 308$

N = .5 COHERENCY FACTOR
AREA = $(7\lambda)^2$

NOISE SPECTRAL DENSITY = $P_N G_N / 4\Pi R_o^2$

$P' = 7 \times 10^{-21}$ WATTS/m^2/Hz
= -201.5 dbw/m^2/Hz

EXTERNAL FILTER
CAN PROVIDE
ADDITIONAL ATTENUATION

KLYSTRON

$P_N = 7 \times 10^9 \times 10^{-16} = 7 \times 10^{-7}$ W/Hz

G_N = 3650 FOR AV. AREA PER KLYSTRON OF 8.7 m^2

$P' = 1.54 \times 10^{-19}$ WATTS/m^2/Mf
= -187.4 dbw/m^2/Hz

MULTIPLE CAVITY DESIGN PROVIDES
24db/OCTAVE ATTENUATION

This Work Accomplished
Using Boeing IR&D Funds

Solid State Technology Recommendations

- WORK WITH RCA ON POWER MODULE DESIGN VERIFICATION
  - CONSTRUCT AND TEST BASIC POWER MODULE
  - EVALUATE PERFORMANCE OF PHASE LOCKED LOOP AROUND MODULE
- COMPLETE COMPARATIVE NOISE ASSESSMENT WITH TUBE APPROACH
- CONDUCT POWER–RELIABILITY–COST TRADE STUDY
  - REFINE THERMAL ANALYSIS
  - CONTINUE DESIGN INTEGRATION INCL. STRUCTURAL INTERFACE AND PHASE CONTROL
- INITIATE LABORATORY VERIFICATION OF HYBRID MULTICHIP MODULAR APPROACH
  - EVALUATE LOW LOSS MULTIPLE FEED COMBINER CONCEPT
  - OBTAIN PATTERNS INCL. MUTUAL COUPLING ON MICROSTRIP CAVITY RADIATOR
  - VERIFY OBTAINABLE EFFICIENCIES IN SWITCHED MODE OPERATION

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MPTS Midterm Review

- SPS PHASE CONTROL IMPLEMENTATION
  - COMMENTS ON LINCOM SYSTEM
  - INITIAL REDUNDANCY CALCULATIONS
  - FIBER OPTIC FEASIBILITY ASSESSMENT
- SOLID STATE DESIGN FOR SPS
  - DEVICE PARAMETERS ASSESSMENT
  - POTENTIAL CIRCUIT FOR SPS INTEGRATION
  - COMMENTS ON NOISE BEHAVIOR
- MPTS COMPUTER PROGRAM
  - COMPUTER MODEL STATUS
  - PLAN FOR NEXT PERIOD

OCTOBER 19, 1978

SPS Computer Model Status

- "TILTMAIN" PROGRAM ACCOMPLISHMENTS
  - CONVERSION OF TILTMAIN ONTO BOEING SYSTEM
  - GRATING LOBE SEARCH MODIFICATION FOR NASA-JSC
  - MEAN PHASE VS. RADIAL DISTANCE CAPABILITY

- INITIATION OF "MODMAIN"
  - PROPOSED PROGRAM WHICH DETAILS THE ARRAY MODEL TO THE KLYSTRON LEVEL
  - DEVELOP CAPABILITY TO ACCESS NASA-JSC COMPUTER
  - SET UP FILES FOR MAIN PROGRAM AND ITS FOUR SUBROUTINES
  - COMPLETED PRELIMINARY PROGRAM MODIFICATION WHICH EXCITES THE SPACE ANTENNA FOR EACH GROUND POINT WHERE THE PATTERN IS CALCULATED.

Computer Model—Plan for Next Period

- DEVELOP "MODMAIN" TO MATCH A NO ERROR TILTMAIN RUN. "MODMAIN" WOULD HAVE A STRUCTURE IN WHICH EACH 10 m BY 10 m MODULE IS EXCITED ONLY ONCE AND THE CONTRIBUTION OF A MODULE IS SUMMED AT EVERY GROUND POINT.

- INCORPORATE THE "ERROR" SUBROUTINE INTO "MODMAIN" AND MATCH TO TILTMAIN RUNS.

- DETAIL THE MODEL BY CHANGING THE SIZE AND SPACING OF THE MODULES. THERE WILL BE TEN DIFFERENT SIZES OF KLYSTRON MODULES CORRESPONDING TO THE TEN STEP QUANTIZED ILLUMINATION TAPER.

Electric Orbit Transfer Vehicle Analysis

ELECTRIC ORBIT TRANSFER VEHICLE ANALYSIS

The state of work for this task requested that the cost effectiveness of an electric orbit transfer vehicle (EOTV) used to support GEO construction of an SPS be compared with a LO_2/LH_2OTV used for GEO construction and also the self power module transfer concept when LEO construction is utilized. The key variables in this task were the use of silicon and gallium arsenide solar cells and also consideration of an equatorial launch site. The initial statement of work emphasized the analysis of the orbit transfer vehicle. The addition of an ECP expanded the analysis to assess all implications of the GEO construction, EOTV concept.

The EOTV mid-term discussion will cover the Silicon vehicle and its performance, cost, design, operations, and construction characteristics.

Electric Orbit Transfer Vehicle Analysis

SPS-2248

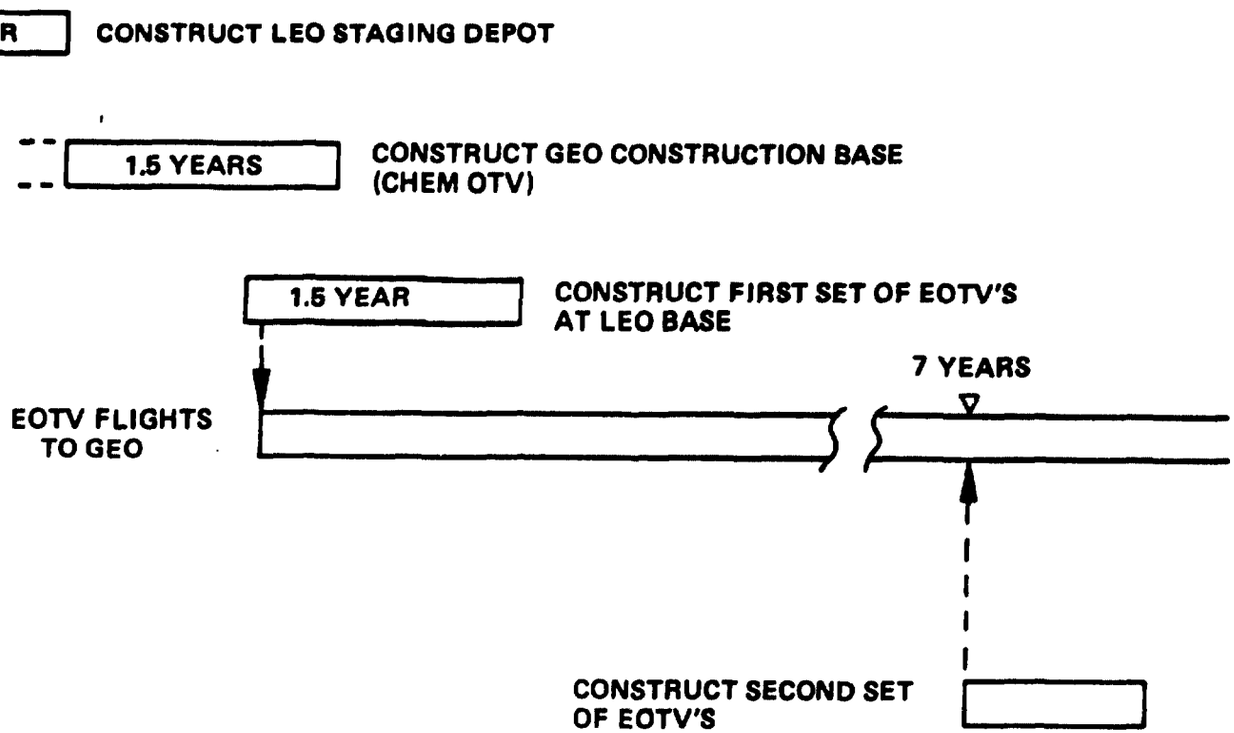
- SOW
  - ASSESS THE COST EFFECTIVENESS OF AN ELECTRIC OTV TO BE USED IN GEO CONSTRUCTION WITH RESPECT TO OTHER OTV'S USED FOR LEO AND GEO CONSTRUCTION
  - KEY VARIABLES
    - SILICON AND GALLIUM ARSENIDE CELLS
    - EQUATORIAL LAUNCH SITE

- MIDTERM TOPICS
  - SILICON EOTV
  - PERFORMANCE AND COST OPTIMIZATION
  - DESIGN CHARACTERISTICS
  - MISSION OPERATIONS
  - CONSTRUCTION
  - LEO BASE DEPOT OPERATIONS
  - LEO BASE CHARACTERISTICS
  - COST
  - PRELIMINARY COMPARISON WITH LEO CONSTRUCTION

GEO CONSTRUCTION/EOTV PROGRAM SCENARIO

The time-phasing of the major steps associated with a GEO construction/EOTV program are illustrated. It should be noted that this scenario does not reflect a precursor or demonstration satellite program which would most likely include some form of an orbital base. The emphasis however is to develop the capability to construct SPS(s) to produce 10 GWe per year. The LEO base will initially be used to support the construction of the large GEO construction base. Prior to the completion of the GEO base, the LEO base will also be used to construct the first set of EOTV's which will be used to deliver SPS components to the GEO construction base. The actual construction of the EOTV's will begin at a point in time when the arrival of the first EOTV at the GEO base corresponds to the operational status of the GEO base. The reference EOTV in this program has a 10 flight life corresponding to approximately 7 years of operation. Accordingly, at the end of seven years a second set of EOTV's are constructed.

GEO Construction/EOTV Program Scenario



PERFORMANCE AND COST OPTIMIZATION FACTORS

The first EOTV topic to be discussed will be that of the performance and cost optimization analysis. Several key factors relate to these optimizations and are so indicated. The annual mass to be delivered relates to satellite(s) capable of producing 10 GWe ground output. Delivery of all cargo associated with the satellite in 330 days allows sufficient time for final installation and checkout so that a satellite can come on line at the end of one year. Satellite mass includes a growth factor of 26%. The total cargo delivery mass includes not only components but the containers for the components and the rack to support the containers. Five percent of the component mass has been allocated to both the containers and the payload rack. The majority of the containers such as those associated with the solar arrays will be used in the actual installation process. Other containers are judged not to be worth the value of recovery so consequently the down requirement is only the 5% associated with the payload rack.

Payload delivery capability for each EOTV is somewhat arbitrarily established at 4,000 metric tons after considering such factors as the size of the vehicle and the number of vehicles in flight for different payload capabilities. Payload return requirements again reflect the 5% associated with the payload rack itself. The 120 cm argon ion thrusters are the same as what has been used in the self-power LEO construction concept. As in the self-power LEO construction concept, key variables in the optimization include specific impulse and trip time, and with the EOTV concept the number of flights performed by each EOTV now becomes an important variable.

Several factors also have a limiting influence on the outcome of the optimization, most notable of these being the solar array performance which will be discussed immediately following this chart and thruster lifetime which has a less significant impact on performance however it is a key factor in terms of vehicle refurbishment and will be discussed in subsequent charts.

Performance and Cost Optimization Factors

SPS-2247

- SILICON CR=1 SOLAR POWER SATELLITES AT RATE OF 10 GW_e GROUND OUTPUT PER YEAR
- CARGO DELIVERY COMPLETED WITHIN 330 DAYS OF FIRST DELIVERY TO GEO
- SATELLITE(S) MASS OF 99000 MT
- TOTAL CARGO DELIVERY MASS:

  UP = 110000 MT (COMPONENTS + CONTAINERS + RACK)
  DOWN = 5500 MT (RACK)

- EOTV DELIVERY CAPABILITY

  UP = 4000 MT (COMPONENTS + CONTAINERS + RACK)
  DOWN = 200 MT (RACK)

- 120 cm ARGON ION THRUSTERS
- KEY VARIABLES IN OPTIMIZATION
  - SPECIFIC IMPULSE
  - TRIP TIME
  - EOTV LIFE (NUMBER OF FLIGHTS)
- KEY LIMITING FACTORS
  - SOLAR ARRAY PERFORMANCE/DEGRADATION
  - THRUSTER LIFETIME

SOLAR ARRAY PERFORMANCE

The next three charts will deal with several factors relating to solar array performance.

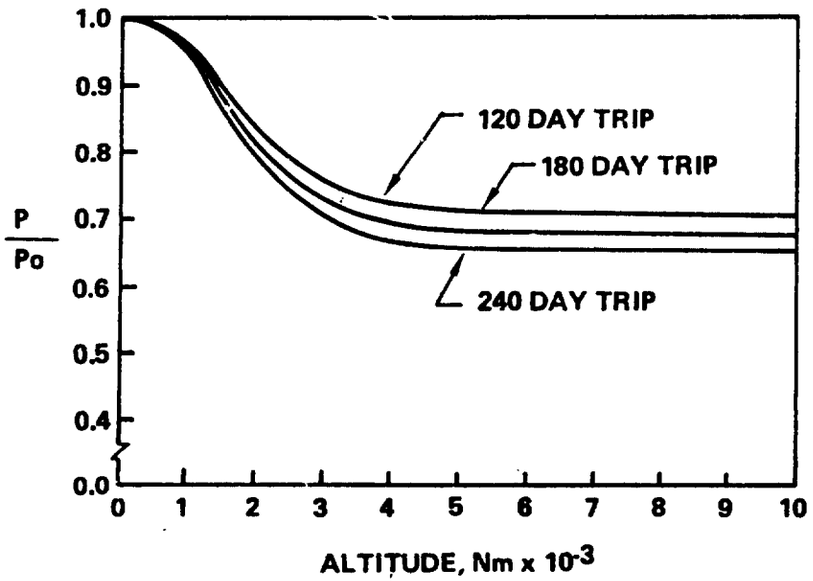
The first chart deals with the sensitivity of solar array performance to trip time and cover glass thickness. In the case of the trip time sensitivity, longer trip times mean more time in the Van Allen belts, resulting in a greater degree of degradation and lower power output. However, in all cases indicated, the degradation levels off after approximately 4,000 nautical miles have been reached. Approximately 8% difference in power output exists between the 120 and 240 day trip times.

Regarding cover glass sensitivity, it can be seen that by going from the 3 mil cover used in the SPS satellite to a 6 mil cover for EOTV application, approximately an 8% improvement can be achieved in terms of average power output. However, since the mass per square meter increases approximately 70% the thicker cover glass does not initially appear an effective method of achieving a higher power capability.

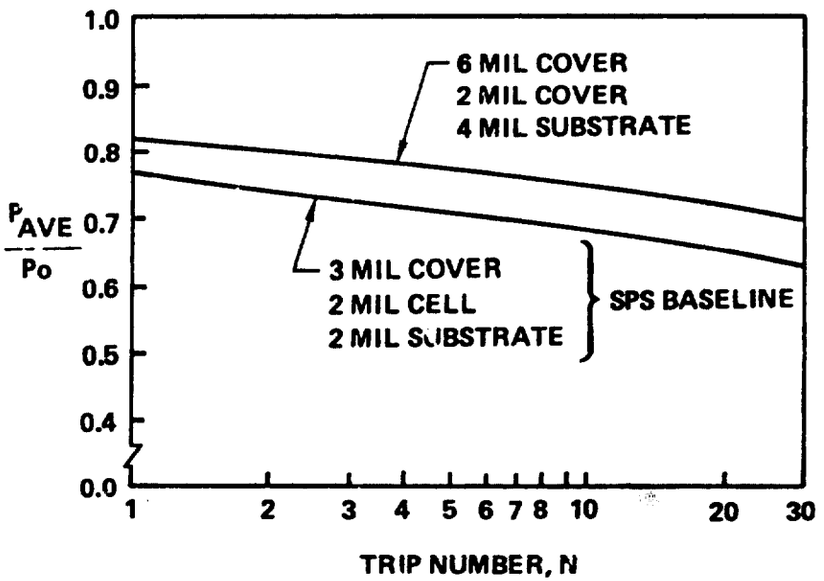
It could well indicate that should an 8% greater power be required, an oversizing of 8% in area with a basic blanket including a 3 mil cover is more effective. Cost and performance of an EOTV using a blanket with a 6 mil cover will be established after the mid-term.

Solar Array Performance

- TRIP TIME SENSITIVITY



- COVER GLASS SENSITIVITY

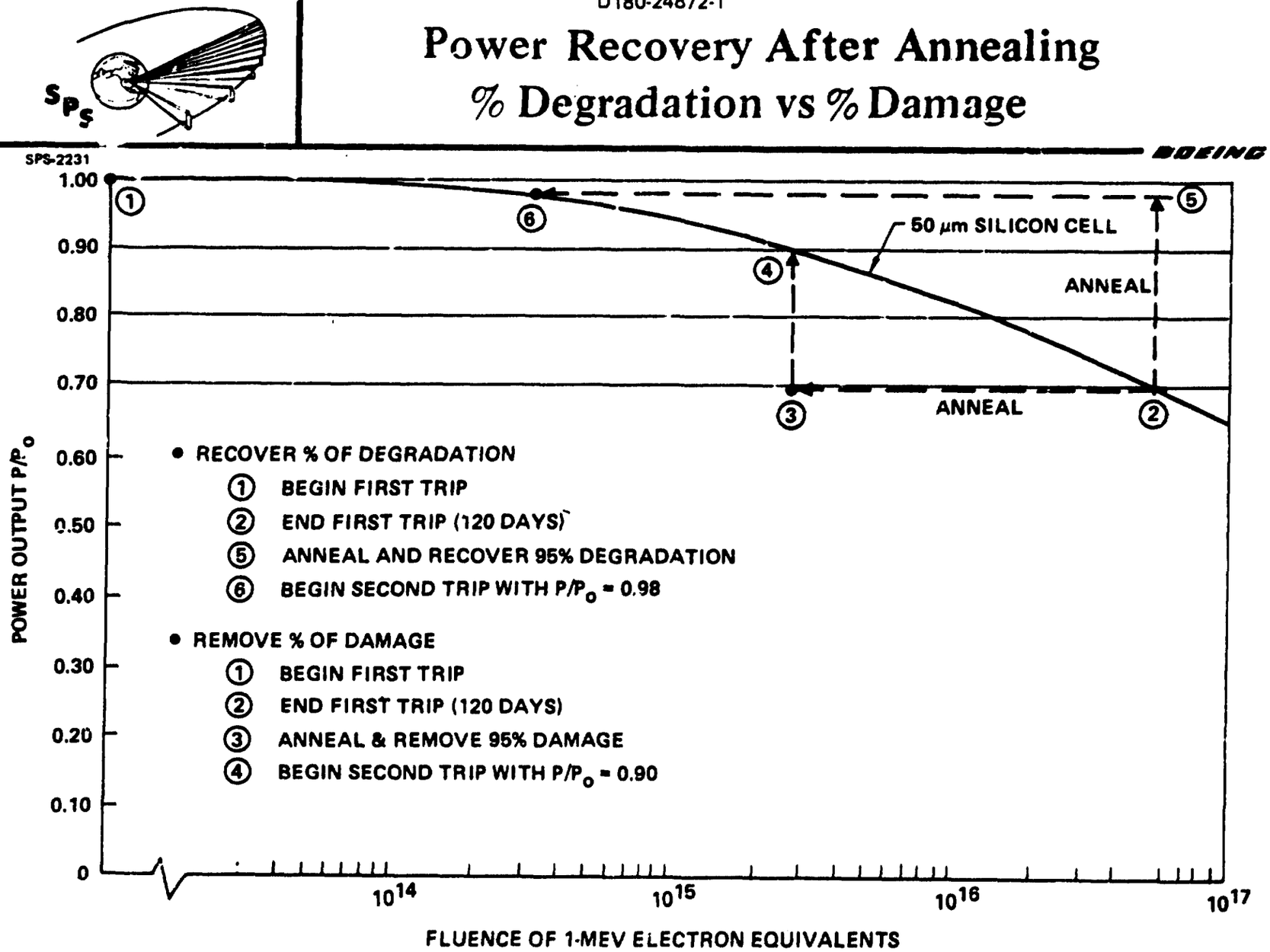


POWER RECOVERY AFTER ANNEALING

PERCENT DEGRADATION VS PERCENT DAMAGE

Prior to discussing the value of annealing solar arrays to remove radiation damage, and therefore improve power output, it is necessary to establish an understanding of what happens as a result of the annealing operation in terms of the method used to establish the resulting array output. In this chart, power output is shown as a function of fluence (amount of deposited energy) using a blanket consisting of 3 mil cover, 2 mil cell and 2 mil substrate. During a typical 180 day transfer from LEO to GEO, the power output will degrade to approximately 70% of the initial output as indicated by point 2 on the chart. Previous analysis has assumed recovery after annealing to be 95% of the degradation. This percent of recovery reflects the results of annealing tests performed by SPIRE. It should be noted, however, the degraded cell only had 1/15 as much fluence as a cell exposed during an orbit transfer and, in addition, was a 6 mil cell rather than 2 mil. With this approach, the power output would be approximately 97% as indicated by point 6. Our current belief however is that the annealing operation actually removes damage fluence with the resulting power output being a function of the remaining damage. The SPIRE test removed 98% of the damage, but since the EOTV damage is much more severe, a damage removal value of 95% is used which results in the use of points 2, 3, 4 and an output of 90%. In the case of the self-power transfer, the difference between these two approaches is not significant since it only occurred one time. However, in the case of the EOTV operation where multiple trips will be made by an EOTV, considerable differences will result when the vehicle is flown, 5, 10, 15 times. Consequently, the approach to be used hereafter will be that of removing a percent of the damage from the array rather than removing a percent degradation. The percent of damage removal however remains to be a large uncertainty due to the large disparity between the results of a few tests and the predicted fluence expected during transfer. This uncertainty can only be removed by performing additional radiation annealing tests specifically designed for EOTV operations.

Power Recovery After Annealing
% Degradation vs % Damage

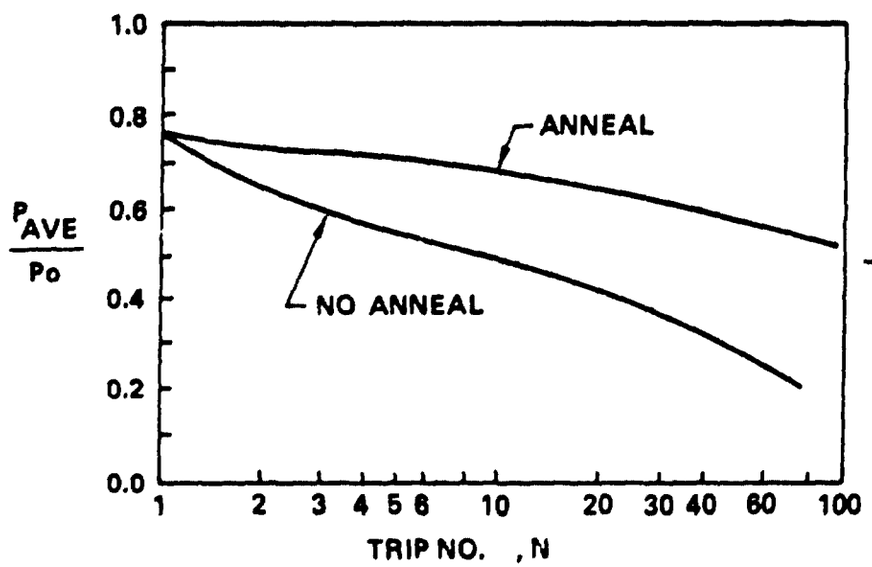


SOLAR ARRAY PERFORMANCE

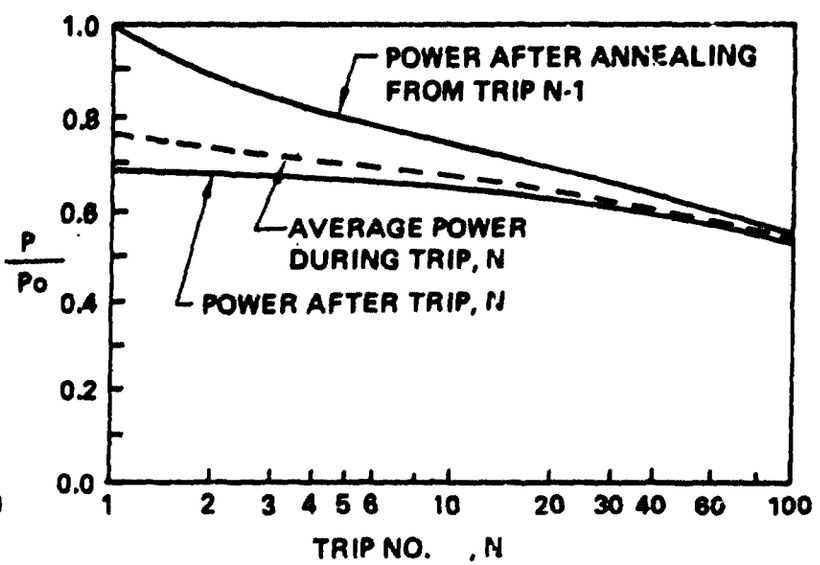
The value of annealing is indicated by the left hand plot. For example, should the EOTV be designed for 10 trips, the difference between annealing and non-annealing would be approximately 20%. In the Future Space Transportation System Study, annealing was not included in the analysis, which to some degree explains why the EOTV concept was not found to be cost effective. The power range before annealing and after annealing for each trip is indicated in the right hand plot along with the average power expected during the trip as a function of the number of trips the EOTV may make. It should also be remembered that as the average power decreases within a given trip as well as each subsequent trip, the voltage will also be decreasing at about 50% the rate as power output. (Should power go down 30%, voltage will go down 15%).

Solar Array Performance

- VALUE OF RECOVERY
  - 120 DAY UP
  - 30 DAY RETURN



- TYPICAL POWER OUTPUT
  - 120 DAY UP
  - 30 DAY RETURN



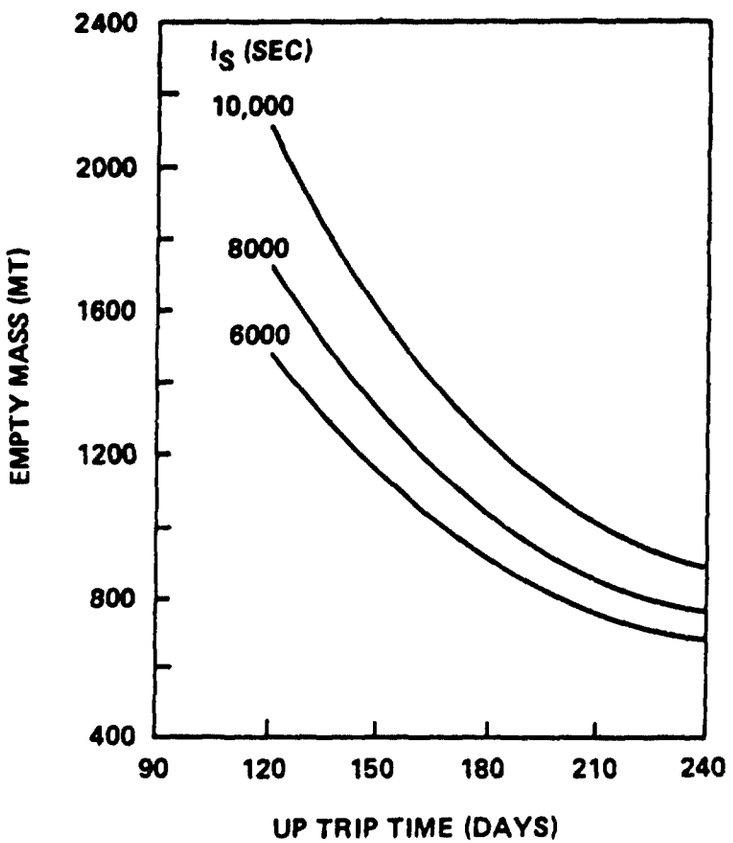
EOTV PERFORMANCE TRENDS

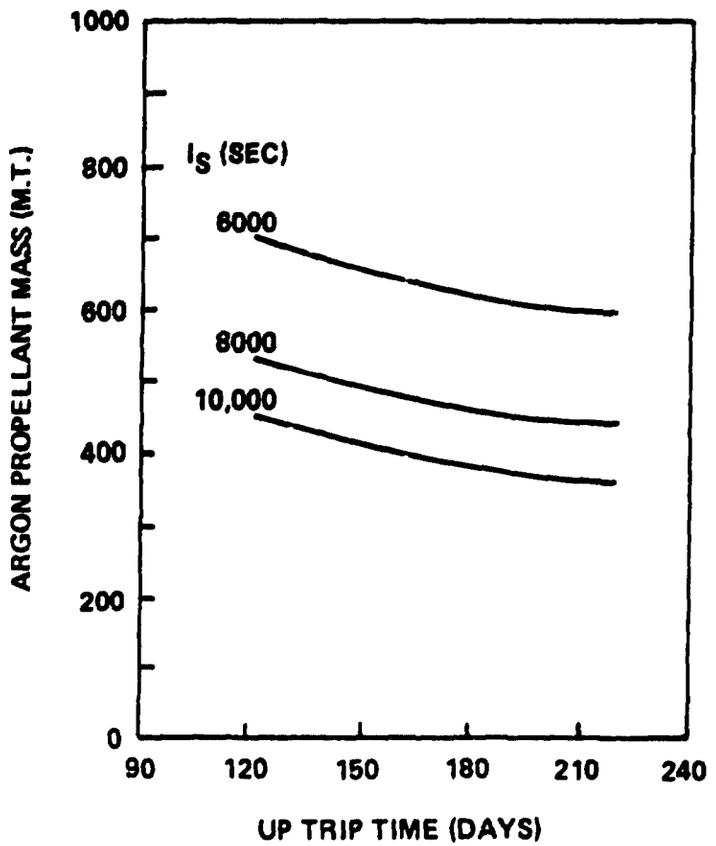
First Trip

The first trip flown by the vehicle is used to obtain the optimum vehicle in terms of performance and cost. Previously indicated solar array performance and thruster characteristics specified in prior OTV analysis are used in the analysis. Empty mass of the EOTV and its propellant requirements are indicated as a function of specific impulse and up trip time which sizes the vehicle and therefore dictates the down time. Empty mass characteristics reflect the situation that for a given specific impulse, mass goes down with trip time because less acceleration is required which means less power is required. For a fixed trip time, mass goes up with an increase in specific impulse because more power is required. Propellant requirements go down with trip time since the vehicle empty mass is smaller and has it's lowest value for the highest specific impulse. Since the empty mass and the propellant mass are the key mass contributors and require different values of specific impulse to give their minimum values the combination of trip time and specific impulse which results in the least total mass is the key point of interest. This comparison is presented on the next chart.

EOTV Performance Trends First Trip

- SILICON CELLS



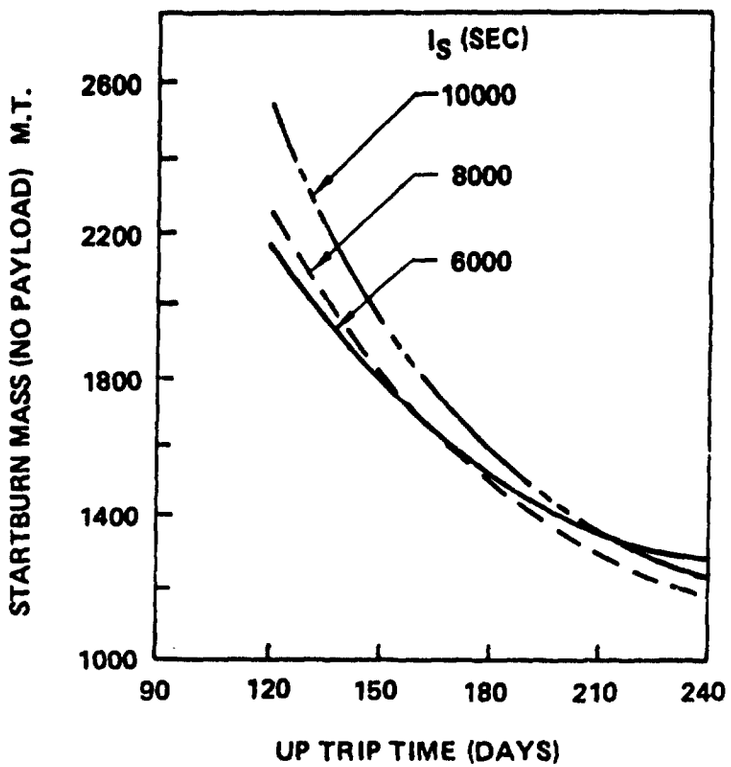


EOTV PERFORMANCE OPTIMIZATION
First Trip

Total vehicle start-burn mass is shown as a function of specific impulse and up trip time, and indicates the the minimum mass has not been reached at 240 days however the optimum specific impulse appears to be 8000 seconds. More significantly however, is the optimization in terms of cost. The indicated cost reflects the amortized hardware cost, the cost of refueling and refurb and trip time interest cost. Not included is the cost of launching the payload. The cost is minimum with a combination of a specific impulse of 8,000 seconds and trip time of 180 days and also a combination of a specific impulse of 10,000 seconds and approximately 210 ten days of trip time. The system using an I_S = 8,000 seconds and 180 days up trip time is selected for the reference system since it results in a smaller vehicle and shorter vehicle trunaround time.

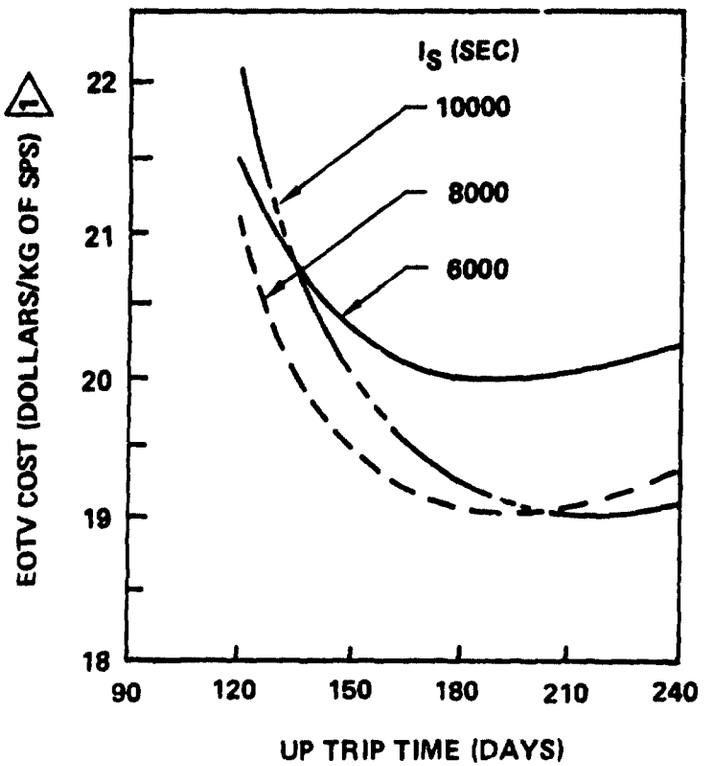
EOTV Performance Optimization First Trip

STARTBURN MASS



EOTV COST

1 COST TO LAUNCH PAYLOAD NOT INCLUDED

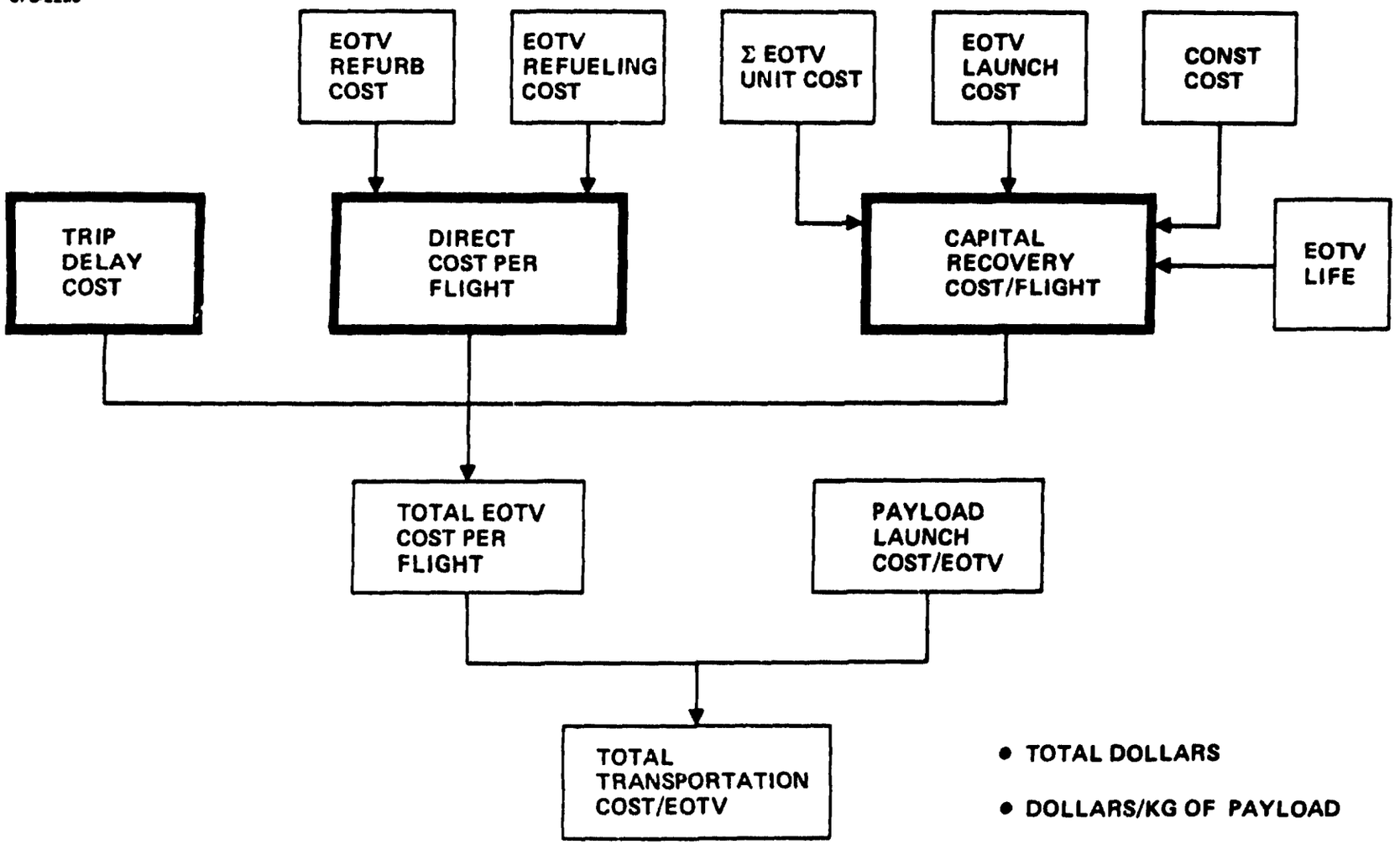


EOTV FLIGHT COST FACTORS

To give more insight into what is included in the cost optimization of the EOTV's, the indicated factors are included. Three major elements make up the EOTV cost per flight. The capital cost factors are those that are one time expenditure and will consequently be amortized over the life or number of flights flown by the vehicle. Direct cost deal with the fueling and refurbishment of the vehicle for each flight. Trip delay cost relates to the time required to make the last EOTV flight which is effectly delaying the construction. Added to these three factors is that of the launching of the payload itself which in combination gives the total transportation cost for each EOTV flight.

EOTV Flight Cost Factors

SPS-2229



- TOTAL DOLLARS
- DOLLARS/KG OF PAYLOAD

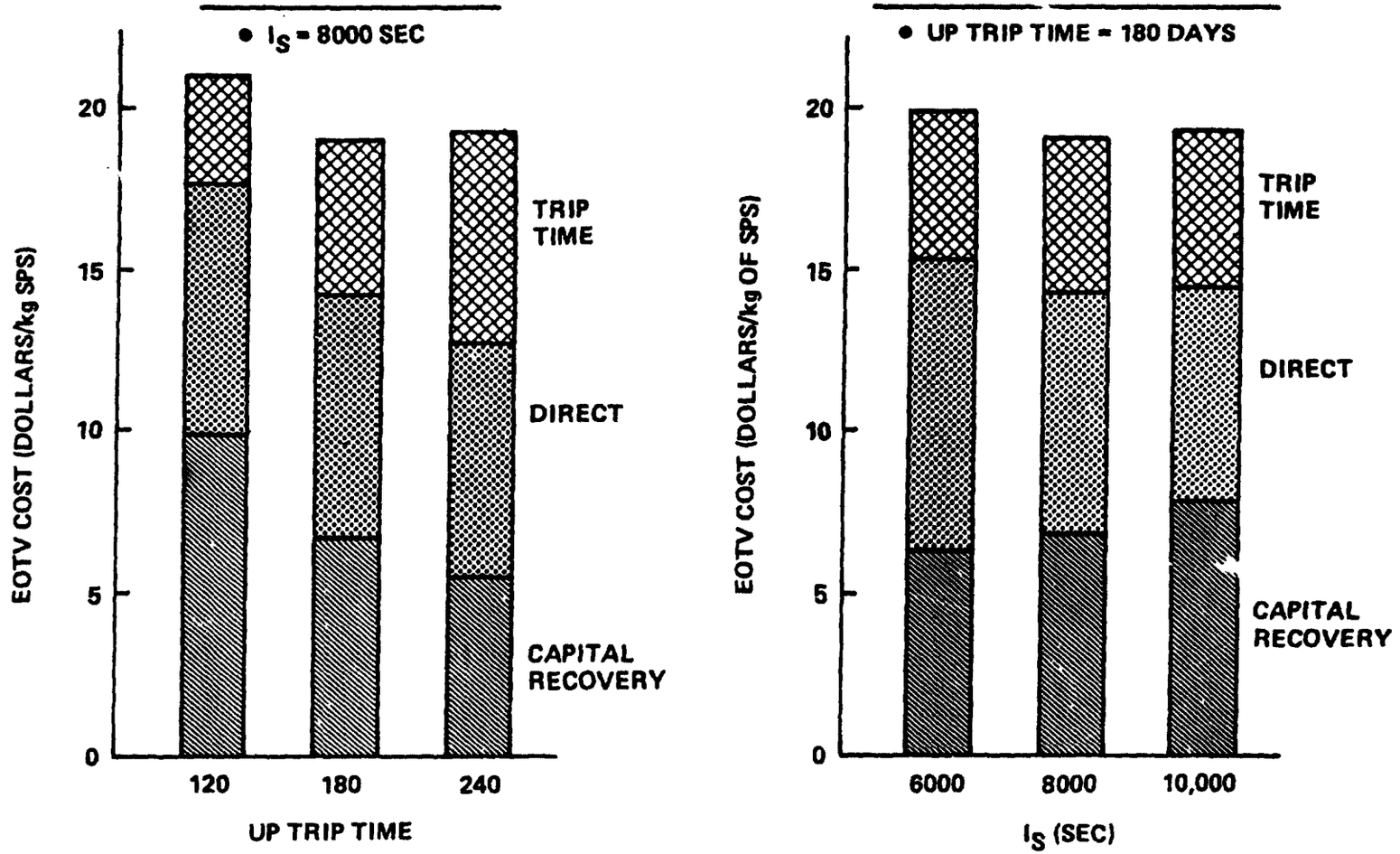
EOTV COST OPTIMIZATION
First Trip

This chart illustrates the variation that occurs in each cost element for different combinations of specific impulse and trip time. In the case of the trip time sensitivity, specific impulse is fixed and trip time is varied. In this case, the trip time cost increases with longer trip times, since more interest cost occurs. Direct cost such as that related to propellant is about constant and finally the capital cost is decreasing since the size of the vehicle gets smaller with longer trip times.

When trip time is fixed and specific impulse varied trip time cost stays constant, direct cost goes down with an increase in specific impulses because there is a smaller propellant requirement, and capital cost will go up with increased specific impulse since a greater amount of power is required resulting in a larger vehicle.

EOTV Cost Optimization First Trip

SPS-2243



EOTV ROUND TRIP COMPARISON

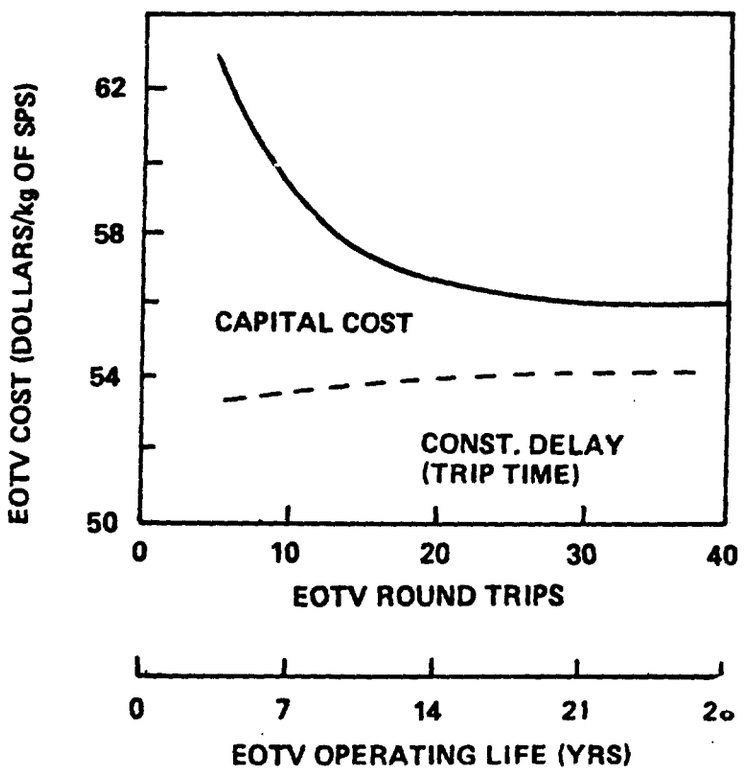
In addition to establishing the first trip optimum performance characteristics associated with an EOTV, it is also necessary to decide how many trips should be made by a given OTV vehicle. In other words, what is its lifetime. This decision can be based to some degree on available cost data, but also must include considerations related to uncertainty in performance characteristics and hardware limitations. The left hand portion of this chart shows the total transportation cost per EOTV trip as a function of the number of round trips that a EOTV may make. Several cost items such as the launching of the payload as well as the direct cost are for the most part constant. Construction delay (trip time) cost increases with additional number of round trips since the average power become less with each subsequent trip, thus increasing the total round trip time. Capital cost is decreasing since the initial cost is amortized out over more flights. One cost increment not included in this data is that associated with a larger refurbishment cost with each ten trips because the complete thruster is replaced rather than just the grids and cathodes. Cost to date however indicate that $56 per Kg. of SPS component can be achieved. It should be noted that when 20-25 round trips per EOTV are assumed this corresponds to approximately 17 or 18 years of operating life. Before making the selection of the number of round trips for each EOTV, one must also consider the limitation that may occur in terms of component lifetime. No problem appears to exist for the structure, power distribution, power processing components. Thruster can be refurbed on a component basis after each trip and as previously indicated complete units can be replaced at the end of ten trips. There is great uncertainty however relative to the life of the solar array and it's performance. Several points should be considered. In the case of degradation/recovery characteristics, there is the fact that each leg of an EOTV trip will experience a fluence level ten times greater than that to be experienced by the satellite in 30 years of GEO operation. At this point in time little is known relative to the recovery capabilities from this amount of radiation nor the number of times that recovery can be performed. The cell-to-cell mismatch problem occurs from the very fact that each cell will not be affected exactly alike interms of its radiation characteristics, thereby resulting in additional contribution to overall power output loss. The thermal cycle impact must consider both the case of occultations that occur during the orbit transfers as well as the annealing of the solar array. In the case of the occultations ten times as many occultations occur during one transfer as in thirty years of operational life of the SPS system. Another factor to be considered is the 10-15% variation in voltage that occurs throughout a trip.

The selection of the number of trips that should be flown by a EOTV becomes difficult. On one hand the cost of optimization would indicate 20 to 30 round trips per vehicle. However, in terms of expected limitations in terms of components, it drives one into selecting something in the neighborhood of ten flights, which still corresponds to approximately 7 years of EOTV operating life. Therefore the reference EOTV will perform 10 flights.

EOTV Round Trip Comparison

COST

- DIRECT COST $ 7.4/kg
- P/L LAUNCH $41.1/kg



VEHICLE LIFE LIMITATIONS

- STRUCTURE – >15 YRS
- POWER DISTRIB – 15 YRS
- POWER PROCESSING – 15 YRS
- THRUSTERS
  - COMPONENTS – PER ROUND TRIP
  - UNITS – 5-10 YRS
- SOLAR ARRAY – UNKNOWN
  - DEGRADATION/RECOVERY CHARACTERISTICS
  - CELL-CELL MISMATCH
  - THERMAL CYCLE IMPACT
  - WIDE RANGE OF VOLTAGE

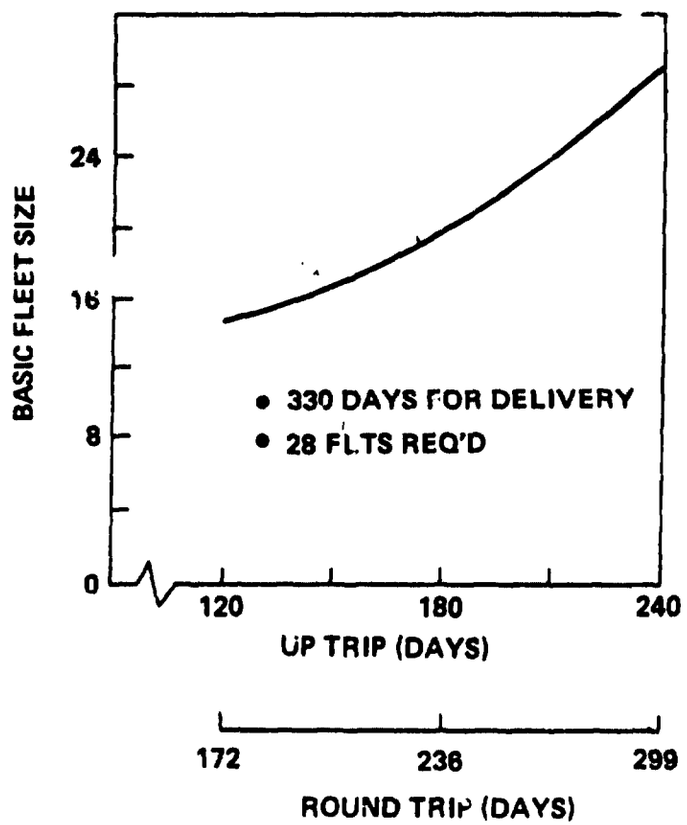
EOTV FLEET SIZE

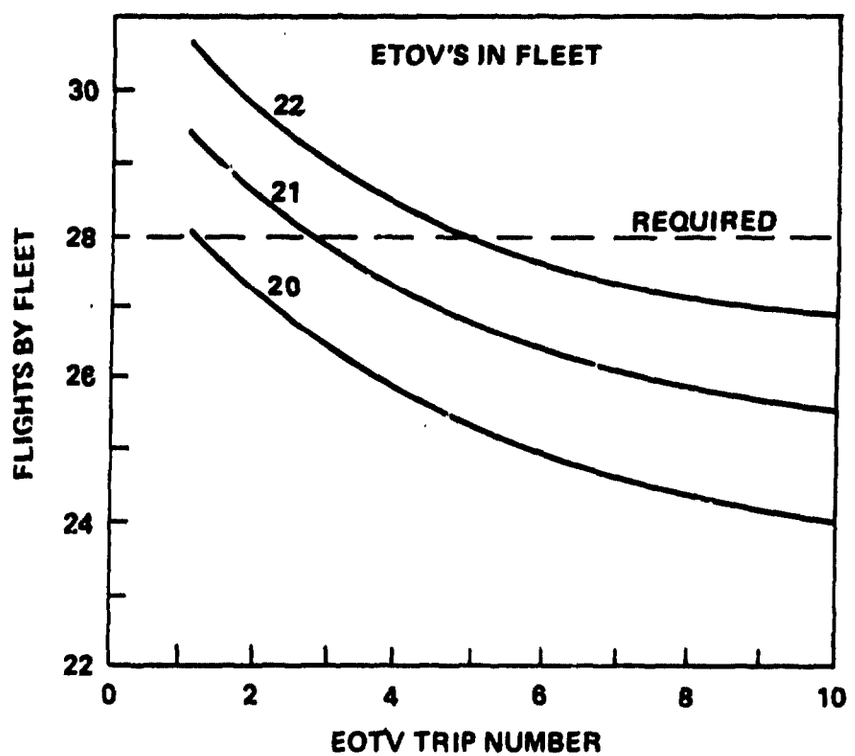
The final parameter to be influenced by EOTV performance is that of the total number of vehicles required to satisfy the yearly delivery requirements. The key factor in the relationship is that of total round trip time which includes the trip up, trip down and the time for non transfer functions such as the refurbishment of the vehicle and cargo handling. As will be noted later, a total of 16 days has been allocated for the non transfer functions. The first step in establishing the fleet size involves defining the basic fleet size which means establishing the fleet based on first trip characteristics As indicated in the left hand plot, delivery must be accomplished in 330 days and 28 flights are required to deliver the components for a satellite. With the previously found optimum trip time of 180 days, a total of 20 vehicle is required in the basic fleet. Since each additional trip to be flown by an EOTV will take longer (due to array degradation), the 20 vehicles which initially fly 28 flights per year, will only fly 24 flights on their tenth trip. Consequently, to maintain an average of 28 deliveries per year a total of 22 vehicles will be required in the fleet. By prior agreement, one additional vehicle is added to the fleet for a spare giving a total of 23 vehicles.

EOTV Fleet Size

SPS-2293

- BASIC FLEET SIZE (ONE TRIP/EOTV)
- TOTAL FLEET SIZE (MULTIPLE FLIGHTS/EOTV)





NOTE: WITH ONE SPARE TOTAL FLEET SIZE IS 23.

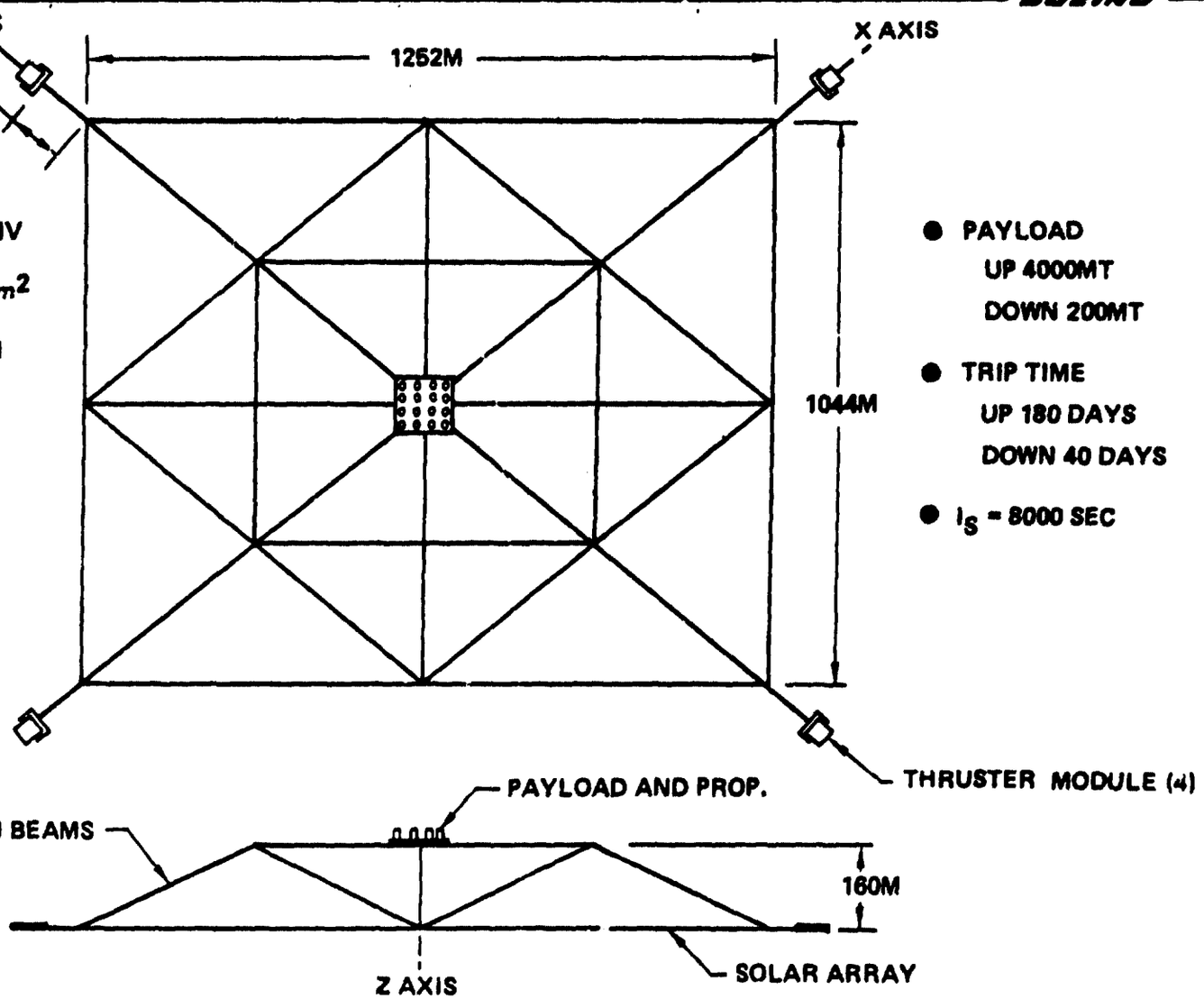
ELECTRIC OTV CONFIGURATION

The next few charts deal with the EOTV design characteristics as well as mass and cost. The configuration of the silicon EOTV is similar to that which was shown at the orientation although a few key changes have been made. In general, the configuration consists of four bays, with each shaped as a pentahedron and the apex of each pentahedron structurally tied together. Solar arrays cover the lower surface. The payload and propellant tanks have been moved from near the plane of the solar array to the plane formed by the apex of the pentahedrons. This location provides an improvement in the inertia balance of the configuration resulting in less penalty for gravity gradient torque control and also simplifies the docking of the payloads as well as propellant tankers. The vehicle is sized to deliver 4,000 metric tons and return is 200 metric tons with an up trip time of 180 days and down time of 40 days and a specific impulse of 8,000 seconds. The total dry mass of the vehicle is 1195 metric tons while the total propellant loading is approximately 480 metric tons.

Electric OTV Configuration

SPS-2236

- INITIAL POWER = 230MV
- ARRAY AREA = 1.23 Km^2
- ELEC THRUST = 3048N
- DRY MASS = 1195 MT
- ARGON = 442MT
- LO_2/LH_2 = 44MT



- PAYLOAD
  UP 4000MT
  DOWN 200MT
- TRIP TIME
  UP 180 DAYS
  DOWN 40 DAYS
- I_S = 8000 SEC

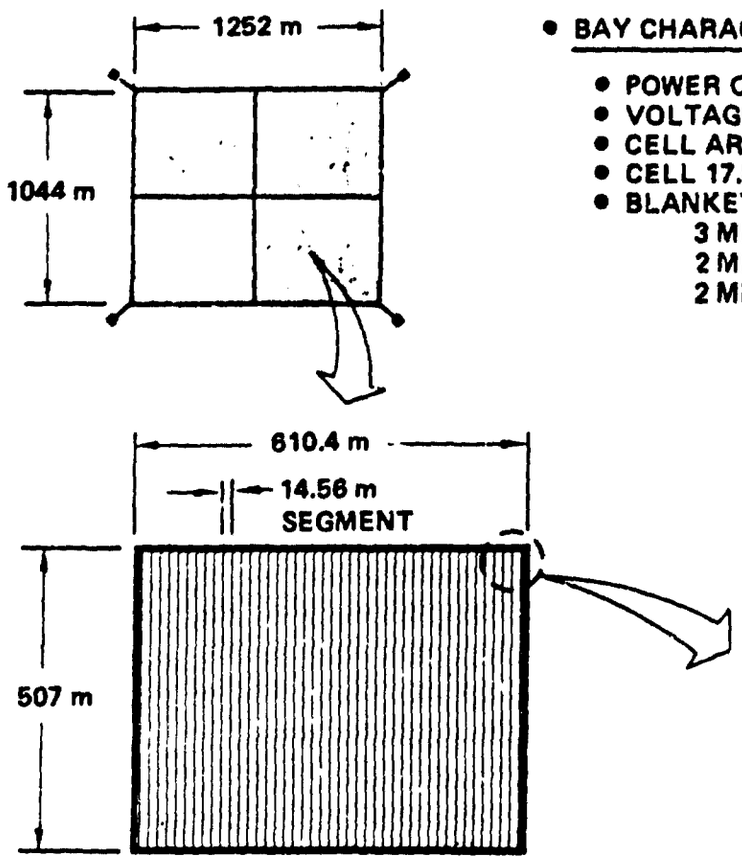
EOTV POWER GENERATION SYSTEMS

In terms of power generation and distribution systems,the EOTV is actually divided into four separate bays with each bay providing power to a thruster module. Each bay is divided into forty-two 14.5 meter segments and produces approximately 58 megawatts of power at 2685 volts. Each segmant consists of 20 strings, with each string in turn consisting of 498 panels. Each of the panels include (140) 5 x 10 centimeter cells, rather that 7 centimeter by 7 centimeter cells used in the satellite. The cell shape change is the result of wanting to achieve a nearly square satellite but at the same time having power and voltage requirements dictated by the propulsion system.

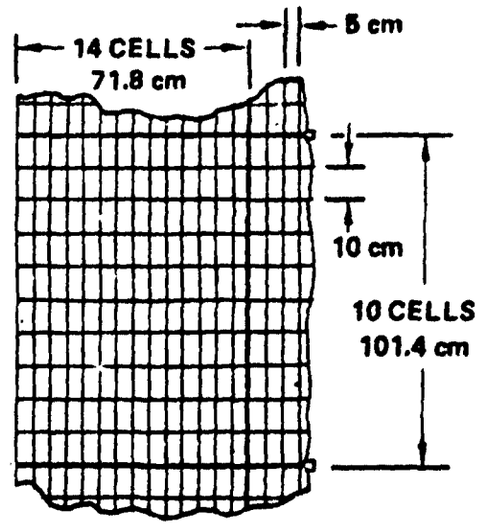
EOTV Power Generation System

BOEING

SPS-2244

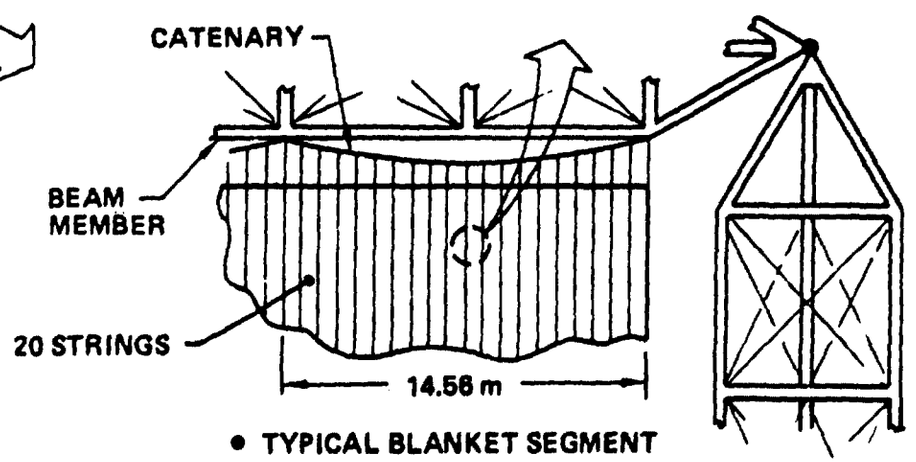


- BAY CHARACTERISTICS
  - POWER OUTPUT = 57.5 MW
  - VOLTAGE = 2685 V
  - CELL AREA = 0.309 km^2
  - CELL 17.5% AMO -25°C
  - BLANKET
    - 3 MIL COVER
    - 2 MIL CELL
    - 2 MIL SUBSTRATE



- TYPICAL STRING PANEL

- TYPICAL BAY
  - 42 – 14.56 SEGMENTS/BAY
  - 840 STRINGS/BAY
  - 498 PANELS/STRING LENGTH



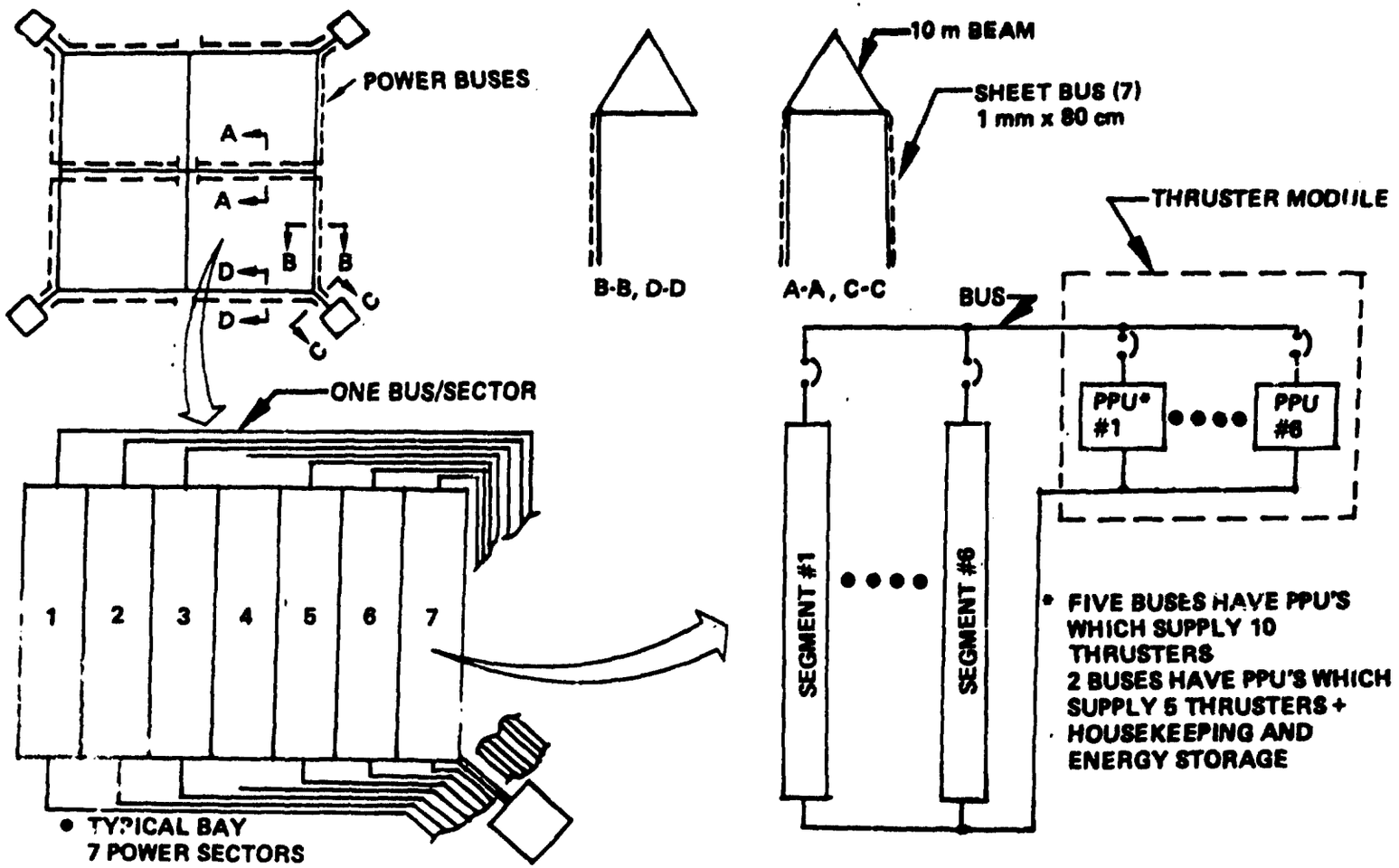
- TYPICAL BLANKET SEGMENT

POWER COLLECTION AND DISTRIBUTION

Power busses are located on three sides of each bay of the EOTV. Each bay is divided into 7 sectors in order to minimize the impact on the switch gear complexity should a fault occur. Each sector in turn ties together 6 segments. A buss from each sector runs to the associated thruster module where the power is processed. Each of the busses is one milimeter thick by 80 centimeters deep.

Power Collection and Distribution

SPS-2246

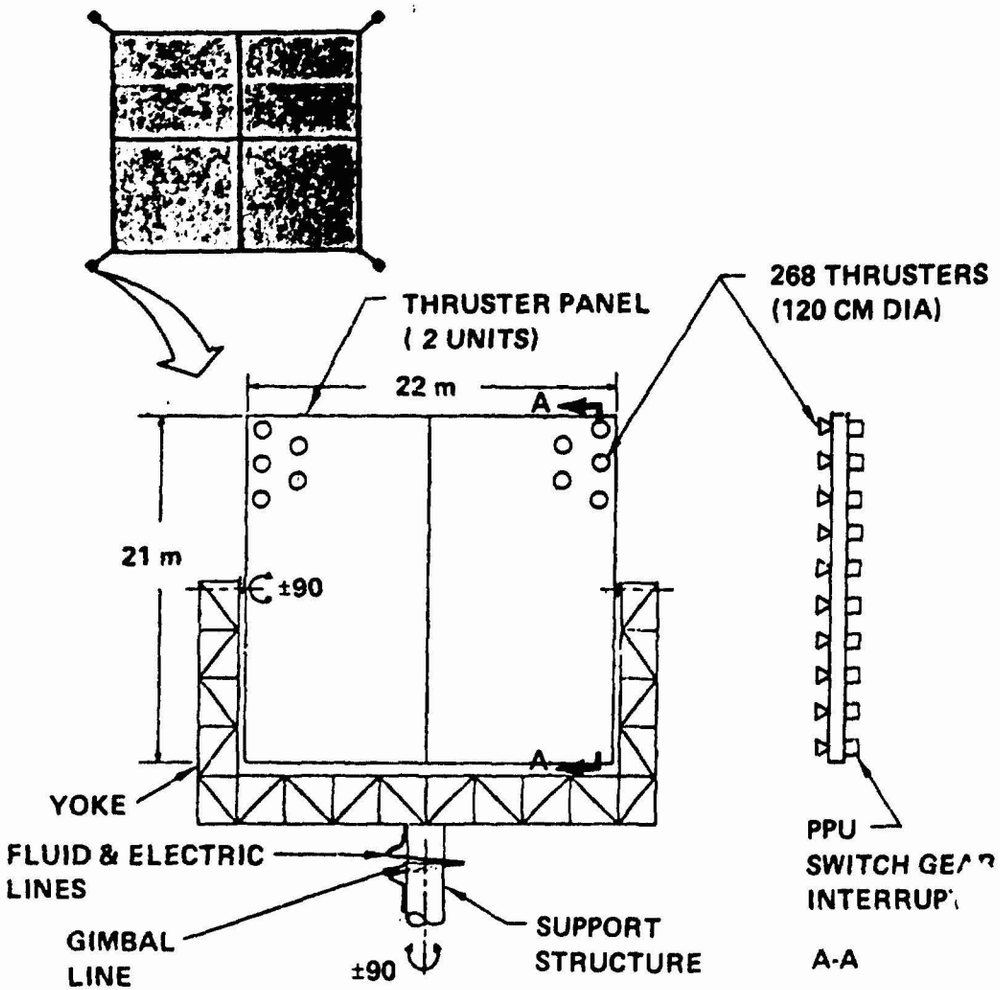


ELECTRIC PROPULSION SYSTEM

Electric propulsion modules are located at four corners of the EOTV. Each module consists of a gimbal, yoke, thruster panel containing thrusters and power processing units and a thermal control system. For the reference design, 268 thrusters are used at each of the four corners. Several methods were considered for supplying power to the thrusters. One of these options involves obtaining power directly from the arrays with no processing or no regulation. The chief disadvantage in this option is that the voltage is decreasing at the same time the power is degrading. As the flight proceeds, the lower voltage will result in a loss of approximately 1,000 seconds of specific impulse. A second option regulates and sectionalizes the array so that as additional power is required, additional sectors can be switched into operation. The main disadvantage of this concept is the extremely complicated switch gear system. The final power supply method considered involves processing all the power. The array voltage generated in this concept is the optimum voltage from the standpoint of I^2R and plasma losses. The resulting voltage is 2685V rather than 1400V required by the thrusters. A complete comparison was not done on these concepts however the all-processing method appears to be the most straightforward and since some of the power needs to be processed anyhow this method was selected for the reference. The type of processing equipment selected was that of solid state due to its longer MTBF. Thermal control of the processing equipment is required and is accomplished using an active radiator.

Electric Propulsion System

SPS-2291



- THRUSTER POWER SUPPLY
  - DIRECTLY FROM ARRAY
    - NO PROCESSING
    - NO REGULATION
  - NO PROCESSING
    - ARRAY REGULATION
  - ✓ PROCESS ALL POWER
- TYPE OF PROCESSING
  - MOTOR/GENERATOR
  - ✓ SOLID STATE
- PROCESSING THERMAL CONTROL
  - ACTIVE RADIATOR
  - 850 M^2
  - LIMIT ELECTRONICS TO 200°C

EOTV MASS SUMMARY

The mass characteristics associated with a given EOTV flight are indicated in terms of the total start burn mass and subsystem breakdown for the burnout (inert) condition. The high performance of the EOTV results in a start-burn mass only 9% greater than the empty mass. It should also be noted that the LO_2/LH_2 provided for supplemental control is only approximately 10% of the argon mass as compared to 35% in the case of self-power modules. This factor is the result of the EOTV having very little gravity gradient torque due to its favorable moment of inertia characteristics. In terms of the burnout mass, the array dominates the power generation and distribution system while the power processing units are the most dominant elements in the electric propulsion system.

EOTV Mass Summary

- **STARTBURN WITH PAYLOAD**

ITEM	MASS (M.T.)	%
PAYLOAD	4000	70
BURNOUT	1195	21
PROPELLANT		
ARGON	440	8
LO_2/LH_2	45	1
	5680	100

$$\frac{\text{STARTBURN}}{\text{BURNOUT}} = 1.088$$

- **BURNOUT (NO PAYLOAD)**

ITEM	MASS (M.T.)	%
POWER GEN & DISTRIB	(736)	
ARRAY	608	51
STRUCTURE	95	8
DISTRIBUTION	33	3
ELEC PROPUL SYS	(459)	
THRUSTERS	71	6
POWER PROCESS.	195	16
THERMAL CONT	55	4
STRUCT/MECH	80	7
PROP SYS	46	4
AUXILIARY SYS	12	1
TOTAL	1195	100

EOTV COST SUMMARY

Costs of the EOTV are presented on a per flight basis and for the individual subsystem hardware elements. In the case of cost per flight, capital costs are shown for the initial procurement cost as well as the amoritization that occurs as a result of using the EOTV for ten flights. The total cost per flight is $220 million dollars or $61/kg of satellite mass. The EOTV hardware cost is dominated by the cost of the array and the power processing unit, as was the case in the mass of the EOTV. It should also be noted that the cost of the hardware reflects the same specific cost as used in the satellite and for the self-power electric propulsion system. The associated values are $95 per kilogram of power generation and distribution system and $115 per kilogram of electric propulsion system. In all probability, the indicated costs are optimistic since the number of components and differences in design features will result in higher unit cost. The final cost estimates will be done using a bottoms up approach rather than high level parameters.

EOTV Cost Summary

SPS-2297

● COST PER FLIGHT ($\$10^6$)

	BASIC	AMORTIZED
● CAPITAL COST	(181)	(26)
● EOTV HRDW	124	
● EOTV LAUNCH	44	
● CONST. BASE	13	
● DIRECT COST		(28)
● REFUELING		18
● REFURB		10
● CONST TIME DELAY		(18)
● PAYLOAD LAUNCH		(148)
TOTAL		220

● EOTV HARDWARE

	$\$10^6$		%
● POWER GEN & DISTRIB		(69.9)	
● ARRAY	61.0		49
● STRUCTURE	2.3		2
● DISTRIBUTION	6.6		6
● ELEC PROPULSION		(53.7)	
● THRUSTERS	5.4		4
● POWER PROCESSING	24.1		19
● THERMAL CONT	5.8		5
● STRUCT/MECH	7.2		6
● PROPELLANT SYS	9.4		8
● AUXILIARY SYS	1.0		1
TOTAL		123.6	

● FROM OPTIMIZATION ANALYSIS

MISSION EVENTS

Mission events that occur while using an EOTV for GEO construction are indicated. A total of 16 days of on-orbit time has been indicated for the turnaround of the vehicle, in addition to the 219 days of time required for the up and down transfers. Most of the events are self-explanatory however a few words of further explanation will be provided for some of the events. Once the vehicle reaches GEO, it will be placed in a standby condition approximately 1 kilometer from the base. At that time a small LO_2/LH_2 tug(s) will be used to move the cargo from the EOTV to the GEO construction base. Annealing of the solar arrays will occur at GEO and will be discussed in more detail in a subsequent chart. Once the vehicle has returned to low earth orbit, it will again be placed in a station keeping standby condition approximately 1 kilometer from the LEO base. Again, small tugs will fly out from the LEO base to the EOTV to perform refurbishment operations on the thrusters, unload and load cargo propellant and deliver propellant. The propellant resupply will be done by tankers rather than removal of the propellant tanks.

Mission Events

SPS-2232

EVENT	DESCRIPTION	Δ TIME (DAYS) ON-ORBIT	Δ TIME (DAYS) TRANSFER
• TRANSFER TO GEO	COST OPTIMIZED FIRST FLIGHT		180
• TERMINAL MANEUVERS	RENDEZVOUS AND PLACE ON STANDBY CONDITION	1	
• UNLOAD CARGO	(10) 400 MT UNITS	1	
• ANNEAL SOLAR ARRAY	1.2 MILLION SQ METERS	4	
• PREPARE FOR RETURN	ACTIVATE, CHECKOUT AND LOAD CARGO	1	
• TRANSFER TO LEO	DICTATED BY POWER AVAILABLE		39
• TERMINAL MANEUVERS	RENDEZVOUS AND PLACE ON STANDBY CONDITION	1	
• REFURB ELEC THRUSTERS	1600 UNITS	4	
• CARGO HANDLING	UNLOAD CARGO AND LOAD (10) 400 MT UNITS	1	
• UNSCHEDULED MAINT	– – –	1	
• PROPELLANT RESUPPLY	ARGON, LO_2, LH_2	1	
• PREPARE FOR TRANSFER	ACTIVATION AND CHECKOUT	1	
	TOTAL	16	219

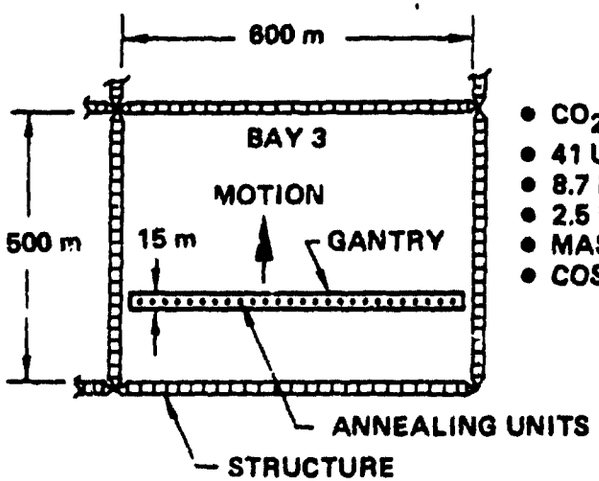
EOTV ANNEALING OPERATIONS

The method of annealing the EOTV solar array is essentially the same as that employed by the operational satellite. In general, the method consists of CO_2 laser systems attached to a gantry that can move across each bay. Each gantry system anneals a 15m strip the entire width of the bay. For EOTV application, 2.5 hours is required per bay with a continuous power requirement of 8.7 MW. The total time required to do the annealing is of course a function of total area involved and the number of gantries employed. For the reference EOTV, a total of 1.2 million square meters is required. Use of only one gantry would result in approximately 20 days of annealing time which is judged to be too excessive. Although no optimization has been done at this point, the reference system will use four annealing gantries, thus resulting in an annealing time of approximately four days. When using four gantries, however, two are placed in each of two bays so that power can be drawn from the other two bays to operate the annealing systems. When a given bay has been completely annealed, the gantries will move to a bay that has not been annealed and repeat the annealing operation. Annealing can be performed at either LEO or GEO, however, such factors as continuous sunlight to generate power and minimum orbit keeping propellant suggest annealing at GEO will be slightly better than if the operation performed at LEO.

EOTV Annealing Operations

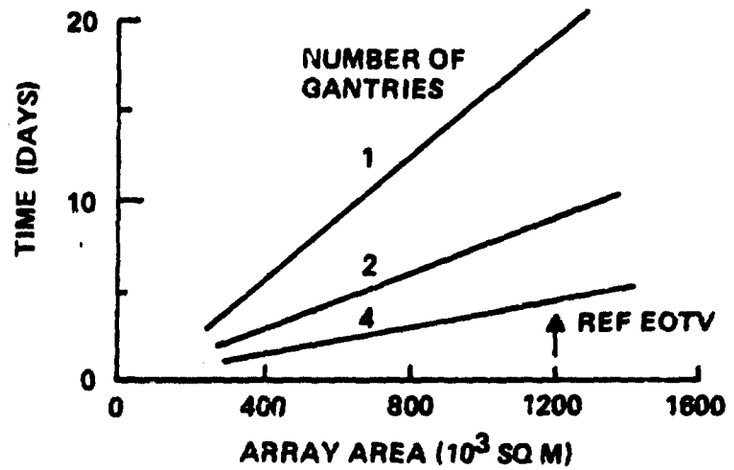
SPS-2230

- TYPICAL ANNEALING SYSTEM

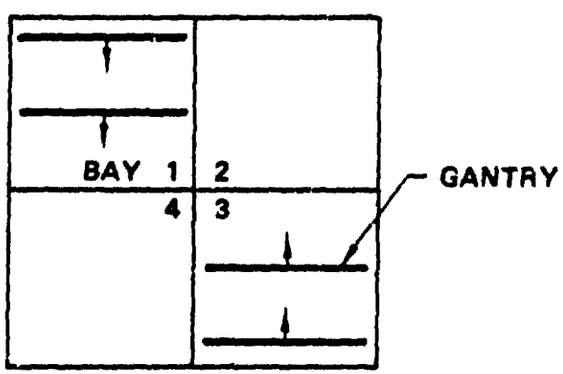


- CO_2 LASER UNITS
- 41 UNITS/GANTRY
- 8.7 MW/GANTRY
- 2.5 HR/STRIP
- MASS: TBD
- COST: TBD

- ANNEALING TIME



- EOTV INSTALLATION



- ANNEALING LOCATION

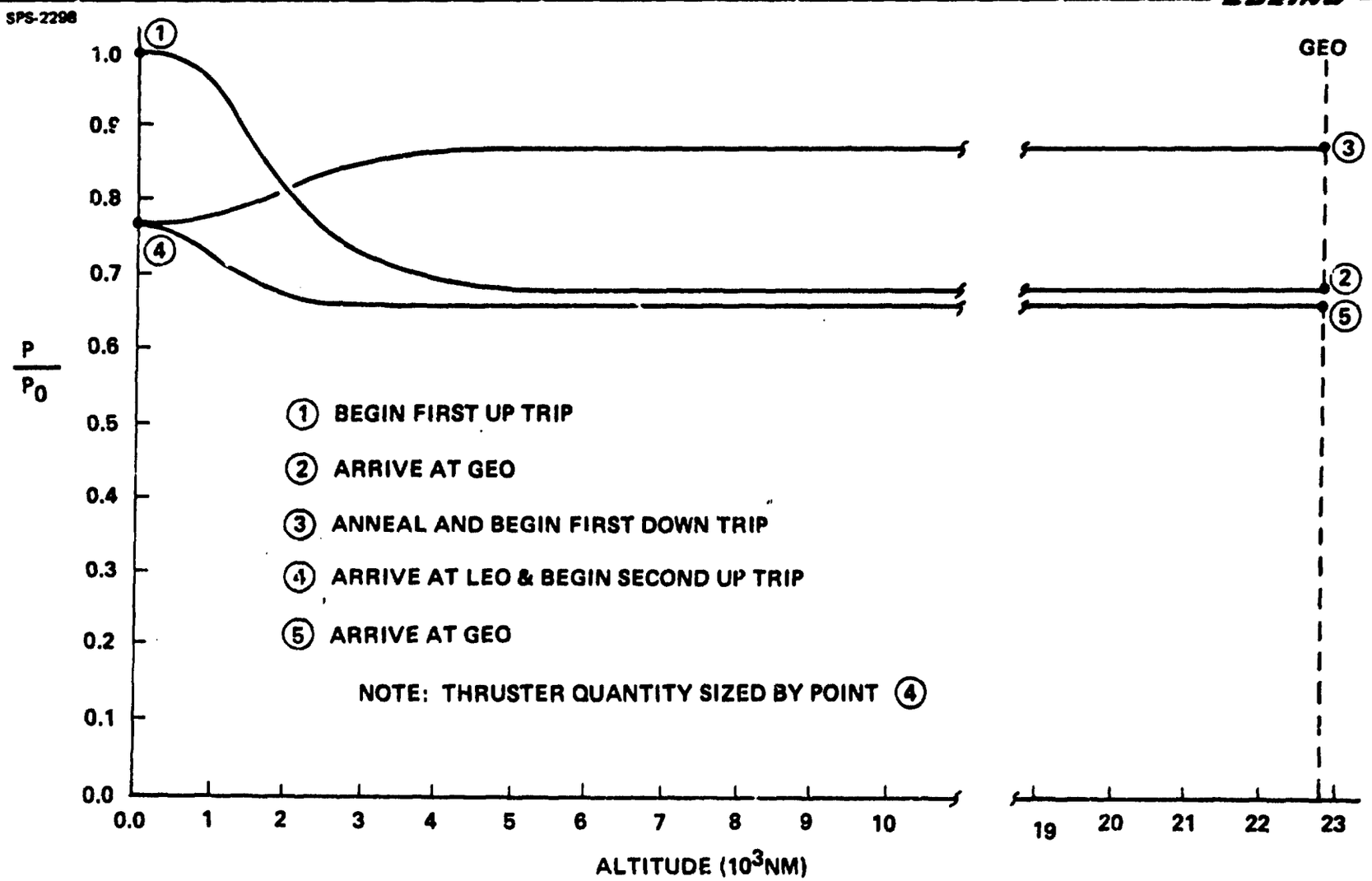
FACTORS	GEO	LEO
• ANNEALING TIME/ POWER SOURCE	✓	
• STATION KEEPING	✓	
• TURNAROUND TIME		✓
• FLIGHT PERFORM (POWER AVAIL)	— EVEN —	

SELECT GEO

TYPICAL TRANSFER POWER PROFILE

Using the approach of annealing the array GEO, the EOTV would have a power profile as indicated. The trip would begin at LEO and by the time 4,000 nautical miles has been reached, the array output has decreased to 68% of the initial power output and essentially remains at that level until GEO is reached. At GEO, annealing is performed thus bringing the power level up to 86% of the initial power output. The vehicle is then flown back to LEO and once 4,000 kilometers is reached degradation again occurs. The percent of degradation during the down leg will be less however because the down transfer through the belt is considerably faster than during the up leg. The total number of thrusters installed on the vehicle is determined by the power output of point 4 which corresponds to the array capability at the beginning of its second trip.

Typical Transfer Power Profile

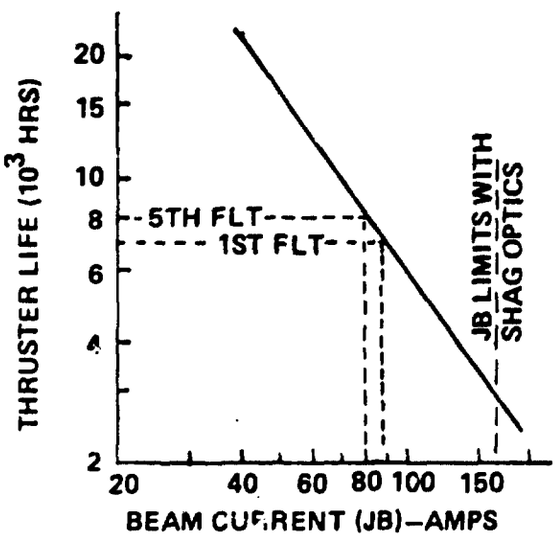


THRUSTER REFURB

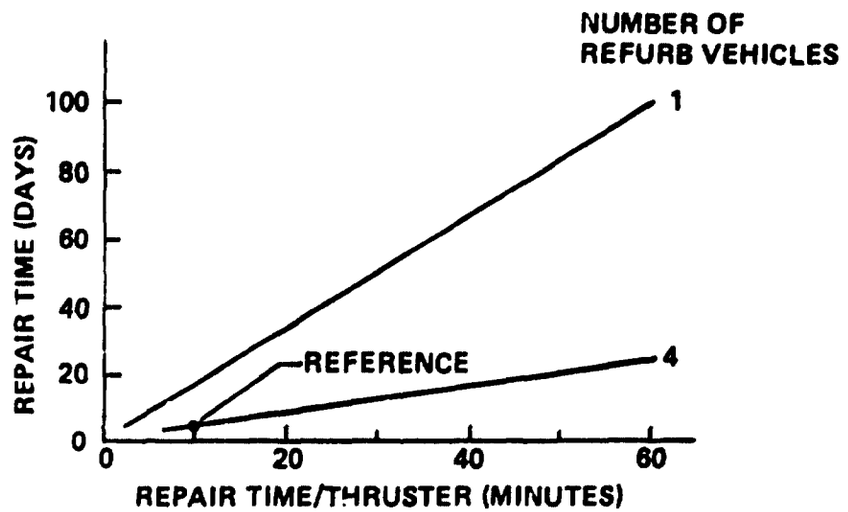
The other key mission event to be discussed is that of refurbishment of the EOTV thrusters. The first point to establish is the frequency of the refurbishment. In this case, the life of the grids of the thruster are the major concern, although there is some indication that the cathodes will also have a life problem. On the left is a plot of the thruster grid life as a function of beam current This data is a result of combining the results of a model that predicts the double ion production rate (which is the major factor in erosion) as a function of beam current with another model that predicts erosion. Using this data to check the erosion rates of a 30 cm mercury thruster whose erosion characteristics are known has resulted in a very good correlation and consequently confidence that this data can be used. Thruster life requirements are indicated for the first and fifth trips of an EOTV and reflect the actual burn time plus a 50% margin. These burn times indicate that 80 amps is about the most that can be expected and corresponds to the thruster design and performance characteristics that have been used in the Boeing SPS studies to date. The second point to establish is the amount of time required for the refurbishment and the amount of equipment required. The plot on the right generally indicates that regardless of the time to refurbish each thruster, four vehicles would be required in order to result in a reasonable refurb time. The reference system assumes that each thruster is repaired in ten minutes resulting in a repair time of four days and four refurb vehicles. Refurb could be done at either LEO or GEO, with LEO providing the lower transportation cost while the chief advantage of the GEO being a reduction in the turnaround time since it can be done in parallel with annealing of the solar array. At this point in time it is judged that the reduced transportation cost would be more beneficial, consequently, the refurb of the thrusters are done at LEO. As indicated earlier, the vehicle would be placed approximately 1 kilometer away from the base. Refurb on the thrusters can be done in place at the vehicle which eliminates fluid and electrical disconnections or the complete thruster panel immediately removed and flown back to the base where it would be refurbed with another panel immediately installed to allow the next trip. The latter approach would reduce the turnaround time but would present the problem of disconnecting fluid and electrical wirings. Consequently, the in-place concept is selected for the reference case.

Thruster Refurb

- FREQUENCY OF REFURB



- REFURB TIME/EQUIP



- LOCATION
  - ✓ LEO–REDUCE TRANSP. COST
  - GEO–COULD REDUCE TURNABOUND TIME

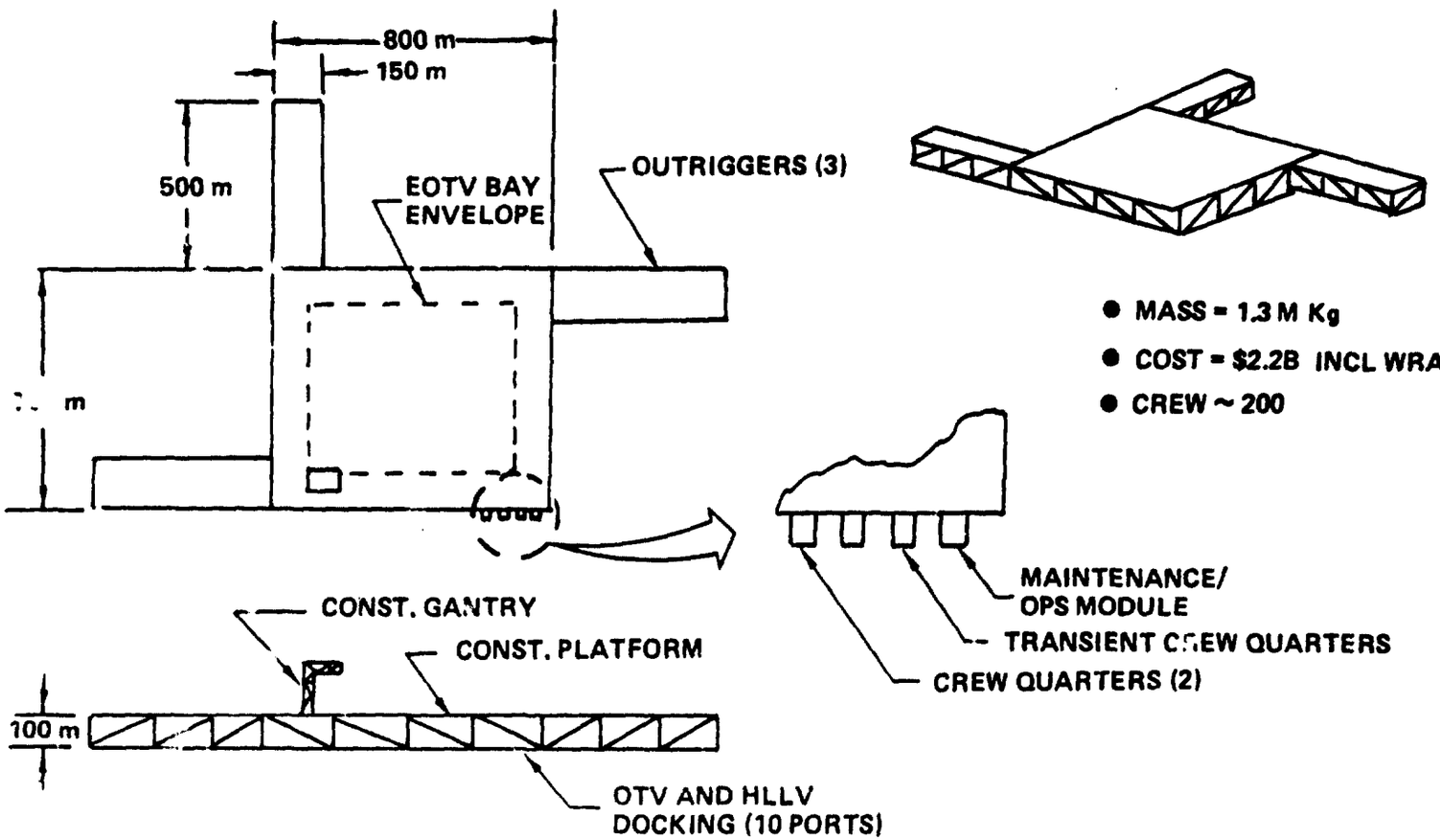
- MODE
  - ✓ IN PLACE–NO FLUID/ELEC DISCONNECTS
  - REMOVE & REPLACE MODULE–REDUCE TURNAROUND TIME

LEO BASE FOR GEO CONSTRUCTION/EOTV

Preliminary

The LEO base configuration used in support of a GEO construction concept is illustrated. Primary functions of the base are to support construction operations associated with the EOTV's and also to perform depot type operations during the ongoing satellite construction operations. The base is sized to construct one bay of an EOTV at a time. Outriggers are used to support the bays as they are being constructed. Opposite of the construction platform is the location used for the docking of the OTV's and HLLV's. Crew modules are located at one corner of the facility and consist of two crew modules for the primary crew, one module for personnel involved in rotation operations and a maintenance and operations module. Total mass of base is estimated at 1.3 million kilograms and cost estimated at $2.2 billion. The average crew size is 200 during the construction operations.

LEO Base for GEO Construction/EOTV Preliminary



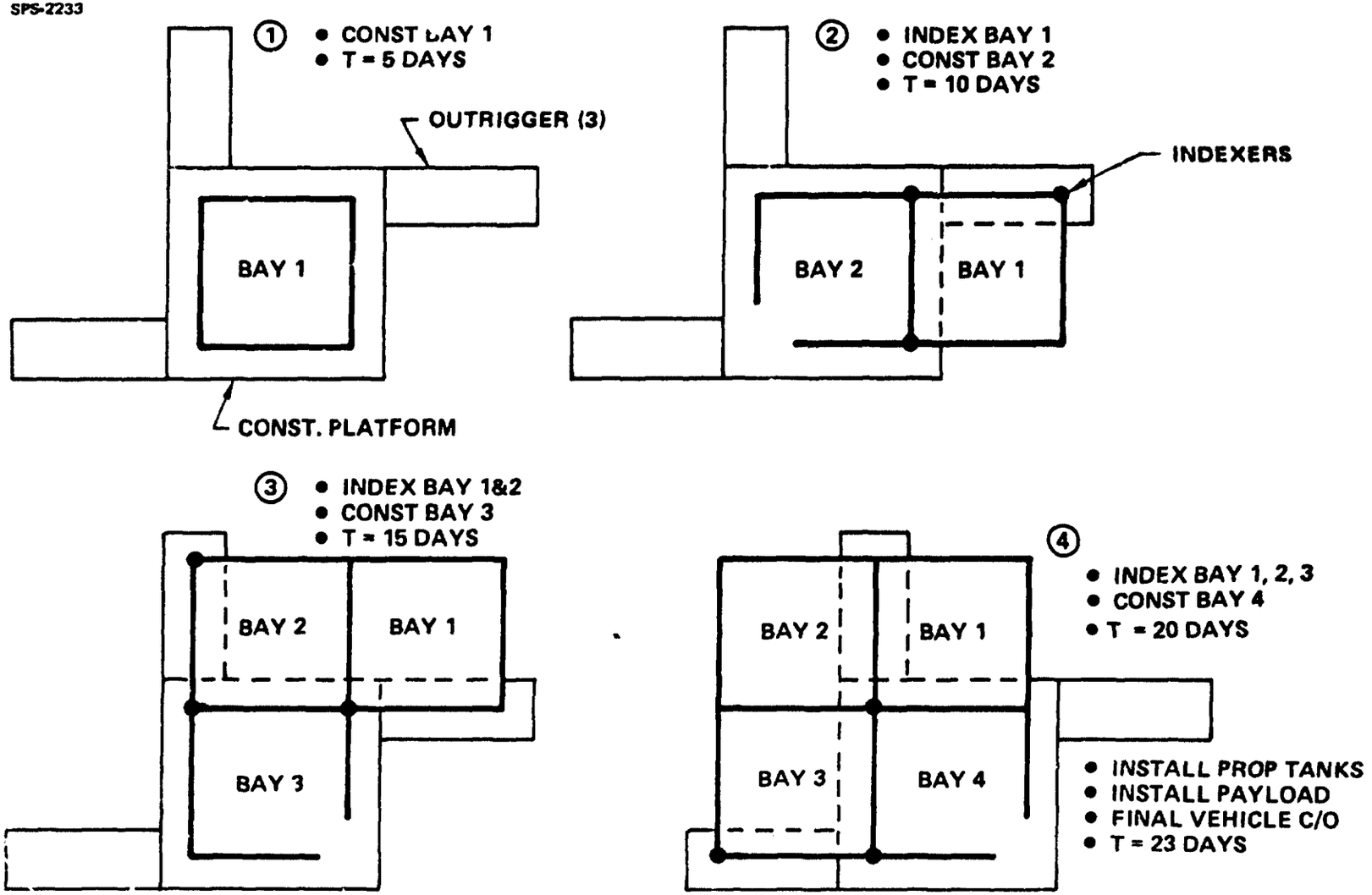
- MASS = 1.3 M Kg
- COST = $2.2B INCL WRAP-AROUND
- CREW ~ 200

EOTV CONSTRUCTION SEQUENCE

The overall construction sequence associated with the four bays forming an EOTV are illustrated, including the utilization of the outriggers. The following chart provides details regarding the construction of each bay. In the overall sequence, a simple diagram is used to illustrate each bay. Five days are required to construct each bay of the EOTV. Indexing occurs following the construction of each bay. Construction of the EOTV is completed at the end of 20 days. The final operations involve installation of propellant tanks, payload and the final vehicle check-out so that the vehicle is ready for flight at the end of 23 days. With 23 vehicles required in the fleet approximately 1-1/2 years is required to construct the entire EOTV fleet.

EOTV Construction Sequence

SPS-2233

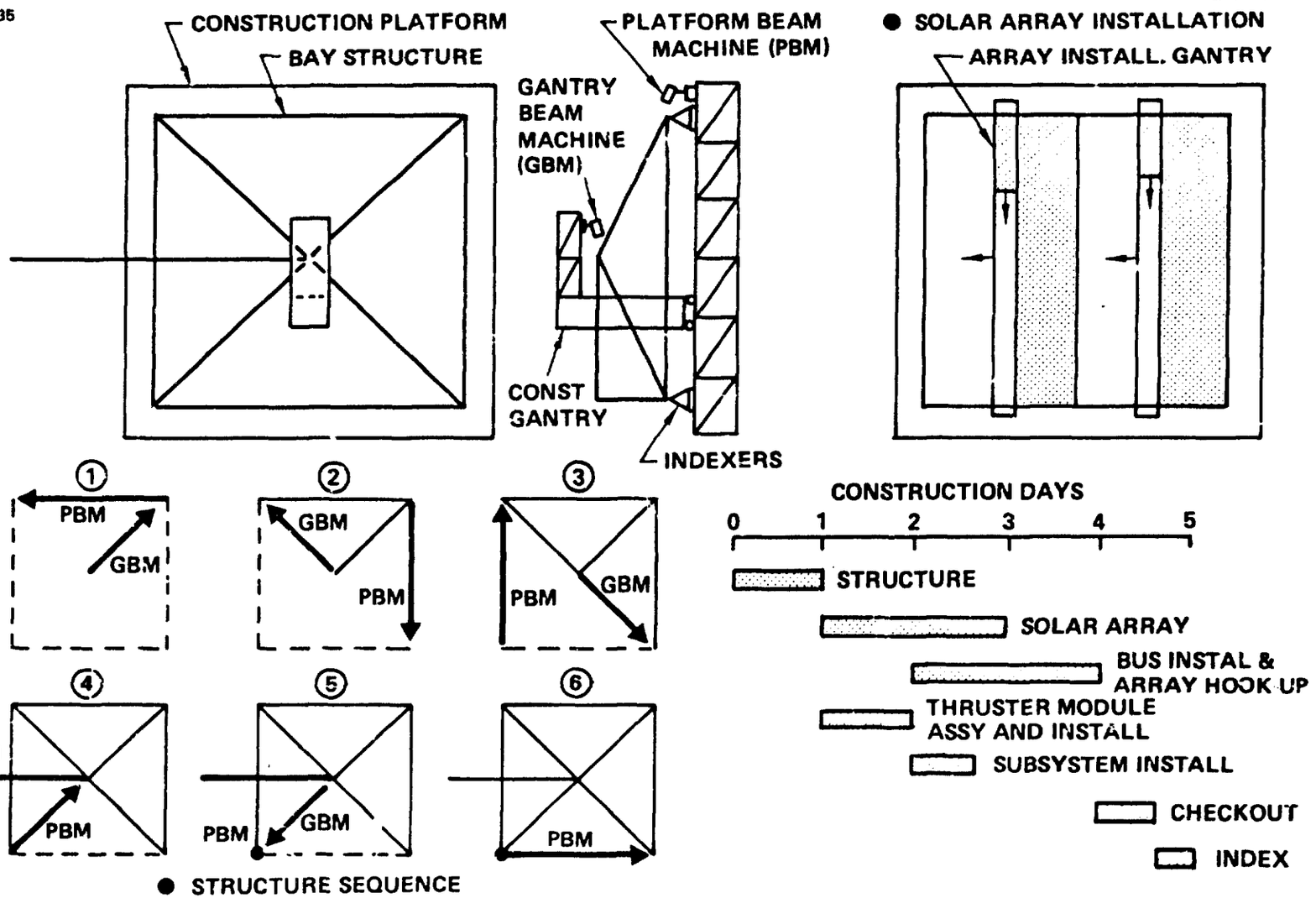


EOTV BAY CONSTRUCTION OPERATIONS

Details of the construction operation associated with each bay of the EOTV are illustrated. Again it should be emphasized that the base has been sized to construct one bay at a time, rather than a complete EOTV. The construction operation requires a construction platform, beam machines, cherry pickers, solar array deployers, indexers and a construction gantry which is used to support several beam machines and cherry pickers. The sequence which is used to form the structure of each bay is illustrated in the lower left hand portion of the chart. Both the gantry beam machine and the platform beam machine work in parallel forming the beams. In this particular operation, the platform beam machine is relocated one time in order to complete the formation of its designated beams and the gantry must be moved to the side to allow the last beam of the pentahedral base to be installed. Total construction time to complete a single bay of the EOTV including checkout and its indexing so the next bay can be made is 5 days with the provision that two solar array machines are used. Should only one solar array machine be used, then the construction time per bay will be increased to seven days.

EOTV Bay Construction Operations

SPS-2235

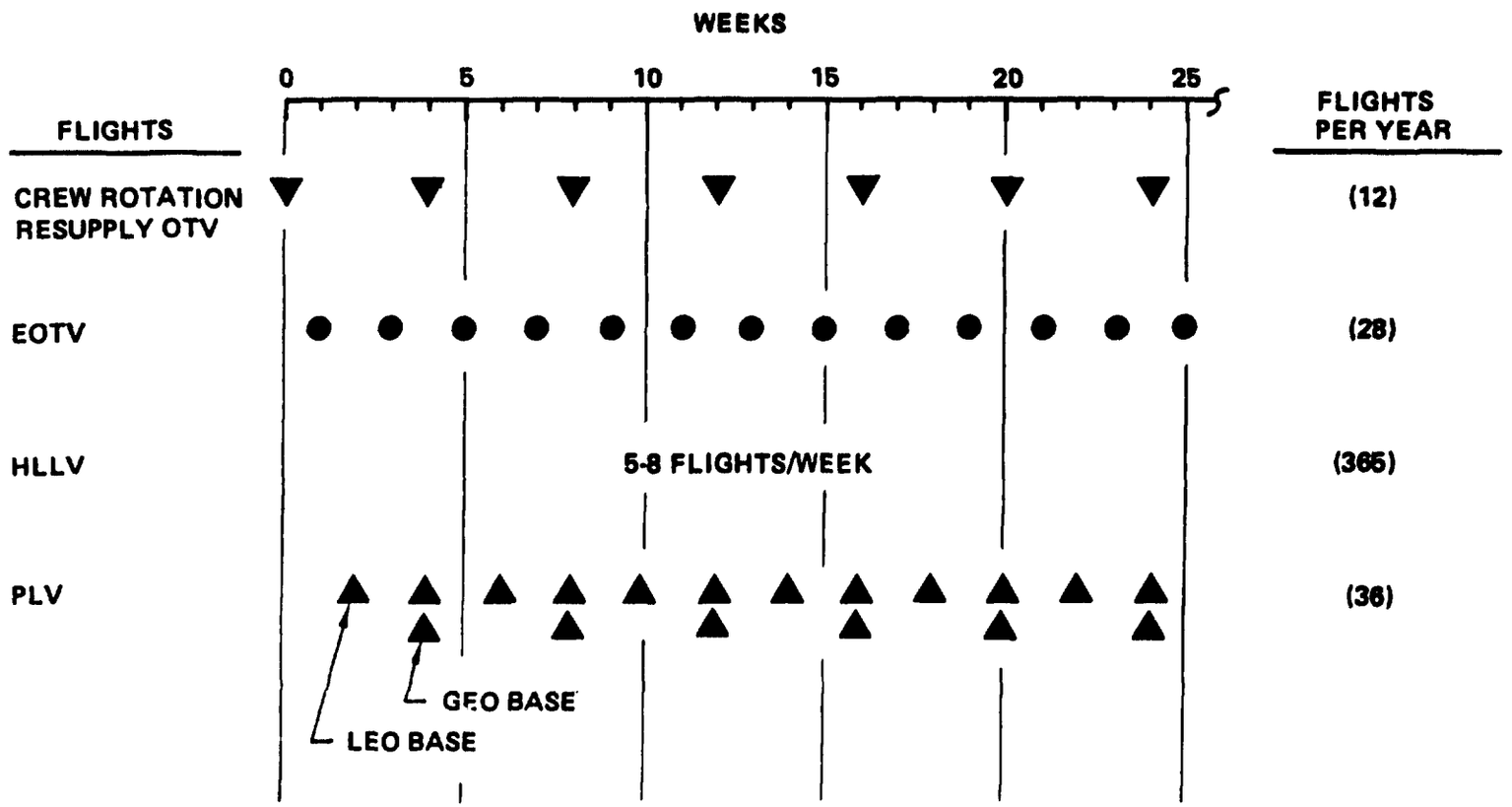


LEO BASE DEPOT OPERATIONS

Flight Support Schedule

Another function to be performed by the base is to provide support to the transportation operations or flights which interface with the base. Four types of flights are considered. First, crew rotation/resupply flights which occur at four week intervals. EOTV flights will occur at approximately 11 day intervals. HLLV's will deliver payloads to the LEO base on an average of 7 times per week. Personnel launch vehicles deliver new crewmen to orbit approximately every two weeks. Double flights are indicated for the GEO base PLV flights because each crew OTV transports 160 people while the PLV transports only 80 per flight.

LEO Base Depot Operations Flight Support Schedule



GEO CREW ROTATION/RESUPPLY

GEO Construction

Several options exist for the delivery of crew and supplies between LEO and GEO. Basically these options are 1) to combine the two functions in one flight and 2) have separate flights for each function. Transportation requirements for these two options are indicated, along with the propellant requirements per flight and annual propellant requirements. On a per flight basis, the option consisting of the combined crew rotation/resupply requires approximately 800,000 kilograms per flight, while the propellant loading for the option having separate crew and supply delivery has an average of approximately 500,000 kilograms which is approximately the OTV size for the LEO construction concept. On an annual basis, the combined crew rotation/resupply flight reduces the total propellant requirement by 2 million kilograms resulting in approximately 100 million dollars savings per year. Consequently, the combined crew rotation/resupply option has been selected for the GEO construction/EOTV option.

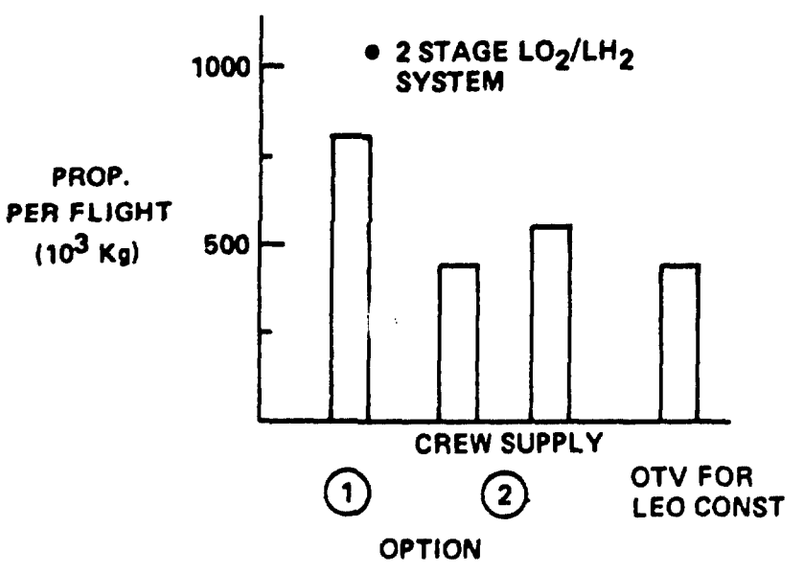
GEO Crew Rotation/Resupply GEO Construction

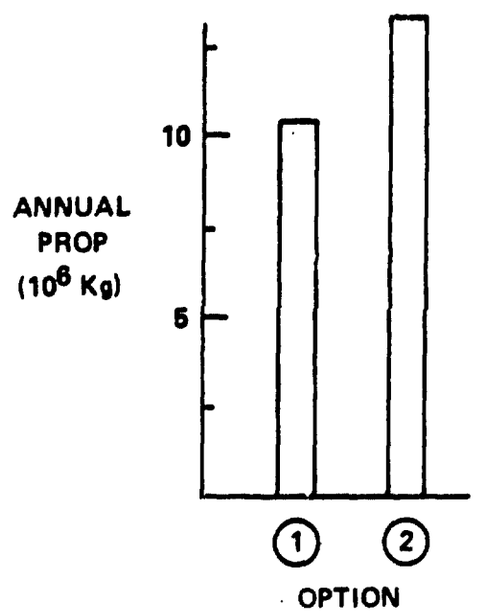
SPS-2228

- REQUIREMENTS
  - 480 PEOPLE
  - 3 MONTH STAYTIME
  - 230 Kg/MAN MONTH

- DELIVERY OPTIONS

	(1) COMBINED CREW + SUPPLY	(2) SEPARATE CREW	(2) SEPARATE SUPPLY
• FLT/MO	1	1	1
• CREW	160	160	–
• MAN MO. SUPPLIES	480	–	480
• P/L UP (10^3 Kg)	150	52	96
• P/L DN (10^3 Kg)	90	52	48





SELECT COMBINED

- SAVES APPROX. $100 MILLION/YEAR

LEO STAGING DEPOT CREW SIZE

The crew size to maintain the base is presented for three different time periods. The EOTV construction period requires approximately 200 people, the on-going operation period when EOTV flights are delivering SPS components to GEO requires 134 people and the time period which has on-going operations as well as the construction of the second set of EOTV's requires a total of 220. To accommodate this crew size, a total of two large crew modules will be provided. The characteristics of these modules are the same as described for the crew modules used with the LEO base of the LEO construction concept described in Part III of Contract NAS9-15196.

LEO Staging Depot Crew Size

	EOTV CONSTRUCTION	ON-GOING OPERATIONS	EOTV CONST + OPERATIONS
BASE MGMT	(7)	(7)	(7)
CONSTRUCTION	(77)	(0)	(77)
MGMT	6		6
EOTV CONST	46		46
SUBASSY	10		10
TEST & QC	15		15
BASE OPS & SUPPORT	(93)	(84)	(93)
MGMT	6	6	6
MAINTENANCE	14	10	14
VEH/CARGO HANDLING	16	13	16
FLIGHT CONTROL	6	6	6
COMMUNICATION	8	8	8
DATA PROCESSING	6	6	6
UTILITIES	12	12	12
HOTEL OPS	16	16	16
MED/DENTAL	9	7	9
TRANSPORTATION OPS	(21)	(43)	(43)
MGMT	4	4	4
PROP HANDLING	8	8	8
FLIGHT READINESS	7	7	7
EOTV MAINT	0	22	22
VEHICLE COORD	2	2	2
TOTAL	198	134	220

LEO BASE MASS AND COST

Mass and cost are both dominated by the crew/work modules. Again, there are two modules the serve as full time crew quarters, one module for transient crews (and as back-up primary module) and a fourth module which serves as a combination maintenance/operation center. Base subsystems include a solar array for primary power, nickel hydrogen battery for secondary power and a LO_2/LH_2 flight control subsystem. Vehicle and cargo handling elements include on-base transportation systems for moving cargo and personnel, as well as the docking ports required in support of the various transportation systems. Since the base will also be serving as an OTV support base, a propellant storage and distribution system is provided. The construction equipment includes the capability of building each EOTV in approximately 23 days and the total fleet of 23 vehicles in 1.5 years. This concludes the basic difinition the silicon EOTV, its operations and support systems for GEO construction concept.

LEO Base Mass and Cost

WBS	MASS (10^3 Kg)	COST ($\$10^6$)
STRUCTURE	200	20
CREW/WORK MODULES	810	1150
BASE SUBSYSTEMS	50	5
VEHICLE/CARGO HANDLING	50	40
PROP. STORAGE/DELIV.	35	15
CONSTRUCTION EQUIP.	115	260
DRY	1260	BASIC 1490
CONSUMABLES (90 DAY)	60	WRAPAROUND 47% BASIC 700
	1320	2190

DATA USED FOR COST COMPARISON

A preliminary comparison of the LEO construction/self-power concept with a GEO construction/EOTV concept is provided. The first chart presents some of the key inputs into the basic cost comparison. Although, the majority of these items are self-explanatory, a few words will be provided relative to several items. Satellite mass for the LEO construction option does present a greater transportation requirement due to its modularity and initial oversizing due to radiation degradation during the transfer of the modules from LEO to GEO. The orbit transfer hardware mass is somewhat smaller for the LEO construction approach, primarily because of the smaller fleet size. Because a large portion of the self power electric propulsion system is recovered and reused only five sets (one set per module) are required rather than eight. Propellant mass for the OTV is considerably greater for the self-power module, because it presently has a high gravity gradient torque penalty. This point is illustrated by flight performance simulations which currently indicate an effective specific impulse of 2800 seconds for the self-power option while the EOTV has an effective specific impulse of 6400 seconds. Both transportation options assume a design life of 10 flights. In the cases of self-power option, only 63% of the systems are recovered in terms of the cost, whereas the complete EOTV is returned and reused. The trip time for the self power modules is less because LO_2/LH_2 system used to supplement the electric system during periods of high gravity gradient torque also provide an increase in the velocity of the vehicle thereby reducing trip time. Crew size of the two options are approximately the same during the on-going operations, although the GEO construction approach does have the majority of its crew located at GEO requiring a greater transportation cost. Base mass differences reflect differences in crew size, function of the base and its location in terms of environment impact. HLLV cost primarily reflects the difference in number of flights required for each of the options with the self-power option requiring more flights due to the greater propellant requirements for the transfer of the satellite as well as the use of LO_2/LH_2 OTV's to return the electric propulsion system components.

Data Used For Cost Comparison

SPS-2292

ITEM	LEO CONSTRUCTION/ SELF POWER	GEO CONSTRUCTION/ EOTV	LEO CONCEPT DIFFERENCE
SATELLITE MASS (M.T.)	102,000	99,000	MODULARITY OVERSIZING
OTV HRDW MASS (M.T.)	9,600	28,300	EPS VS EPS + PGDS
OTV PROP. MASS (M.T.)	31,000	14,700	HIGH GGT PENALTY
REUSABILITY	63% OF EPS COST 10 FLIGHTS	100% OF EOTV 10 FLIGHTS	CHEM OTV FOR RECOVERY
TRIP TIME COST BASIS	140 DAYS	180 DAYS	BOTH COST OPTIMIZ.
CREW SIZE: LEO	480	130/220	NO OTV CONST &
GEO	65	480	BETTER UTILIZ OF CREW FOR REFURB
BASE MASS (MT) LEO	5,870	1,320	
GEO	880	6,535	
HLLV COST/FLT ($\$10^6$)	$13.3	$14.0	452 VS 358 FLTS/YR
PLV COST/FLT ($\$10^6$)	$12	$12	
POTV COST/FLT ($\$10^6$)	$ 4	$ 4	
INTEREST RATE	7.5%	7.5%	
SATELLITE COST ($\$10^9$)	8	8	

PRELIMINARY COST COMPARISON
LEO/Self-Power vs. GEO/EOTV

Preliminary cost comparison between the two construction options is indicated for three conditions. First, the time period associated with the "preparation for construction" which means procurement and placement of the construction bases. The second time period called the "first satellite for each OTV set" is that point in time when the orbit transfer vehicle hardware is procured and also involves the placement of the first satellite which means direct operation costs. The final condition indicated is called "average per satellite" which takes into consideration the amoritization of all capital costs in addition to the direct cost and construction trip time delay. In the case of the preparation for construction cost, the LEO option results in approximately a $2 billion savings primarily due to the fact that the orbital bases for the LEO construction option require fewer and less costly crew modules as well as the location of the construction base requires less transportation cost. Crew and supply delivery costs reflect one-half the size as occurs during the on-going operations but continues over a two year time period.

For the case of placing the first satellite, the LEO construction option again results in a cost savings of approximately $2 billion. For this condition, the orbit transfer vehicles have been bought and show a decided advantage for the LEO construction approach due to the few number of units that must be procured. Amoritization of the LEO construction bases reflect a 25 year time period. Direct cost for this time period favors the GEO construction approach primarily due to the low propellant requirements for the OTV and the more efficient recovery operations associated with electric propulsion systems.

The final comparison reflects the overall average per satellite and amoritizes all capital cost. The orbit transfer vehicle is amoritizated over a period of approximately 7 years. On this basis, the capital cost of the LEO approach is less but the direct cost is considerably higher resulting in the GEO construction concept being approximately 600 million dollars cheaper per satellite, which translates into approximately $6 per Kg of SPS. It should be emphasized however, that several possibilities exist to reduce the cost of the LEO construction/self-power concept. One possibility is the reduction of propellant to overcome gravity gradient torque by improving the module moment of inertia characteristics. In the case of the higher cost associated with recovery and refurb, the self-power module option can consider recovering more components as well as the use of a less costly small electric orbit transfer vehicle instead of a LO_2/LH_2 OTV for recovery. The resulting LEO construction/self-power cost is expected to be equal to or slightly less than the GEO construction EOTV concept especially when the EOTV is costed on a more detailed basis and the uncertainty in the concept is included in the cost.

Preliminary Cost Comparison LEO/Self Power vs GEO/EOTV

SPS-2314

NOTE: ONLY INCLUDES THOSE COST ELEMENTS SENSITIVE TO CONST. LOCATION

ITEM	PREPARATION FOR CONSTRUCTION		FIRST SATELLITE FOR EACH OTV SET		AVERAGE PER SATELLITE	
	LEO	GEO	LEO	GEO	LEO (6)	GEO (7)
• CAPITAL COST	(8585)	(10505)	(2035)	(4660)	(925)	(1430)
• SAT. OTV LAUNCH	–	–	355	1100	1 155	490
• SAT. OTV HARDWARE	–	–	910	2620		
• BASE TRANSPORT.	385	700	1 770	940	770	940
• BASE HARDWARE	8200	9805				
• DIRECT COST	(490)	(860)	(6170)	(5365)	(6615)	(5365)
• SAT. LAUNCH	–		3760	3850	3760	3850
• SAT. OTV PROP LAUNCH	–		1080	540	2 1080	540
• SAT. Δ HARDWARE	–		160	0	160	0
• OTV RECOVERY/REFURB	–		685	120	3 1130	120
• CREW/SUPPLY DELIV.	490	860	485	855	485	855
• CONST. TIME DELAY	–	–	(380)	(490)	(380)	(490)
TOTALS (10^6 DOLLARS)	9075	11365	8585	10515	7920	7285
$/kg OF SATELLITE			~86	~80	~79	~73

1 AMORTIZED

2 CAN BE REDUCED WITH BETTER MODULE INERTIA CHARACTERISTICS

3 CAN BE REDUCED WITH RECOVERY BY AN EOTV

FINDINGS TO DATE

Preliminary findings to date for the GEO construction/EOTV are indicated. In summary, it should be realized that although the cost of the GEO construction/EOTV concept presently is lower than that of the LEO construction/self-power concept, performance characteristics for the EOTV have a considerable degree of uncertainty. In addition, cost for the EOTV is expected to go up when more detail costing analysis is performed. Finally, it is also expected that the cost for the self-power concept can be reduced through the utilization of a higher performance recovery system, recovery of more components and better moment of inertia characteristics.

Findings To Date

- PREVIOUS SELF-POWER THRUSTER PERFORMANCE AND LIFETIME CHARACTERISTICS HAVE BEEN VERIFIED
- CONFIGURATION INERTIA BALANCING NOT AS IMPORTANT AS FOR SELF POWER MODULES
- A CONSIDERABLE DEGREE OF UNCERTAINTY EXIST REGARDING SOLAR ARRAY PERFORMANCE AS A RESULT OF REPEATED DAMAGE AND ANNEALING
- EOTV COST OPTIMIZATION NOT AS SENSITIVE TO SPECIFIC IMPULSE AND TRIP TIME AS SELF POWER DUE TO AMORTIZATION
- INITIAL INVESTMENT COST ARE HIGHER FOR GEO CONSTRUCTION/EOTV DUE TO MORE MASSIVE BASES AND THEIR LOCATION AS WELL AS ADDITIONAL OTV HARDWARE
- AVERAGE COST PER SATELLITE ARE LOWER FOR THE EOTV CONCEPT SINCE SAVINGS FROM LESS PROPELLANT, FULL REUSABILITY AND RECOVERY MODE MORE THAN OFFSET ADDITIONAL OTV MASS AND ITS COST
- SELF POWER COST PER FLIGHT CAN BE REDUCED TO BE COMPARABLE OR LOWER THAN THAT FOR EOTV'S'

EOTV TASKS REMAINING

Those tasks to be performed to complete the EOTV analysis following the mid-term are indicated. In the case of the silicon EOTV, a performance and cost analysis will be done for the case of using six mil cover glass rather than the three mil cover glass on the solar cells. As previously indicated, there will also be a bottoms up costing that will better reflect the number of components and design features of this concept and how they are different from the basic satellite and the self-power transfer propulsion systems. The gallium arsenide EOTV will be analyzed in a manner similar to that performed on the silicon EOTV. Self-power orbit transfer system will be briefly analyzed to improve on its moment of inertia characteristics, investigate having a higher degree reusability of its components and use of a small electric orbit transfer vehicle for the return of the components. Finally, a complete over all assessment of these two construction options will be performed along the same lines as the previous Boeing analysis in comparing a GEO conception/chemical OTV concept with LEO construction/self-power.

EOTV Tasks Remaining

- SILICON EOTV
  - COST ADJUSTMENT FOR COMPONENT RATES AND DESIGN FEATURES DIFFERENT FROM THE SATELLITE AND SELF POWER ORBIT TRANSFER SYSTEMS
  - PERFORMANCE/COST PARAMETRICS FOR 6 MIL COVER GLASS
- GALLIUM ARSENIDE EOTV
  - ANALYSIS SIMILAR TO SILICON EOTV
- SELF POWER ORBIT TRANSFER
  - INVESTIGATE ALTERNATE TRANSFER CONFIGURATIONS TO REDUCE GGT PENALTY
  - INVESTIGATE REUSABILITY OF ADDITIONAL COMPONENTS
- PERFORM OVERALL GEO CONSTRUCTION/EOTV VS LEO CONSTRUCTION/ SELF POWER ASSESSMENT

Small SPS's

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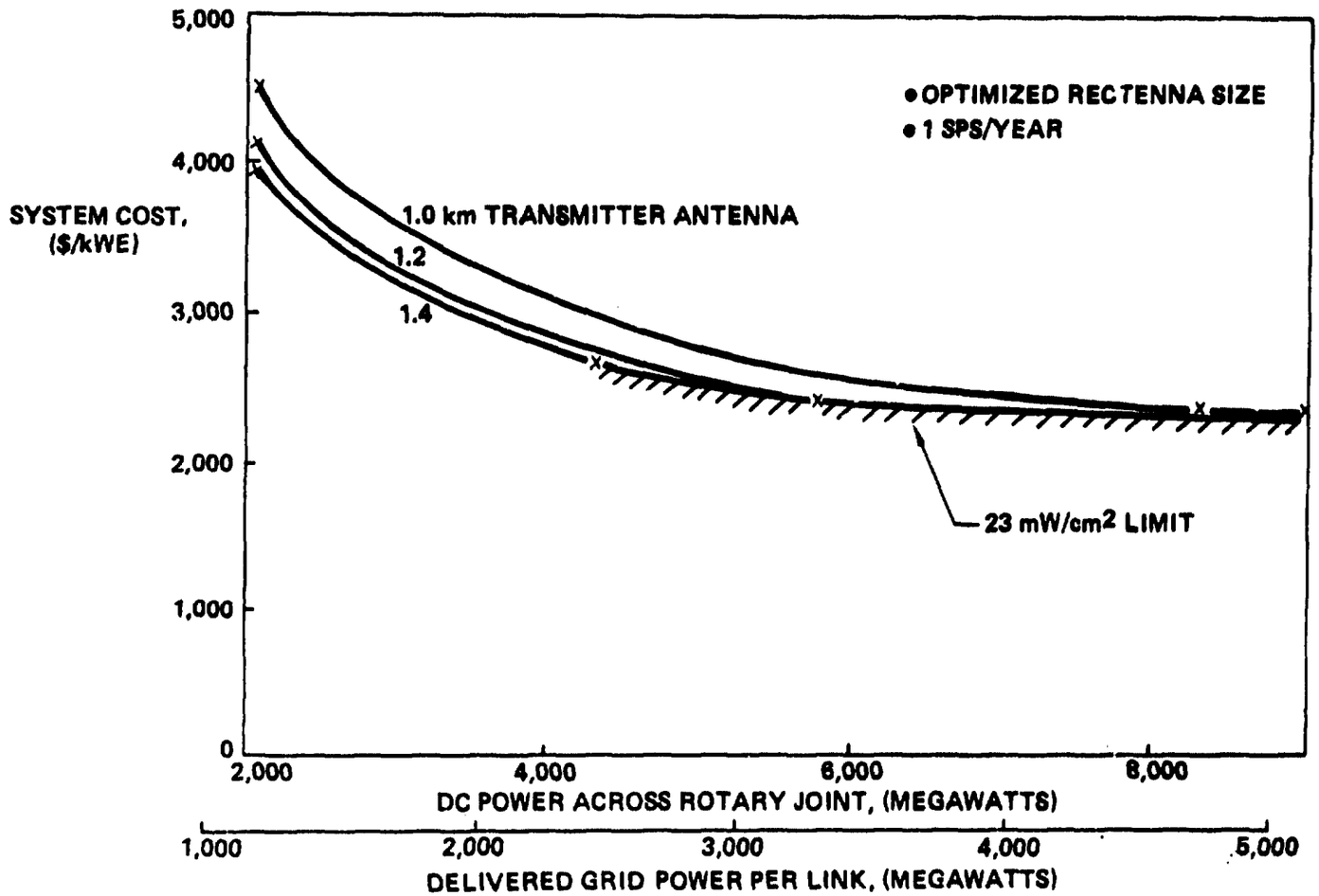
SIZE SENSITIVITY ANALYSIS POWER LEVEL AND TRANSMITTER DIAMETER

Shown is a joint optimization of transmitter diameter and power level holding the rectenna size constant at the optimum value. This result was developed on the earlier contract, and did not include packaging density considerations. As the system power level is reduced it is possible to employ somewhat larger transmitting antennas without violating the 23 mw/cm^2 limit. Transmitter diameters larger than 1.4 kilometers do not pay off; the minimum system cost in dollars per kilowatt follows along the 23 mw/cm^2 limit to about 2500 megawatts and then follows up the 1.4 kilometer diameter transmitter curve. Note that comparatively little cost penalty is incurred going down as low as 3000 megawatts of grid power. Below 3,000 megawatts the system cost in dollars per kilowatt begins to turn up rapidly.

The present effort has expanded on these earlier results to consider packaging and specific configuration effects arising from asymetric configurations.

Size Sensitivity Analysis Power Level and Transmitter Diameter



SMALL SPS'S

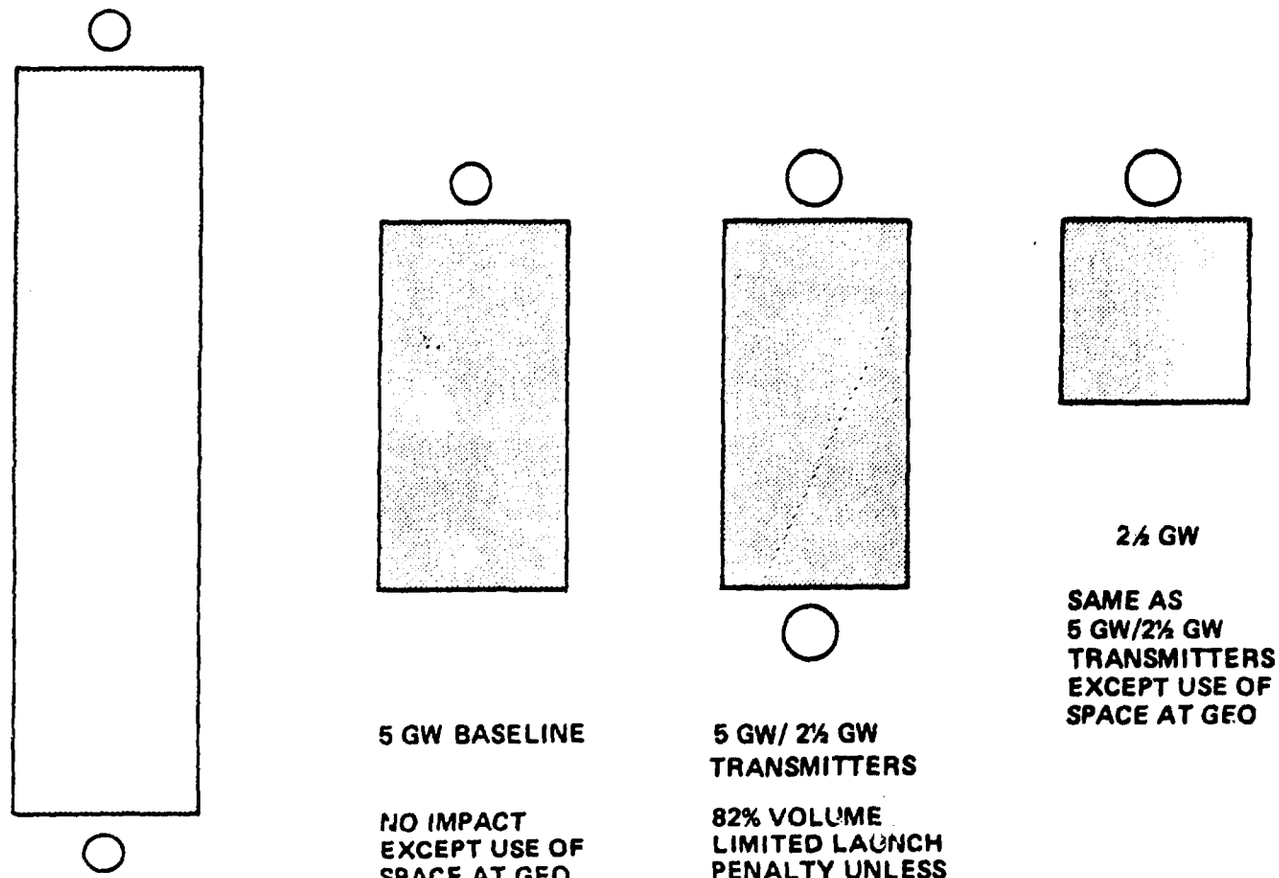
Three smaller SPS configurations are compared to the original 10 gigawatt baseline. The first of the three shown is the present NASA 5 gigawatt baseline with one transmitting antenna. Analysis of the control requirements for this asymmetric configuration determined that because of the overriding importance of solar pressure compensation in the control thrust scheme, no propellant penalties were incurred by the lack of symmetry. Also, no packaging differences have been identified that would arise from dividing the original configuration into two equal halves. Therefore, the only consequence of this alternative to the original baseline is the requirement for more positions in geosynchronous orbit to effect a given total installed generating capacity.

The next alternative shown is also a five gigawatt system, but the power is divided into two power transmission links each rated at 2½ gigawatts. In order to minimize land use and rectenna costs, it is desirable when reducing the link power to increase the transmitter aperture, in turn reducing the receiving station area. This design option, however, has approximately 4 times as many transmitter subarrays as the single-transmitter 5 gigawatt satellite. As a result, it incurs a significant payload packaging problem because of the low packaging density of completely assembled transmitter subarrays. The packaging density situation appears to be much improved through use of a solid state transmitter. In the solid state option all of the active functions are included in a planar sheet only about 2 centimeters thick (including the resonant cavities). Thus, a much higher packaging density per unit of aperture area can be achieved.

The final option shown, like the second option, results from effectively dividing a symmetric configuration in half. As for the other case, no penalties were determined for this design option excepting the use of more geosynchronous orbit space.

Small SPS's

SPS-2251



10 GW BASELINE

5 GW BASELINE

NO IMPACT EXCEPT USE OF SPACE AT GEO

5 GW/ 2½ GW TRANSMITTERS

82% VOLUME LIMITED LAUNCH PENALTY UNLESS TRANSMITTER IS SOLID STATE

2½ GW

SAME AS 5 GW/2½ GW TRANSMITTERS EXCEPT USE OF SPACE AT GEO

SPS PACKAGING ESTIMATES

Tabulated on the facing page is a summary of a packaging update. This packaging update includes allowances for orbit transfer hardware and orbit transfer propellants (both of which package relatively densely), thus density determined for the 10 gigawatt reference configuration has increased somewhat from earlier estimates. Nonetheless, a significant problem is identified for the systems of the reference type with 2½ gigawatt transmitter links. The problem is much alleviated in the solid state transmitter case.

SPS Packaging Estimates

	PACKAGING DENSITY	HLLV FLIGHTS TO DELIVER SPS	VOLUME-LIMITED PENALTY, %
10 GW, REF. DESIGN	125 kg/m^3	415	0
5 GW, REF. DESIGN	125 kg/m^3	208	0
2.5 GW, ONE ANTENNA	42 kg/m^3	207	82%
5 GW, TWO ANTENNAS	42 kg/m^3	414	82%
2.5 GW, ONE ANTENNA, SSPA	77 kg/m^3	111	0
5 GW, TWO ANTENNA SSPA	77 kg/m^3	222	0

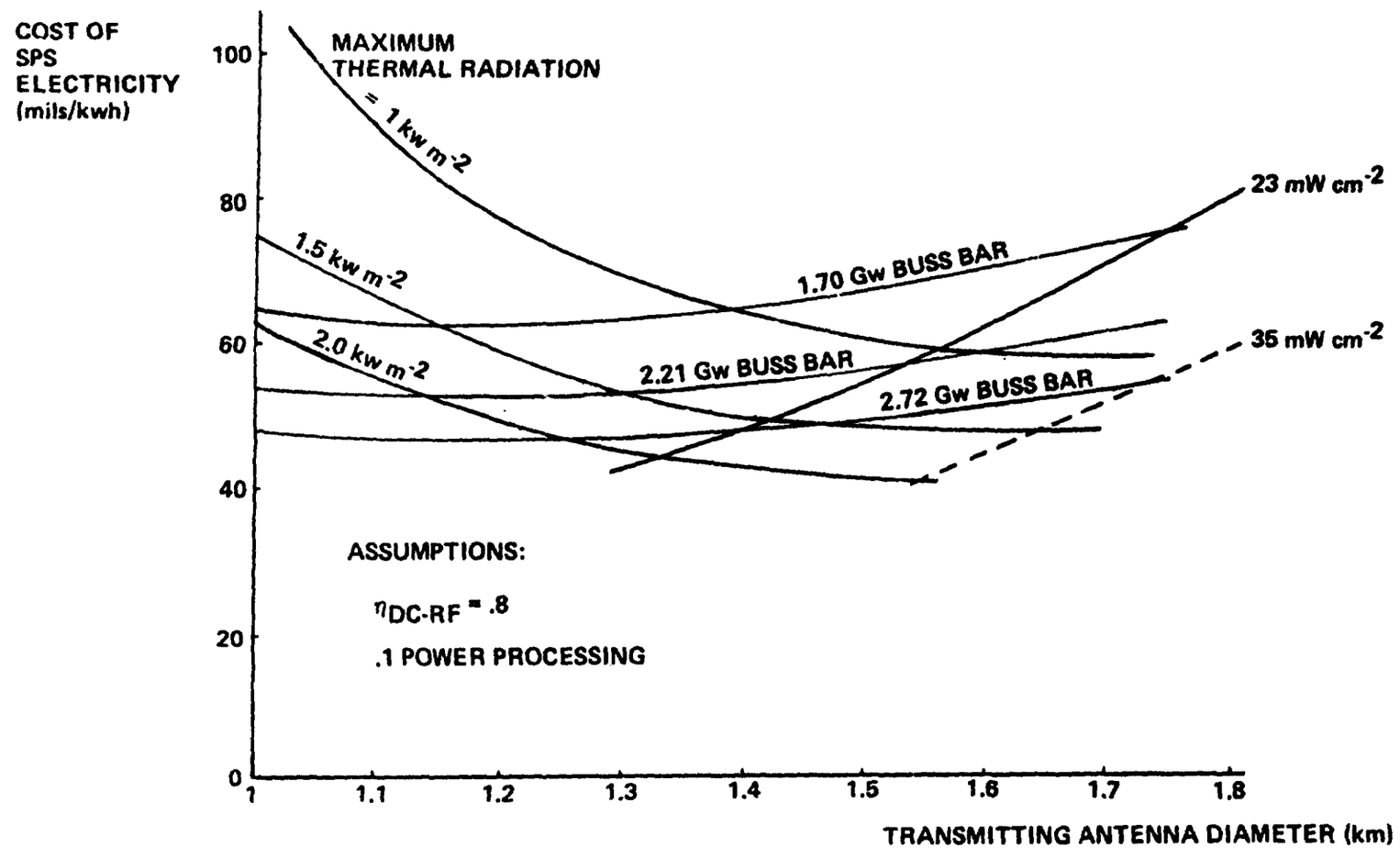
PACKAGING DENSITY INCLUDES SPS AND APPLICABLE ORBIT TRANSFER HARDWARE

REPRESENTATIVE SOLID STATE SPS COSTS AND SIZING

The solid state transmitter is limited by maximum allowable device temperature to a thermal dissipation of roughly 1.5 kilowatts per square meter. At a conversion efficiency of 80% with a 10 dB Gaussian taper the thermal constraints and ionosphere power density constraints follow characteristic curves as illustrated on this map of SPS power cost indicators versus transmitter diameter and power level. As can be seen, the solid state system is constrained to a total power level of approximately 2½ gigawatts with a transmitter aperture of 1.4 kilometers. Thus, this system is well-suited to the smaller size lower power SPS application and in fact may be limited to such lower power transmitter links.

Representative Solid State SPS Costs and Sizing

SPS-2345



SMALL SPS'S

The main points of the small SPS investigation are summarized here.

Small SPS's

- NO PROBLEMS WITH DIVIDING 10-GW SPS INTO TWO 5-GW SPS'S
- LOW POWER SYSTEMS ARE DIFFICULT TO PACKAGE FOR LAUNCH
- SOLID-STATE MPTS APPEARS TO MINIMIZE THIS PROBLEM

Launch Site

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UPPER BOUND PERFORMANCE DELTA SUMMARY

LOW LATITUDE VERSUS KSC

An initial attempt at performance simulation for a low latitude transfer from 5° inclination to geosynchronous orbit actually exhibited reduced performance as compared to the reference 30° case. Increased loss due to sun occultations apparently more than offset the reduction in delta V and in gravity gradient losses. In fact, the variations in performance due to variations in orbit geometry and season are greater than performance differences between low latitude and 30° inclination starting orbits. Therefore, in determining the cost benefits from performance improvement between low inclination and high inclination orbits an upper bound analysis was adopted. This analysis is summarized on the facing page and shows that cost advantages for the low latitude transfer are minimal.

Although it is not likely that this small cost advantage can overcome the cost increases associated with departing from an existing facility, such as KSC, other reasons may exist for setting up a new launch site for SPS operation. These reasons include the likelihood that the scale of SPS transportation operations will eventually outgrow KSC as well as potential desirability of an international launch site for what could eventually become an international project.

Upper Bound Performance Delta Summary Low Latitude Versus KSC

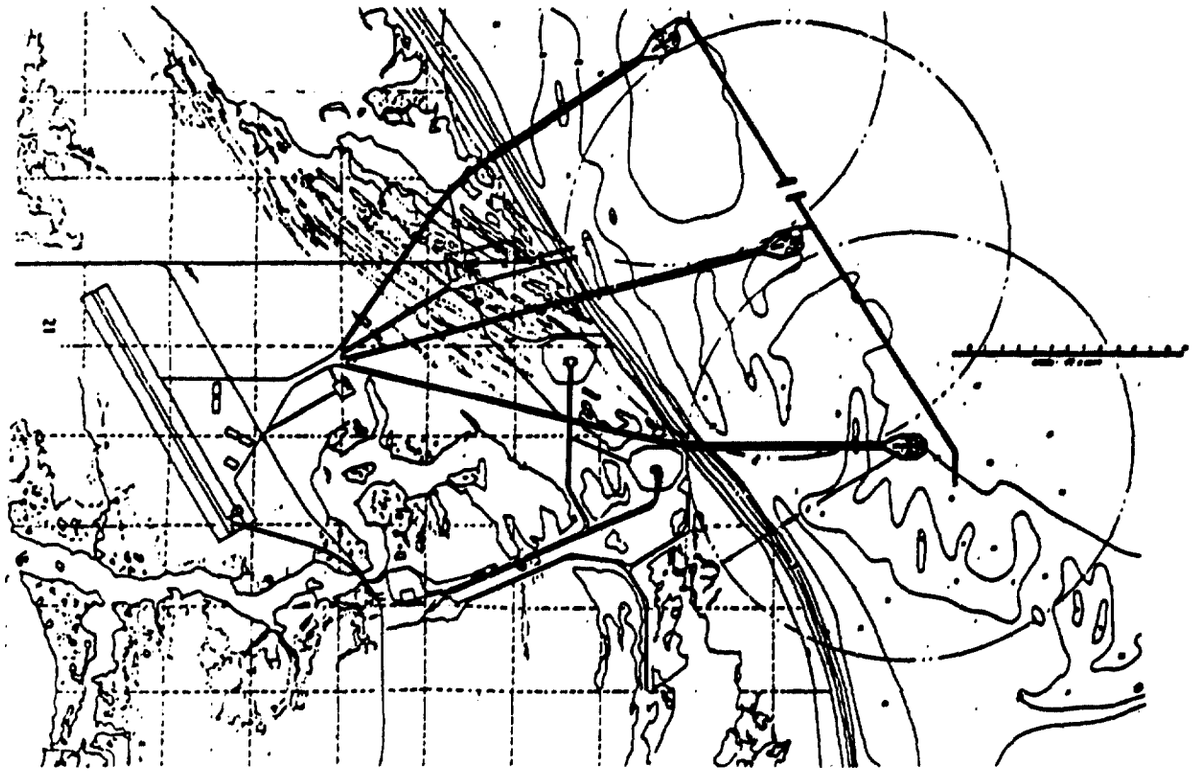
- MASS RATIO FOR 30° PLANE CHANGE FROM LEO TO GEO (1.25 SELF-POWER; ABOUT 1.1 FOR IEOTV)
- MASS RATIO FOR NO PLANE CHANGE FROM LEO TO GEO = 1.20
- DELTA NUMBER OF HLLV FLIGHTS = 17 (400 RATHER THAN 417)
- DELTA TRIP TIME–20 DAYS (LESS FOR NO PLANE CHANGE)
- VALUE OF DELTA TRIP TIME ≈ 35 MILLION
- COST FOR REFERENCE CASE 5,570 MILLION NOT INCLUDING TRIP TIME COST
- INCLUDING DELTA TRIP TIME, 400 FLIGHTS FROM 0° CAN COST 5,605 MILLION OR $14 MILLION PER FLIGHT, COMPARED TO $13.35 MILLION AT KSC

OVERLAY OF HLLV PADS ON KSC MAP

This map illustrates the problem attendant to accommodating a large SPS transportation operation at the Kennedy Space Center. If as many as three launch pads for a large heavy lift launch vehicle are desired, safety requirements for pad separation may restrict the number of pads to as few as three and even then may necessitate placing the pads in shallow offshore waters with potential deleterious environmental impact. Alternative pad location schemes are possible and may avoid the offshore arrangement. This is particularly true if the number of pads can be reduced to two.

With the turnaround times expected for HLLV launch operations, three pads could support something like 400 flights a year, sufficient to place in orbit 10,000 megawatts of generating capacity per year.

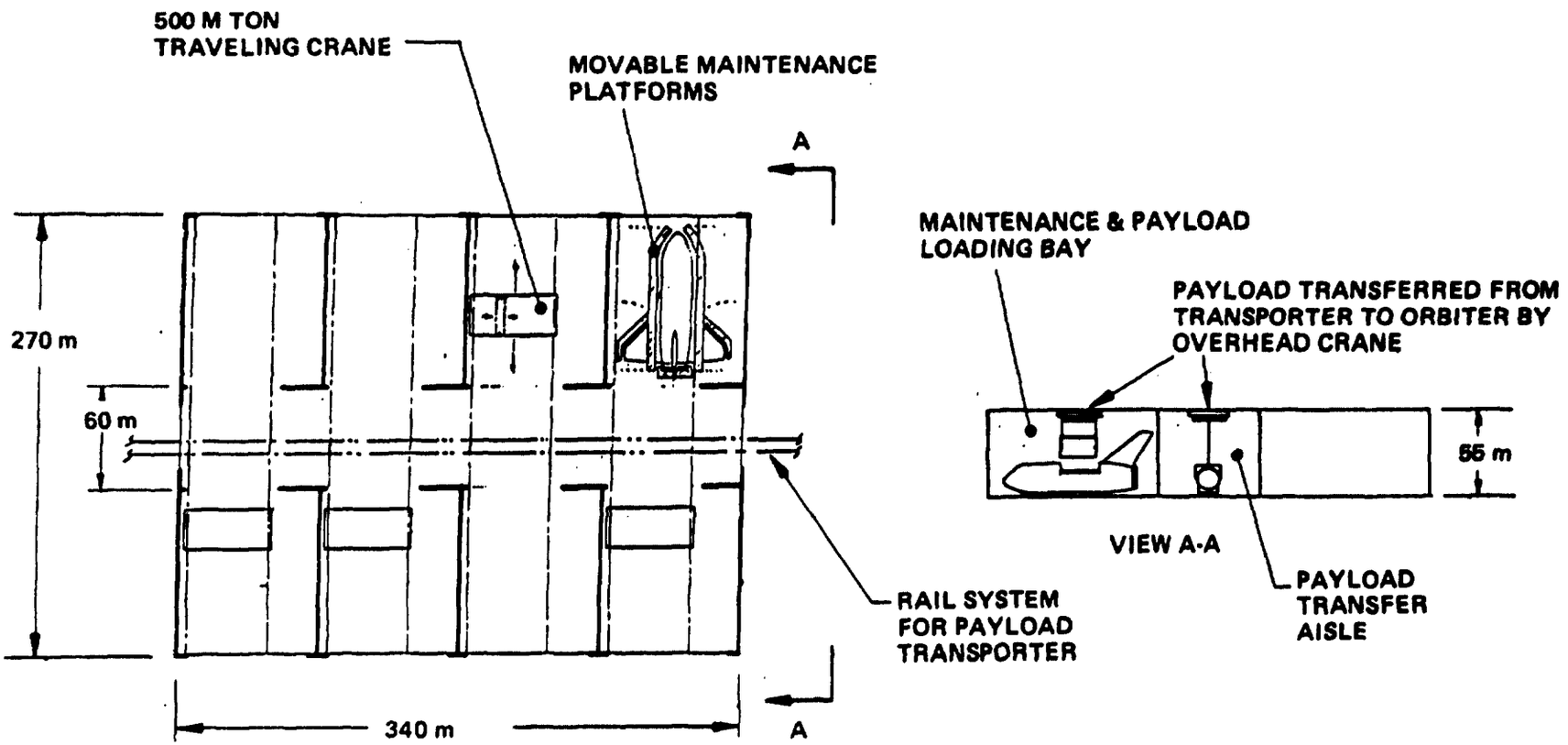
Overlay of HLLV Pads on KSC Map



ORBITER PROCESSING FACILITY

The process of defining requirements for handling facilities for launch operations is continuing. This diagram shows an orbiter vehicle processing facility sufficient to accommodate 400 HLLV flights per year.

Orbiter Processing Facility

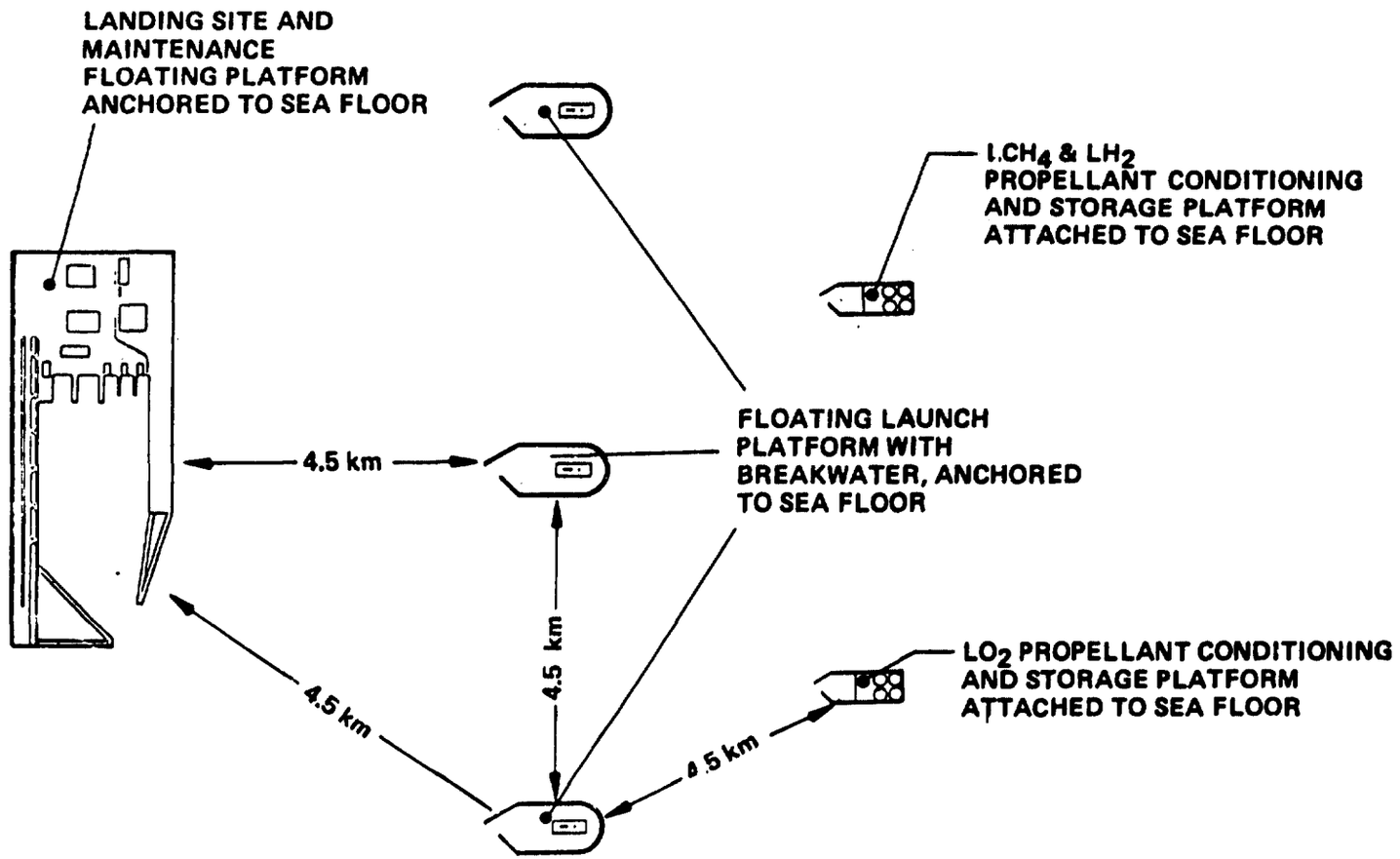


SEA BASED LAUNCH SITE CONCEPT

The concept of a sea based launch site was originated at JSC under studies of SPS launch alternatives. The sea based site depicted here is a large floating structure anchored to the sea bottom in waters up to 100 to 150 fathoms depth. Several potentially attractive low latitude sites and ocean areas, generally free from severe storms and sea states, have been identified where such a facility could be constructed and operated. The major elements of the facility are a landing runway, vehicle and payload processing facilities. Vehicles would be launched from the remotely located floating launch pads. The vehicles would be transported to these pads after being loaded with payloads. There they would then be erected and propellant barges brought to the location for fueling. Finally, a crew barge would bring the flight crew to the launch pad shortly before liftoff.

Sea Based Launch Site Concept

SPS-2358

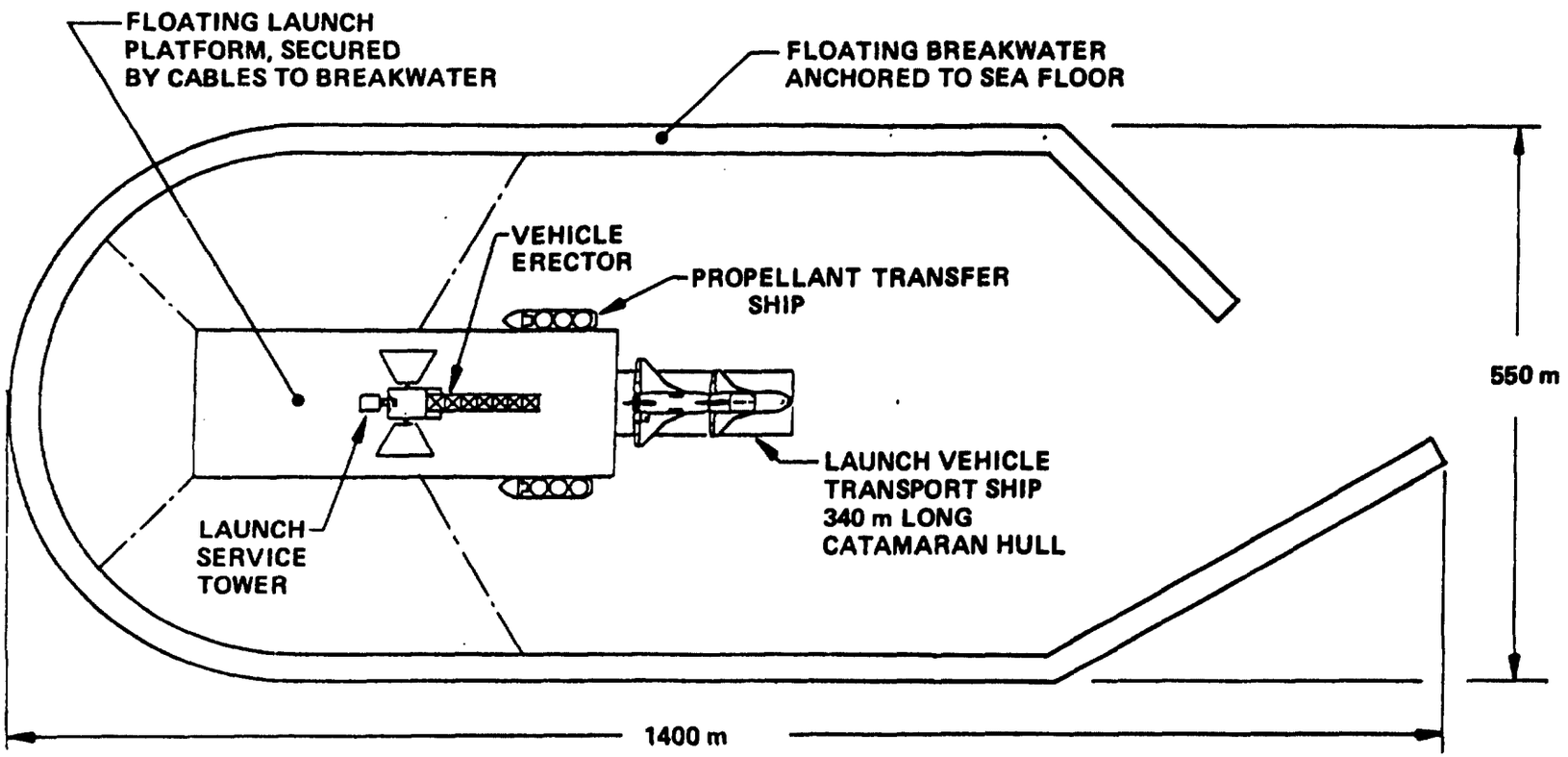


- MATED LAUNCH VEHICLE DELIVERED TO LAUNCH PLATFORM BY SHIP FROM MAIN PLATFORM
- PROPELLANTS DELIVERED TO LAUNCH PLATFORM BY SHIP FROM PROPELLANT STORAGE FACILITIES

SEA BASED LAUNCHED PLATFORM CONCEPT

The launch platform illustrated here in more detail includes a floating breakwater to minimize wave action at the launch platform so that docking of vehicle and propellant transfer barges can be more easily accomplished.

Floating Launch Platform

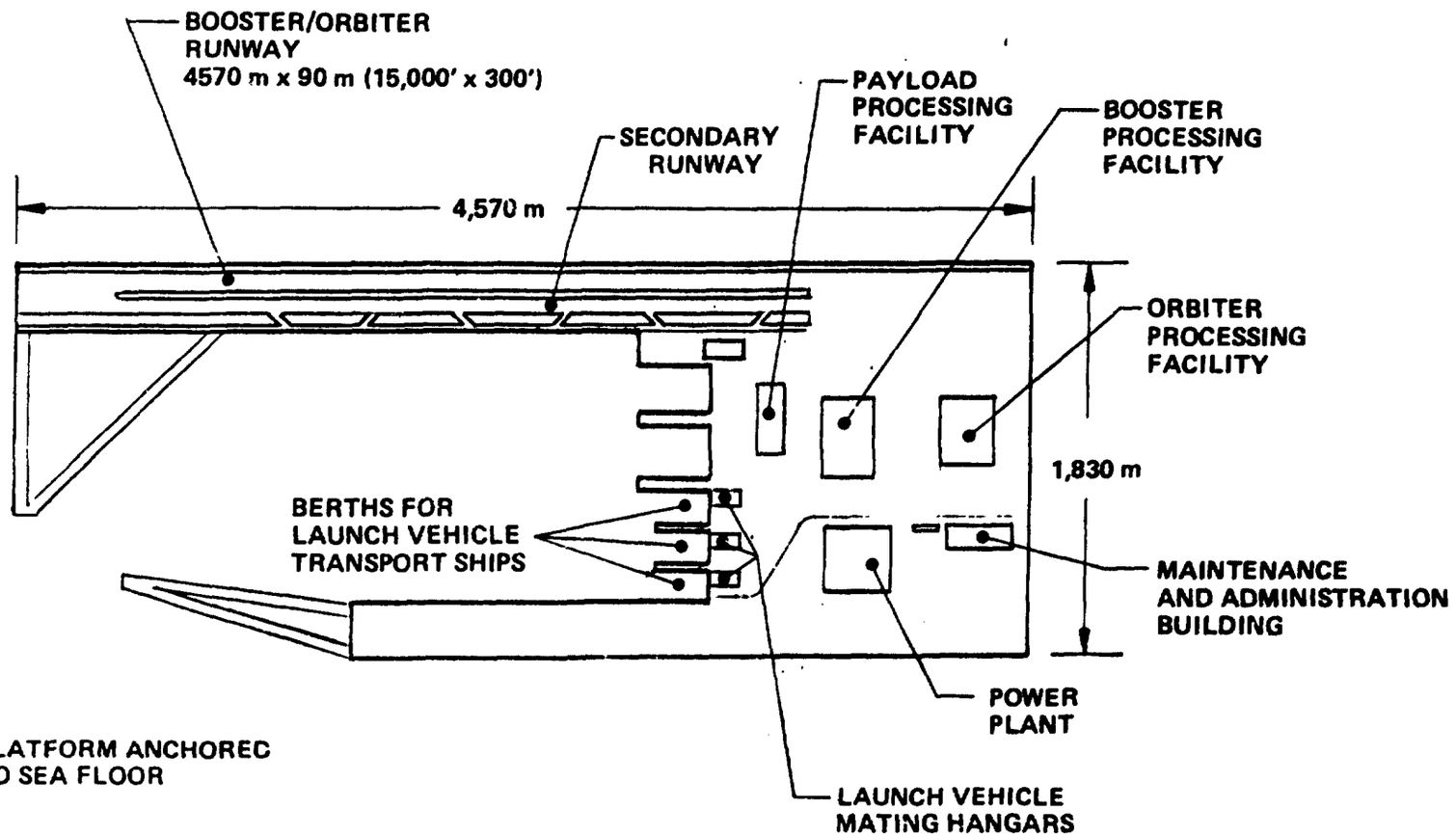


LANDING SITE AND MAINTENANCE FACILITY FLOATING PLATFORM

The major facility element is shown here in more detail with principal sizes and arrangements indicated.

Landing Site and Maintenance Facility Floating Platform

SPS-2356



- PLATFORM ANCHOREC TO SEA FLOOR

LAUNCH SITE SELECTION

The launch site analysis task was motivated by the premise that selection of a low-latitude site would offer significant cost advantages with respect to operations from the Kennedy Space Center, where earth-to-low-orbit space transportation arrives at a 30° inclination orbit. With a 30° inclination orbit for staging or construction operations a 30^{c} plane change is required to reach a geosynchronous equatorial orbit. It was presumed that this plane change would incur significant performance penalties relative to a zero-degree or low-inclination low earth orbit. However, with electric propulsion this performance difference in terms of cost is minimal. Therefore, the principal motivation for leaving KSC for a remote site will stem from the eventuality of SPS operations outgrowing KSC. Our estimates to date indicate that KSC can handle approximately 10 gigawatts per year of SPS construction.

Remote site options include land-based sites such as the mouth of the Amazon in Brazil and ocean-based sites employing large floating structures such as the western Pacific low latitude sites identified by Jim Akkerman in studies at the Johnson Space Center. Large uncertainties presently exist as to the cost of large floating structures. The two orders of magnitude range is indicated on the facing page.

Launch Site Selection

- PERFORMANCE ADVANTAGE FOR LOW LATITUDE IS SMALL (<10%) FOR ELECTRIC PROPULSION
- PRINCIPAL MOTIVATION FOR REMOTE SITE WILL OCCUR IF SPS OPERATIONS OUTGROW KSC
- KSC APPEARS SUITED FOR ABOUT 10GW/YEAR
- OCEAN SITE POTENTIALLY ATTRACTIVE DEPENDING ON COST OF LARGE FLOATING STRUCTURES
  - AIRCRAFT CARRIERS ~ $50 000/M^2
  - DRYDOCKS & BARGES ~ $5 000/M^2
  - CONCRETE FLOATS < $500/M^2 (HOUSEBOATS)

Space Construction

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Space Construction

- INTRODUCTION
  - TASK OVERVIEW
  - OPTIONS
  - GROUNDRULES
  - SELECTION CRITERIA
- BASELINE CONSTRUCTION CONCEPT DERIVATIVES
  - LEO SINGLE DECK
  - GEO SINGLE DECK
- ALTERNATIVE CONSTRUCTION CONCEPTS
  - END BUILDER OPTIONS
  - INTERNAL CONSTRUCTION BASE
  - BOOTSTRAP
- OVERVIEW OF REMAINING PHASE I TASKS

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SPACE CONSTRUCTION ANALYSIS PRIMARY OBJECTIVE

The primary objective of the Phase One construction analysis is to refine and develop alternative construction approaches. NASA-JSC has emphasized that they understand the baseline 2-deck LEO facility construction concept and are convinced that it will work. However, it is appropriate to re-examine the construction concepts to see if there are refinements or new, viable alternatives to the baseline approach.

To accomplish this task, Boeing has identified and characterized, two derivatives of the baseline concept and our subcontractor, Grumman Aerospace, has focused on three new generic construction alternatives. At this point in time, some of these concepts can be set aside. The remaining viable concepts will require another month to bring them all up to comparable levels of detail so that a preferred concept can be selected.

Space Construction Analysis
Primary Objective

OBJECTIVE

"IN VIEW OF THE RELATIVE IMMATURITY OF THE SPACE CONSTRUCTION DISCIPLINE . . . JSC CONSIDERS IT DESIRABLE TO *REFINE* OR *DEVELOP ALTERNATE CONSTRUCTION* APPROACHES." RFP, TASK 4.2.1

STATUS

- *A DERIVATIVE* OF THE BASELINE CONCEPT AND *3 GENERICALLY DIFFERENT CONCEPTS (TOTAL OF 6 OPTIONS)* ARE IN THE PROCESS OF BEING CHARACTERIZED
- *SOME* OF THE *ALTERNATIVES* CAN BE *DELETED* NOW
- *WITHIN ONE MONTH*, THE VIABLE ALTERNATIVE CONCEPTS WILL BE COMPARED AND A *PREFERRED CONCEPT SELECTED*

ALTERNATIVE CONSTRUCTION CONCEPTS

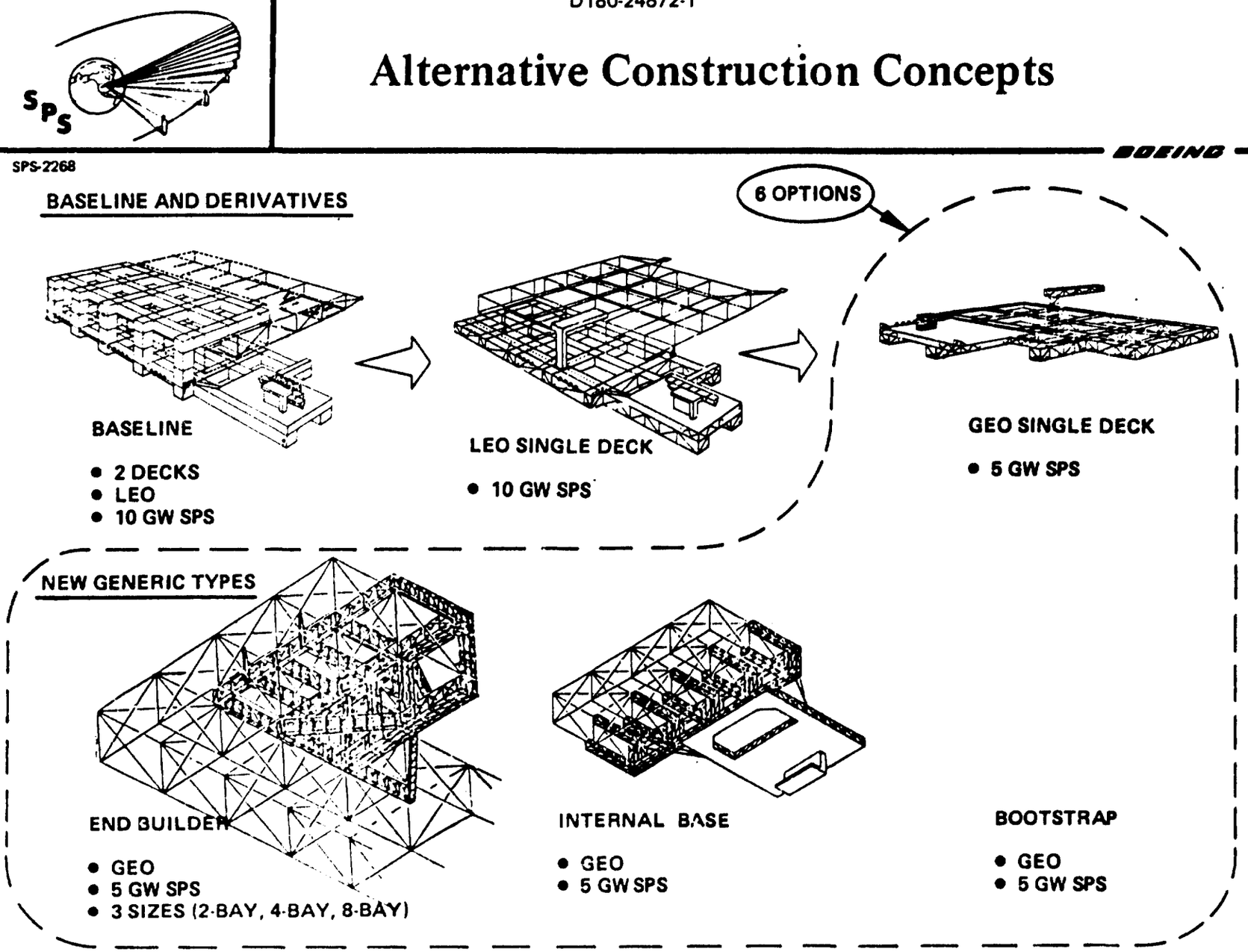
This figure depicts the scope of the various alternative construction concepts that have been explored. The LEO Single Deck base is a direct derivative of the baseline 2-deck LEO base. This concept was then modified into the GEO Single Deck base configuration that would be used to build a monolithic 5 GW SPS.

Grumman has been working on three versions of an End Builder - GEO base, an Internal Jig, and a Bootstrap construction approach. Each of these new generic types will be discussed in detail in the ensuing pages.

The six options within the dashed line are the concepts that will be directly compared when making the preferred concept selection.

Alternative Construction Concepts

SPS-2268



ALTERNATIVE CONSTRUCTION CONCEPTS GROUNDRULES

It was jointly decided by NASA-JSC and the contractors that the alternative construction concepts should be based upon building a 5 GW monolithic SPS at GEO. These groundrules were specified because it was deemed necessary to explore GEO construction in more depth. It was agreed that the winning construction concept was probably neutral to where the SPS was constructed. If the results of the EOTV study reconfirms our earlier assessment that LEO construction is the most economical, then the winning construction concept could easily be adapted to LEO construction.

This chart lists only a few of the groundrules that were established in order to make the competing construction concepts easier to directly compare. The full list of groundrules are found in Monthly Progress Reports No. 2 and 3.

Alternative Construction Concepts Evaluation Groundrules

- 5 GW, MONOLITHIC, PHOTOVOLTAIC SPS
- GEO CONSTRUCTION
- 180 DAYS ±5%
- CONTIGUOUS FACILITY (ANTENNA AND POWER COLLECTION MODULE CONSTRUCTION AREAS ATTACHED)
- 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

ALTERNATIVE CONSTRUCTION CONCEPT SELECTION CRITERIA

This chart lists the various factors that will be qualitatively and quantitatively assessed for each of the alternative construction concepts that survive our initial screening process. Our intent is to eliminate some of the competing concepts using as few of these eight selection factors as possible and to save the complete, detailed assessments for only the better candidates.

Alternative Construction Concept Selection Criteria

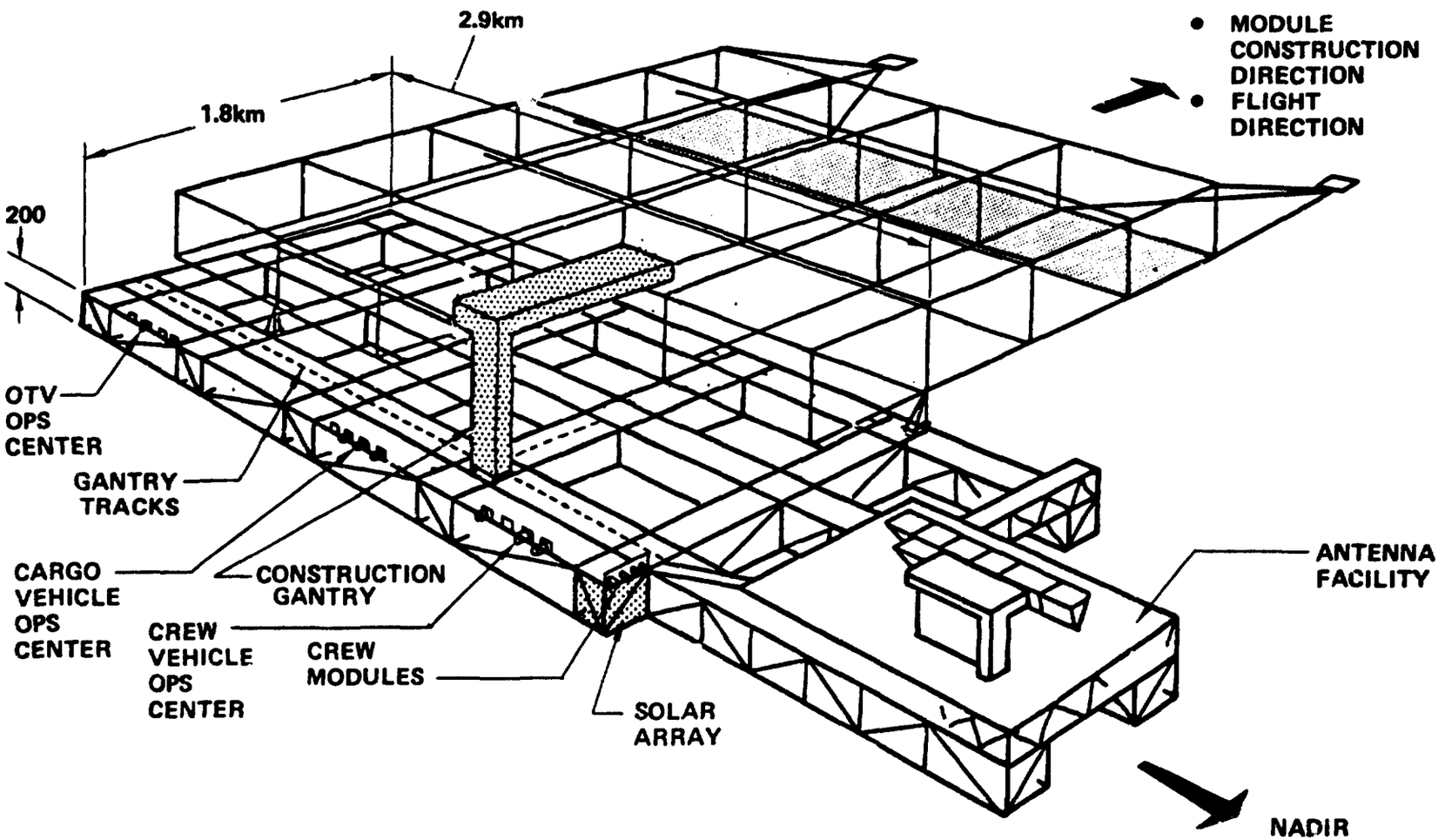
SELECTION CRITERIA	EVALUATION FACTORS
• COST	• CONSTRUCTION SYSTEM UNIT COST • SATELLITE COST DELTA
• PERFORMANCE CAPABILITY	• CONSTRUCTION SYSTEM MASS (BASE AND EQUIP) • PRODUCTION TIMELINE POTENTIAL • SATELLITE DESIGN IMPACT (MASS)
• SYSTEM COMPLEXITY	• BASE SIZE • NO. AND TYPE CONSTRUCTION EQUIPMENT • CREW SIZE • BASE LOGISTICS TRACK AND EQUIPMENT
• OPERATIONS COMPLEXITY	• MAJOR PARALLEL/SERIES CONSTRUCTION OPERATIONS • UNIAXIAL/BIAXIAL INDEXING • ANTENNA MATING MODE • NO. COUPLED/DE-COUPLED OPERATIONS
• GROWTH CAPABILITY	• ADAPTABLE TO SMALLER/LARGER SATELLITES

LEO SINGLE DECK CONSTRUCTION BASE

This LEO base configuration is a direct derivative of the baseline 2-deck LEO base. The upper deck and supporting back wall have been deleted. A construction gantry has been added to provide a way to support the construction equipment that was located on the now deleted upper deck.

LEO Single Deck Construction Base

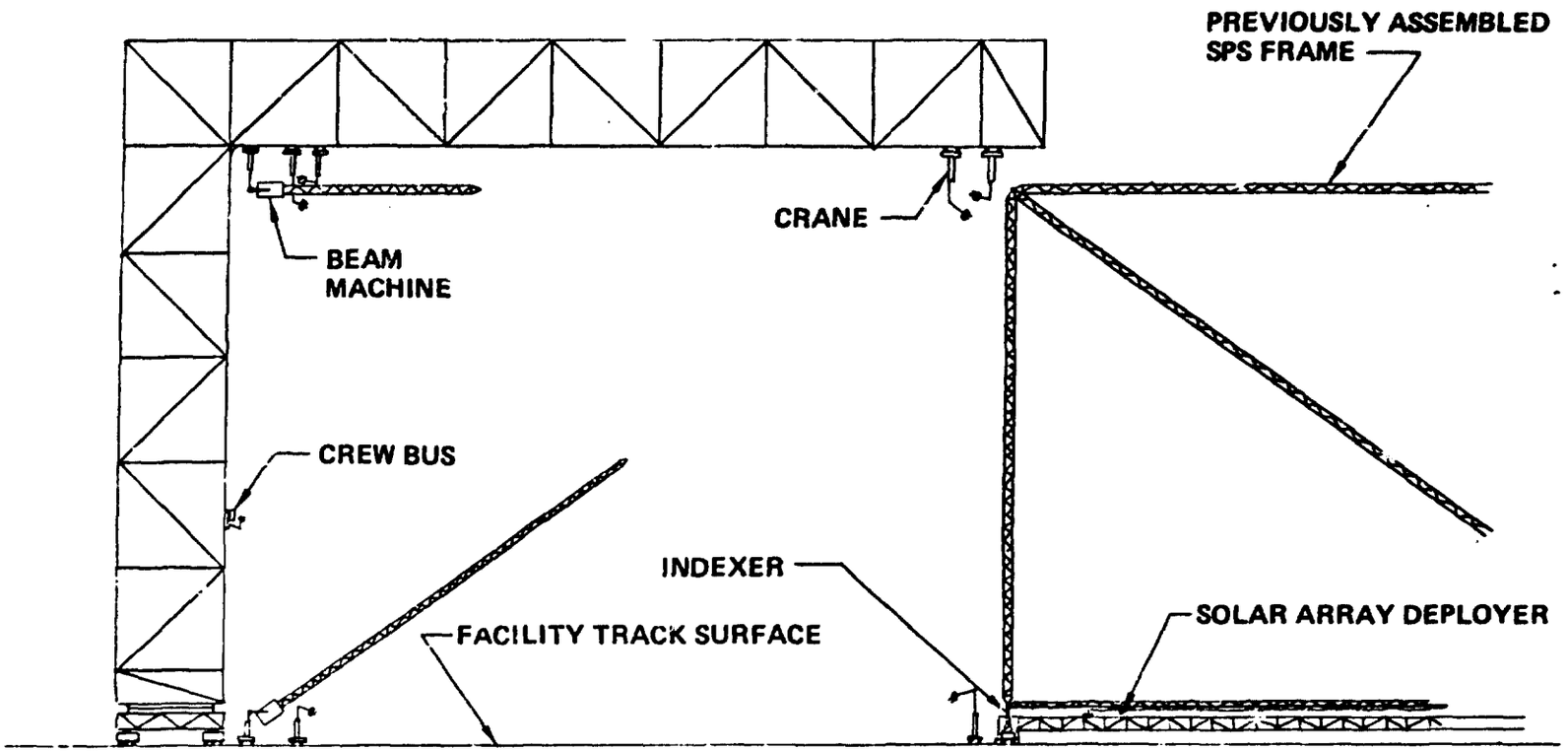
SPS-2205



CONSTRUCTION GANTRY

This figure shows a side view of the construction gantry. The beam machines and cherrypickers used to fabricate and assemble the upper framework and supported by the gantry. A dedicated crew bus is installed on the gantry to carry the crewmembers from the facility deck up to the construction equipment.

Construction Gantry



LEO SINGLE DECK CONSTRUCTION BASE ATTRIBUTES

The significant differences between the LEO Single Deck base and the baseline LEO 2-Deck Base are listed. The mass and cost deltas will be computed later.

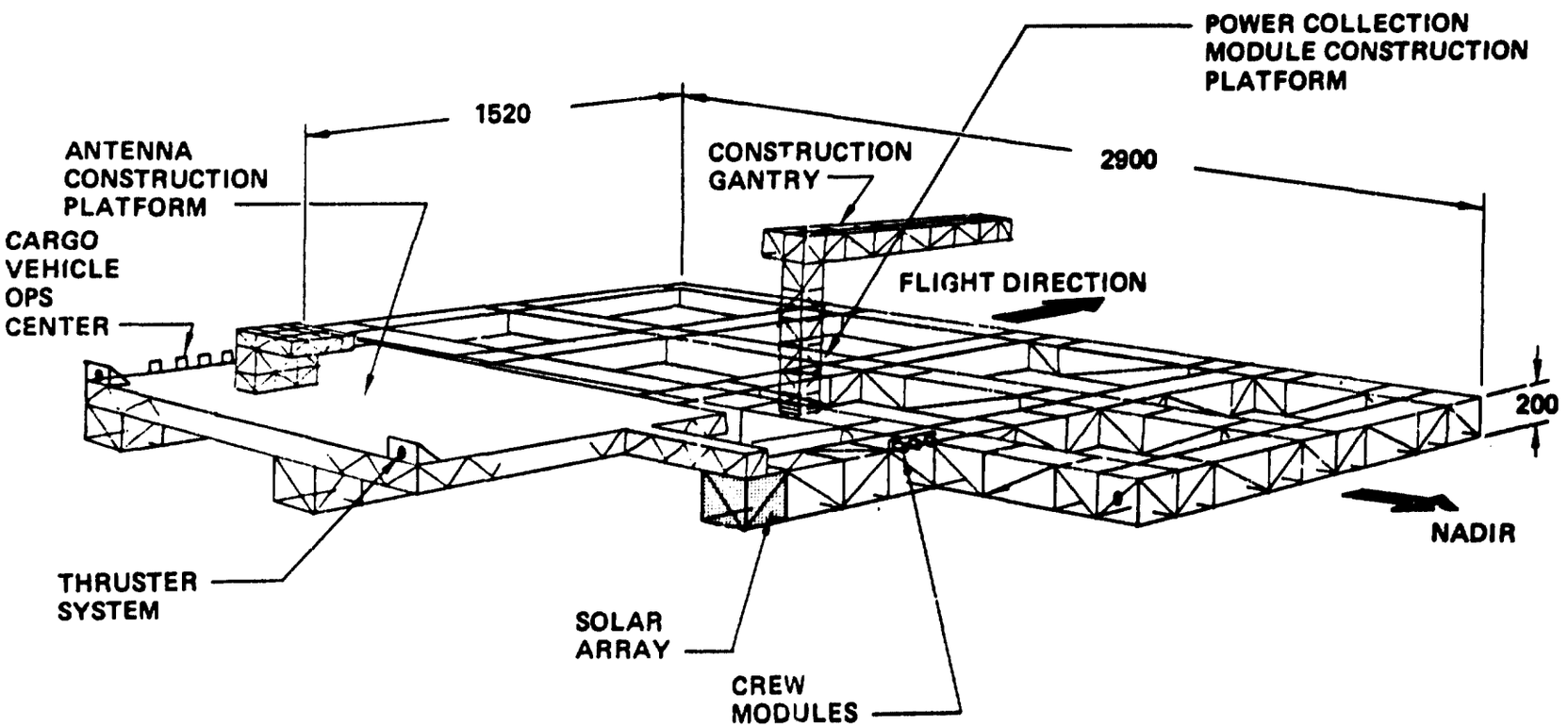
LEO Single Deck Construction Base Features

AS COMPARED TO 2 DECK BASELINE	BASELINE QTY'S
● CONSTRUCTION EQUIPMENT	
• ADD CONSTRUCTION GANTRY	0
• DELETE 2 250 m CRANES	2
• (ALL OTHER EQUIP QTY'S SAME AS BASELINE)	
● CREW SIZE	
• SAME AS BASELINE	510
● BASE STRUCTURE	
• REDUCED APPROXIMATELY 34%	822,000 m of beam
● BASE LOGISTICS SYSTEM	
• DELETE 59 TURNTABLES	525
• DELETE 34,500 m OF TRACK	114,000 m
• ADD ONE CREW BUS	4
● TOTAL MASS AND COST DELTAS TBD	

GEO SINGLE DECK CONSTRUCTION BASE

This base is a derivative of the LEO Single Deck. This base was configured to enable the construction of a monolithic 5GW SPS. For reasons which will be described on the following pages, the antenna facility was moved from the end of the base to a position behind the base. It was also necessary to reorient the solar array deployers so that the array could be deployed in the direction of the long dimension of the base. Construction of a monolithic satellite requires both longitudinal and lateral indexing (see next page). Due to time lost during indexing (48 days), it was necessary to add additional construction equipment in order to be able to assemble the satellite within the time constraints.

GEO Single Deck Construction Base



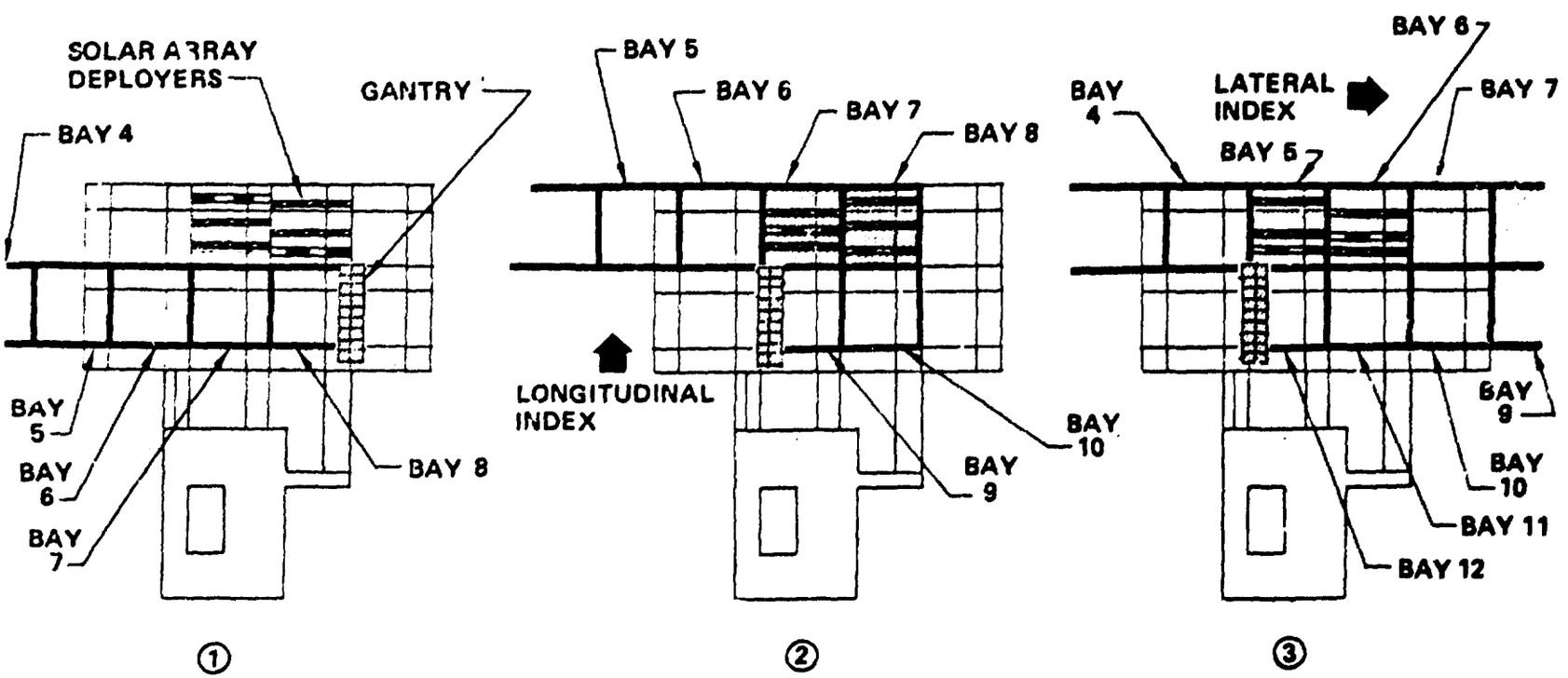
POWER COLLECTION SYSTEM CONSTRUCTION SEQUENCE

(GEO CONSTRUCTION)

Construction of a monolithic, 8-bay wide SPS requires both longitudinal and lateral indexing maneuvers as illustrated.

SPS-2214

Power Collection System Construction Sequence (GEO Construction)



- FIRST ROW OF BAYS COMPLETED (8 BAYS WIDE)

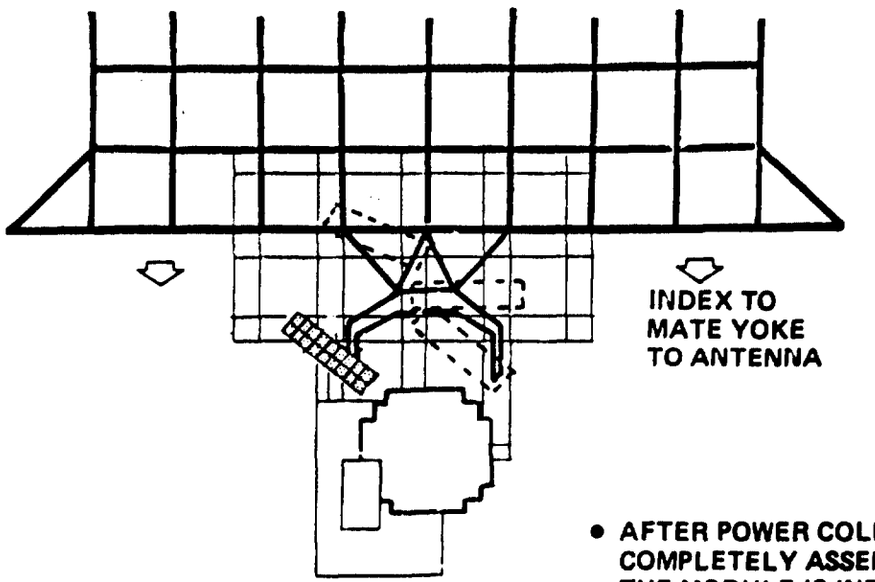
- FRAME INDEXED LONGITUDINALLY ONE BAY
- SOLAR ARRAY DEPLOYED IN BAYS 7 AND 8
- ASSEMBLE FRAMES FOR BAYS 9 AND 10 (SECOND ROW OF BAYS)

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

YOKE ASSEMBLY AND MATING OPERATIONS

This chart illustrates and describes the operations required to perform yoke assembly and yoke-to-antenna mating.

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 ATTRIBUTES

The most significant "attribute" of the GEO Single Deck base concept is that in order to make up the time lost indexing that it is necessary to add equipment and operators. There are other offsetting savings, but the net cost and mass delta is yet to be determined.

GEO Single Deck Construction Base Features

SPS-2271

AS COMPARED TO 2 DECK BASELINE	BASELINE QTY'S
● CONSTRUCTION EQUIPMENT	
• ADD CONSTRUCTION GANTRY	0
• ADD 2 BEAM MACHINES	4
• ADD 8 CHERRYPICKERS	8
• ADD 2 SOLAR ARRAY DEPLOYERS	4
• ADD 1 BUS DEPLOYER	1
• DELETE 2 250 m CRANES	2
• (ALL OTHER EQUIPMENT QUANTITIES THE SAME AS BASELINE)	
● CREW SIZE	
• ADD 52 EQUIPMENT OPERATORS	510
● BASE STRUCTURE	
• REDUCED APPROXIMATELY 34%	822,000 m of beam
● BASE LOGISTICS SYSTEM	
• DELETE 59 TURNTABLES (INCLUDES GANTRY)	525
• DELETE 34,500 m OF TRACK (INCLUDES GANTRY)	114,000 m
• ADD ONE CREW BUS	4
● TOTAL MASS AND COST DELTAS TBD	

SOLAR POWER SATELLITE SYSTEM DEFINITION STUDY MIDTERM BRIEFING FOR BOEING AEROSPACE COMPANY

ALTERNATE CONSTRUCTION CONCEPTS & ALUMINUM SOLAR ARRAY STRUCTURE

OCTOBER 19, 1978

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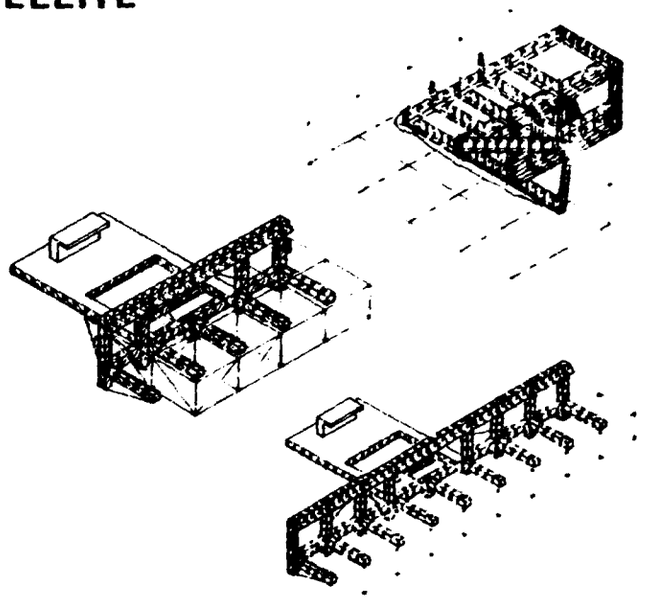
ALTERNATE GEO CONSTRUCTION CONCEPTS

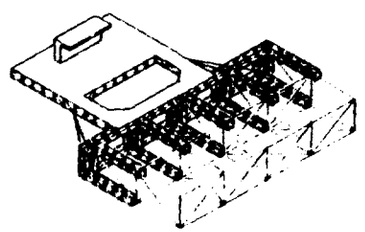
FOR:

5 GW MONOLITHIC SATELLITE

END BUILDERS

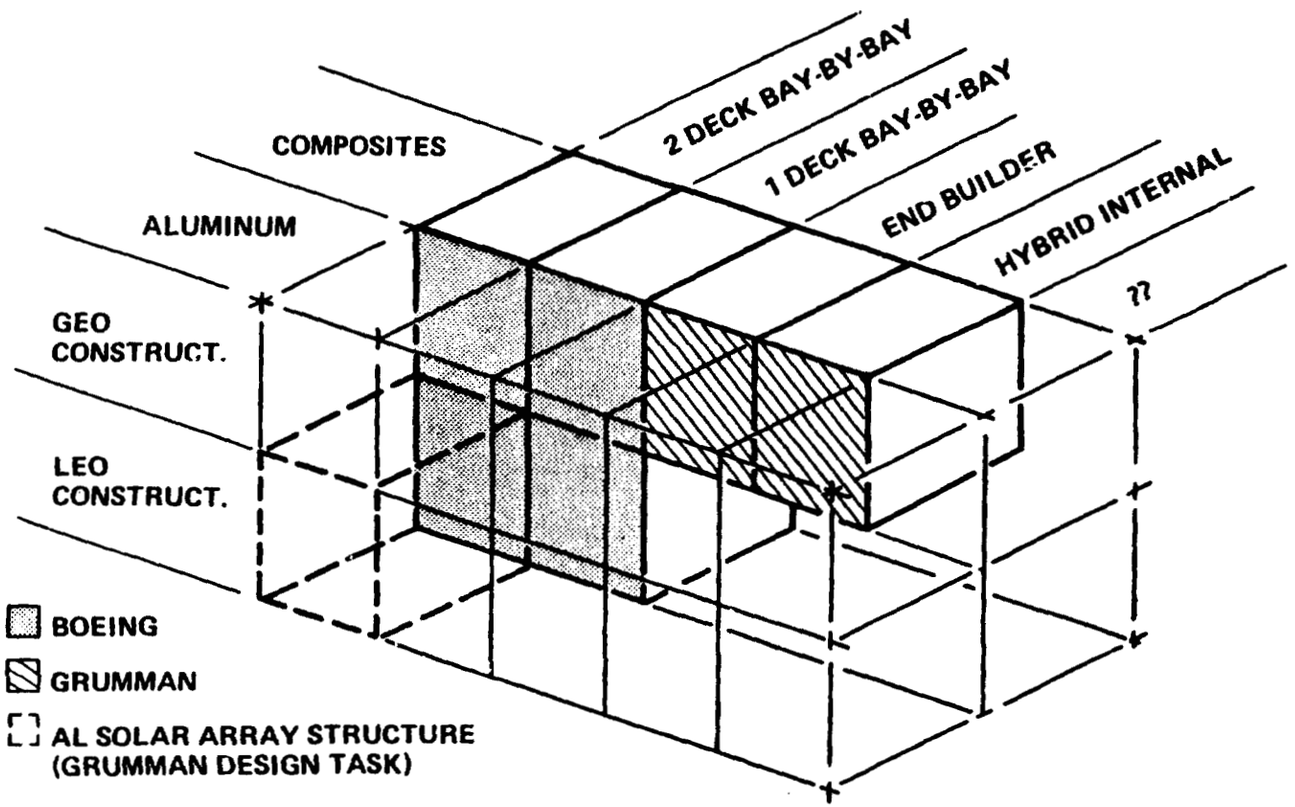


INTERNAL BASE



BOOTSTRAP ?

SATELLITE CONSTRUCTION EMPHASIS



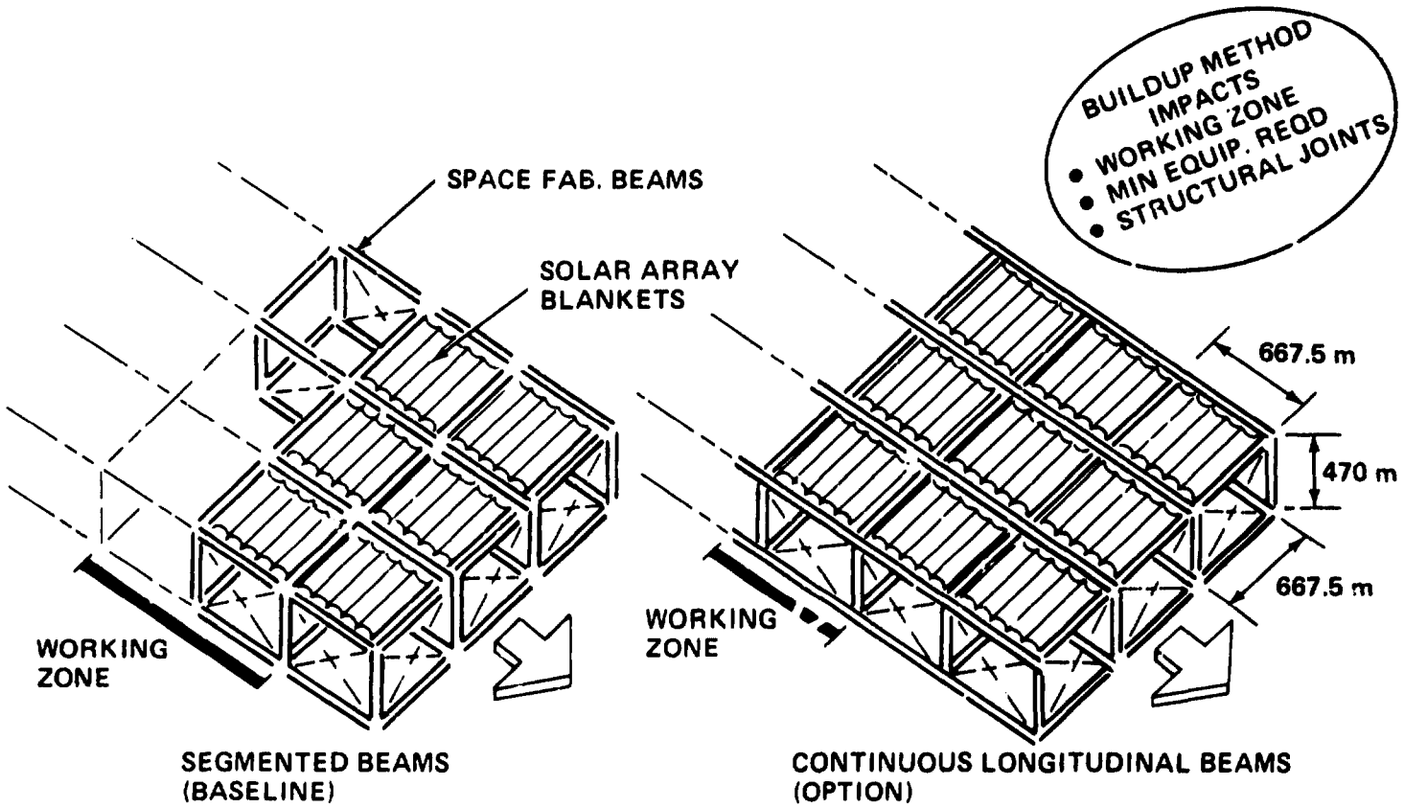
ALTERNATE SPS CONSTRUCTION METHODS

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 accommodate 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



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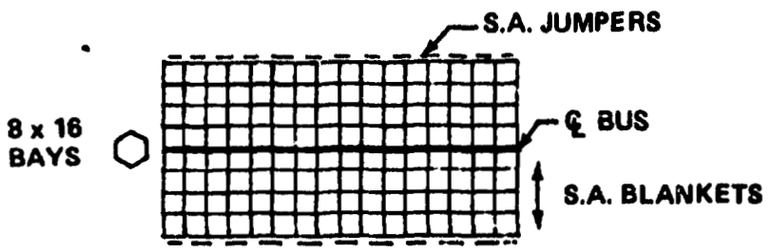
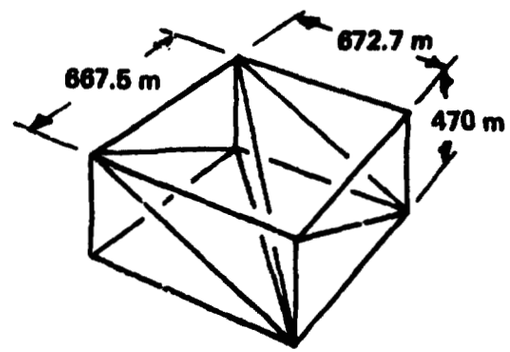
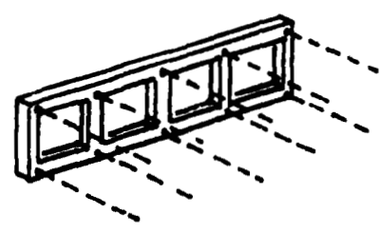
SPS END BUILDER CONSTRUCTION REQUIREMENTS & ISSUES

- 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 INDEXING

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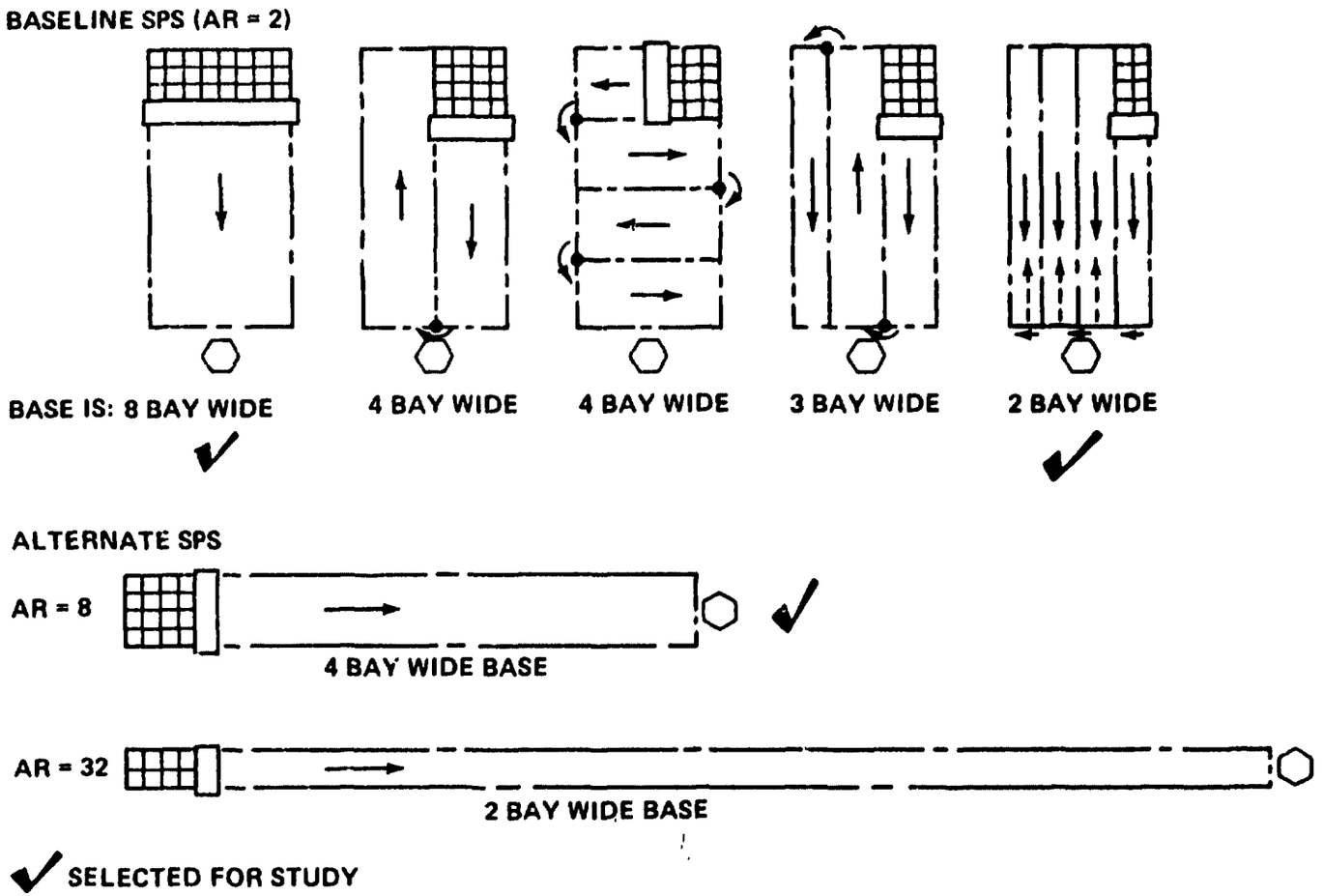
END BUILDER SATELLITE CONSTRUCTION OPTIONS

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 are considered (aspect ratio = 8 and 32) 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, 3 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 must phase the antenna installation to coincide with either a half built or fully built power collection module. The 8 bay wide and 2 bay wide options were selected for further study because they 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 a single pass production buildup. One, a four bay wide base constructs an SPS whose aspect ratio (8) is not considered outside the bounds of feasibility. In the other, the advantage of having the smallest base size is probably overshadowed by its inordinate aspect ratio (32) and by related penalties in satellite attitude control and power distribution systems. Hence the single pass 4 bay end builder was also chosen for study and comparison with the 8 bay wide and 2 bay wide bases.

END BUILDER SATELLITE CONSTRUCTION OPTIONS



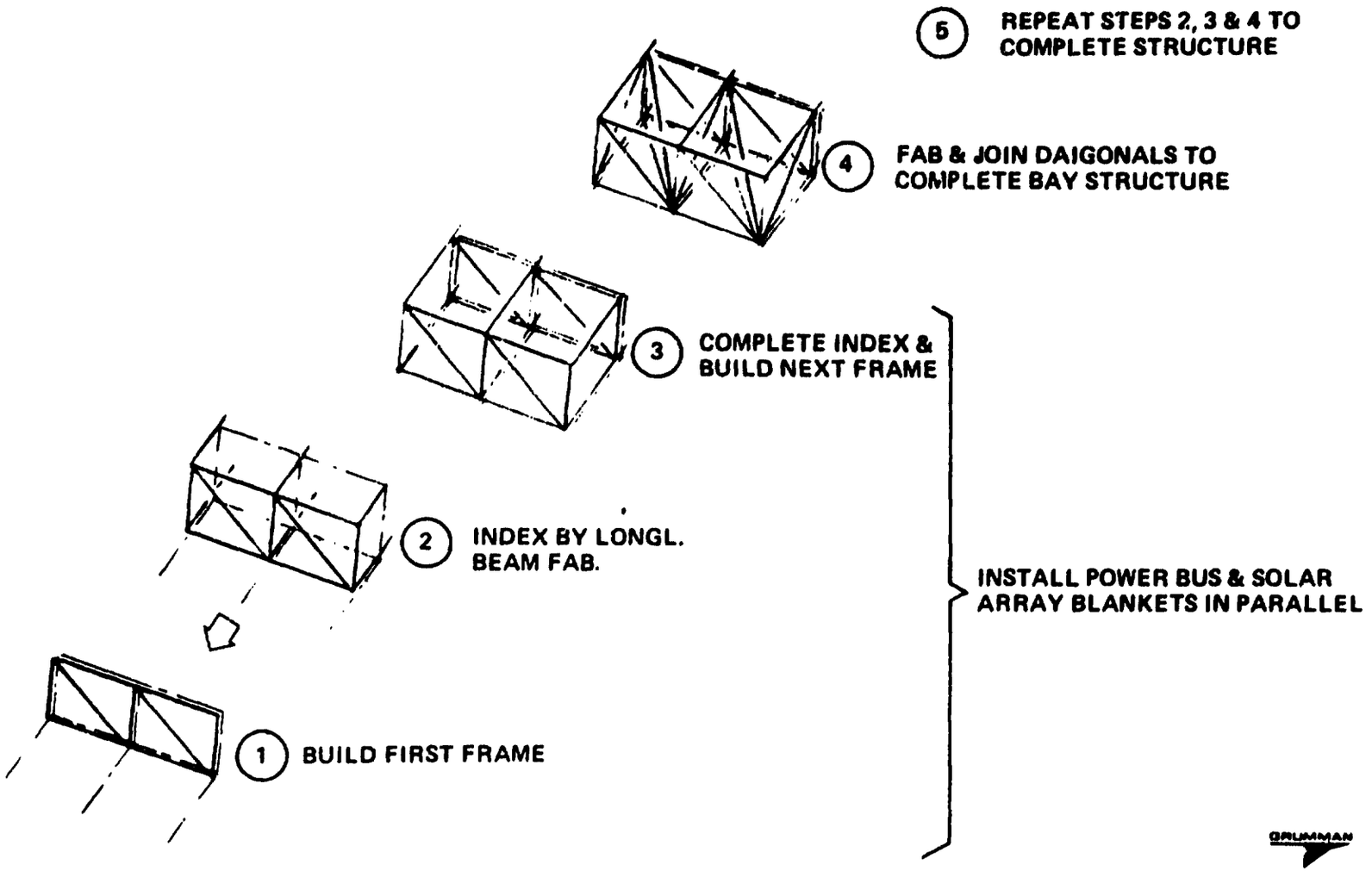
TYPICAL END BUILDER STRUCTURAL ASSEMBLY SEQUENCE

The end builder construction system is tailored to the structural cross section of the satellite and uses dedicated beam machines to automatically fabricate continuous longitudinal members. Additional beam machines are used to fabricate the required lateral and diagonal members employed 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 and 8-bay builder.

As shown the assembly process begins with the construction of the first frame. Each frame can be constructed with members made by either using a beam machine located on the base at each beam intersection point or at a central beam building distribution yard. Gimballed beam machines could be provided in the limit next to each dedicated fixed machine, to fabricate the connecting beams in a desired direction. The horizontal beams are fabricated in parallel, their length is then adjusted and the beam positioned for assembly. During this adjustment and positioning, the machine is pivotted and the other beams for this frame fabricated in parallel. These are then adjusted and the frame assembled. 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



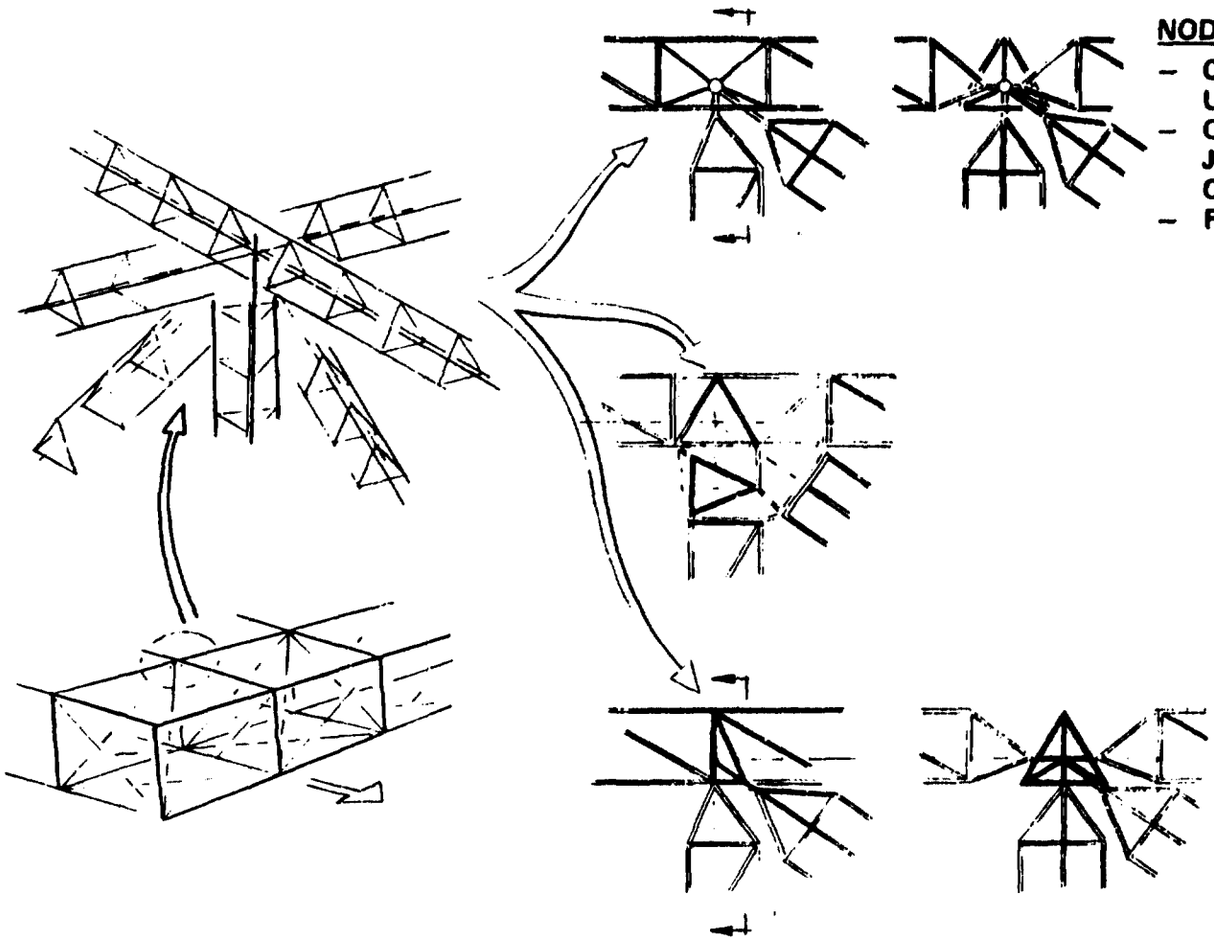
STRUCTURAL JOINTS DURING END BUILDING CONSTRUCTION

A typical intersection of beams is shown, together with its location on the structure. Three types of joint which could be used at this intersection, are illustrated. The preferred joint is termed a 'nodal fitting.' Here, the continuous beam caps are uninterrupted and the pitch of the lateral posts maintained. In the appropriate bay of the beam, diagonals are replaced by a fitting which provides an anchor point for the pin jointed ends of the other intersecting beams. This anchor point is at the centroid of the continuous beam, and the tubular end of each other beam is aligned with the centroid of that beam. The lengths of tube ends will be dictated by access to the fitting past the continuous beam members. Ground fabrication of the fitting, with folding of its legs for launch, seems feasible.

A second joint option provides for butt joining the beams ends. All beams are interrupted to accommodate a comprehensive fitting which presents a face to each intersecting beam for it to butt and attach to. Such a joint would demand adjustment of each butting face to accommodate eccentricities, etc., in each beam. The fitting itself would be either space fabricated, or ground fabricated in pieces and space assembled. It would be volumetrically inefficient to launch the completed fitting from the ground.

The third option shown is a space frame which does not interrupt the continuous beam caps. It replaces one set of lateral posts. Lateral and diagonal beams attach to points on the periphery of the frame. These attachments may be either pinned or fixed joints. The joints are located so that the end load in each beam is aligned with the centroid of the continous beam. Eccentricities or misalignments of the beams will result in torsion in the continuous beams. This frame would also be space fabricated, or ground fabricated in pieces and space assembled.

STRUCTURAL JOINTS DURING END BUILDING CONSTRUCTION



NODAL FITTING

- CONTINUOUS BEAM UNINTERRUPTED
- OTHER BEAMS PIN JOINT AT INTERSECT. OF CENTROIDS ✓
- FOLD FOR LAUNCH

BUTT FITTING

- ALL BEAMS INTERRUPTED
- ALL BEAMS FIXED ENDS (ASSY?)
- FAB. OR ASSEMBLE FITTING IN SPACE

SPACE FRAME

- CONTINUOUS BEAM UN-INTERRUPTED
- OTHER BEAMS ATTACH TO PERIPHERY (ECCENTRICITIES?
- FAB. OR ASSEMBLE IN SPACE

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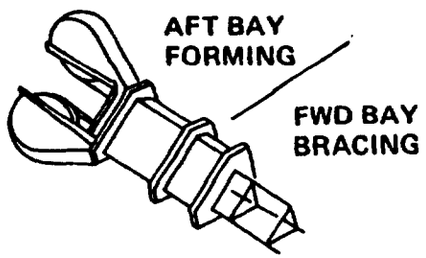
SPS COMPOSITE BEAM FABRICATION

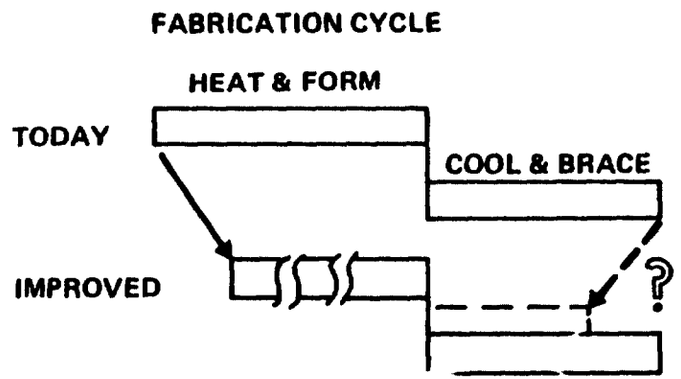
Early in the study a detailed production rate analysis was performed on the composite beam builder (beam machine) since related design data were readily available and because this equipment is common to all SPS segmented and continuous construction concepts.

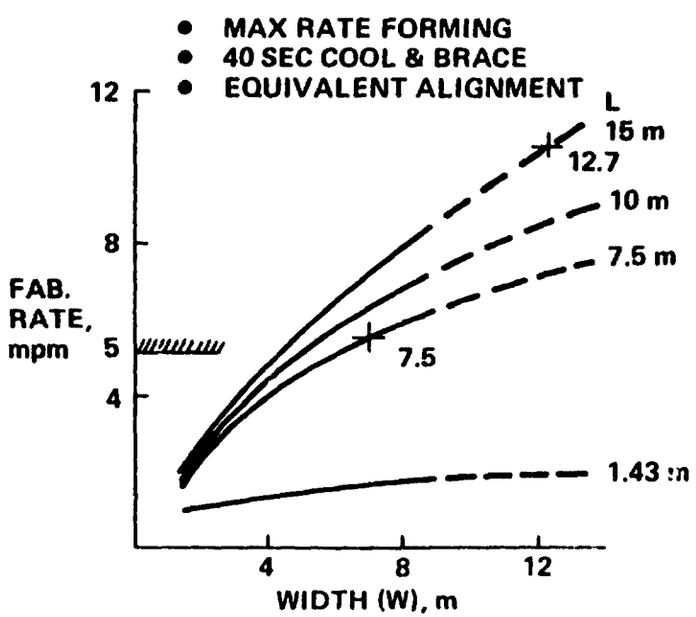
Projected beam builder output rates were determined for range of possible SPS space fabricated beam sizes. For example a production rate of 5.7 meters/min. for the 7.5 m beam, and 10.5 meters/min. for the 12.7 m beam (both composites) can be reasonable expected from a study of growth potentials available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

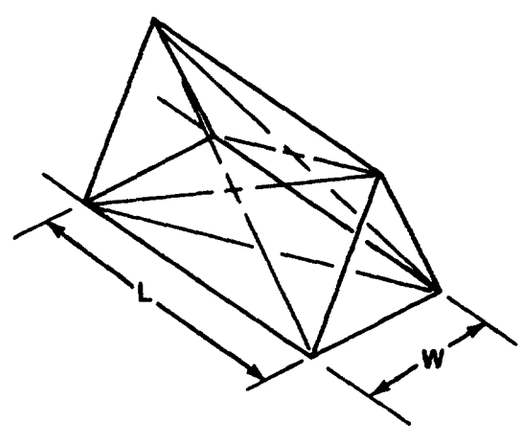
Growth potential areas include: higher cap forming rates, permissable because larger depth beams are less sensitive to beam geometry (bow effect) problems than beams of shallower depth; and, larger batten spacings permit the beam machine (which operates on a run/stop cyclic basis) to operate in the run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

SPS COMPOSITE BEAM FABRICATION









LONGITUDINAL BEAM FABRICATION REQUIREMENTS

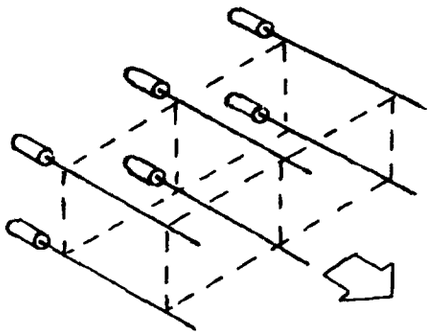
Beam fabrication and satellite indexing are closely related in the end-builder construction operations. The longitudinal beam builders provide the driving force to index the satellite structure, while performing their basic function of beam-element fabrication. This end builder characteristic leads to 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 progress 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.

LONGITUDINAL BEAM FABRICATION REQUIREMENTS

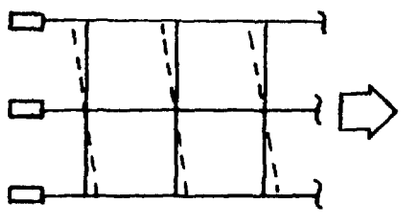


LIMIT STARTUP & SHUTDOWN ACCELERATIONS

ISSUES FOR STUDY:

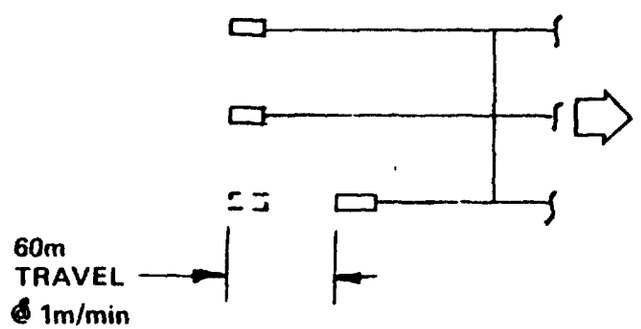
- LOADING COND'S. (C.G. OFFSET, S/A TENSION, ETC)
- IMPACT OF LOADS ON:
  - BASE & SATELLITE STRUCTURE
  - BEAM-BUILDER S/S OPERATION

PROVIDE FOR SYNCHRONIZED INDEXING



CONTROL TOLERANCES
GENERATE BASE/SATELLITE INTERFACE LOADS

PROVIDE FOR CONTINUITY OF CONSTRUCTION OPS



- RELIABILITY/REDUNDANCY
- 60 MIN REPAIR TIME

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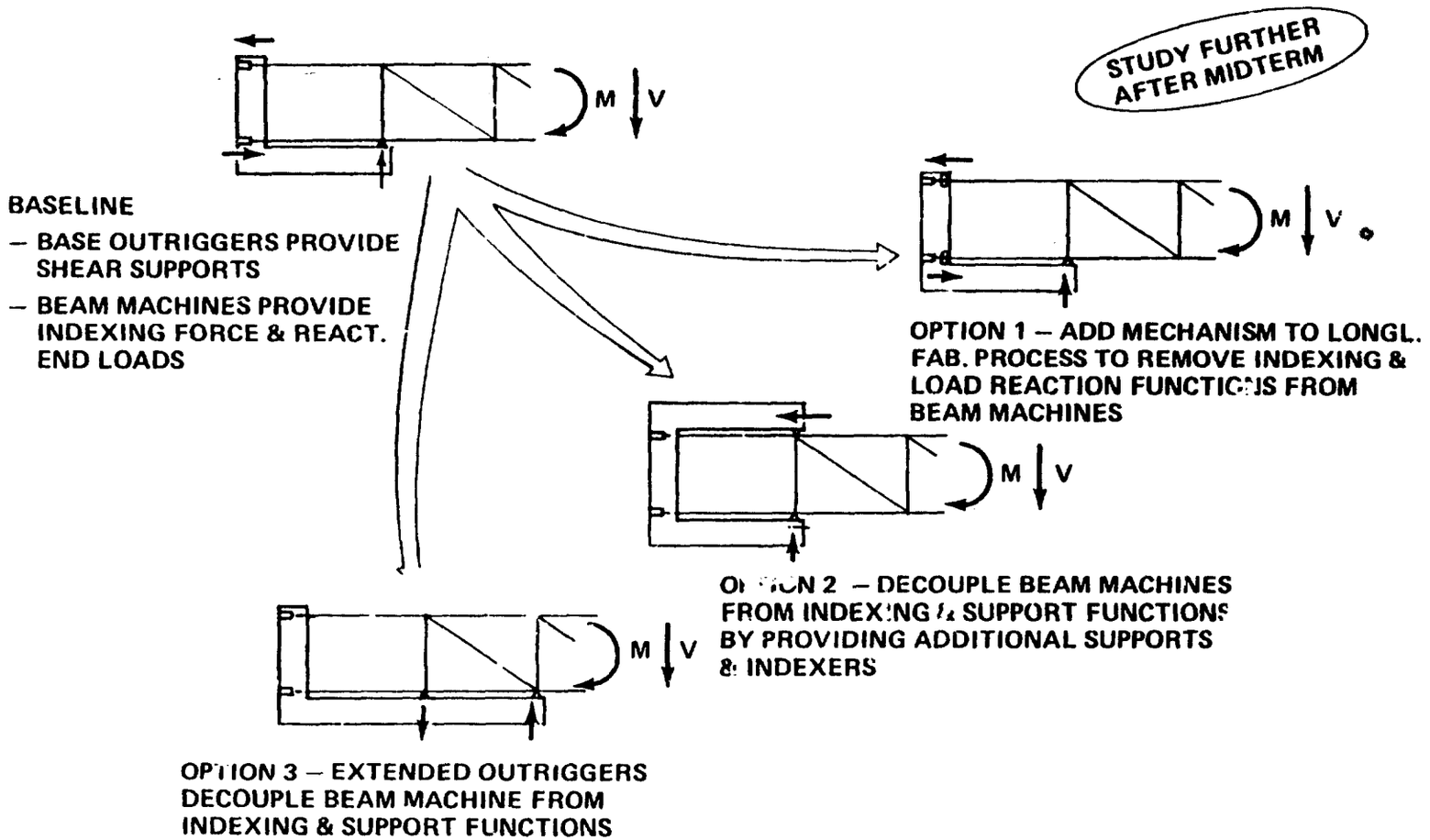
SATELLITE SUPPORT DURING END BUILDER CONSTRUCTION

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, disturbance 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 structure may be suspect and require further study.

Three options are presented on this chart for relieving the beam machines of this function. Option 1 adds mechanisms to the process of fabricating the longitudinal beams. They are dedicated to indexing the beams and to reacting disturbance end loads. 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 disturbance loads and index the structure.

SATELLITE SUPPORT DURING END BUILDER CONSTRUCTION



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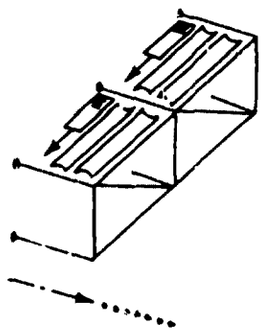
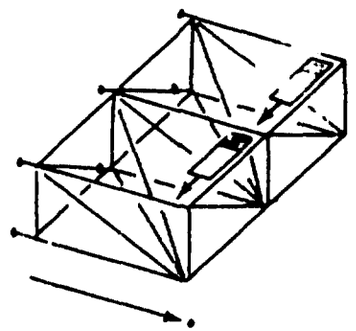
SOLAR ARRAY/STRUCTURE ASSEMBLY METHODS

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. An alternate 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.

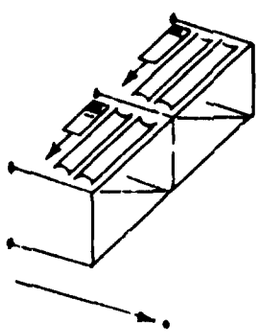
SOLAR ARRAY/STRUCTURE ASSEMBLY METHODS



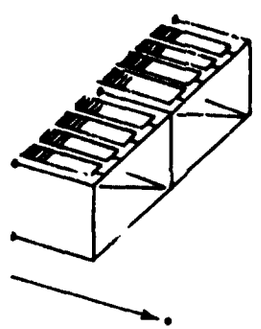
PROGRESSIVE
(15 OR 30 m
STEPS)



SERIES
COMPLETE STRUCTURE
FIRST



SYNCHRONIZED
FRAME-TO-FRAME



UNIDIRECTIONAL
FRAME-TO-FRAME

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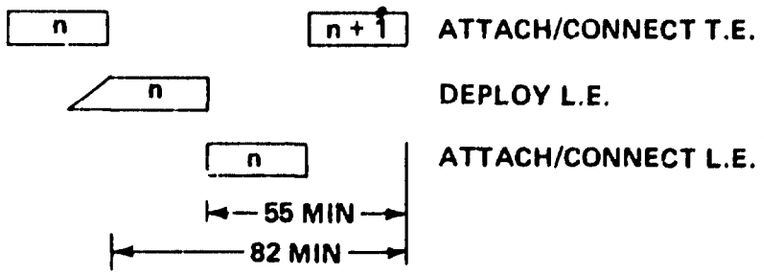
SOLAR ARRAY BLANKET INSTALLATION CONSIDERATIONS

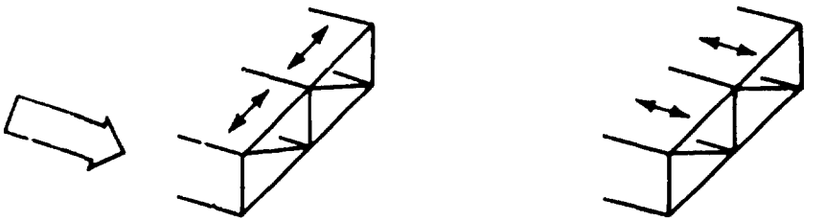
The solar array installation method must deal with the mechanical and electrical requirements for hooking up the opposite ends of each blanket and the required rate of deployment. The baseline solar array installation cycle takes 82 minutes, which includes 55 minutes for attaching and connecting the 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.

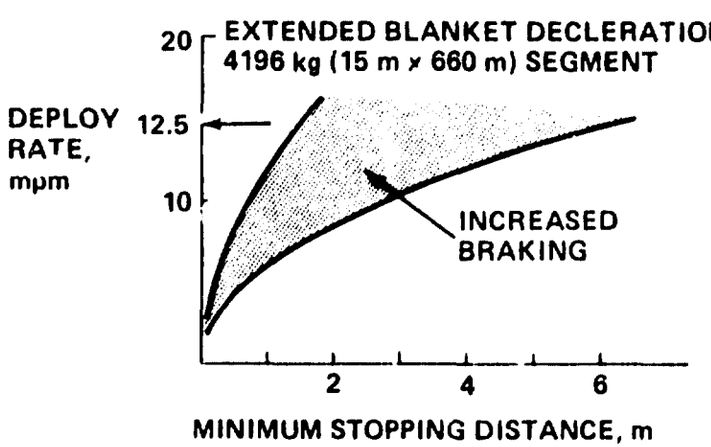
SOLAR ARRAY BLANKET INSTALLATION CONSIDERATIONS

MECHANICAL/ELECTRICAL HOOKUP

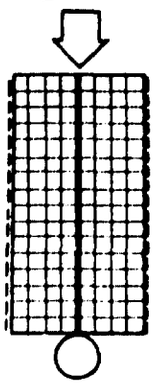


BLANKET ORIENTATION & RATE OF DEPLOY

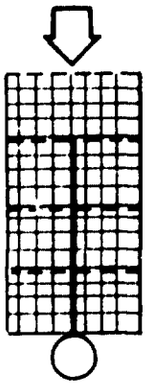




BASELINE
FAST S/A DEPLOY
AND
℄ BUS



ALTERNATE ALIGNED
SLOW S/A DEPLOY
AND
MULTI-BUSES



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2636-002W

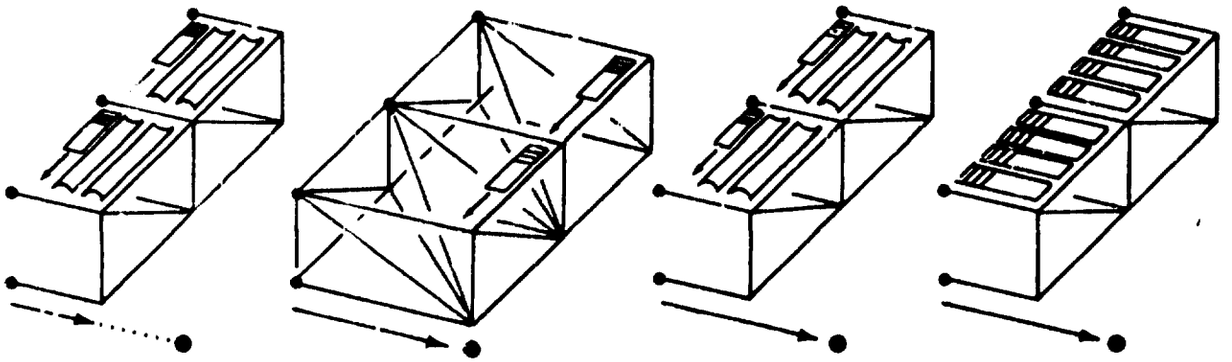
SOLAR ARRAY/STRUCTURE ASSEMBLY COMPARISON (128 BAYS)

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 progressive method of assembly was selected for the 8 bay and 4 bay base designs since 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	(L. BEAM & S/A)	(L. BEAM & S/A)	(L. BEAM & S/A)	(L. BEAM & S/A)
8-BAY WIDE RATES (mpm)	0.17 & 12.5 √	0.17 & 12.5	0.09 & 5.8	0.12 & 0.12
4-BAY WIDE RATES	0.36 & 12.5* √	0.36 & 12.5*	0.18 & 12.3	0.54 & 0.54
2-BAY WIDE RATES	–	–	0.42 & 28.4	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

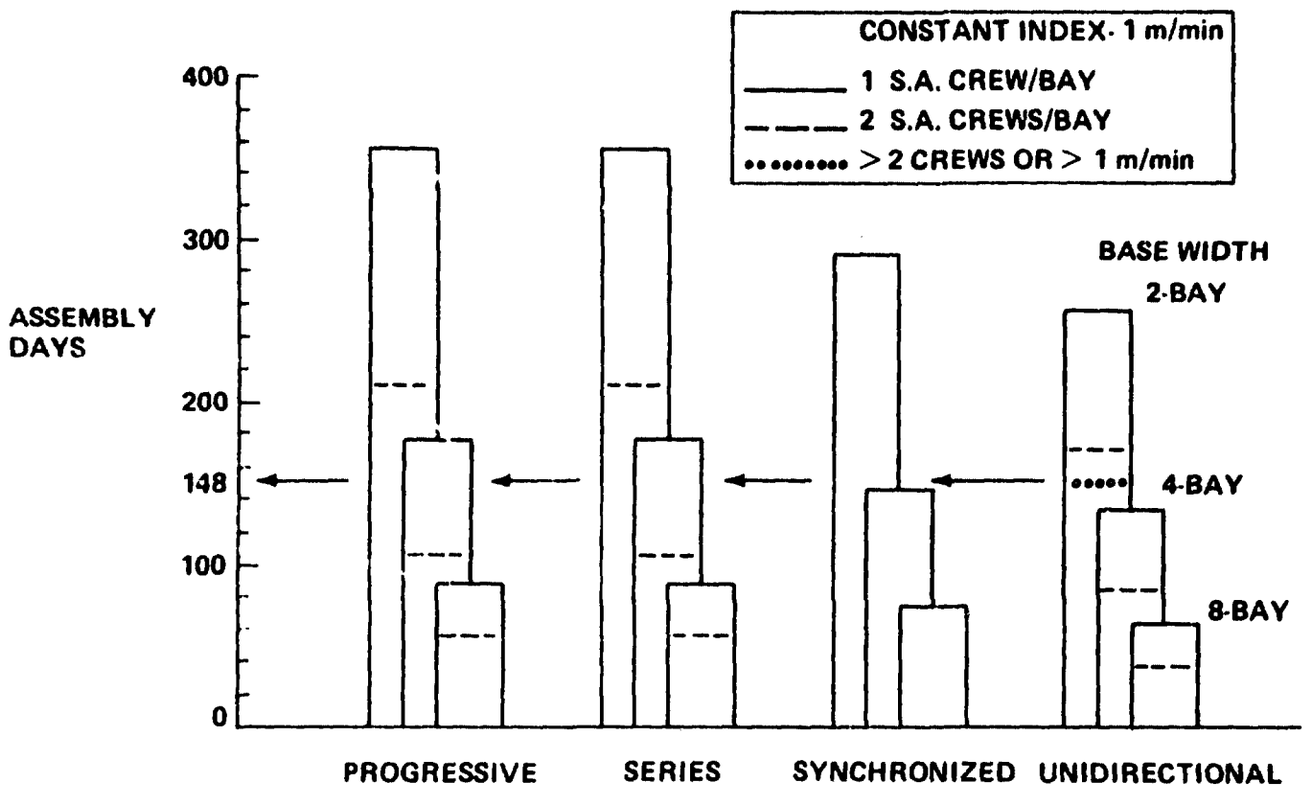
√ SELECTED FOR FURTHER STUDY

2636-045W

SOLAR ARRAY/STRUCTURE ASSEMBLY TIMES

Comparative times for assembling the 128-bay power collection module are on the facing page for the four solar array/structure assembly methods (i.e., progressive, series, synchronized, and unidirectional). The total time needed to complete power collection mobile construction with a 2-bay, 4-bay, and 8-bay wide bases are shown for a constant longitudinal beam fabrication rate (1 mpm). The effect of using 1 or 2 solar array installation crews in each bay is also shown where feasible. The unidirectional method has the potential for saving 100 days in total assembly time, compared either with progressive or series methods for single crew 2-bay base operations. With 2 crews, the unidirectional method saves also 50 days for the 2-bay base, 20 days for a 4-bay base, and about 15 days for an 8-bay base using the progressive and series methods.

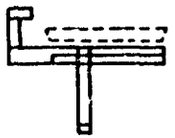
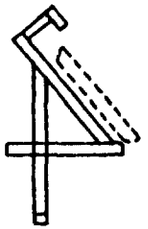
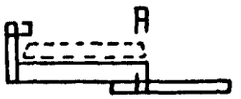
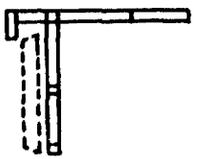
SOLAR ARRAY/STRUCTURE ASSEMBLY TIMES



END BUILDER ANTENNA CONSTRUCTION LOCATION

Five options were investigated for locating the end builder construction site. These options included top plane (horizontal and canted), rear deck (forward and aft mounting) and back plane concepts as shown. The horizontal top plane concept was selected as the preferred approach primarily on the basis of lowest impact on base size and weight. The rear deck concept, featuring desirable inline antenna handling for yoke mating and installation, was retained as an alternate approach. The slide-through feature of the rear deck concept, of course, requires that the construction base be greater than 2-bays wide.

END-BUILDER ANTENNA CONSTRUCTION LOCATION

CONFIGURATION / COMPARISON ISSUES	 TOP DECK	 CANTED	 REAR DECK: AFT MOUNT	REAR DECK: FWD MOUNT	 BACK SIDE
BASE SIZE/WT IMPACT*	LEAST	LARGEST	MEDIUM	MEDIUM	MODERATE
BASE LOGISTICS IMPACT*	LOW	LARGEST	MODERATE	MODERATE	LARGE
SPS DES. IMPACT*	ANT.-ROTATION PROVISIONS	ANT. GIMBAL	POSSIBLE YOKE BEEFUP	NONE	NONE
ANTENNA HANDLING*	ROTATION (PIVOT ARMS)	TRANSLATE (EXTENDER ARMS)	IN-LINE INDEXER	IN-LINE INDEXER	• EXCESSIVE HANDLING
PARALLEL/SERIES OPS	SERIES	SERIES	PARALLEL	SERIES	PARALLEL
1ST SPS LEAD-TIME	LONG	LONG	SHORT	LONG	SHORT
C/O LIMITATION	NONE	NONE	LOW RF POWER	NONE	INCOMPLETE CONFIG
SEPARATION COMPLEXITY	LOW	LOW	GUIDED EXTRACTION REQD	LOW	TWO-PLANE RELEASE
BASE REPOSITION PROPELLANT REQMT	MODERATE	HIGHEST	LOW	HIGH	LOW
	PREFERRED			ADD'L STUDY RECOMMENDED	

*KEY ISSUES

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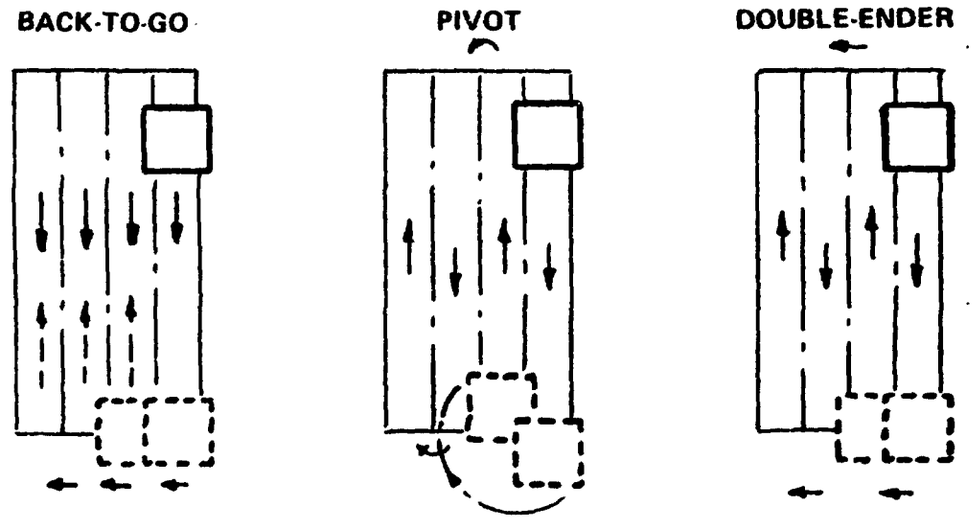
BASE INDEXING OPTIONS

Three base indexing options were evaluated on the basis of operational simplicity of the construction base as well as satellite design impact. The "pivot" option was deemed least desirable, mainly because of an undesirable two-point structural tie to the satellite during the pivot maneuver. The "double-ender" requires duplication of certain base construction equipment to permit production at both ends. It also imposes the need to reverse the cross-bay diagonal in the power-collector structure each time the base indexes to the next "strip".

The "back-to-go" option appears to offer the simplest approach. Although its re-indexing time is the greatest of the three, other production operations (e.g. yoke, thruster structure, lateral beams, etc.) can be performed in parallel during this time.

BASE INDEXING OPTIONS



	BACK-TO-GO	PIVOT	DOUBLE-ENDER
RE-INDEX TIME (DAYS)*	30.2	20.7	3.4
CONSTRUCT EQUIP. IMPACT	RETRACT B/B (1 SET)	RETRACT B/B (2 SETS)	DUPLICATE EQUIP. & RETRACT B/B (1 SET)
INDEXING COMPLEXITY	ONE SIDE ONLY	BOTH SIDES	ONE SIDE ONLY
SATELLITE IMPACT	NONE	PIVOT LOADS	REVERSE WEAVE
ANT. MATING COMPLEXITY	TRANSFER YOKE	TRANSFER YOKE	YOKE IN-SITU

PREFERRED

& EXPLORE UTILIZATION OF RE-INDEX TIME FOR YOKE, THRUSTER, ETC, CONSTRUCTION

*1 mpm FOR 20 HOURS/DAY

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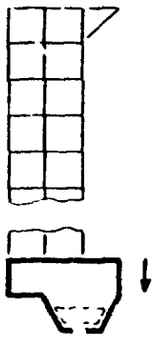
2-BAY END BUILDER - CONSTRUCTION SEQUENCE

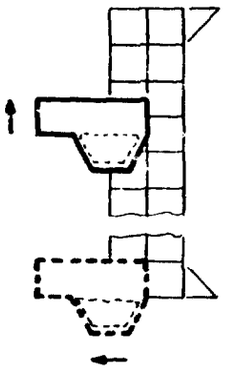
The 2-bay base constructs the 8 x 16 bay satellite in 4 passes, fabricating a 2-bay strip in each pass. Both longitudinal and lateral indexing rails are provided for. After completing the first pass, the base is indexed laterally (2 bays) and then longitudinally (16 bays) to begin, at that point, the second pass. Note that the antenna is constructed in parallel. After completing the second pass, the yoke is constructed while the base is re-indexed longitudinally to the point where it can start the third pass. Arriving at this point, the yoke is completed and is transferred laterally one bay to its proper position on the power collection module and fastened in place. Antenna construction is also complete at this point. (Note: the off-center antenna construction site on the base is mandated by the desirability for an in-line antenna mating operation). When approximately 165 meters of the 3rd pass is completed, the remainder of the yoke/power collection module interface structure is installed and the production sequence is ready for antenna mating. After performing antenna transfer, the 3rd pass is continued. The remaining 4th pass completes the 8 x 16 bay structure.

2 BAY END-BUILDER – CONSTRUCTION SEQUENCE

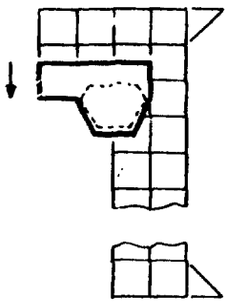


1ST PASS

- BUILD 2-BAY WIDE STRIP
- PARALLEL ANTENNA BUILDUP

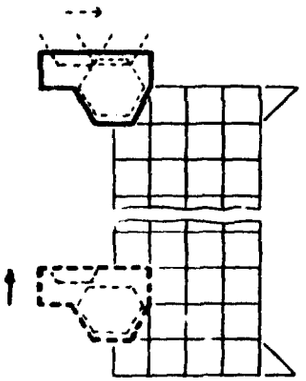


- COMPLETE 2 x 16 BAYS
- INDEX LAT.
- GO BACK-TO-GO

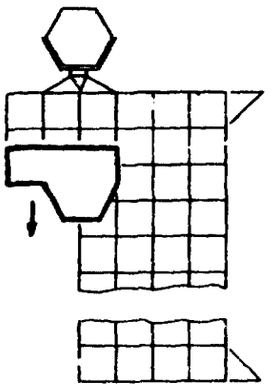


2ND PASS

- BUILD 2ND 2-BAY STRIP



- COMPLETE 4 x 16 BAYS
- INDEX LAT.
- GO BACK-TO-GO
- BUILD YOKE
- TRANSFER YOKE



3RD PASS

- MATE ANTENNA
- BUILD 3RD STRIP
- GO BACK-TO-GO
- BUILD 4TH STRIP
- COMPLETE 8 x 16 BAYS

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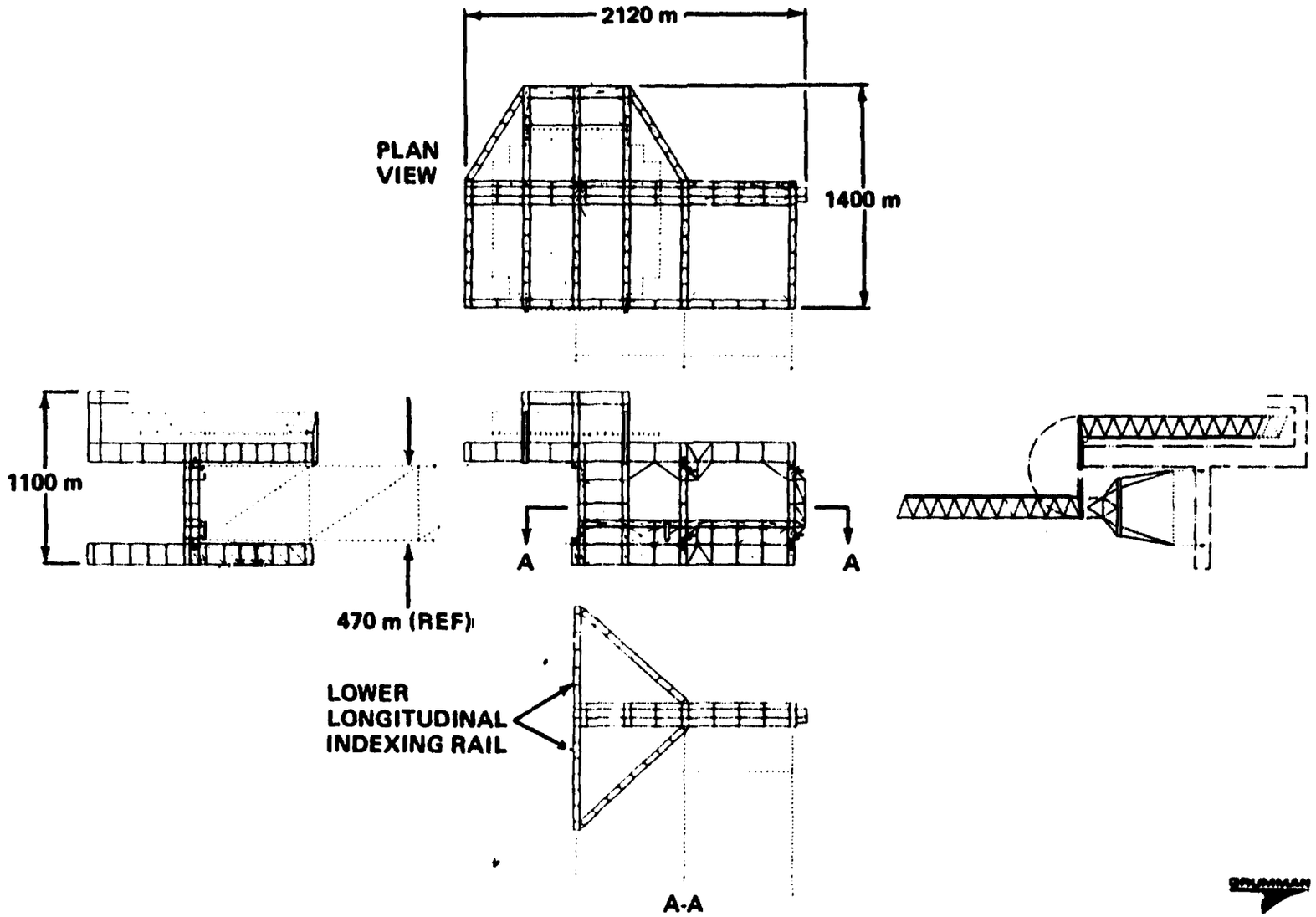
2-BAY END BUILDER CONSTRUCTION BASE

The 2-bay end builder construction base builds an 8-bay wide SPS, 16-bays long, in four passes. While defined as a 2-bay base, its width (2120m) encompasses a 3-bay segment of the power collector structure, mainly, to provide a 1-bay overlap for lateral indexing operations. Provisions are made for both lateral and longitudinal rails during base indexing operations. Its overall height (1100m) permits the power collection module and antenna to be constructed one above the other. Its depth (1400m) is sufficient to encompass the span of the antenna and to provide a minimum 1-bay overlap for longitudinal indexing. Antenna pivot arms rotate the completed antenna to a position in line with the solar array. Note that a short length (approximately 165m) of solar array structure is completed at this time to provide for yoke support during antenna mating operations.

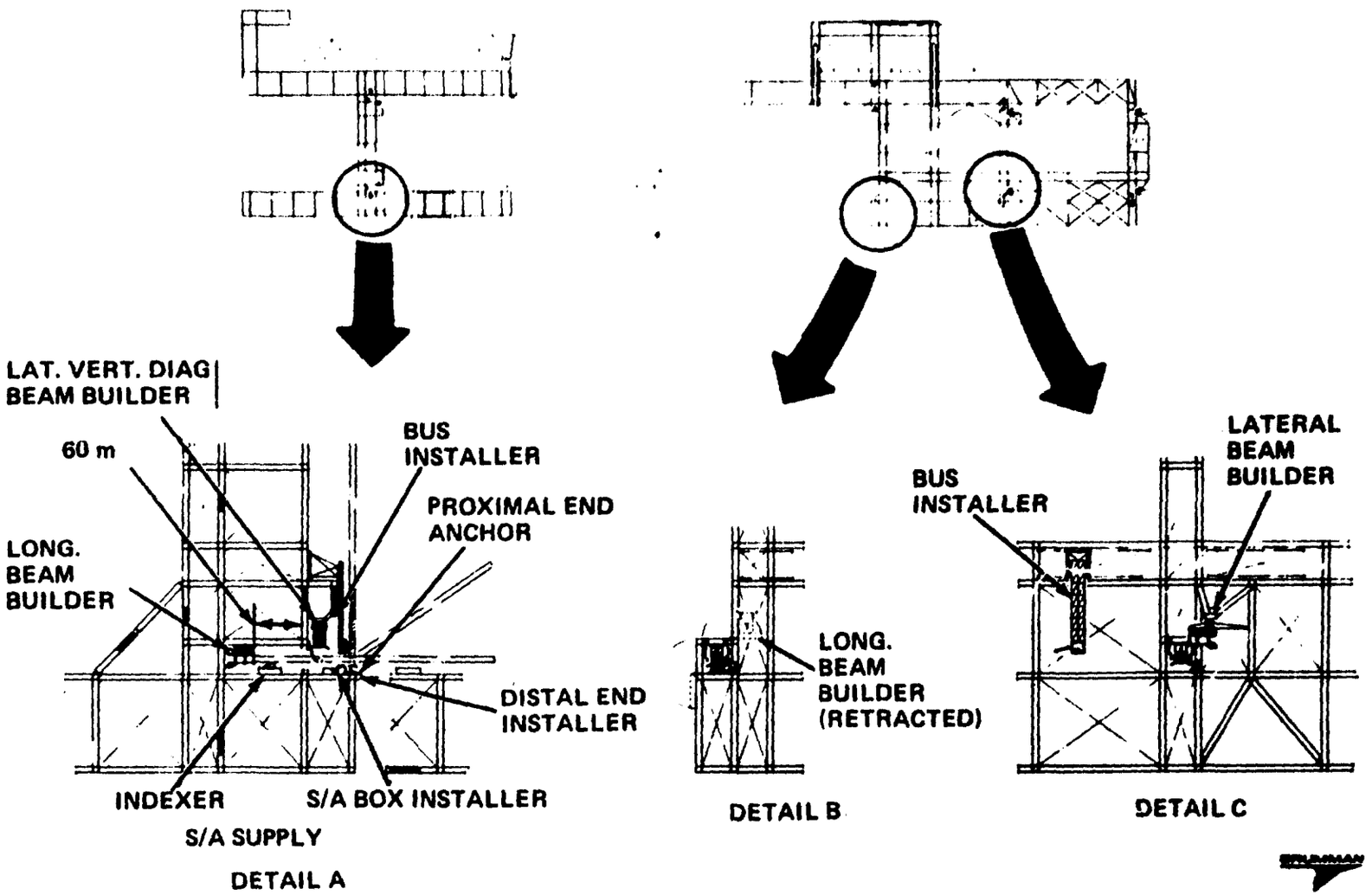
2 BAY END-BUILDER – CONSTRUCTION BASE



2 BAY END BUILDER CONSTRUCTION SYSTEM

Major equipment functions and their specific locations in the base are identified. Note that, in set A, a 60 m travel distance is provided the longitudinal beam builders to permit failure correction in a 60 min. period (assuming a synchronized fabrication rate of 1m/min) without shutting down the whole operation. In Set B, the longitudinal beam builders shown are used only during the first "pass" and are retracted during the 2nd, 3rd and 4th construction passes. No lateral beam builders are required at this station. During the 1st pass construction, the lateral beam builders in the adjacent station supply the necessary structural elements. In Set C the lateral beam builders are gimbal mounted on tilting platforms to provide the beam builder orientations necessary to fabricate lateral, vertical and diagonal beam elements.

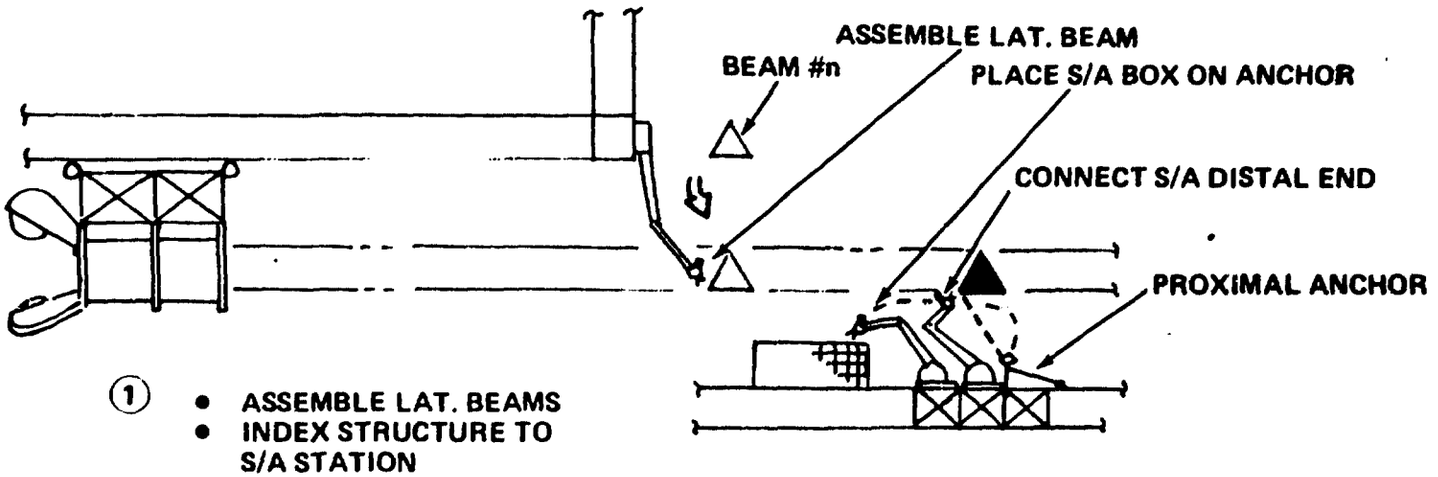
2 BAY END-BUILDER – CONSTRUCTION SYSTEM



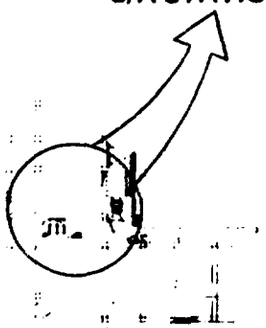
2 BAY END BUILDER - CONSTRUCTION APPROACH

Detail operations for assembling lateral frame beams and for placement of solar array blankets are shown. The lateral beam is assembled when the power collection module structure is in plane with the lateral beam builders. The satellite structure is then indexed (about 40 m) for installation of power bus and solar array elements. The solar array installer removes a solar array box from the supply crib shown and fastens it to the proximal anchor on the base. A distal end installer then connects the blanket to the lateral frame beam. After the frame has been indexed one-bay away, the solar array blankets are fully deployed and the box is disconnected from its anchor and fastened to the next lateral frame beam. Both solar array and bus (not shown) installation are performed in parallel at a station 40 m from the lateral beam builder site.

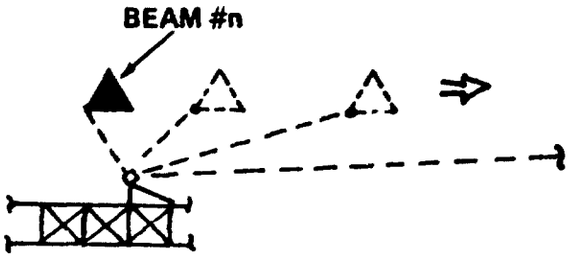
2 BAY END-BUILDER – CONSTRUCTION APPROACH



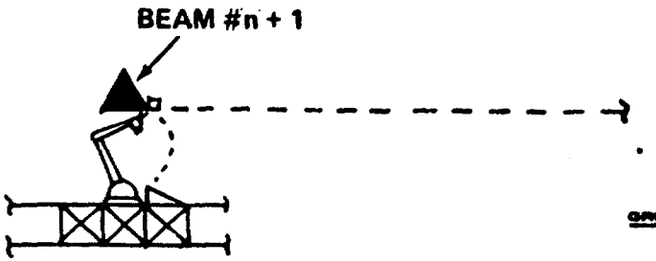
① • ASSEMBLE LAT. BEAMS
• INDEX STRUCTURE TO S/A STATION



② • DEPLOY S/A



③ • CONNECT S/A DISTAL END



2 BAY END BUILDER - YOKE CONSTRUCTION/ANTENNA MATING

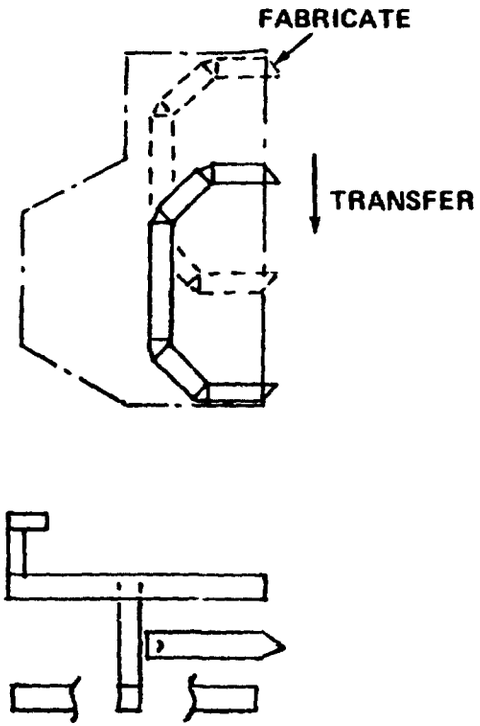
The yoke is constructed in the main S/A production facility after the second pass and is completed by the time the base has re-indexed "back-to-go" (to begin the 3rd pass). The yoke is then transferred laterally (one bay length) in alignment with, and for attachment to, the power generation and distribution system structure. After the yoke is attached, the antenna is rotated into alignment with the yoke and an off-site antenna/yoke attachment is effected.

This approach to yoke construction and antenna mating requires further study. A detailed fabrication sequence for the yoke elements, rotary joint, and yoke-support structure needs to be defined. It is probable that yoke construction will center close to the base's upper outriggers where base structure already exists and where the necessary support for lateral transfer is already provided.

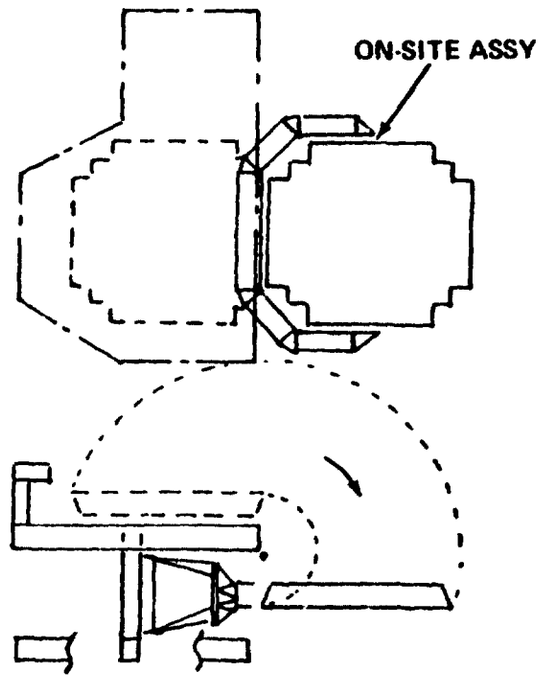
Also, procedures need to be defined (with the addition, possibly, of a deployable outrigger-extension) for the mechanical/electrical hookup of the antenna.

2 BAY END-BUILDER YOKE CONSTRUCTION/ ANTENNA MATING

YOKE FABRICATION & TRANSFER



ANTENNA ATTACHMENT



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2 BAY END BUILDER TIMELINE

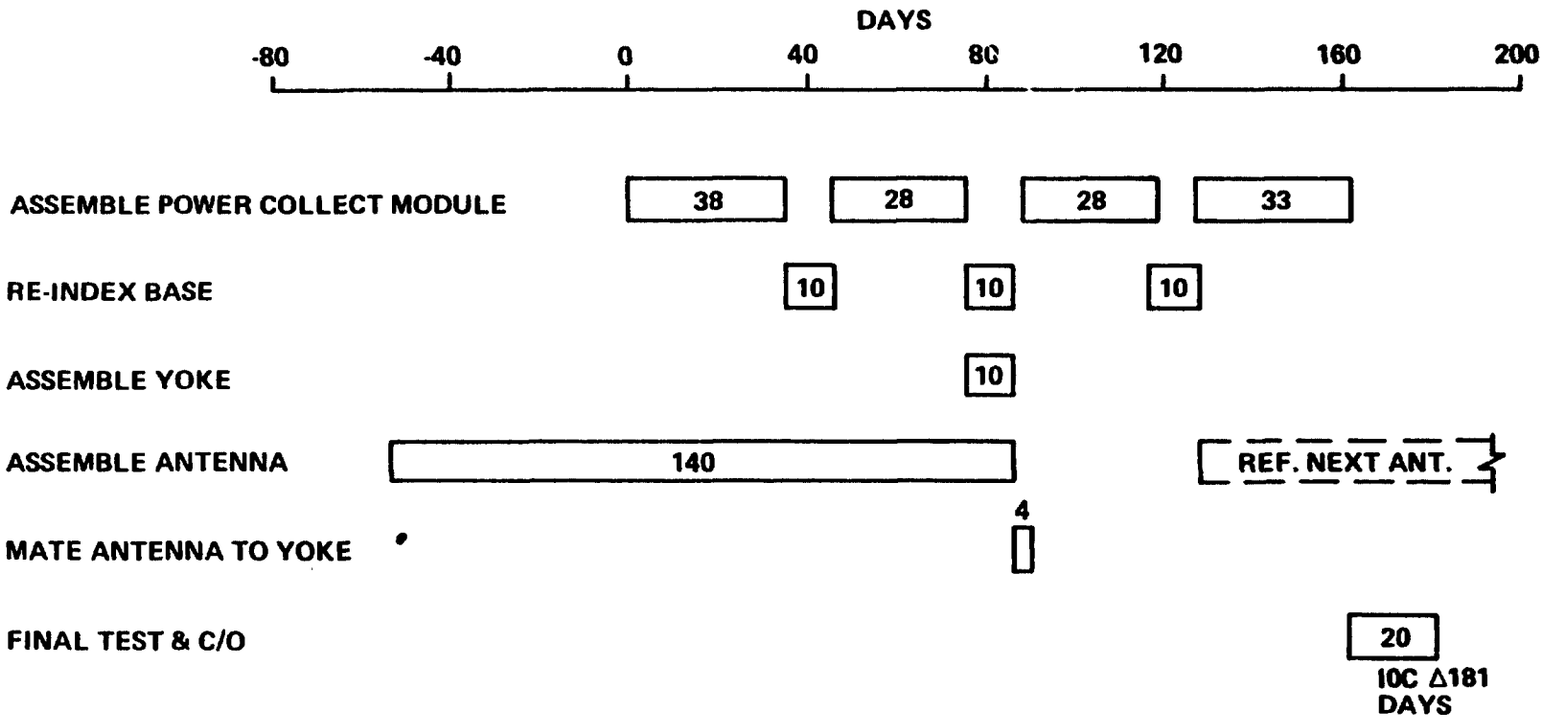
SPS assembly operations commence with the construction of the antenna which is timed for completion at the appropriate time in solar collector assembly. The antenna and yoke completion is shown after the second pass of the end builder. Note that the yoke is constructed in parallel with indexing the end builder so no serial time allocation is required.

The collector construction operations can now be shown by scheduling the first and second assembly passes. The first pass module construction operations continue as described on the previous chart with the following variations. Bay 8 requires additional time because collector and secondary busses are installed for the end of the first string of solar arrays and beginning of the next. Bay 16 construction time is shorter than the others because fabrication of the beams for the next bay have not been included. 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 and no lateral translation of these beams is required. The last pass assembly operations take the same time as the previous two passes however the total time is increased to accommodate the remaining thruster installations.

Allowing additional time beyond collector construction for reindexing the base and mating the yoke to the collector and antenna to the yoke, the total two bay end builder construction time is 181 days.

2 BAY END BUILDER TIMELINE

(5 GW MONOLITHIC SPS)



2 BAY END BUILDER SATELLITE MODULE ASSEMBLY OPERATIONS

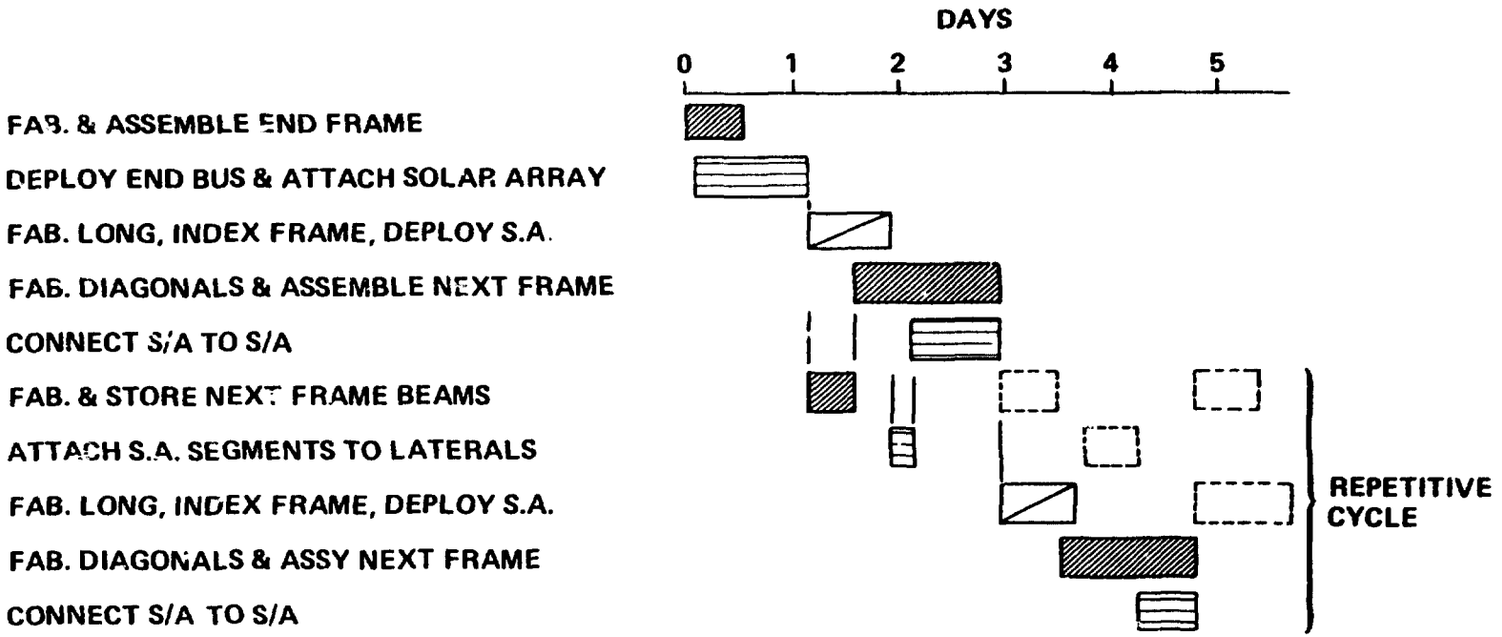
The main feature of the 2-bay construction approach is the deployment of the solar array panels parallel to the longitudinal beams. No solar array deployers are needed and no time is required for deployment. However, this approach requires the addition of lateral busses that connect to the main bus at the longitudinal center of the collector.

Construction commences with the mounting of solar array canisters on the end builder structure and the fabrication of short lengths of the longitudinal beams for the joints to which the end frame will be connected. Then the lateral beams of the end frame are fabricated and joined to the longitudinal beams, while the collector busses and switches are mounted on the beams and the proximal end of the solar arrays are mechanically and electrically fastened. Finally, the remainder of the 2-bay end frame is assembled.

Upon completion of the end frame, the secondary busses are attached to the structure and electrically connected to the collector busses. Then, the structure is indexed longitudinally at one mpm. Meanwhile, the fixed beam machines fabricate the 667 meter longitudinal beams, the gimbled beam machines fabricate the beams needed for the completion of the bay and position them for assembly, when the indexing is completed. (This results in high utilization of the gimbled machines.) The indexing also causes the solar array panels to be deployed. After the arrays are deployed, the distal ends are mounted on the lateral beams and the pigtails from the series solar array segments are joined together.

Construction operations are based on 12 crews (including shift leaders and related staff) working on two shifts. Each crew consists of two astroworkers, who work at 75% productivity for 10 hour shifts.

2 BAY END BUILDER SATELLITE MODULE ASSEMBLY OPERATIONS



48 TOTAL CONST CREW
2 SHIFTS
10 HOURS EACH
75% PRODUCTIVITY

2-BAY END BUILDER CONSTRUCTION EQUIPMENT

The number of beam builders required was established as the basis for the construction approach, as explained previously. The driving operation for the quantity of indexers occurs when the end builder translates along the edge of existing structure. The same bus deployer is used for both main and secondary busses. Railed cherry pickers are the most versatile piece of equipment identified, being used to join beams, install collector busses, fasten solar array segments, and transport beams. Joint operations required the highest number of cherry pickers.

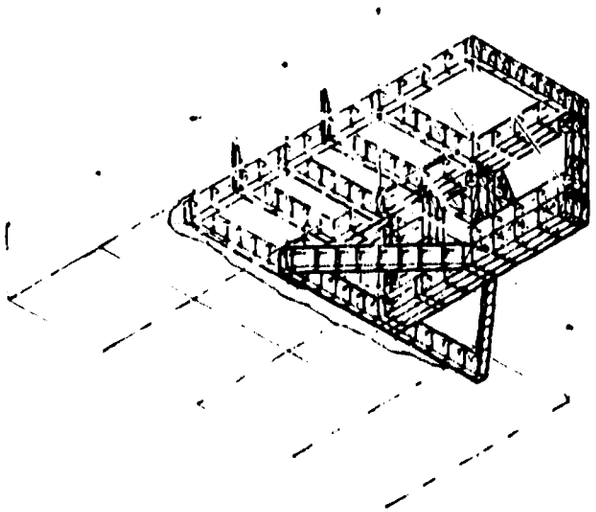
2 BAY END BUILDER CONSTRUCTION EQUIPMENT

EQUIPMENT	NUMBER
AUTO BEAM BUILDERS	
• GIMBALLED	4
• FIXED	6
INDEXERS	8
BUS DEPLOYER	1
30 m RAILED CHERRY PICKERS	10
(JOINTS 10, COLLECTOR BUS 2, SOLAR ARRAY 6, TRANSPORT BEAMS 2)	

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 bays 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 $) = $5.91B
  - SIZE L x W x H = 1.4 x 2.12 x 1.1 km
  - MASS
    - STRUCTURE = 2.02×10^6 kg
    - TOTAL BASE = 4.89×10^6 kg
  - CREW TOTAL = 447
  - CREW MODULES = 4
- ARRAY MODULE CONSTR. EQUIP.
  - BEAM MACHINES = 10
  - CRANE/C.P. = 10
  - INDEXERS = 8
  - BUS DEPLOYERS = 1
  - SOLAR BLANKET DEPLOYERS = 0
- SATELLITE IMPACTS
  - SOLAR ARRAY ORIENTATION = LONGITUDINAL

2636-067W

4 BAY END BUILDER CONSTRUCTION BASE

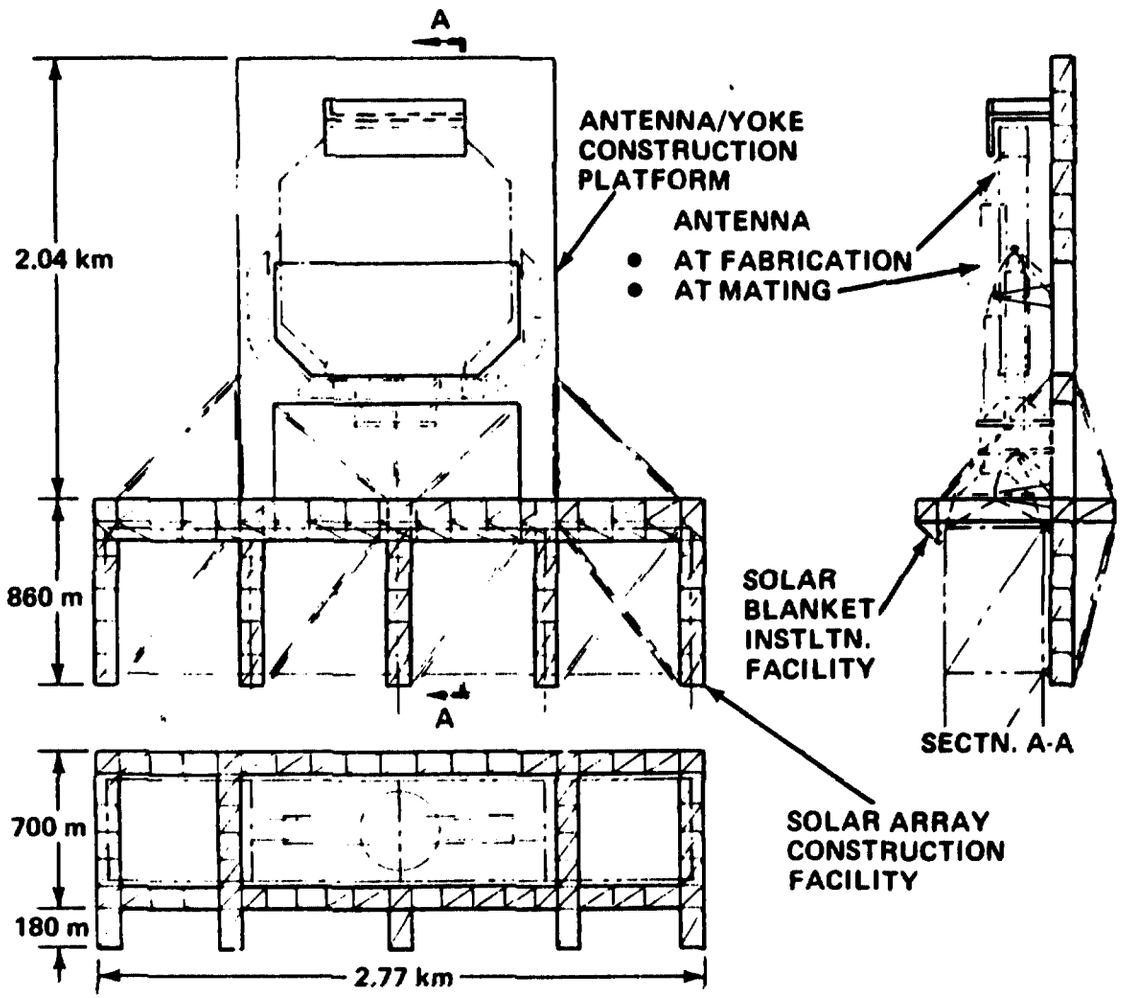
This concept builds a 4 bay wide SPS, 32 bays long, in a single pass. The solar array structural configuration is the SPS baseline, with the exception of the longitudinal beams which are continuous. The antenna is constructed as baselined. This base mates the antenna to the solar array in the preferred 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 comprising a spine, 700 m x 2.77 km, and five outriggers. This facility is constructed from the joining of square section open truss beams, provisionally sized at 100 M per side. The spine has a wide, deep slot through which the antenna can be indexed for assembly. Mounted on the spine are such construction equipments as beam machines and handling devices, solar blanket installation facility, bus installation mechanisms, as well as habitation, docking, storage, etc. Typical beam machine and solar blanket installations are shown on a following chart. The five outriggers guide and support the longitudinal beams of the SPS until the bay structure is completed and self supporting. A typical construction sequence was shown and described on a previous chart. A following chart gives more detail of the 4 bay end builder overall approach.

The antenna, yoke, and rotary joint are built on a platform which extends from the spine in line with the outriggers. It constructs the antenna as baselined. The yoke is then built around the antenna or, if time permits, it may be built in the solar array facility and indexed to mate with the completed antenna. When built and assembled, the antenna/yoke combination is repositioned, as shown, on rotating indexers to a mating position which centers it on the slot in the spine and in the desired position for assembly to the solar array. This repositioning maneuver of the antenna can be avoided by relocating the platform to build the antenna directly in its mating position. This, however, reduces the clearance between antenna and platform as the satellite is indexed and separated from the base.

Support struts, shown typically, will be dictated by stiffness requirements for the base.

4 BAY END BUILDER CONSTRUCTION BASE



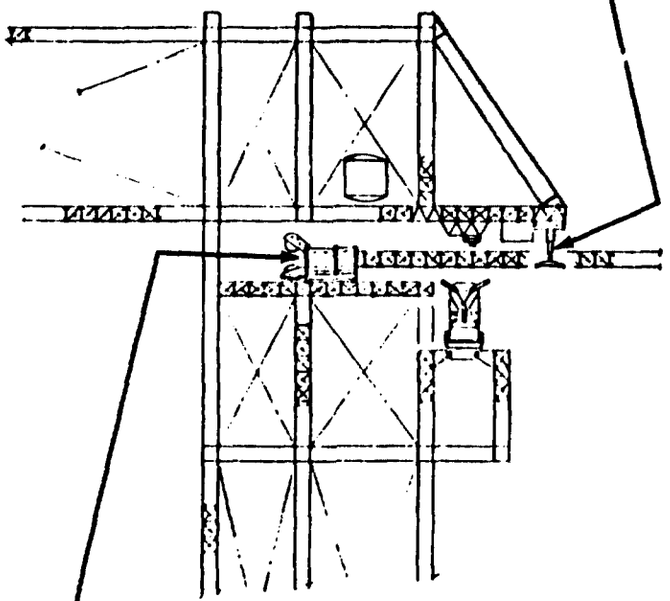
4 BAY AND 8 BAY END BUILDER CONSTRUCTION SYSTEM

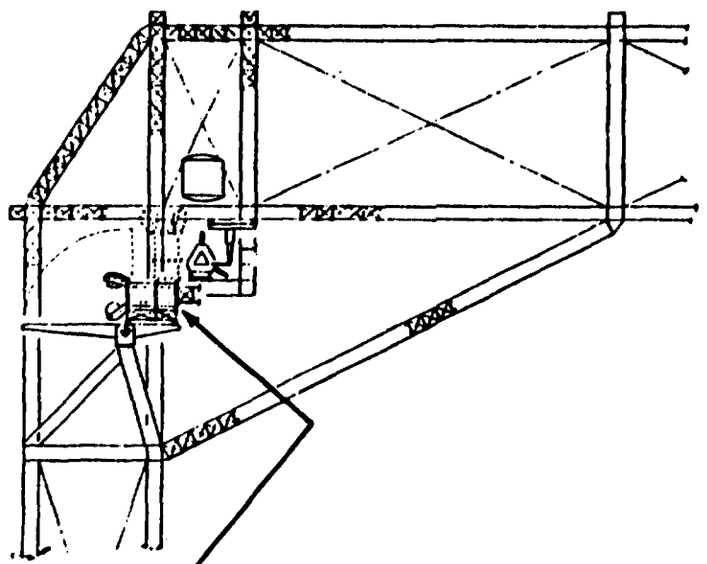
This chart illustrates the mountings of two types of beam machines and a typical solar array blanket deployment facility on the end builder base. Longitudinal beams are continuous and are, therefore, fabricated by a fixed mount beam machine dedicated to that purpose. Transverse and diagonal beams are segmented and do not each require a dedicated beam machine. To minimize the number of such machines, they are mounted on pivotable mounts which can direct a beam where required and thus produce beams for different locations.

As described in the 4 bay and 8 bay construction approach, solar blanket strips are strung laterally across the bays as the structure is indexed in increments. To string these blankets, a deployer, which installs, deploys and connects the strings, runs on a track across the face of the base. The track is mounted on an overhang as shown. The overhang can be extended to accommodate parallel deployer tracks as needed.

4 BAY & 8 BAY END BUILDER CONSTRUCTION SYSTEM

- SOLAR ARRAY BLANKET DEPLOYER
  - RUNS ON TRACK LATERALLY ACROSS FACE OF BASE TO INSTALL & DEPLOY BLANKET STRIP





- LONGITUDINAL BEAM FAB. MACHINE
  - FIXED LOCATION
  - CONTINUOUS BEAM

- TRANSVERSE & DIAGONAL BEAM FAB. MACHINE
  - PIVOT MOUNT TO DIRECT BEAM WHERE REQUIRED
  - SEGMENTED BEAMS

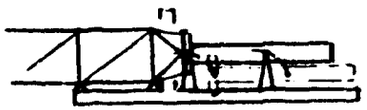
4 AND 8 BAY END BUILDER CONSTRUCTION APPROACH

Structural assembly of a satellite by end builders was described in a previous chart, which also indicated at which point solar array blankets, etc., may be installed. The present chart addresses the overall approaches to construction in the 4 bay and 8 bay end builder bases. The first step constructs the first frame of the solar array and starts building the antenna on its platform. In the second step, the completed frame is indexed outboard for one bay length by fabrication of the longitudinal beams. This indexing is done in increments of 60 m. After each increment, four 15 m wide solar blanket strips are strung laterally across the emerging structure to span the longitudinal beams. They are attached, in segments, to each beam and connections are made. The blanket installation is performed by machines running on an overhang which projects from the face of the base. This is illustrated on a following chart. Also, during indexing, longitudinal busses are added on the fly as the structure passes a facility mounted to the base. Lateral busses are added during assembly while the structure is stationary. After indexing is completed, structure is assembled to complete the bay. Building of the antenna continues. Step 3 repeats the previous activities until the entire array is complete. During this time, the antenna is completed, the yoke and rotary joint built and assembled. The antenna is repositioned for mating to the array, as illustrated in the 4 bay end builder base description, and the mating structure added. Supports mounted on the array and the yoke index the satellite until the array is clear of the base to leave one set of supports to the yoke. To put a positive relative movement between the satellite and the base, thus avoiding collision, a slow rotation is applied to the base. The antenna is kept parallel to the base outriggers by actuating the elevation joint. When the antenna is clear of the slot in the base through which it was indexed, the satellite is separated from the base.

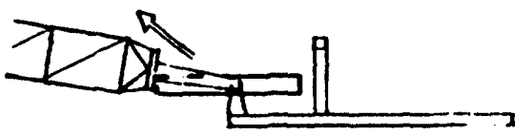
4 & 8 BAY END BUILDER CONSTRUCTION APPROACH

- BUILD FIRST FRAME
- START ANTENNA BUILD

- INDEX FRAME 667.5 INCREMENTS TO ADD SOLAR BLANKETS ACROSS EACH BAY
- BUILD REST OF BAY STRUCTURE
- CONTINUE ANTENNA BUILD



- REPEAT TO COMPLETE SOLAR ARRAY
- COMPLETE ANTENNA BUILD
- BUILD YOKE & ROTARY JOINT AROUND ANTENNA
- RE-POSITION ANTENNA & MATE

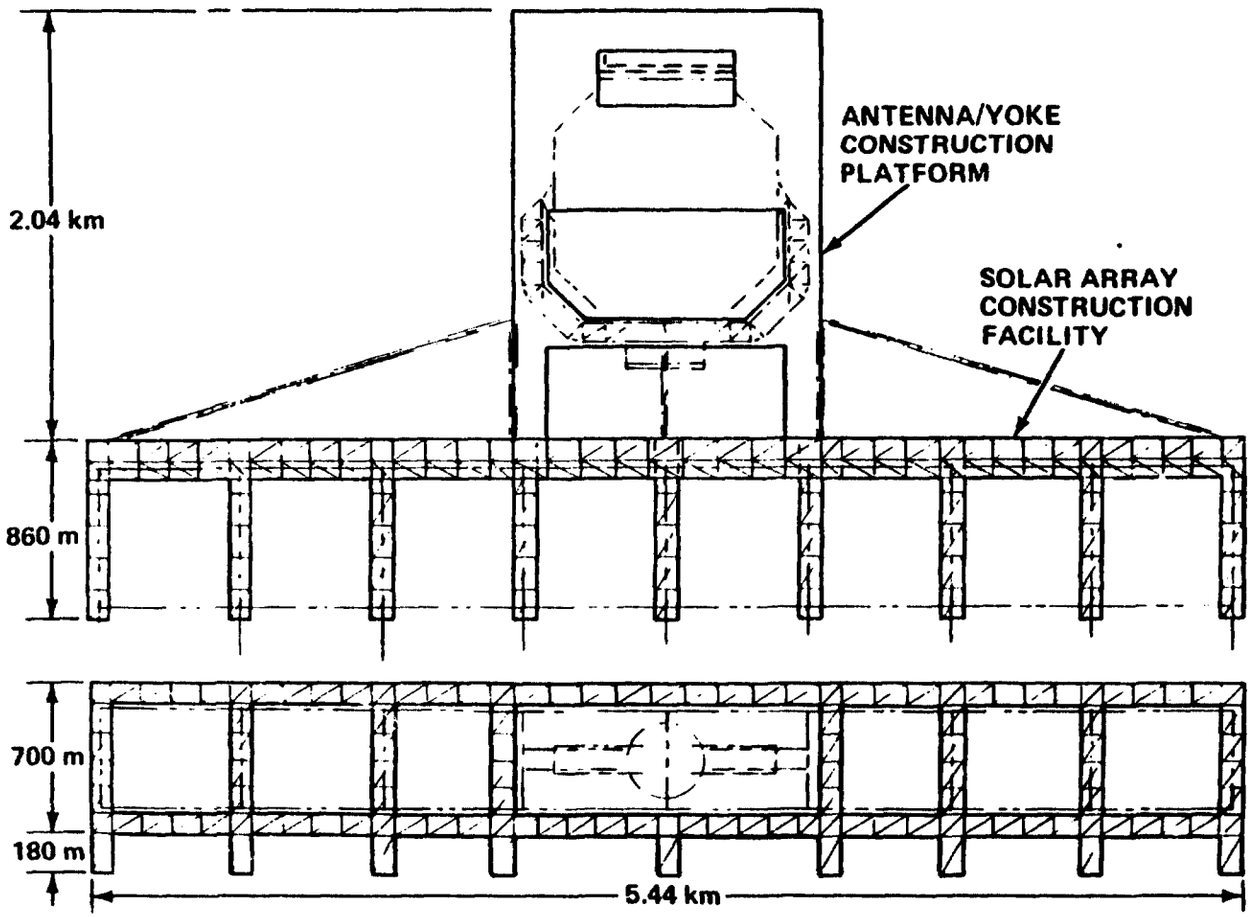


- INDEX SATELLITE FROM BASE
- WHEN ARRAY IS CLEAR, APPLY SLOW ROTATION TO BASE ONLY
- USE ELEVATION JOINT TO KEEP ANTENNA PARALLEL TO BASE
- WHEN ANTENNA IS CLEAR, SEPARATE FROM BASE

8 BAY END BUILDER CONSTRUCTION BASE

This base builds an 8 bay wide SPS, 16 bays long, in a single pass. It is identical to the 4 bay end builder, which is described in depth elsewhere, except that it has eight construction bays, rather than four, to build the wider solar array.

8 BAY END BUILDER CONSTRUCTION BASE

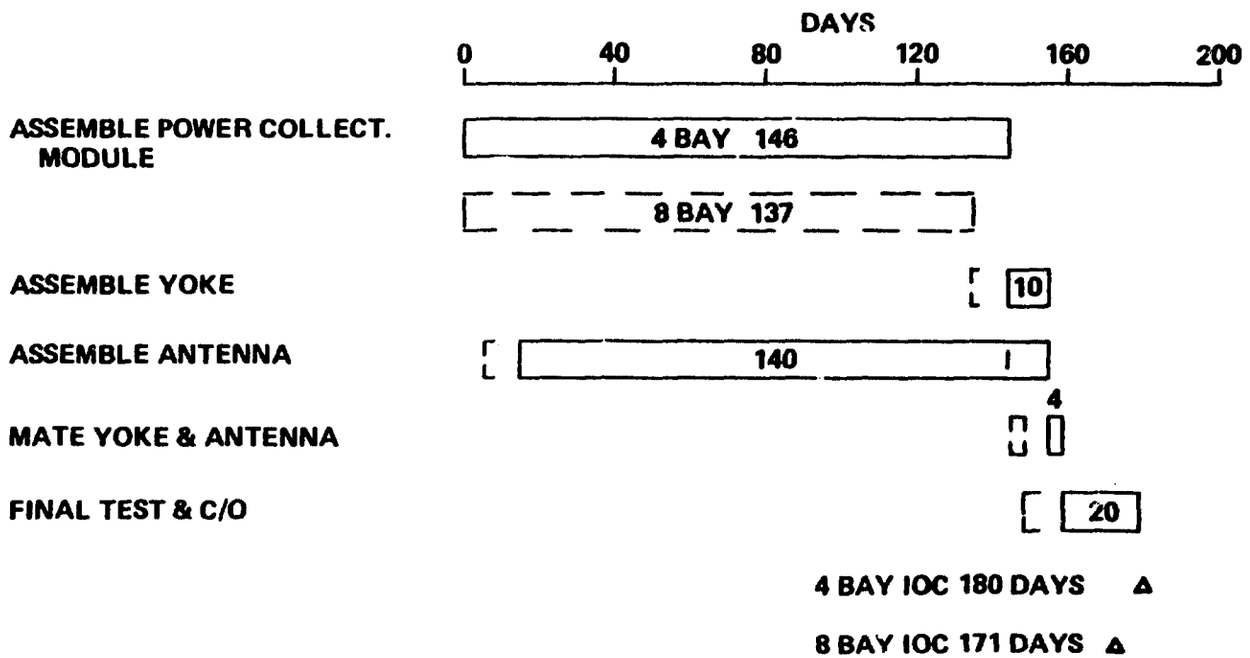


NOTE: ANTENNA & SOLAR ARRAY BUILD, SAME AS 4 BAY BASE

4 BAY AND 8 BAY END BUILDER TIMELINES

The overall assembly operations for the 4-bay and 8-bay configurations are relatively simple and straight forward. The basic structure consists of 32 four-bay modules (or 16 eight-bay modules) constructed in series with a pair of thrusters assembled and installed after the second module and another pair after the last module. The completion of the basic structure is immediately followed by a ten day period for the construction of the yoke. Meanwhile, the antenna has been constructed within a 140 day period, so as to be available by the time the yoke was completed. The next four days are spent connecting the yoke and the antenna. The remaining 20 day period is set aside for test and checkout in accordance with the Boeing ground rules. The assembly of the entire SPS will be completed in 180 days for the 4-bay version and 171 days for the 8-bay version.

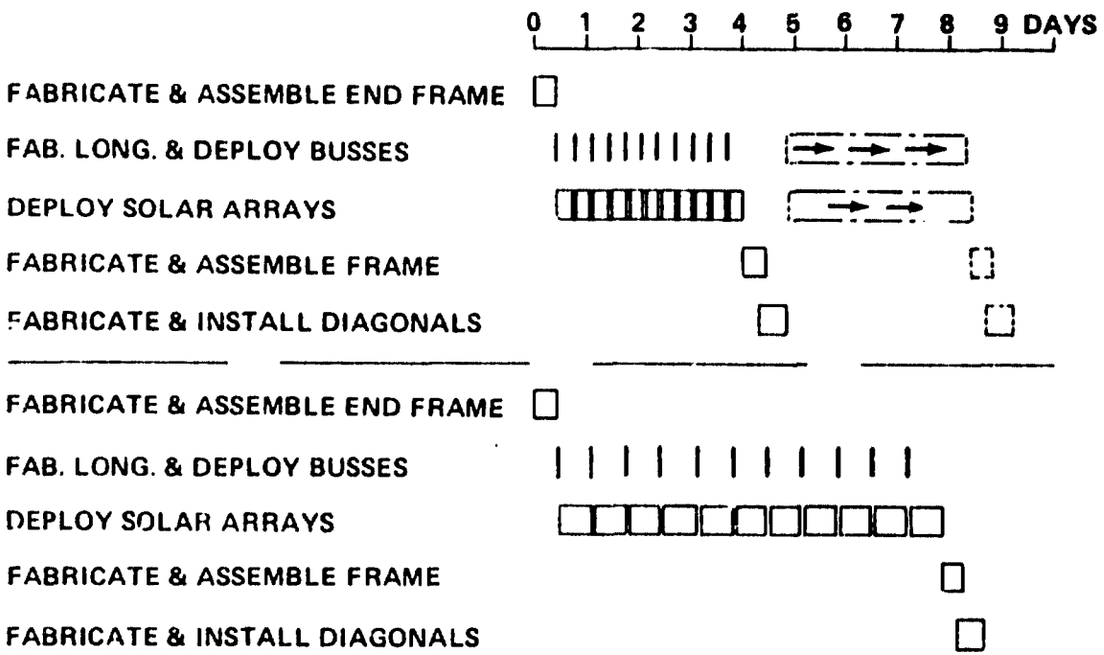
4 BAY & 8 BAY END BUILDER TIMELINES (5 GW MONOLITHIC SPS)



4-BAY AND 8-BAY END BUILDER SATELLITE MODULE ASSEMBLY OPERATIONS

The assembly operations for the 4-bay and 8-bay end builder modules are essentially identical, varying only in the duration of the various phases. Both versions begin with the construction of the end frame. That is followed by 11 iterations of a two step process which consists of (1) the fabrication of 9 meters of longitudinal beam and busses and (2) the simultaneous deployment of four solar array segments laterally across the 4 or 8 bays. At the conclusion of those 11 iterations, another frame is constructed and then the necessary diagonals are fabricated and installed between the two frames. Note, that two 4-bay wide modules are completed in approximately the same time as the 8-bay wide module; and the total crew required, assuming two 10-hour shifts per day and a 75% productivity factor, is 60 men for the 4-bay version and 92 for the 8-bay version.

4 BAY & 8 BAY END BUILDER SATELLITE MODULE ASSEMBLY OPERATIONS



60 & 92	TOTAL CONST CREW (4 BAY & 8 BAY)
2	SHIFTS
10	HOURS/SHIFT
75%	PRODUCTIVITY

4-BAY AND 8-BAY END BUILDER CONSTRUCTION EQUIPMENT

By definition the end builder concept requires one fixed end builder for the construction of each longitudinal beam. Thus, the 4-bay end builder will use 10 fixed beam machines and the 8-bay version will use 18. The remainder of the structure is manufactured by stationary, gimbled beam builders. One upper and one lower gimbled beam machine can produce the lateral, vertical and diagonal beams needed for one bay. One more gimbled beam machine is needed for the extra vertical beam and diagonal beam at the edge of the structure. Thus, the number of gimbled beam makers is 2B+1, where B represents the number of bays.

Four indexers are required. One pair, operating in parallel, will be used to advance the structure a distance of sixty meters. Simultaneously with the indexing operation, the fixed beam machines will be manufacturing the longitudinal beams and the bus deployer will deploy the busses. After the indexing, the second pair of indexers will attach to the rear of the section, thus providing adequate support for the structure during the solar array deployment. Then the forward indexers will detach and travel to a position of readiness for the next indexing operation.

During solar array deployment 8 cherry pickers are needed. Two cherry pickers are used in conjunction with each of the four deployers to install the solar array segment containers, attach the leading edge deployer to the catenary end rings, hand off the leading edge catenary to the distal end and connect the electrical pigtail. However, during the construction of the basic structure two cherry pickers are needed to attach the laterals, verticals and diagonals to each longitudinal beam. Thus, 20 cherry pickers are needed for the 4-bay version and 36 are needed for the 8-bay version.

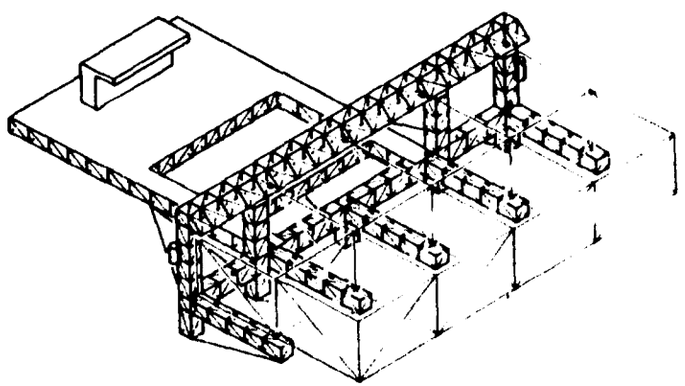
4 BAY & 8 BAY END BUILDER CONSTRUCTION EQUIPMENT

	4 BAY	8 BAY
AUTOMATIC BEAM MACHINE		
• GIMBALLED	9	17
• FIXED	10	18
INDEXER	4	4
BUS DEPLOYER	1	1
S/A DEPLOYER	4	4
CHERRY PICKER	20	36

4 BAY END BUILDER BASE FEATURES

This chart follows the features format of the 2 bay end builder. It constructs an SPS, whose configuration has changed from the baseline to a 4 x 32 bay layout, in a single pass. The construction system features, major equipments and their impacts on the satellite are listed.

4 BAY END BUILDER BASE FEATURES



- SINGLE PASS CONSTR. OF 4 x 32 BAY SPS
- CONSTR. SYS
  - UNIT COST (1977 $) = $6.99B
  - SIZE L x W x H = 2.9 x 2.77 x 0.88 km
  - MASS
    - STRUCTURE = 2.49×10^6 kg
    - TOTAL BASE = 5.58×10^6 kg
  - CREW TOTAL = 459
  - CREW MODULES = 4
- ARRAY MODULE CONSTR. EQUIP.
  - BEAM MACHINES = 19
  - CRANE/C.P. = 20
  - INDEXERS = 4
  - BUS DEPLOYERS = 1
  - SOLAR BLANKET DEPLOYERS = 4
- SATELLITE IMPACTS
  - SOLAR ARRAY ORIENTATION = LATERAL BASELINE
  - BUS I^2R LOSSES = 2.5×10^6 kg

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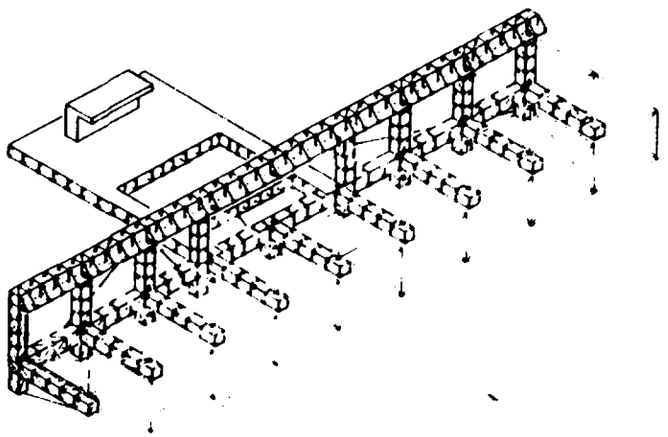
8 BAY END BUILDER BASE FEATURES

This base builds the baseline SPS in a single pass. The chart follows the 2 bay end builder features format in listing the construction system features, major equipments and their impacts on the satellite.

8 BAY END BUILDER BASE FEATURES



- SINGLE PASS CONSTR. OF 8 x 16 BAY SPS
- CONSTR. SYS
  - UNIT COST (1977 $) = $8.94B
  - SIZE L x W x H = 2.9 x 5.44 x 0.88 km
  - MASS
    - STRUCTURE = 3.38×10^6 kg
    - TOTAL BASE = 6.99×10^6 kg
  - CREW TOTAL = 561
  - CREW MODULES = 5
- ARRAY MODULE CONSTR. EQUIP.
  - BEAM MACHINES = 35
  - CRANE/C.P. = 36
  - INDEXERS = 4
  - BUS DEPLOYERS = 1
  - SOLAR BLANKET DEPLOYERS = 4
- SATELLITE IMPACTS
  - SOLAR ARRAY ORIENTATION = LATERAL BASELINE

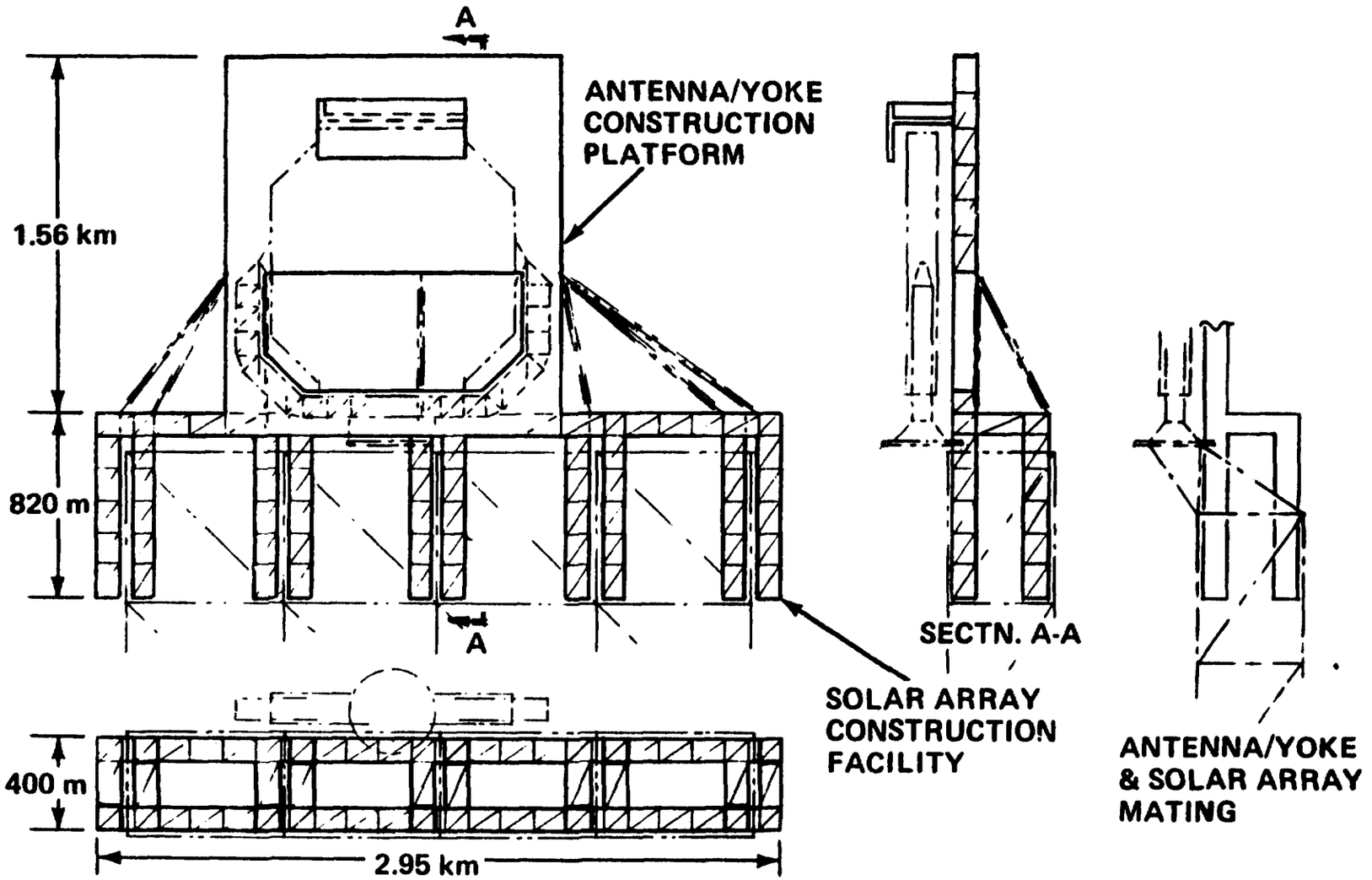
4 BAY INTERNAL CONSTRUCTION BASE

The internal construction base builds the satellite around itself. This particular application builds a 4 bay wide SPS, 32 bays long, in a single pass. It builds the baseline solar array structure. The antenna and its construction are also baseline.

Construction of the solar array takes place in a facility which has a spine with 10 outriggers projecting from it, as shown, The upper and lower outriggers of each pair are offset from each other to enable the lateral diagonal members of the structure being built to pass through when it is indexed. Construction of the array structure is similar to that described already for the end builder concepts, except that the longitudinal members are not continuous and therefore do not require dedicated beam machines. All beam machines are mounted on the spine. The solar array blanket strips are deployed longitudinally, in the direction of structure build, as they were in the original 10 GW SPS. Since the indexing structure can be used to deploy the array blanket, special deployment mechanisms, as were provided for the end builder, are not required.

The antenna, yoke and rotary joint are built as described for the end builder busses. Their construction platform is in line with a set of outriggers, as shown. The antenna/yoke/rotary joint are mated to the solar array in their constructed position. This leaves them offset from the centerline of the solar array in two planes. The lateral offset is to allow the rotary joint to clear the relevant outrigger arm when the completed satellite is indexed to clear the solar array from the base. The larger, vertical offset is to avoid maneuvering the antenna for mating to the solar array. This offset can be eliminated by considerably extending outriggers on one side, to support the completed solar array while maneuvering the antenna clear of its platform and down to be aligned with the centerline of the array. This is a trade off between additional structure, together with antenna maneuvering equipment, and control requirements.

4 BAY INTERNAL CONSTRUCTION BASE

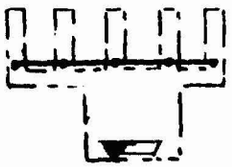


INTERNAL BASE CONSTRUCTION APPROACH

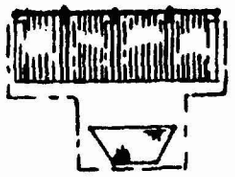
Structural assembly of a satellite by end builders was addressed in a previous chart. A similar procedure will be followed by the internal base. The present chart addresses the overall approach to construction in the internal base. The first step constructs the first frame and attaches solar array boxes. At the same time, antenna construction is started on its platform. The completed frame is then indexed for one bay length which, at the same time, deploys the solar array blanket. Longitudinal busses are installed 'on the fly' from a facility mounted on the base. Lateral busses are installed during construction while the structure is stationary. Having indexed the frame, the rest of the bay structure is then assembled to complete the bay. At the same time, the next row of solar array blankets is installed on the next frame. The antenna build continues. The next step indexes the bay just completed and again deploys the array.

Previous steps are repeated to complete the array build. The antenna is completed and the yoke and rotary joint built around the antenna. The last solar array bay to be built is indexed sufficiently to allow installation of the structure mating it to the antenna assembly. The satellite is then indexed from the base and separated.

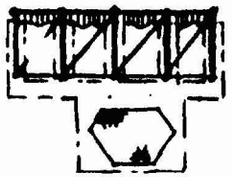
INTERNAL BASE CONSTRUCTION APPROACH



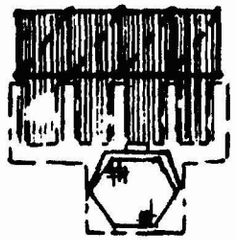
- BUILD FIRST FRAME & ATTACH ARRAY BOXES
- START ANTENNA BUILD



- INDEX FRAME 667.5 m DEPLOYING SOLAR ARRAY
- CONTINUE ANTENNA BUILD



- BUILD REST OF BAY STRUCTURE
- ATTACH ARRAY BOXES TO NEW FRAME
- CONTINUE ANTENNA BUILD



- INDEX BAY 667.5 m DEPLOYING SOLAR ARRAY
- REPEAT THIS & PREVIOUS STEP TO COMPLETE SOLAR ARRAY
- COMPLETE ANTENNA. BUILD YOKE & ROTARY JOINT AROUND ANTENNA

- INDEX LAST BAY 300 m
- ADD STRUCTURE MATING YOKE TO ARRAY
- INDEX ASSY FORM BASE

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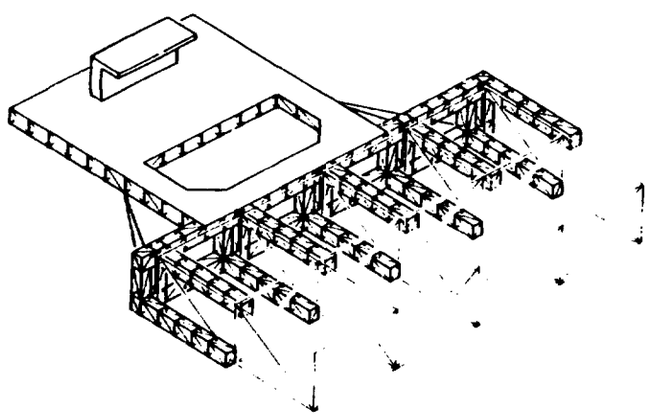
4 BAY INTERNAL BASE FEATURES

This base builds an SPS whose configuration has changed from the baseline to a 4 x 32 bay layout. Unlike the end builder bases, it builds the satellite around itself. The main features of the base are listed under the categories of construction system, construction equipment and the impacts on the satellite.

4 BAY INTERNAL BASE FEATURES



- SINGLE PASS CONSTR. OF 4 x 32 BAY SPS
- CONSTR. SYS
  - UNIT COST (1977 $) = $6.93R
  - SIZE L x W x H = 2.38 x 2.95 x 0.40 km
  - MASS
    - STRUCTURE = 2.51×10^6 kg
    - TOTAL BASE = 5.75×10^6 kg
  - CREW TOTAL = 469
  - CREW MODULES = 5
- ARRAY MODULE CONSTR. EQUIP.
  - BEAM MACHINES = 10
  - CHERRY PICKERS = 20
  - INDEXERS = 8
  - BUS DEPLOYERS = 1
  - SOLAR BLANKET DEPLOYERS = 0
- SATELLITE IMPACTS
  - SOLAR ARRAY ORIENTATION = LONGITUDINAL
  - BUS I^2R LOSSES = 2.5×10^6 kg
  - OFF AXIS ANTENNA MOUNT

BOOTSTRAP CONCEPTS

Two flavors of bootstrap concept are considered. The first uses construction facilities incorporated into a base dedicated to the construction of the satellite. This base fabricates the satellite structural members and assembles them while being supported by the last piece of structure it assembled. The levels of construction functions provided by the base are categorized into (a) where all functions are provided by the facility and (b) where use is made of operational facilities incorporated into the satellite, such as maintenance. The satellite, however, will carry no penalty for such use of its facilities. Thus, we have two options for bootstrap construction.

A third option, and the second concept category, does not use a dedicated facility. Here, all construction functions are provided by the satellite. Use is made of built-in facilities provided for such functions as maintenance, solar cell annealing, etc. Other facilities, including additional tracks for construction equipments, structural stiffness to support large equipments, and adaptation of maintenance facilities to enable construction, are carried as scars by each satellite. Some equipments, such as beam machines, would be removed from the satellite after it is built and used again.

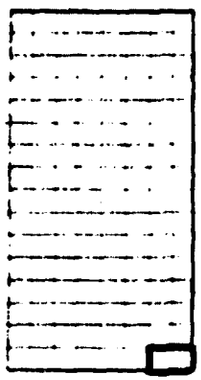
The three options are examined further on the next chart.

BOOTSTRAP CONCEPTS

?

DEDICATED CONSTRUCTION FACILITY SUPPORTED BY STRUCTURE IT BUILDS

- ALL CONSTRUCTION FUNCTIONS PROVIDED BY FACILITY



OPTION 1

- CONSTRUCTION FUNCTIONS UTILIZE SATELLITE MAINTENANCE FACILITIES WHERE PRACTICAL
- ALL OTHER CONSTRUCTION PROVIDED BY CONSTRUCTION FACILITY
- SATELLITE CARRIES NO CONSTRUCTION PENALITIES

OPTION 2

NO DEDICATED CONSTRUCTION FACILITY

- ALL CONSTRUCTION FUNCTIONS PROVIDED BY SATELLITE
- UTILIZE SATELLITE MAINTENANCE FACILITIES WHERE PRACTICAL OTHERWISE INCORP. INTO SATELLITE AS PENALTY

OPTION 3

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BOOTSTRAP OPTIONS

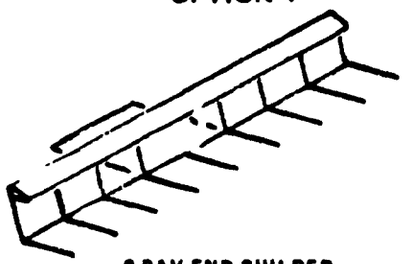
The previous chart considered bootstrap concepts and resulted in three options. The first provides a base which carries all equipments necessary to construct the satellite. This, in fact, is the option presently being studied and is covered by the 2-bay, 4-bay, and 8-bay end builders, as well as the 4-bay internal base. A minimum size facility might use a platform, sized to build the antenna, as a base for solar array construction in 2 bay wide increments.

The second option uses facilities incorporated into the satellite for operational functions such as maintenance. All other construction facilities are provided by a dedicated base. A possible example of such a system is shown in the sketch where a gantry, pernaps provided for access to the solar array for maintenance and repair or to carry cell annealing equipment, serves to deploy the solar blankets. Other construction equipments are carried by the base. This approach appears promising but cannot be developed until the satellite design and the construction approach have matured.

The third option does not have a dedicated base but carries all construction equipments on the satellite. An example shown starts with a habitation/docking/storage module to which beam machines are moored. The machines move radially outward from the module on the ends of the beams that they fabricate, to build a structural bay. This process is then continued by building bay upon bay. Further study of this approach is not recommended, as it appears unduly complicated.

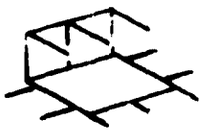
BOOTSTRAP OPTIONS

OPTION 1



8 BAY END BUILDER

OPTIONS

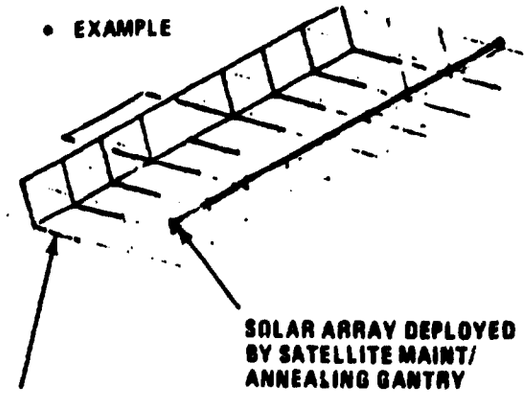


MIN. FACILITY – 2 BAY BASE SIZED BY ANTENNA CONSTRUCT. PLATFORM

THIS OPTION IS COVERED BY ✔ THE ALTERNATES UNDER CONSIDERATION

OPTION 2

- EXAMPLE



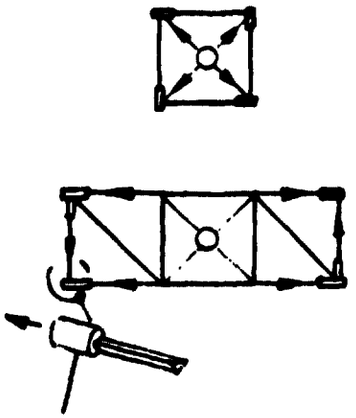
SOLAR ARRAY DEPLOYED BY SATELLITE MAINT/ ANNEALING GANTRY

OTHER CONSTRUCT. IN FACILITY

LOOKS PROMISING –INVESTIGATE FURTHER WHEN SATELLITE DEFN. & CONSTR. APPROACH HAS MATURED

OPTION 3

- EXAMPLE



TRAVELLING BEAM MACHINE

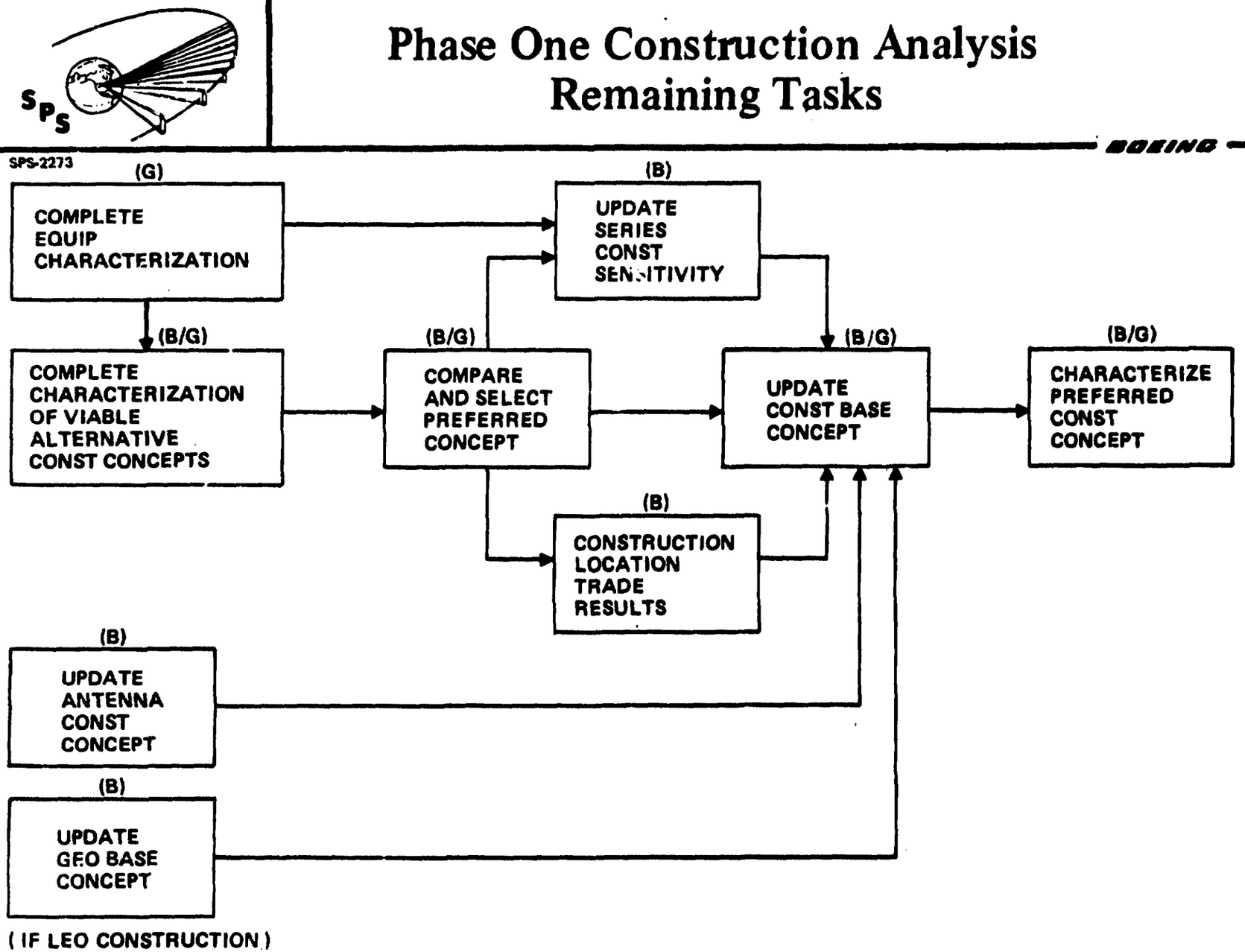
NOT RECOMMENDED FOR THIS APPLICATION
– APPEARS COMPLICATED
– FURTHER STUDY NOT WARRANTED

GRUMMAN

PHASE ONE CONSTRUCTION ANALYSIS REMAINING TASKS

At this point in time, we have narrowed the number of alternative construction concepts from 6 possibilities down to 3 viable options. In the next couple of weeks, these options will be characterized to equivalent levels of detail, including mass and cost estimates. The preferred concept will be selected using the selection criteria described earlier. After selecting the winner, it will be necessary to assess the possibility of series construction rather than parallel construction to see if there is an economic and operational advantage. We will also integrate the construction concept with the construction location trade results. In parallel with the tasks described above, the antenna and GEO base operations will be updated. All of the analyses will then be integrated into a composite preferred construction approach description that will be part of the updated Preferred Concept System Description book that will become the basis for Phase Two studies.

Phase One Construction Analysis Remaining Tasks



STUDY
ALUMINUM STRUCTURE
10 GW SOLAR
POWER SATELLITE

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GROUNDRULES

- LEO CONSTRUCTION 4 BY 8 MODULE 2673 m x 5348 m
- FABRICATION IN DIRECTION OF MAJOR AXIS OF MODULE
- CONSTRUCTION BASE MAJOR AXIS IS EARTH POINTING-CONSTRUCTED IN DIRECTION OF VELOCITY VECTOR
- SOLAR BLANKET PRELOADED UNIAXIALLY
- BEAMS ATTACHED CENTROIDALLY
- FLATNESS REQUIREMENT

DESIGN DATA

- MASS DATA

SOLAR ARRAYS	5.178×10^7 kg
MW ANTENNAS	2.521×10^7 kg
WT GROWTH	2.051×10^7 kg
TOTAL	9.75×10^7 kg

- SOLAR ARRAY BLANKET UNIT WEITHT – 0.427 kg/m^2
- T/W IN TRANSPORT FROM LEO TO GEO – 0.0001
- SPS NATURAL FREQUENCY INCLUDING SOLAR CELLS & ANTENNAS – 0.0012 Hz
- SOLAR BLANKET NATURAL FREQUENCY – 0.0024 Hz
- SOLAR BLANKET PRELOAD NEEDED TO OBTAIN FREQUENCY = 4.285 N/m (0.0245 LB./IN.)
- FACTOR OF SAFETY – 1.4
- 30 YEAR SERVICE LIFE

DESIGN CONDITIONS

The more significant structural loading conditions currently are the solar array blanket preload and loads caused by transport of the 4 bay x 8 bay module to GEO. The first condition causes a high local cap load in the 7.5 meter beam; the second induces the highest column compression load in the 7.5 m by 667.5 m beam. In as much as aluminum has a coefficient of thermal expansion (CTE) greater than the advanced structural composites, the effect of gradients on distortions, stresses etc., are under evaluation. Thermal control features will be incorporated in the design to minimize thermal/structural response. These include thermal coatings, incorporation of lightening holes in members, etc. Loads induced during fabrication and handling will also require assessment.

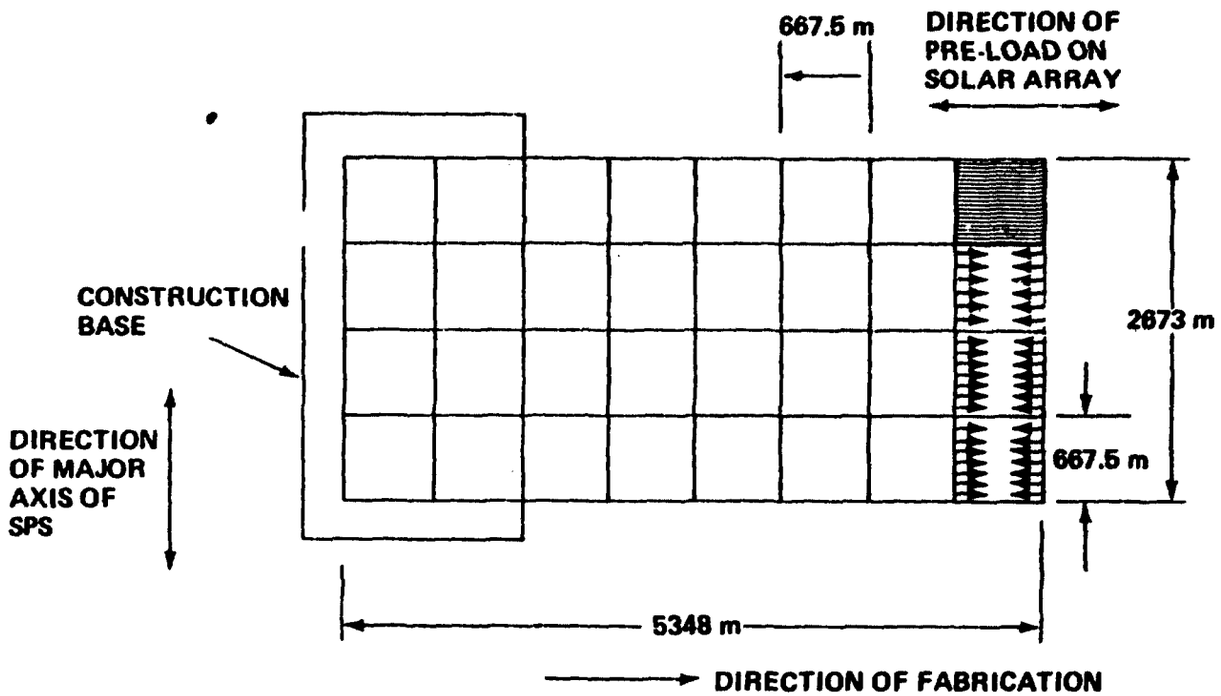
DESIGN CONDITIONS

- SOLAR BLANKET PRE-LOAD
- TEMPERATURES & THERMAL GRADIENT TIME HISTORIES
- TRANSPORT ACCELERATION TO GEO
- ATTITUDE CONTROL & STATION KEEPING TORQUES
- STIFFNESS
- INTERFACE LOADS BETWEEN MODULE & CONSTRUCTION BASE; BEAM HANDLING

SOLAR ARRAY PRELOAD DESIGN CONDITION

The LEO baseline configuration utilizes a four bay wide construction base to fabricate the 4 bay by 8 bay module. During module construction, the 15 meter wide solar array blankets are installed on the two end bays of the 8 bay length as shown. The 15 meter arrays are interconnected along their lengths and uniaxially pretensioned such that the blanket natural frequency is 8.64 cph. Bending moments, caused by the pretension result in high axial compression loads in the caps of the 667.5 m beam. This condition gives the critical load in the cap.

SOLAR ARRAY PRE-LOAD DESIGN CONDITION



FREQUENCY OF UNIAXIALLY LOADED MEMBRANE

$$f_n = \frac{3600}{2\ell}\sqrt{\frac{S}{W}} \text{ cph}$$

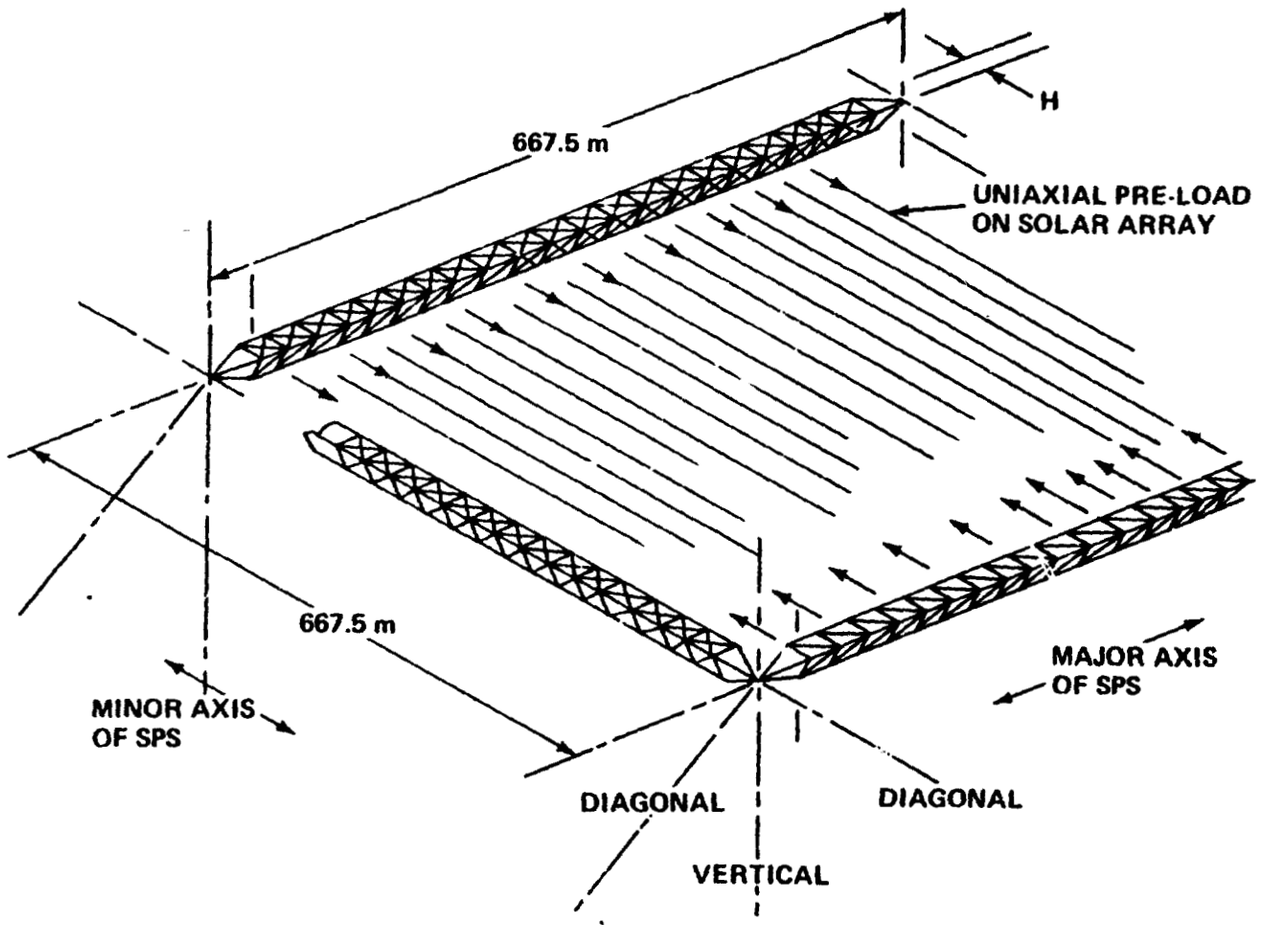
ℓ = LENGTH METERS

S = TENSION PER UNIT WIDTH

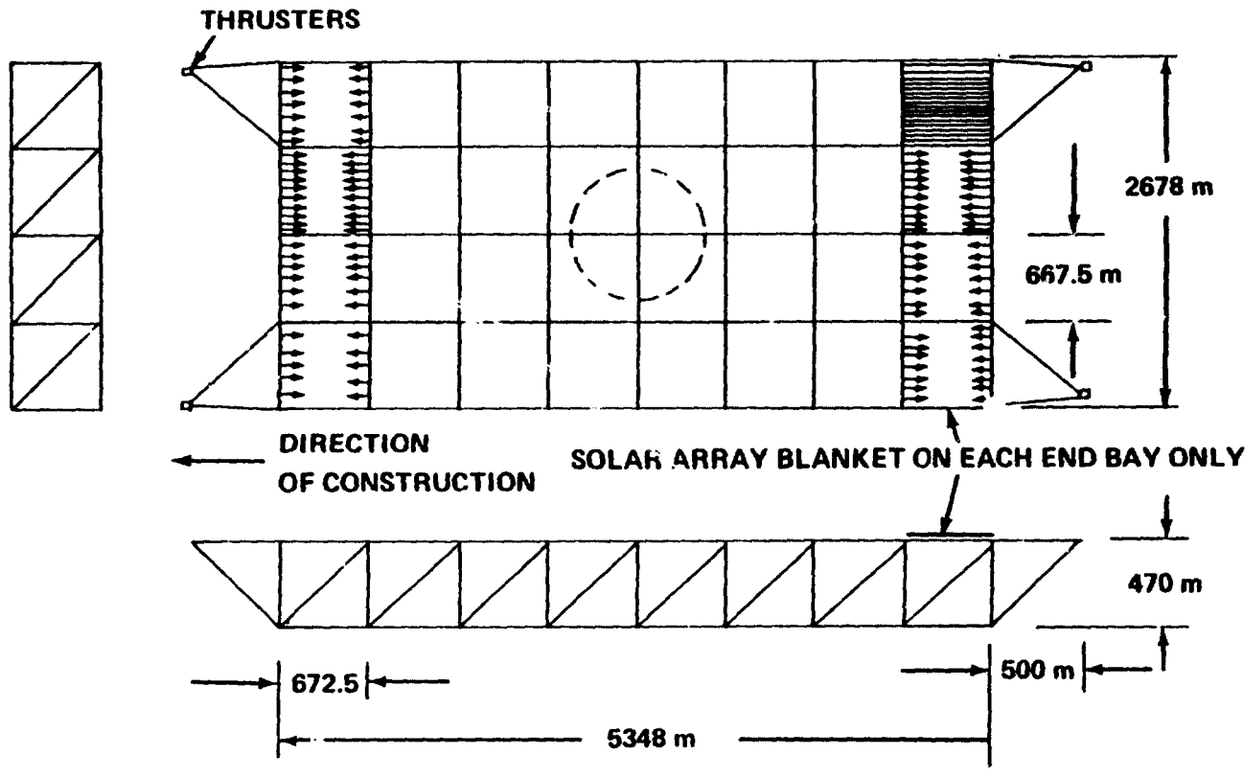
W = ARRAY UNIT WEIGHT

REQUIRED f_n = 8.64 cph

LOADS APPLIED TO BEAM BY SOLAR ARRAY



4 BAY BY 8 BAY MODULE



MODULE MASS - 6,500,000 kg
ANTENNA MASS – 12,200,000 kg

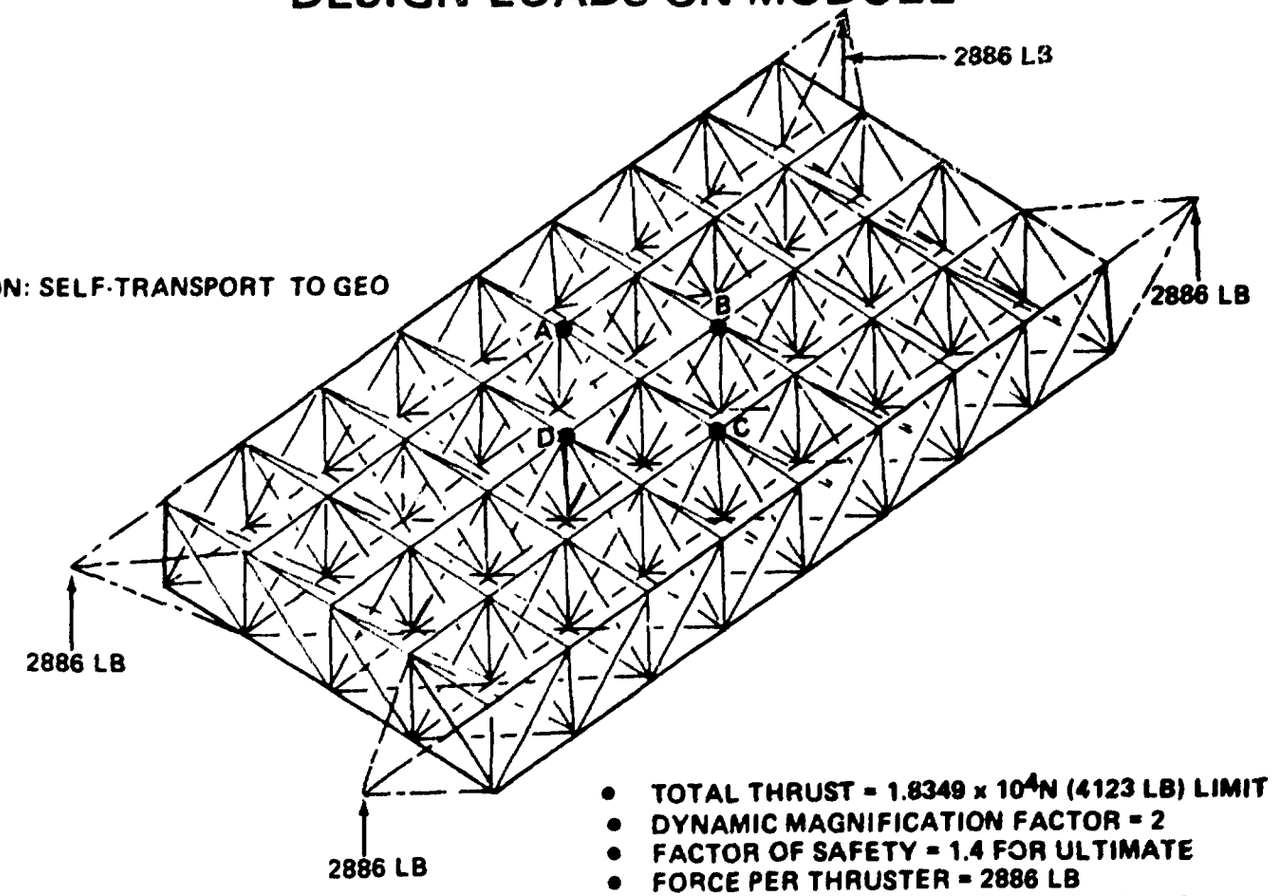
MAXIMUM THRUST TO WEIGHT RATIO = 0.0001

MODULE SELF TRANSPORT TO GEO DESIGN CONDITION

The maximum compression load in the 667.5 meter member results from the module transfer from LEO to GEO. The four thruster forces are applied to the module and antenna masses as shown in the figure. A dynamic magnification factor of 2.0 and a factor of 1.4 are applied to the member loads. The maximum compression load in the 667.5 meter beam is -7544 lbs.

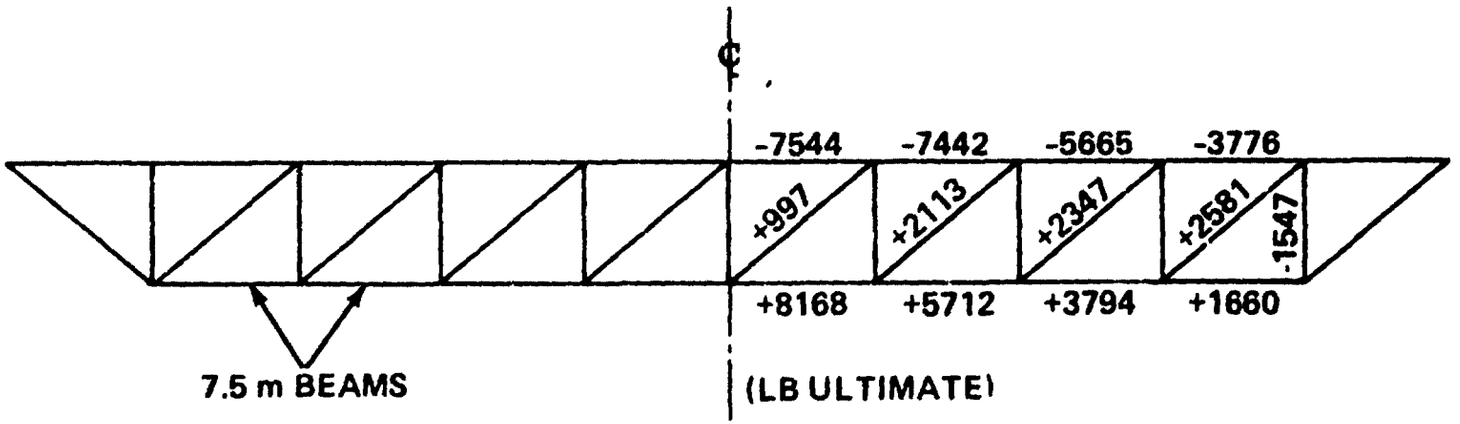
DESIGN LOADS ON MODULE

CONDITION: SELF-TRANSPORT TO GEO



- TOTAL THRUST = 1.8349×10^4N (4123 LB) LIMIT
- DYNAMIC MAGNIFICATION FACTOR = 2
- FACTOR OF SAFETY = 1.4 FOR ULTIMATE
- FORCE PER THRUSTER = 2886 LB
- ANTENNA INERTIA FORCE = 7532 LB ULT.
- MODULE INERTIA FORCE = 4013 LB ULT.
- ANTENNA SUPPORTED AT POINTS A, B, C, D

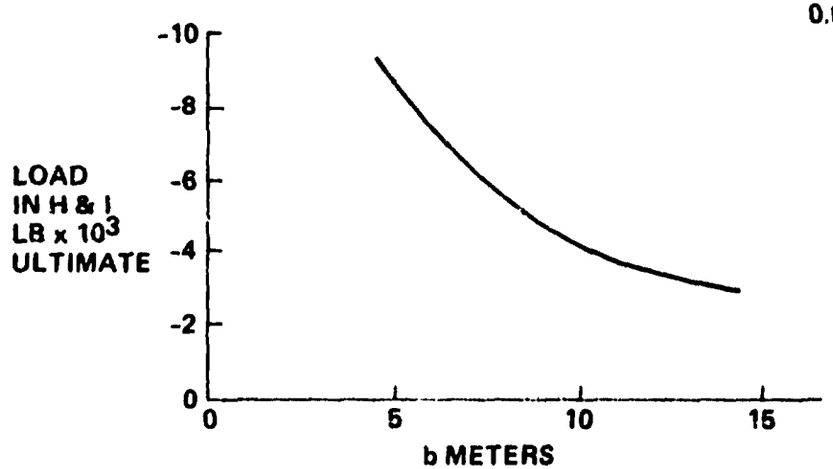
SUMMARY TRUSS LOADS DUE TO ORBIT TRANSFER FROM LEO TO GEO

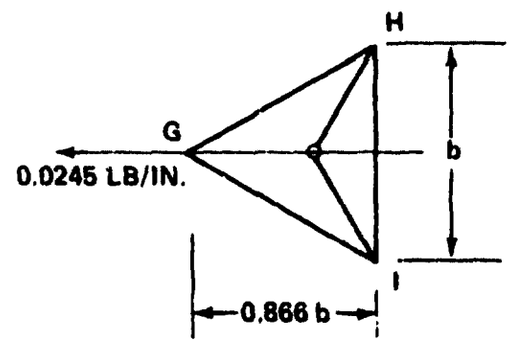


NOTE:
- PRETENSION UNIAXIAL SOLAR BLANKET LOADS ON UPPER BEAMS DO NOT ACT ON ABOVE MEMBERS. BENDING CAUSED BY SOLAR ARRAY PRETENSION OCCURS ON 7.5 m BEAMS NORMAL TO ABOVE BEAMS.
- INCLUDES MODULE & ANTENNA MASSES

VARIATION OF CRITICAL CAP COMPRESSION LOAD VS BEAM DEPTH

MAX MOMENT ON 667.5 m BEAM = 2.96×10^6 IN.-LB ULTIMATE





$$C_{H,I} = -\frac{M_{\mathbb{C}}}{1.732\,b}$$

ALUMINUM BEAM DESIGN 7.5 METER

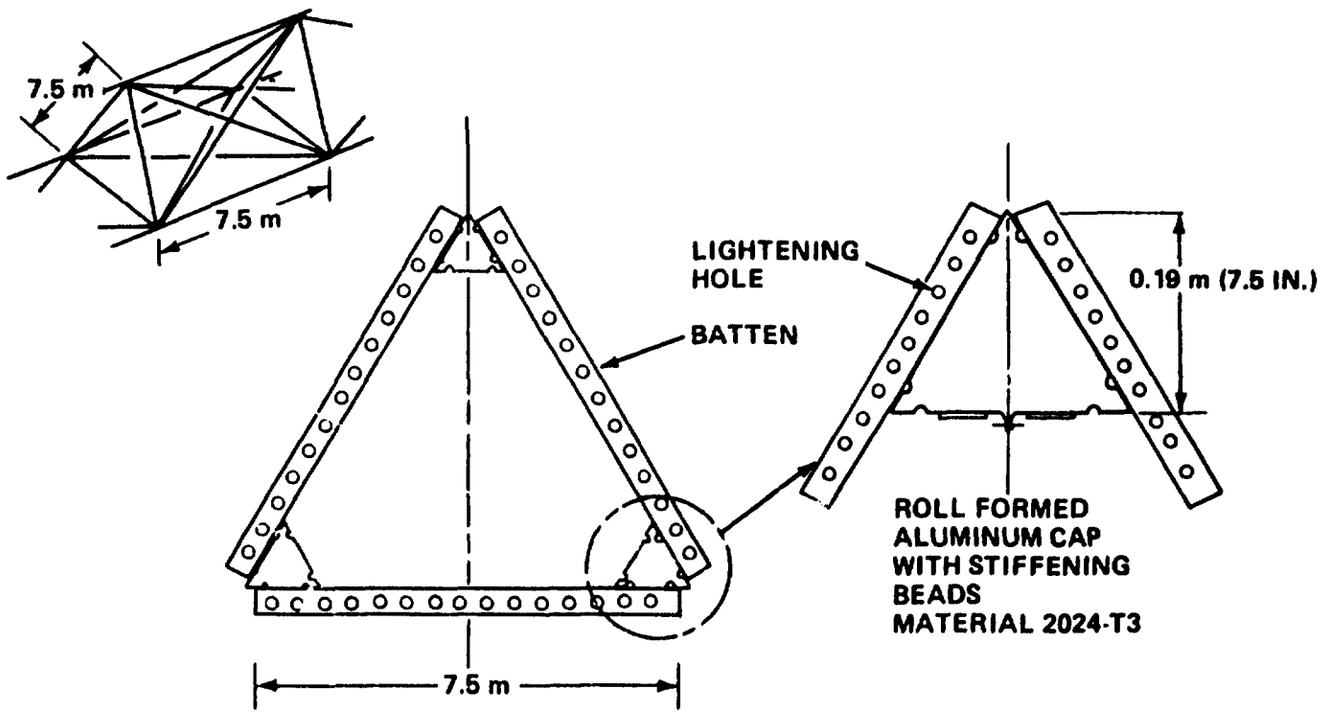
The aluminum triangular cross section beam design incorporates three roll formed closed section caps interconnected by battens spaced at 7.5 meters. Shear stiffness can be provided by either preloaded cross cables or compression/tension members. The cable concept is approximately 20% lighter and has been selected for the baseline aluminum structure. However, pretensioned cables for shear stiffening may induce potential problems such as: adjustment of all cable tensions to the proper preloads to prevent slack at any time, failure of cable attachments, potential for excessive material creep deformation under sustained load and temperature for 30 years increased by an appropriate scatter factor, effect of selected cable system on lattice column capability, etc.

The selected cap size for the design loads is 7.5 inches deep and has a thickness of .028 inches. The batten is also a closed section with the bottom flanges extending outward for attachment to the cap. The depth is 4 inches and thickness of 0.020 inches.

In order to minimize thermal gradients in members and between members, lightening holes have been spaced to reduce shadowing as much as possible. Thermal coatings are also being evaluated to maintain temperatures and gradients within acceptable limits.

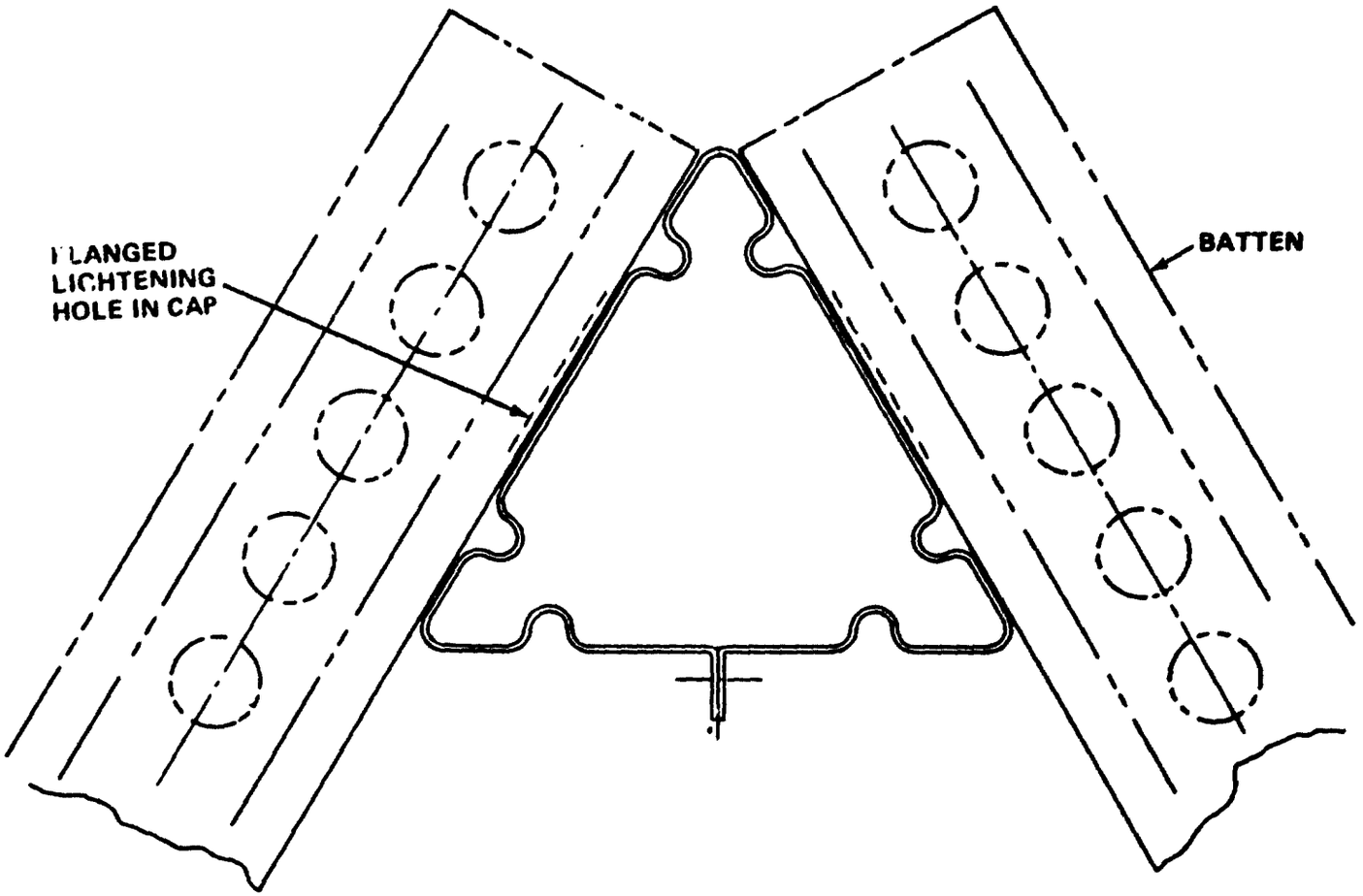
The roll formed cap incorporates longitudinal stiffening beads near the corner sections in order to provide a high compression capability in the corners. Between the lightening holes, beads are rolled into the section for stiffening. The section is formed on a mandrel which is used for support during the attachment operation. The lower attachment on the centerline is not completed until after the battens are connected. The gap between flanges permits the mandrel support to extend inward to the beam machine; the mandrel support ends, and the two flanges are joined.

ALUMINUM BEAM DESIGN (7.5 METERS)

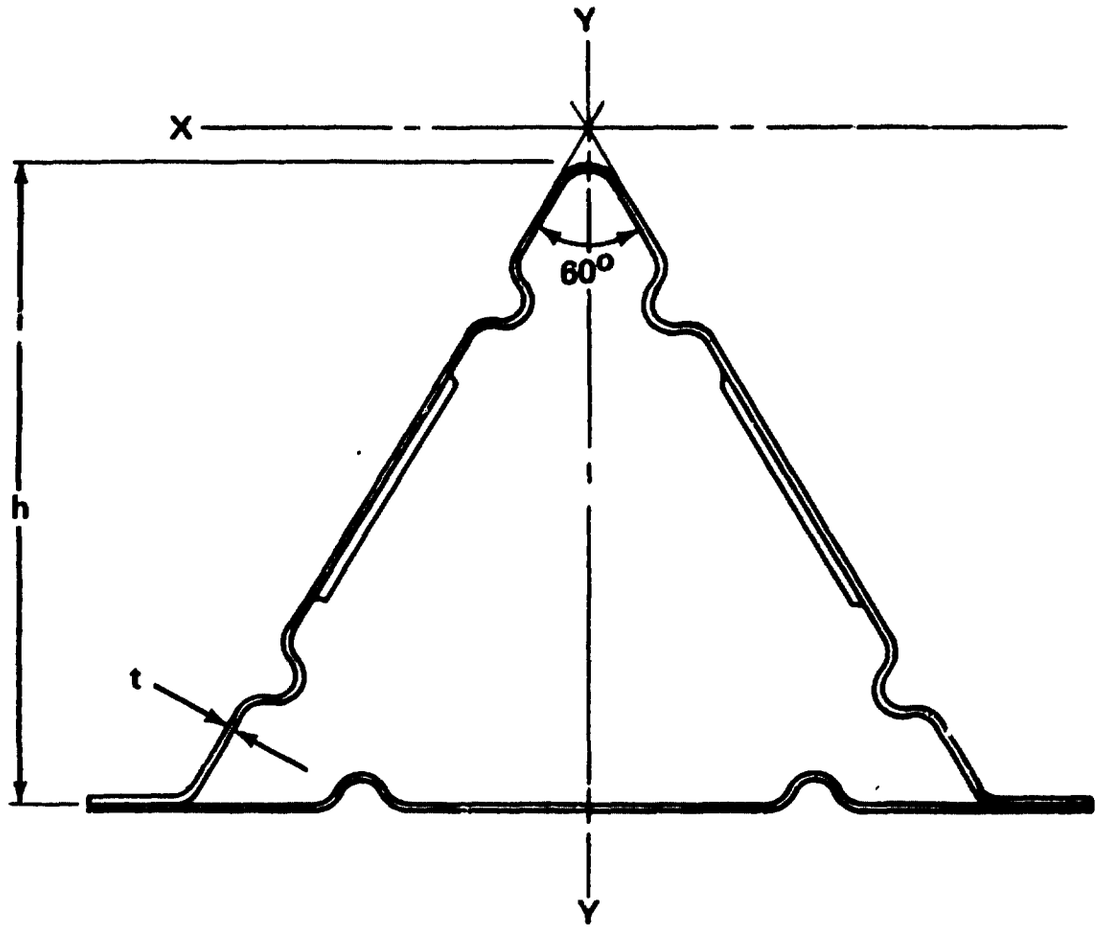


7.5 m CROSS-SECTION

BEAM CAP SECTION ROLL-FORMED ALUMINUM ALLOY



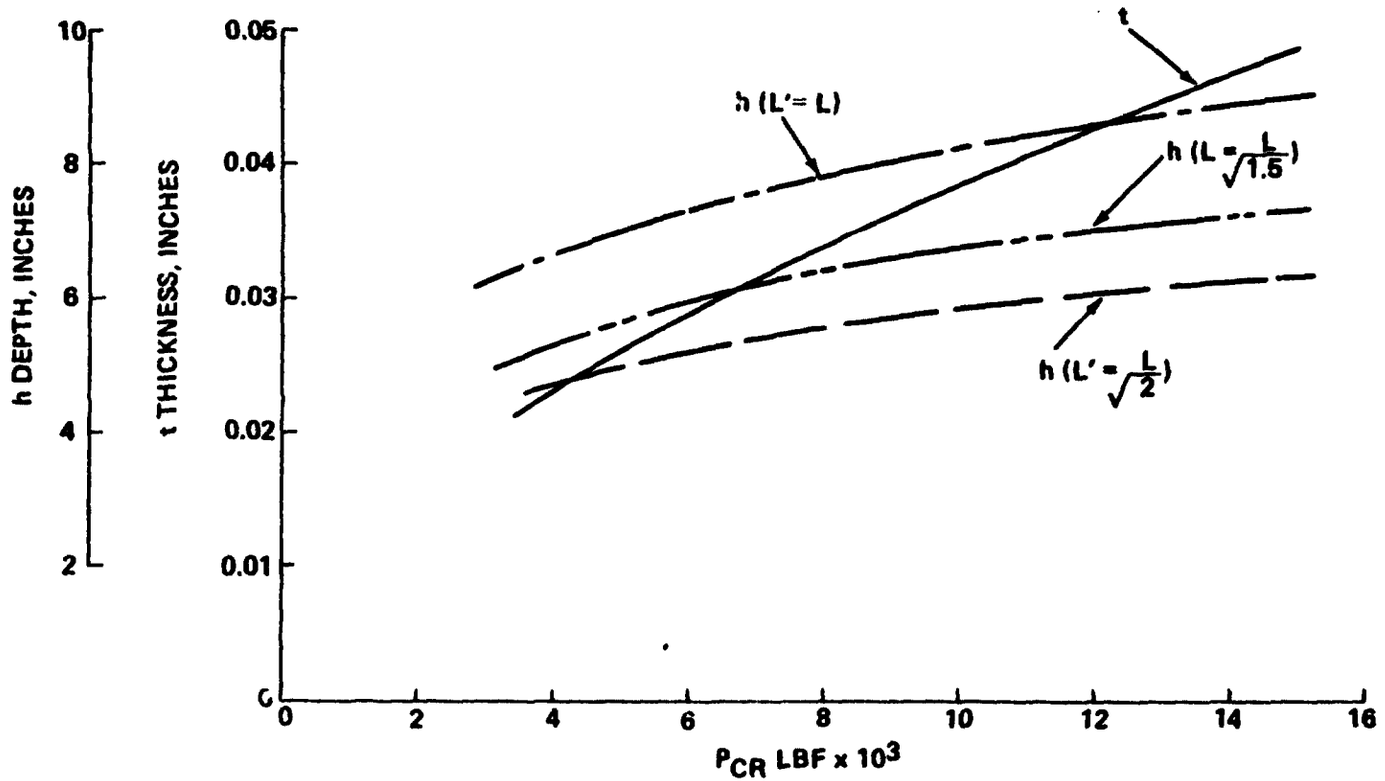
BATTEN SECTION ROLL-FORMED



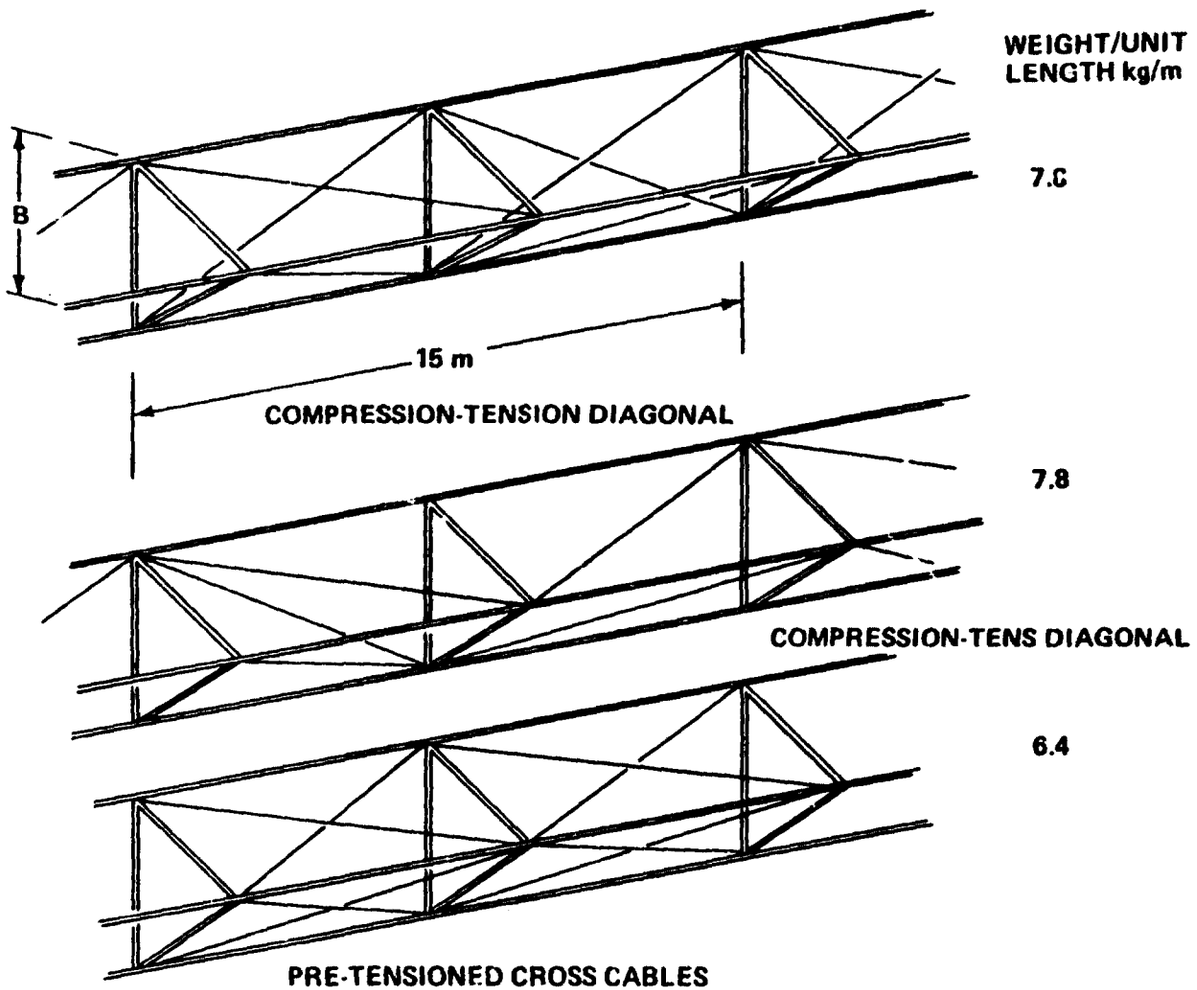
CANDIDATE MATERIAL PROPERTY DATA

	2024-T3	2219-T6	6061-T6
• F_{TU} ksi	64	54	42
• F_{TY} ksi	47	36	36
• F_{CY} ksi	39	38	35
• E_C ksi	10.7×10^3	10.8×10^3	10.1×10^3
• ρ LB/IN.^{3}	0.100	0.102	0.098
• α IN./IN./°F $\times 10^{-6}$ @ 200°F	12.9	12.4	13
• K BTU/(HR) (FT^2) (°F)/FT	80	74	96
• C BTU/(LB) (°F) @ 200 °F	0.22	0.23	0.23

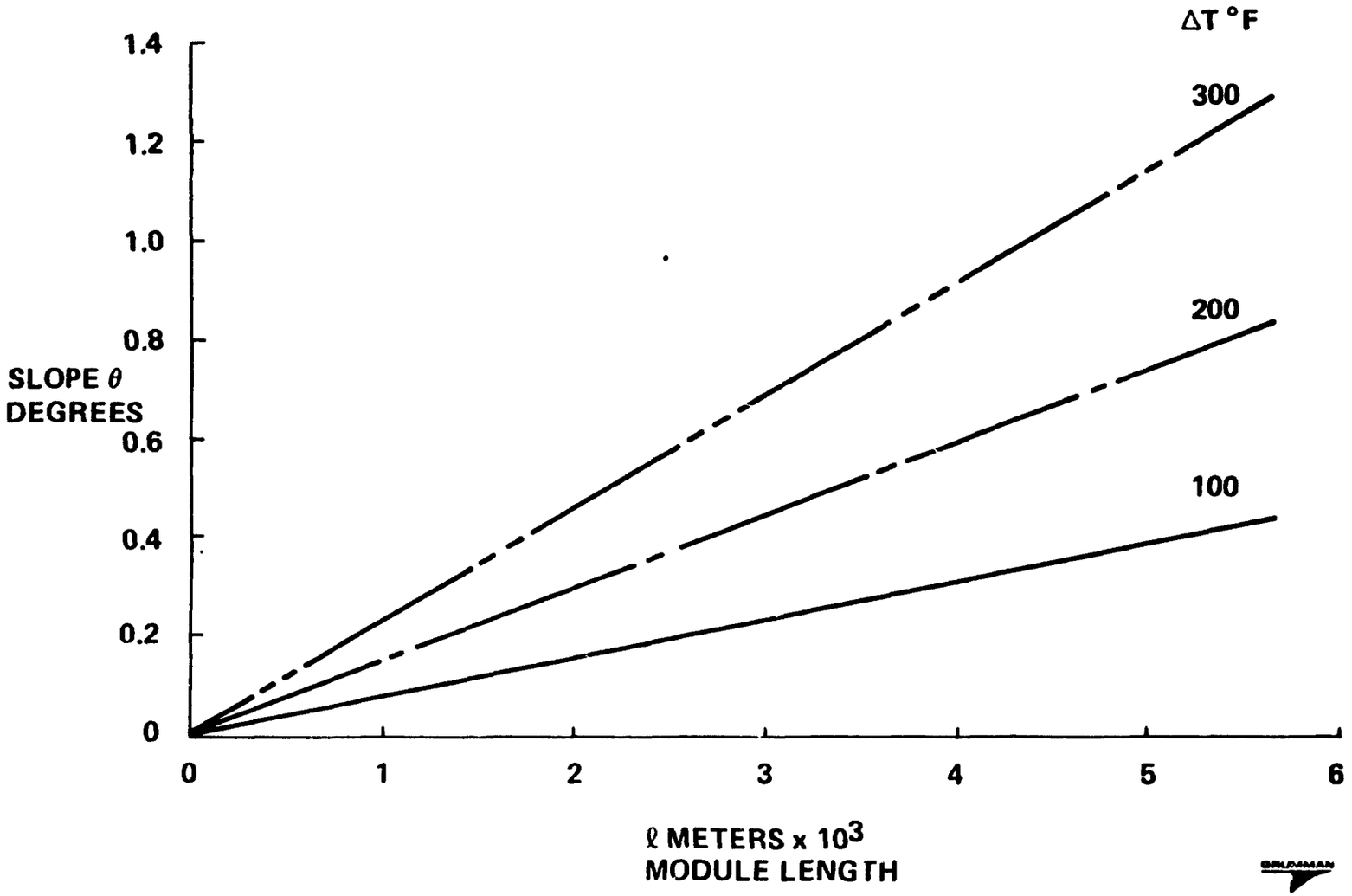
ALUMINUM CLOSED SECTION BEAM CAP THICKNESS & DEPTH VS CRITICAL LOAD; L = 7.5 m



CANDIDATE TRUSS CONFIGURATIONS



PRELIMINARY ESTIMATE OF MODULE SLOPES FOR VARIOUS THERMAL GRADIENTS



ESTIMATED DEFLECTION DUE TO THERMAL GRADIENT

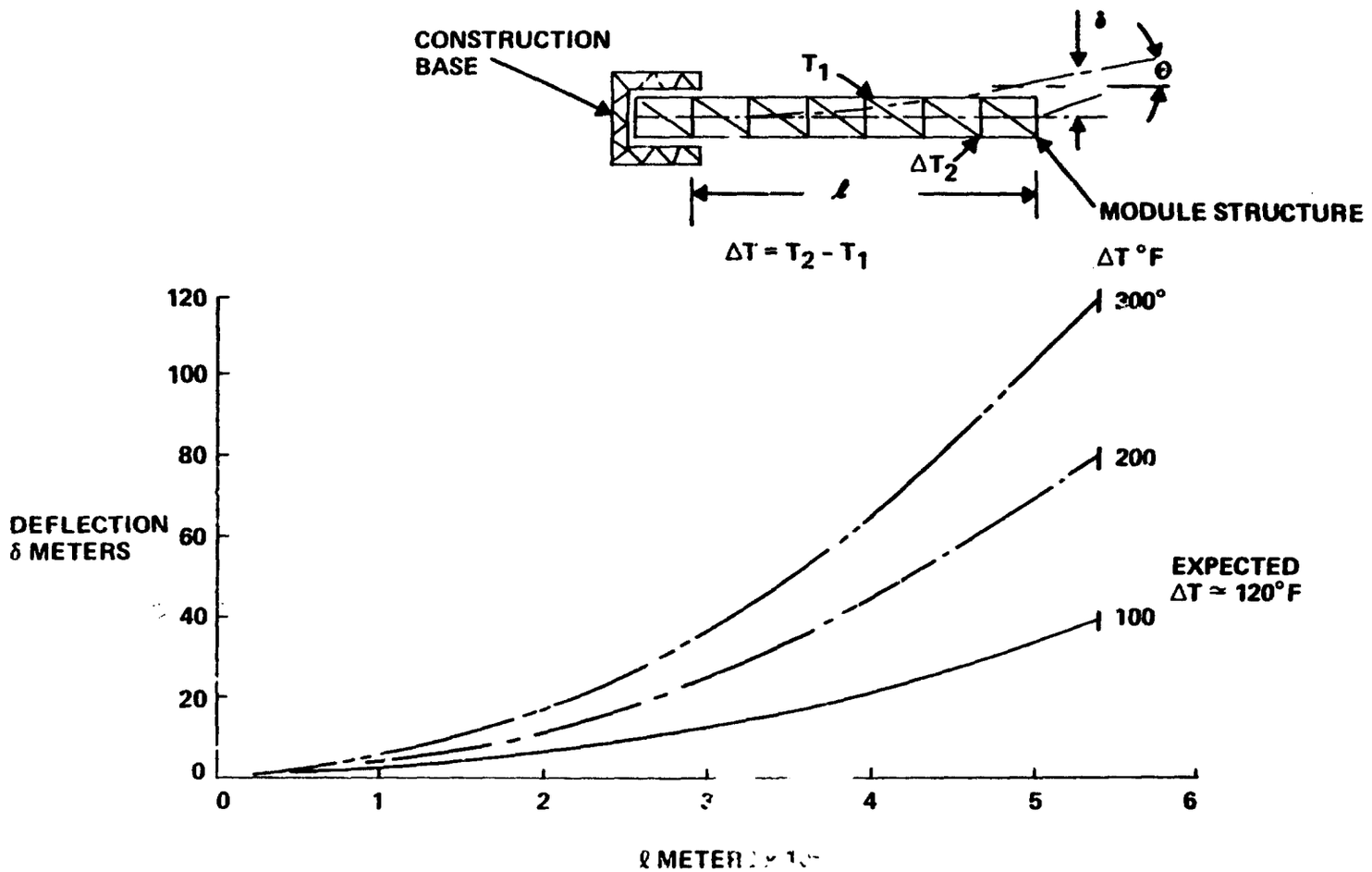
An estimate of the solar array module slopes and deflections was calculated for various temperature gradients. The analysis was based on the following assumptions:

- The module structure was cantilevered from the construction base.
- The temperature gradient between upper and lower surface did not vary spanwise.

The results show that for a temperature difference between upper and lower members of 200°F the tip deflection relative to the base is 8 meters; the slope is 0.8 degrees.

Updated thermal data will be used to reevaluate these estimates.

PRELIMINARY ESTIMATE OF MODULE DEFLECTIONS FOR VARIOUS THERMAL GRADIENTS



ORBITAL ATTITUDE DURING CONSTRUCTION

Thermal analysis of the construction phase is being performed to yield the structural temperature distribution necessary to perfo . the distortion/stress analysis. Both horizontal and vertical beam orientations will be investigated for the first part of this study, to minimize thermal grandients, the horizontal beams were oriented so that the axes of the elements were aligned with the sun's rays so that the sun entering the holes in the two sun-facing surfaces impinged on the third (back) at 0° orbit angle (see sketch). At the back side of the orbit (before entering the earth's shadow) solar energy enters the holes in the back surface to impinge on the other two.

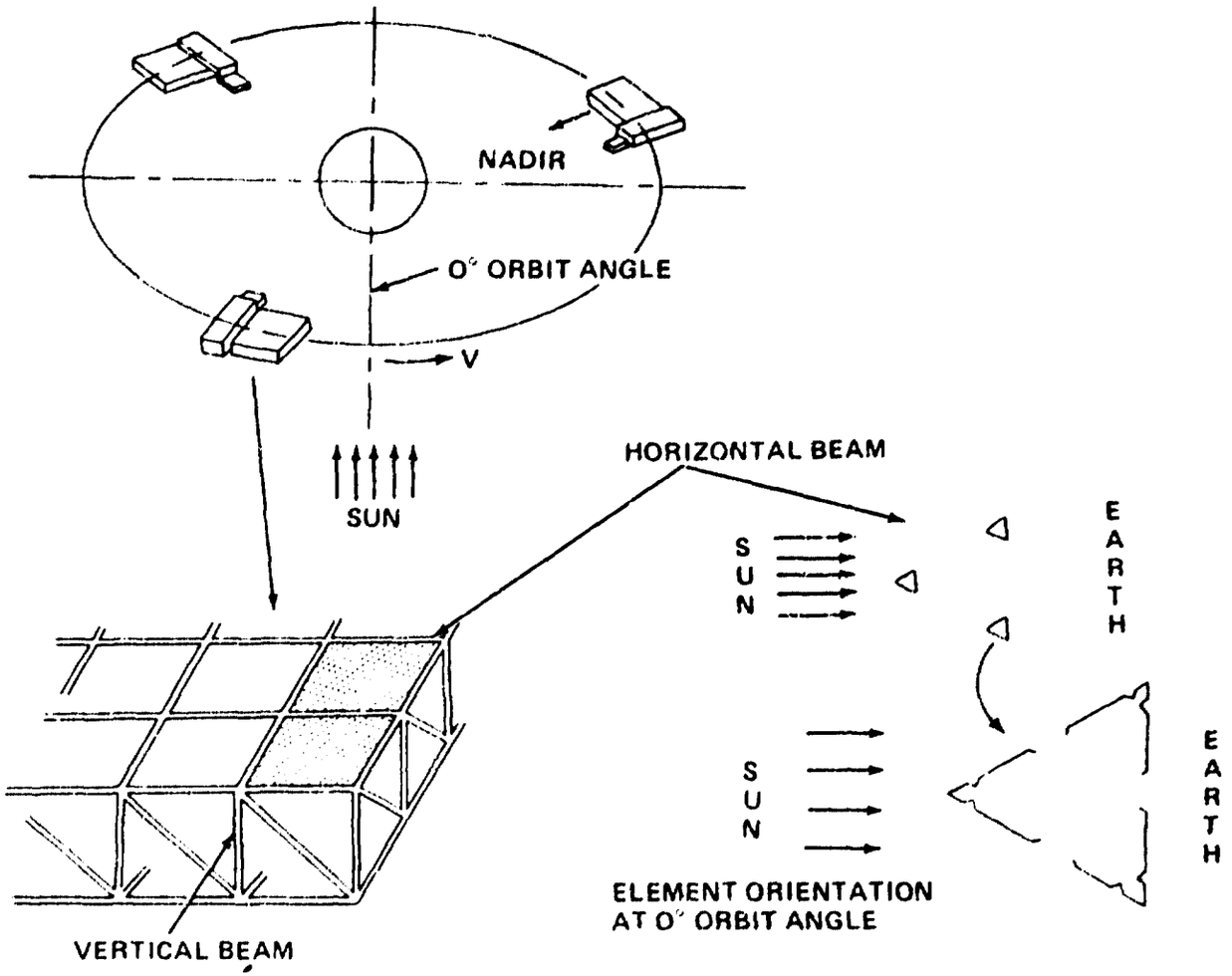
Other arrangements to be considered are the severe cases where the sun is normal to one of the surfaces at 0° orbit angle and where one element shadows another. The vertical beams where intermittent shadowing takes place, is also to be investigated.

For the construction phase, a 300 n. Mi circular orbit is considered.

In GEO-synchronous orbit, the gradients between the sun-side horizontal beams, and those opposite will be calculated.

For this study, the inside of the elements are coated with black anodize (ϵ = .83, α = .86) and the outside surface with Z-93 white paint (ϵ =.90, α =.17).

ORBITAL ATTITUDE DURING CONSTRUCTION



ALUMINUM STRUCTURE STUDY

REMAINING TASKS:

- COMPLETE THERMAL ANALYSES FOR SELECTED ORIENTATION
- EVALUATE STRUCTURAL RESPONSE TO TEMPERATURE EXPOSURE
- COMPARISON WITH COMPOSITE DESIGN

GENERAL ELECTRIC

space division

RECTENNA CONSTRUCTION

GROUND POWER STATION

General Electric is analyzing the rectenna microwave phase control, ground power distribution and utility interfaces from the standpoint of a major ground electrical power generation station.

A design update of the rectenna is being made using the baseline dipole as a receiver. These dipoles are interconnected forming modular panels. Electrical and mechanical interconnections will tie these modules together.

A computerized program for construction and costing analyzes the optimum cost versus construction methodology, labor, materials, maintenance, etc.

The microwave phase control scheme is being implemented into the ground power receiving station; this is being worked in conjunction with the space antenna phase control system layout.

The baseline ground power distribution developed in the last phase of the SPS study is being updated and integrated into the utility interfaces.

The end product of this study will be an end to end ground power generation station definition, construction methodology and cost.

GENERAL ELECTRIC

GROUND POWER STATION

space division

RECTENNA

- DESIGN UPDATE
  - RF
  - ELECTRICAL
  - MECHANICAL
- CONSTRUCTION METHODOLOGY
- COST
  - TYPE (LAND, LABOR, MATERIAL, MACHINES, ETC)
  - PHASE (SITE PREPARATION, CONSTRUCTION, OPERATION, MAINTENANCE)
  - SENSITIVITIES (MAINTAINABILITY, ALTERNATE USE OF LAND, ETC)

OTHER

- MICROWAVE PHASE CONTROL (SPACECRAFT – GROUND STATION)
- GROUND POWER DISTRIBUTION
- UTILITY INTERFACES

AN END TO END GROUND POWER GENERATION STATION IS BEING ANALYZED

RECTENNA CONSTRUCTION STUDY FLOW

This chart shows how we are conducting the rectenna construction task. The critique of the rectenna baseline design has been completed. A substantial effort has been expended in searching out advanced concepts for design and construction methodology. The task is not complete, because we will remain receptive to new ideas, but no significant further effort is planned in this area. The definition of design requirements is complete and reported here except if we find that some of our requirements are too costly.

The major trade-studies have been identified, and preliminary work has been accomplished on some of them. Considerable effort has gone into examing design alternatives, and the major ones have been identified. Similarly, research on construction methods has turned up so many possibilities that it will be difficult to study them all within the remaining scope of our effort.

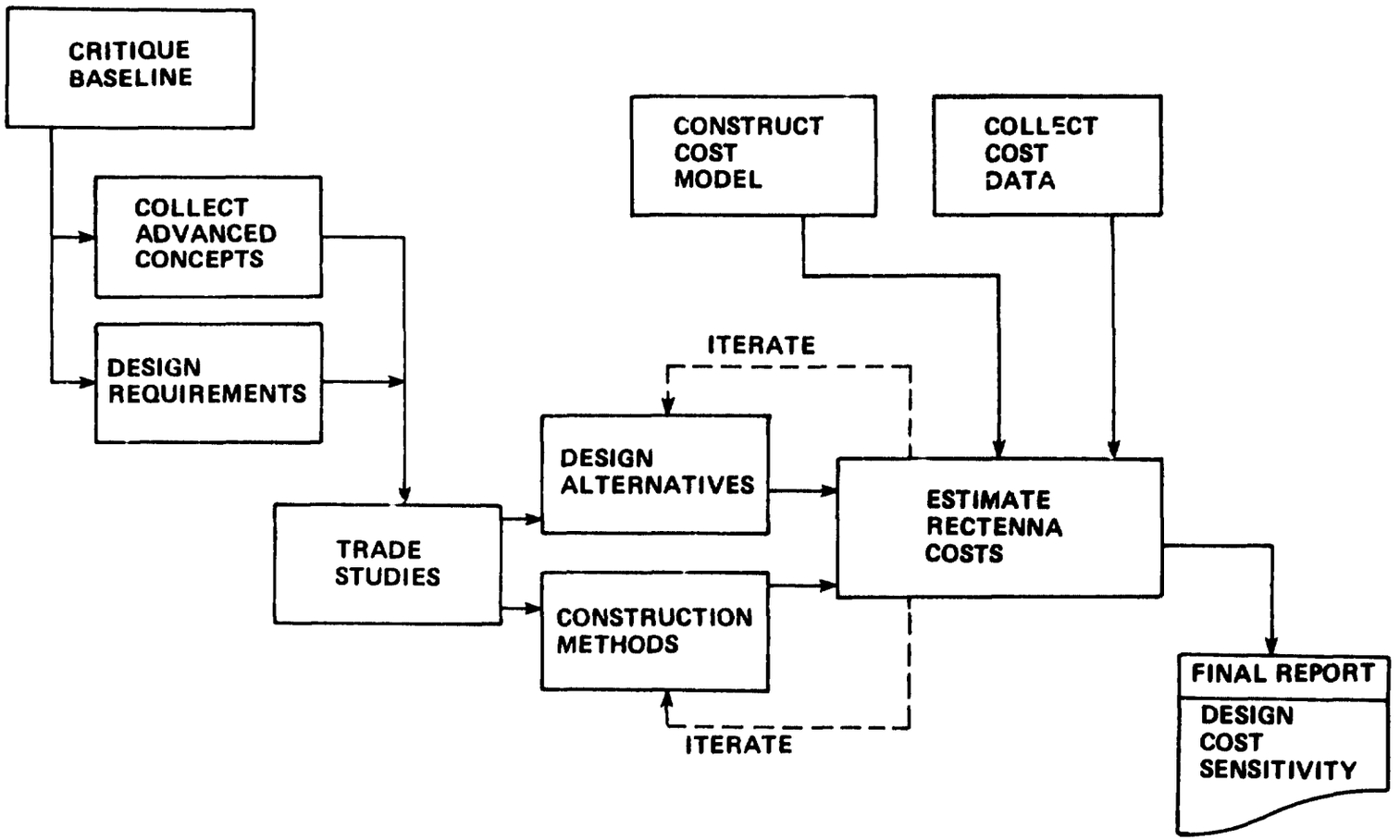
The cost model has been exercised on the computer with example data. Work is just starting on collecting all of the necessary cost data.

The major remaining work is structural analysis to size rectenna elements, complete the cost data collection, and then repeated passes through the cost model to seek the optimum mix of men, machines, and material to provide a minimum cost solution.

GENERAL ELECTRIC

RECTENNA CONSTRUCTION STUDY FLOW

space division



RECTENNA RF BASELINE

The facing illustrations are taken from the Raytheon Company "Rectenna Technology Study", Report PT-155 of March 10, 1978. This is a design concept for a "two plane" rectenna; a "fore-plane" and the ground plane. The fore-plane contains the receiving dipoles, RF matching networks, Shottky diodes, filter, and power bus. All of these elements, except the dipole, are contained within a metal shield to avoid spurious re-radiation of microwave energy. The same shield becomes the longitudinal structural member.

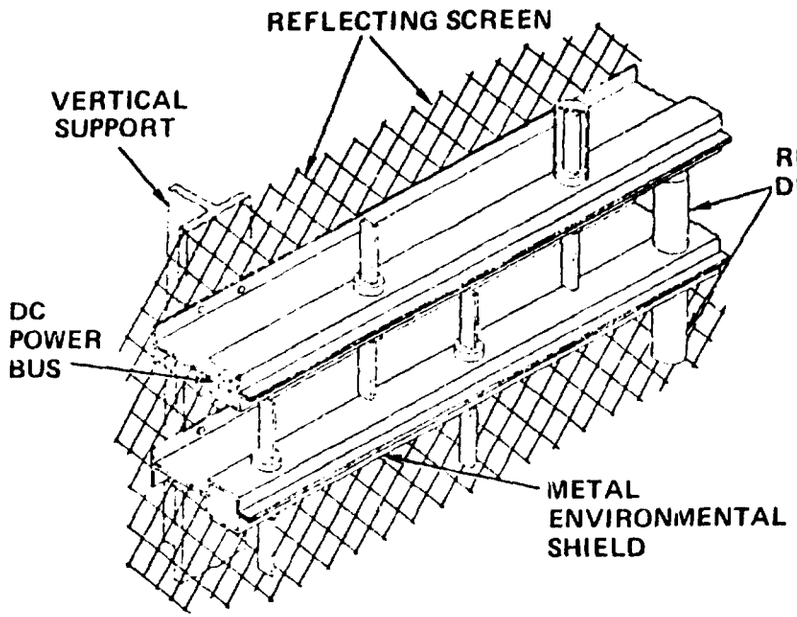
These fore-plane elements are mounted to a wire mesh ground plane and a "vertical support", which is actually 45 degrees from horizontal, as shown on the right. This rectenna panel is two meters wide, and columns driven into the ground two meters apart support these panels.

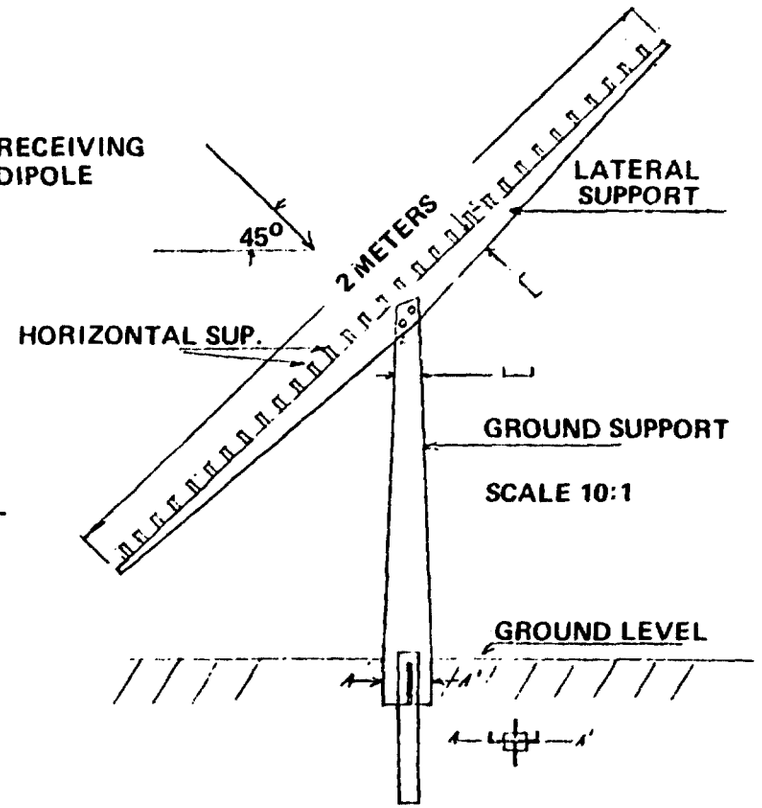
A wind load of 7.5 pounds-force per square foot (359 Pa) was selected for design. This would be inadequate in many areas of the country. The two meter width, at 45 degree elevation means that the distance between rows of rectennas (on a horizontal field) is only 1.414 meters; too small for conventional service vehicles that may be needed for rectenna maintainance. At lower latitudes, the reduced elevation angles would narrow this width substantially.

GENERAL ELECTRIC

RECTENNA RF BASELINE

space division





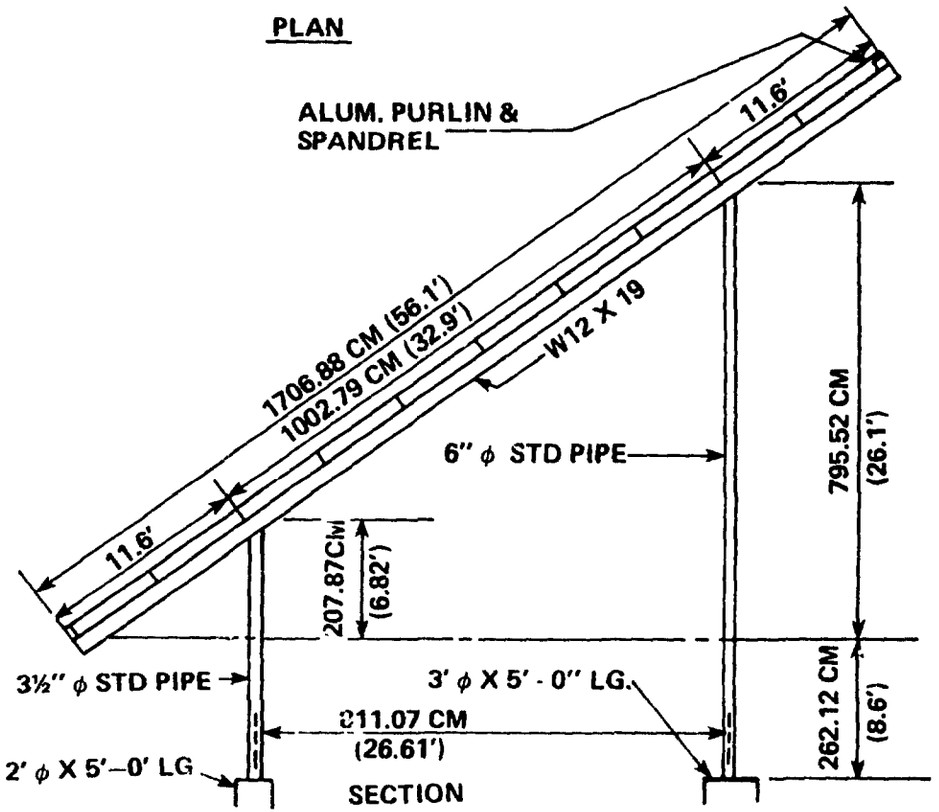
RECTENNA STRUCTURAL BASELINE

The facing illustrations were taken from the study report (May 27, 1977) on rectenna construction by Bovay Engineers, Inc. under NASA contract NAS 9-15280. It represents standard structural design and building techniques. For this typical design some 8 1/2 million ground plane panels have to be manufactured and installed, and nearly a million footings and columns are needed to support the rectenna. All of this work was evidently cost estimated without any consideration of automating these very repetitive tasks.

GENERAL ELECTRIC

RECTENNA STRUCTURAL BASELINE

space division



COST ESTIMATE

QUANTITIES FOR 1–96 FT. MODULE

1422 LBS. ALUMINUM SHAPES @ 1.50	$ 2,133
7584 LBS. LIGHTGAGE STEEL @ .36	2,730
6185 LBS. STRUCTURAL STEEL @ .42	2,598
2 ea. INSULATOR MOUNTS @ 5.00	10
1 ea. SLIDING MOUNT @ 8.00	8
3 ea. 2' ϕ x 4' LG. FTG. @ 40.00	120
3 ea. 3' ϕ X 7' LG. FTG. @ 150.00	450
1 ea. JUMPER CABLE @ 30.00	30
5385.6 SQ. FT. GROUNDPLANE @ .60	3,231
	$11,310
5% CONT.	566
	$11,876
10% PROFIT	1,188
	$13,064

TOTAL NUMBER OF 96' LONG MODULES REQUIRED PER RECTENNA. IS 156,960.

DESIGN REQUIREMENTS

The first listed design requirement is the central focus of our study plan. A cost model, covering all phases of rectenna construction and operation is at the heart of our methodology. We will input various designs, site characteristics, and automation techniques into the cost model and get total life cycle costs. The lowest cost over the rectenna life is best.

Our ground rule for site terrain is that we should be able to build a rectenna anywhere that heavy, off road machinery - typified as a bulldozer - can operate.

We have specified that the rectenna ground plane be (approximately) normal to the incident microwave beam to maximize the power collected and, perhaps even more importantly, to reduce the reflected/re-radiated radiation which becomes an RFI source.

It is our intent that any special purpose automation equipment be generally useful at any site, even though the design environments may dictate different material thickness or panel sizes, varying support column heights and spacing, and so on. A possible exception may be the "foundation machine". It may prove to be cheaper to use special purpose machines tailored to various soil classifications (e.g., rocky vs. sandy) to install foundations. This will be evaluated using the cost model.

GENERAL ELECTRIC

DESIGN REQUIREMENTS

space division

- DESIGN TO MINIMUM LIFE CYCLE COST
- WITHSTAND DESIGN ENVIRONMENTS
- BUILD ANYWHERE A BULLDOZER CAN GO
- MAINTAINANCE ACCESS MUST BE PROVIDED
- GROUND PLANE IS NORMAL TO INCIDENT BEAM
- INCLUDE AMORTIZATION OF MACHINERY

GUIDELINES

- EVALUATE AUTOMATED CONSTRUCTION METHODS
- BASIC APPROACH TO BE SITE INDEPENDENT

MAJOR STUDY ASSUMPTIONS

One important assumption is that we will be building enough rectennas, over a period of years, that specialized construction equipment can be amortized over its full useful life. Costs will be expressed in 1977 dollars because the average cost of aluminum, steel, Portland cement, etc. for all of 1977 is the latest data available.

It is assumed that protective clothing, containing wire mesh to screen out most microwave radiation, can be devised and that this will permit people to work on maintainance tasks from above the rectenna, if necessary, or to work below panels removed for servicing. Such clothing would have to include a helmet and face mask for protection to be adequate.

There appears to be no rational alternative to building the rectenna in modular elements. The size of the module will be selected in the rest of the study.

In order to compare rectenna designs on the basis of usability of the land under the rectenna, the income from such land use will be treated as a negative cost and used to offset operating and maintainance expense. Also, if the land is forested, the timber will be harvested at a profit, and used to offset site preparation costs.

GENERAL ELECTRIC

MAJOR STUDY ASSUMPTIONS

space division

- GROUND PLANE NORMAL TO INCIDENT BEAM
- CONSTRUCTION EQUIPMENT AMORTIZED OVER USEFUL LIFE
- COSTS EXPRESSED IN 1977 DOLLARS
- RECTENNA TO BE BUILT WHERE EVER OFF–ROAD EQUIPMENT CAN GO (ON LAND)
- MAINTENANCE MAY BE DONE FROM ABOVE BY PEOPLE IN PROTECTIVE CLOTHING
- RECTENNA WILL BE BUILT ON MODULES
- MINIMUM DISTURBANCE OF ENVIRONMENT IS A GOAL
- LAND USE UNDER RECTENNA IS A NEGATIVE COST

DESIGN CRITERIA

The first item here is somewhat in question. The added cost of designing to withstand extreme weather conditions may be more than would be required if some failures are accepted and repaired. We intend to cost model both options to see which is cheaper.

The second criteria is an attempt to avoid a worst-worst case situation which could be very costly in structure. It is also a recognition that massive ice accumulations are brittle; if a high wind begins to flex a structure the ice can break and be blown away.

The basic structure of the rectenna should be made of materials which weather so well that virtually no maintainance, such as painting, will be required. Space between rows will be adequate that vehicular access for maintainance purposes will be possible.

If a major investment in automation equipment is made, it will likely be economically important to provide all weather capabilities for the construction phase. Again, the cost model output will permit evaluation of the importance of this concept.

GENERAL ELECTRIC

DESIGN CRITERIA

space division

- DESIGN SHALL WITHSTAND 100–YEAR WIND/ICE LOADS
- MAXIMUM WIND AND MAXIMUM ICE NEED NOT BE COMBINED IF STRUCTURE IS FLEXIBLE
- BASIC STRUCTURE MUST BE MAINTENANCE FREE
- AUTOMATED CONSTRUCTION SHALL BE CONSIDERED
- ALL–WEATHER CONSTRUCTION SHALL BE EVALUATED

RECTENNA HAZARDS

Most of the points on this chart are fairly self evident, but a few points can stand clarification. Many dipole elements will be at a high electrical potential relative to the ground plan. Hence, insulation on these dipoles needs to be resistant to gnawing by the sharp teeth of small rodents.

For some penalty in construction costs, rectennas could make good use of flood plain areas. The rectenna panels would need to be placed high enough to avoid the flood waters, and barriers would have to be placed upstream of the rectenna so that large debris would not drift into the rectenna supports and knock them down.

The problem of fire in underbrush beneath the antenna is likely solved by a combination of a) and b), done as routine maintainance. A sprinkler system built into the rectenna would be a substantial added cost.

GENERAL ELECTRIC

RECTENNA HAZARDS

space division

HAZARD	DESIGN APPROACH
WIND/ICE/SNOW HAIL HURRICANE EARTHQUAKE SMALL ANIMALS	DESIGN TO WITHSTAND
TORNADO FALLING AIRCRAFT	DESIGN FOR QUICK REPAIR
FLOOD	A) AVOID FLOOD PLAINS B) BUILD HIGH, USE HOUSE STRAINER
FIRE IN UNDERBRUSH	A) ROUTINE REMOVAL OF UNDERBRUSH B) IRRIGATE C) SPRINKLER
LARGE ANIMALS	A) EXCLUDE

RECTENNA SITE PLAN

To introduce as much realism into our rectenna costing program as possible, we plan to work with three potential sites; one from each of the co-operating power pools. Topographic maps of possible sites will be "sanitized" for our purposes; i.e. longitude data will be removed, latitude will be changed to a nearly major parallel, place names will be removed, and populated places removed, etc. Then, these sites can be used to estimate the road mileage needed on-site, the number and size of bridges required, the soil and weather data will be "real", etc.

Some of the trades involving site considerations are access road construction vs. more off-road transporters; winter-time construction effects; and transportation costs.

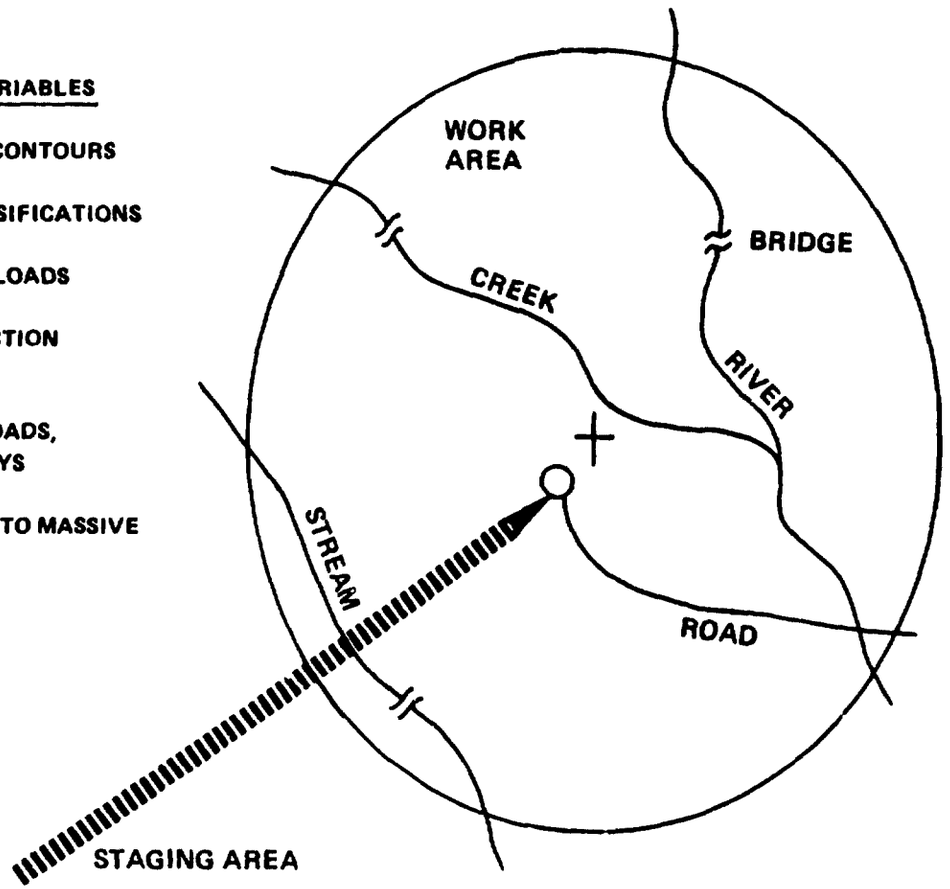
GENERAL ELECTRIC

RECTENNA SITE PLAN

space division

MAJOR SITE VARIABLES

- TERRAIN CONTOURS
- SOIL CLASSIFICATIONS
- WIND/ICE LOADS
- CONSTRUCTION WEATHER
- ACCESS ROADS, WATERWAYS
- DISTANCE TO MASSIVE SUPPLIES



RECTENNA CONSTRUCTION FUNCTIONAL FLOW

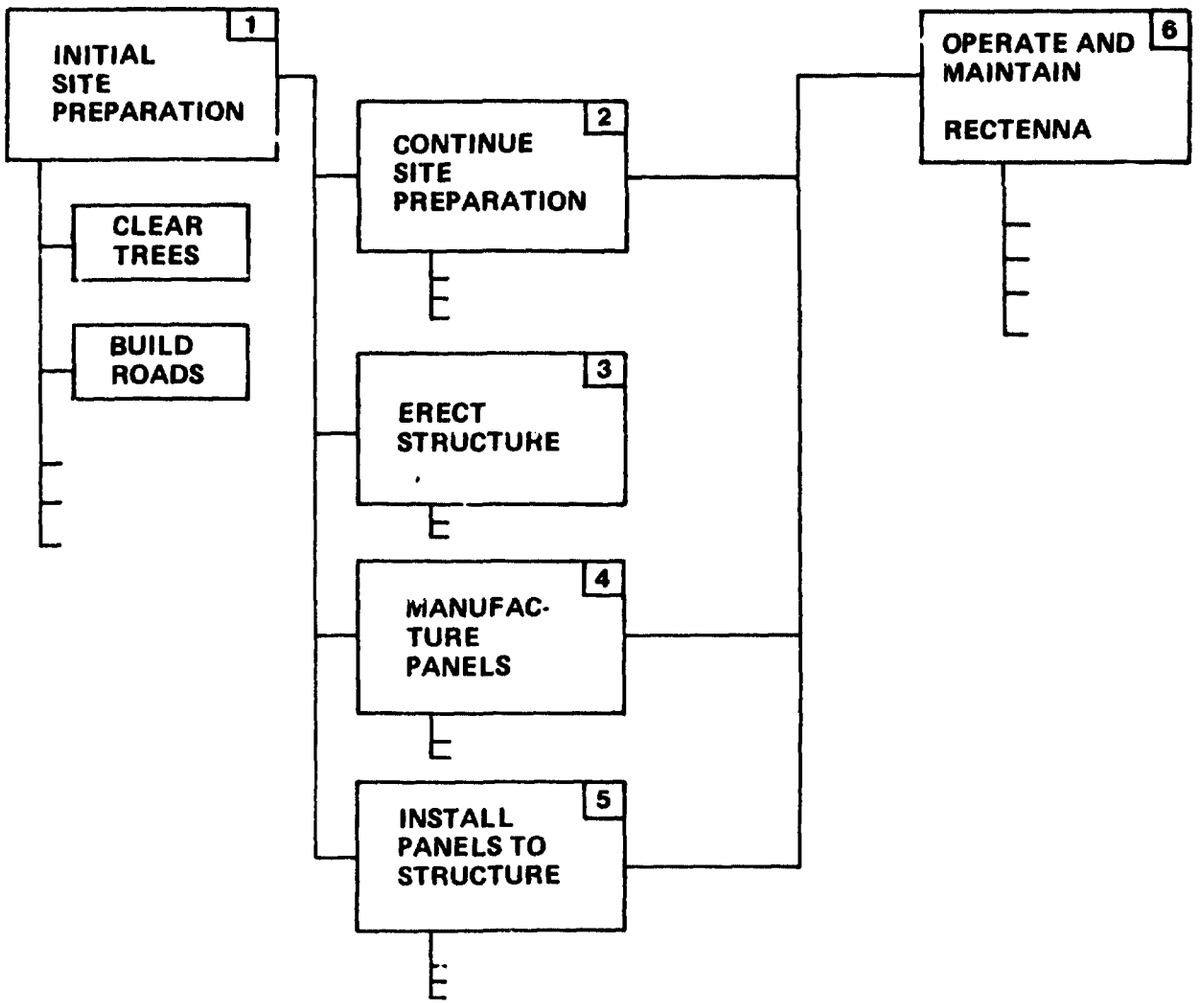
The total rectenna construction (and operation) has been sub-divided into six major tasks as shown here. Each task is sub-divided into a number of jobs. Each job involves people and machines, and is basically either making something, moving something, or installing something. A "machine" can be anything from a screwdriver to a moving rectenna factory. Each machine may have several operators, or a fractional operator - i.e. one person supervising the work of several machines. For "making" jobs, the type and quantities of input raw materials is specified so that material and transportation costs can be calculated.

A few tasks, such as cutting timber, may be "un-manufacturing" jobs and involve negative costs.

GENERAL ELECTRIC

RECTENNA CONSTRUCTION FUNCTIONAL FLOW

space division



RECTENNA CONSTRUCTION COST MODEL

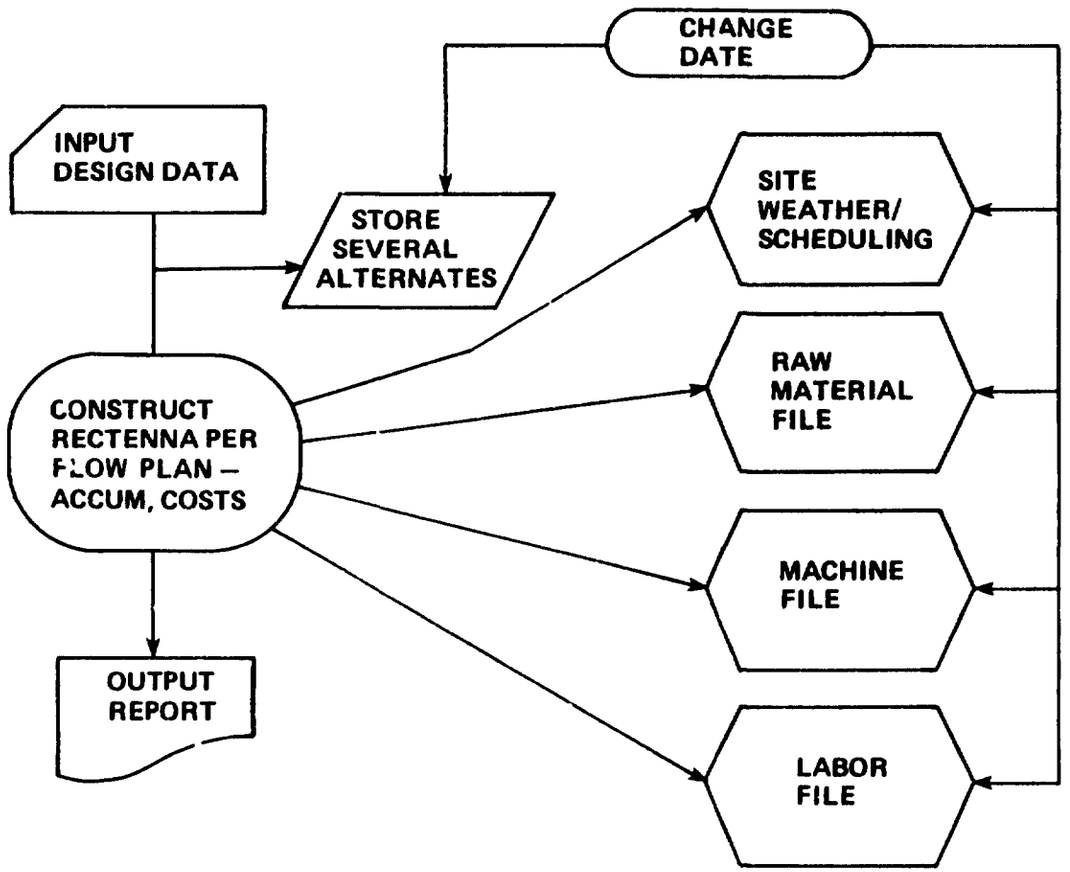
Our rectenna cost model is like the rectenna, simple but large. Although it is implemented on a computer, it does nothing that could not be accomplished with a four function calculator and a very large sheet of paper. The thing that makes a computer essential is the volume of data involved. There may be as many as 2400 input words, and 12000 cost accumulation bins, so that costs can be accumulated by job type, cost element and month. Summary data is printed out to show what the results are.

The input data is stored in disk storage, so that only a few parameters need to be entered from a terminal each run of the cost model. The costs are computed from the lowest elements; the quantity and price of commodities, such as steel, concrete or diodes; labor hours and rates; machine amortization and maintainance, etc.

GENERAL ELECTRIC

RECTENNA CONSTRUCTION COST MODEL

space division



COST MODEL RESULTS

Because the cost model has so many cost bins, choosing a summary output format is difficult. This chart shows our initial plan to display the results of the cost model, at the beginning is a summary of the schedule achieved, and costs by task and major subdivision. Following this is a display of all of the eleven kinds of costs segregated to the sub-task (job) level. Finally, a report of costs by task by month is provided for anyone interested in a cash flow analysis. Task 6, Operation and Maintainance is provided for only a single period - the useful rectenna life, which is defined by input variables.

GENERAL ELECTRIC

COST MODEL RESULTS

space division

SCHEDULE SUMMARY

START FINISH

COST SUMMARY

	LABOR	EQUIP	MAT'L	TRANS	TOTAL
TASK 1					
2					
•					
•					
•					

COSTS BY TASK BY TYPE

TASK 1

MACHINES

NO.	CAPITAL COST	MAINT.	LABOR	FUEL

MATERIALS

QTY	CUST	TRANSP.

COSTS BY TASK BY MONTH

MONTH	TASK 1	2	3	4	5	6
JAN 1999						
FEB 1999						
•						
•						
•						

CONSTRUCTION ALTERNATIVES

The mass of concrete used in the Bovay baseline rectenna (which used steel superstructure) ranged from one to two million metric tons. The transportation costs to move such a mass are far from negligible. Obviously, the sand and gravel used would be taken from the site, or some nearby location. Even so, limestone and shale - the principle ingredients of Portland cement-are so common and widely dispersed that it may be economical to design a portable cement plant to be moved from one rectenna site to another. (Such a capacity addition is plainly not essential; 1974 cement production was about 500 times the amount needed for a rectenna, according to the 1977 US Statistical Abstract.) Because of the availability, and the low cost and low energy content of concrete, it is considered a prime candidate for support columns, which will increase its use.

The nature and extent of automation to be applied to rectenna construction is a major study topic. Clearly, the manufacture of RF elements must be highly automated, since eleven billion are required. (This is about 350 per second for a year.) A labor cost of two cents per element would be $220 M, so automation is essential.

For construction tasks, less repetition is involved, so intense automation may not be cost effective. To illustrate, consider a million footing excavations. If a man on a tractor with a earth auger spent ten minutes boring a hole, and was paid $12 per hour, the total labor cost for footing excavation would be only $2 M, a trifle in comparison with other cost elements.

Movement of heavy equipment around the construction site is expected to be a substantial cost item, and warrents study of cost optimum modes.

GENERAL ELECTRIC

CONSTRUCTION ALTERNATIVES

space division

CONCRETE MAKING
- MOVE CEMENT TO SITE
- PORTABLE CEMENT KILN
- AGREGATE PREPARATION

SUPPORT STRUCTURES
- COLUMNS
  - STEEL
  - CONCRETE
  - OTHER
- ARCHES

PANEL MANUFACTURE
- OFF SITE
- ON SITE, FIXED
- ON SITE, PORTABLE

AUTOMATION
- EXTENT
- FUNCTIONAL COMBINATIONS

MOVEMENT OF HEAVY EQUIPMENT
- HL HELICOPTER
- RIGID AIRSHIP
- GROUND EFFECT MACHINES
- ROADS
- PORTABLE BRIDGES
- RAILROAD

BASIC HOLE MAKING METHODS

As this facing chart suggests, there are numerous ways of setting a support column. The most generally accepted method is to dig a footing and set the column in concrete. This has the experience of centuries to demonstrate its longevity. The ways of making holes for this purpose range from the traditional to the exotic. One new technique of some interest is the work done at Los Alamos Laboratories on "penetrators", or "sub-terrenes, " which involves melting a hole into any kind of soil, leaving a glassy lining.

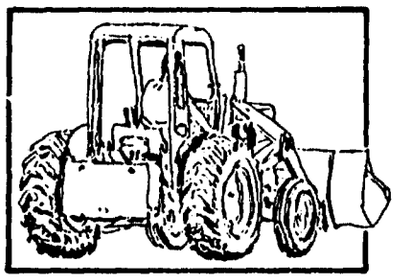
Alternate methods include driving the column into the earth, as in pile driver. Initially we will consider relatively convention hole making techniques. If costs are found to be a significant factor, we will invent an "earth punch" using a combination of conventional and exotic technology that can rapidly make a hole in any soil type encountered on any site.

GENERAL ELECTRIC

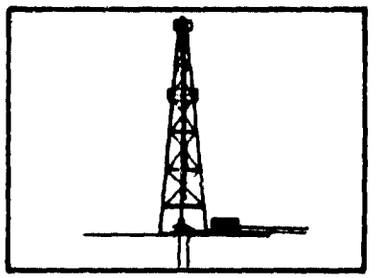
BASIC HOLE MAKING METHODS

space division

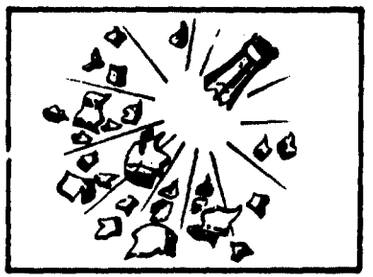
DIG



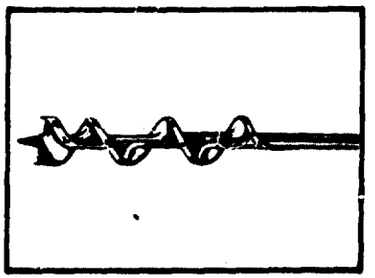
DRILL



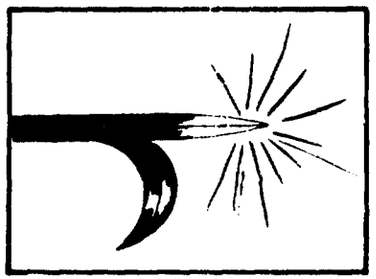
BLAST



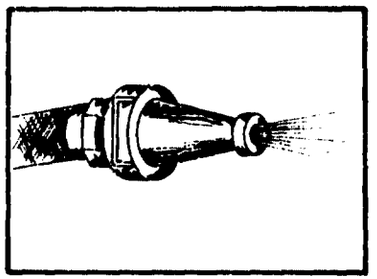
BORE



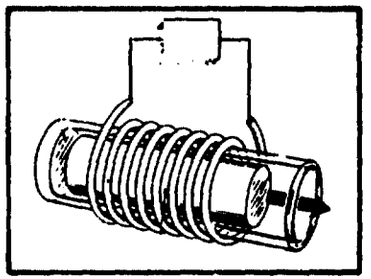
MELT



BLOW

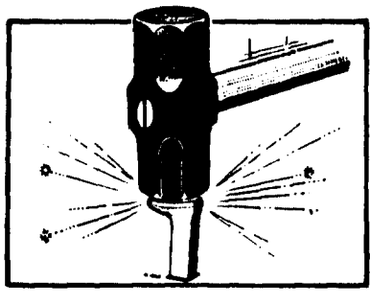


THERMAL SHOCK

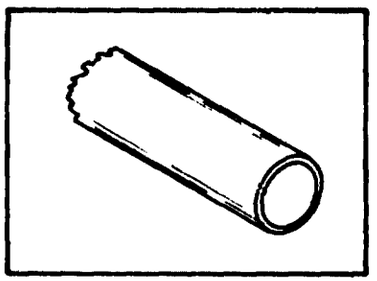


MECH. SHOCK

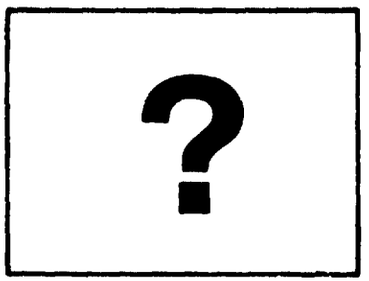
DRIVE



POST DRILL



EARTH PUNCH



ALTERNATE RECTENNA PANEL CONCEPTS

After much thought and discussion and conceptualizing, we have tentatively reduced the field of candidates for rectenna panel construction to the two shown here.

The "low drag" configuration on the left derives directly from the Raytheon baseline shown in an earlier chart. The RF shield/structure box has been made streamlined, and tilted down to face into the wind. The dipoles, now made of formed elliptical wire, are not normal to the bus bars but bent back to be normal to the incident microwave beam. The wire screen has been replaced by streamlined wires, since the beam in linearly polarized. Overall, this arrangement will present much lower drag forces to the wind, which may permit light construction and large panels. This design has one notable drawback. In gusty winds, airflow is not parallel to the ground, so these airfails will be at significant angles of attack and develop substantial lift. The ground plane wires and forward braces must be sized to withstand these loads.

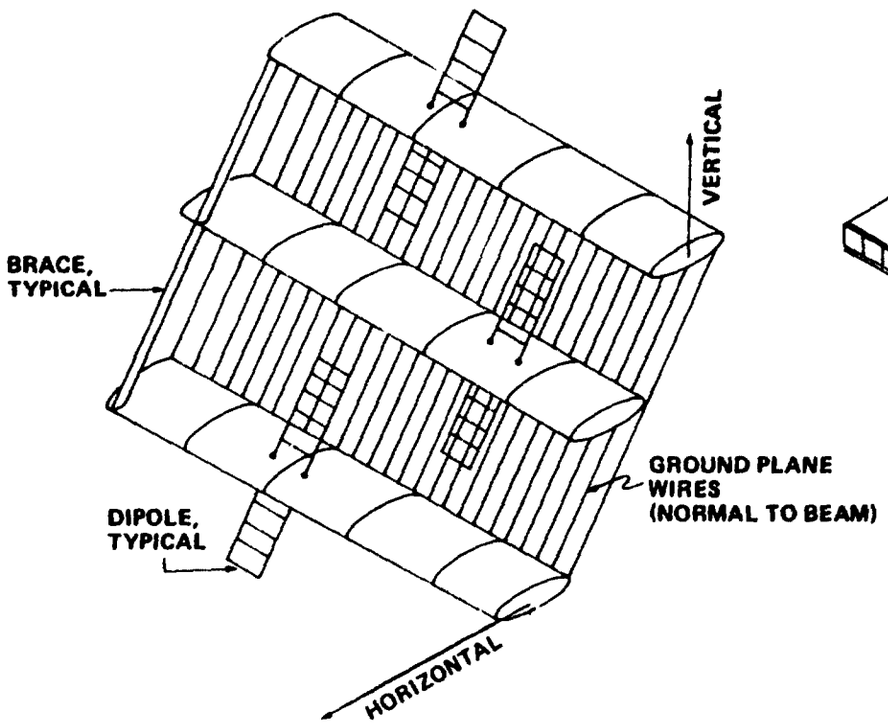
The panel on the left appears simple and cheap to make, and simple to analyze. It will see much larger wind loads, which translates into more substantial support structures. The cost trade-off between these two concepts is by no means obvious.

GENERAL ELECTRIC

RECTENNA PANEL ALTERNATIVES

space division

LOW DRAG



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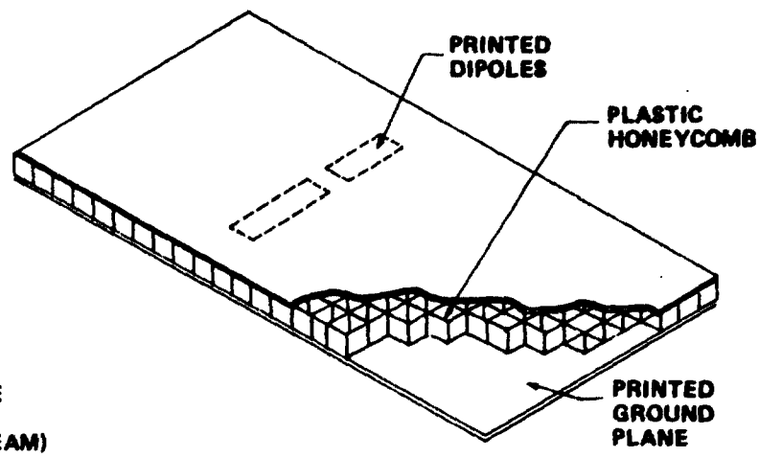

GENERAL ELECTRIC

space division

RECTENNA POWER CONDITIONING

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GROUND POWER COLLECTION AND TRANSMISSION SYSTEM

PHASE I SCOPE OF WORK FOR EUSED (GE)

BASED ON THE PRELIMINARY OPERATIONAL CHARACTERISTICS OF THE SPS POWER SYSTEM, AN ANALYSIS WILL BE PERFORMED ON THE INTEGRATION OF SPS POWER INTO ELECTRIC UTILITY POWER SYSTEMS. THE ANALYSIS WILL CONSIDER USING BOTH AC AND DC AT ALTERNATIVE VOLTAGE LEVELS FOR LONG DISTANCE POWER TRANSMISSION.

THE FAILURE CHARACTERISTICS FOR THE RECTENNA SYSTEM COMPONENTS BETWEEN THE 1 MW PRIMARY UNITS AND THE UTILITY GRID CONNECTION WILL BE DEVELOPED IN TERMS OF FAILURE RATES AND MEAN TIME TO REPAIR. THIS DATA WILL BE DEVELOPED BASED ON AVAILABLE UTILITY STATISTICAL DATA AND BY EXTRAPOLATION FROM AVAILABLE DATA WHEN APPROPRIATE. THE EXTRAPOLATION WILL BE BASED ON UTILITY POWER SYSTEM EQUIPMENT DESIGN AND OPERATING PRACTICES.

AFTER RESULTS COORDINATION WITH THE FAILURE DATA DEVELOPED FOR THE 1 MW PRIMARY UNITS, A PRELIMINARY STUDY WILL BE PERFORMED ON THE EFFECTS OF THE GROUND SYSTEMS FAILURE MAKES ON GROUND POWER OUTPUT.

MAINTENANCE REQUIREMENTS AND DATA FOR UNSCHEDULED MAINTENANCE REQUIREMENTS WILL BE PROVIDED AS INPUTS TO THE OVERALL FAILURE EFFECTS AND MAINTENANCE REQUIREMENTS PLANS.

GROUND POWER COLLECTION AND TRANSMISSION SYSTEM

PHASE I SCOPE OF WORK FOR EUSED (GE)

EUSED TASKS IN PHASE I

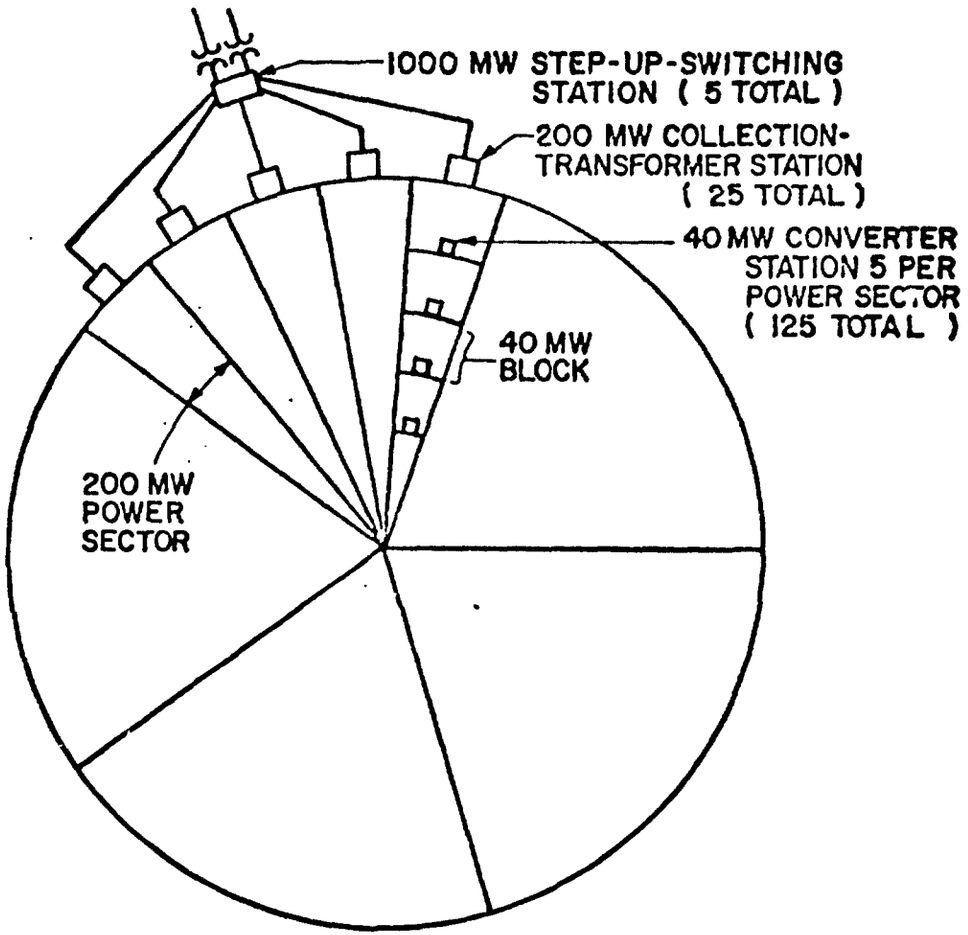
- INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM
- FAILURE CHARACTERISTICS OF SYSTEM ELEMENTS
- FAILURE MODES AND RATES OF THE POWER COLLECTION AND TRANSMISSION SYSTEM ABOVE 1 MW LEVEL
- RESULTS COORDINATION WITH SPACE DIVISION (GE) WORK ON THE 1 MW PRIMARY UNITS
- QUALITATIVE EFFECTS ASSESSMENT OF THE RECTENNA POWER COLLECTION AND TRANSMISSION SYSTEM FAILURE MODES ON GROUND POWER OUTPUT
- MAINTENANCE DATA FOR INPUTS TO MAINTENANCE PLAN
- UNSCHEDULED MAINTENANCE REQUIREMENTS DATA

GROUND POWER COLLECTION AND TRANSMISSION SYSTEM

GENERAL LAYOUT

THE PLOT PLAN IS ASSUMED TO BE CIRCULAR WITH A TOTAL NET OUTPUT OF 5000 MW. THE RECTENNA AREA IS DIVIDED INTO 5 EQUAL AREAS EACH FEEDING ONE 1000 MW STEP-UP-SWITCHING STATION. EACH STEP-UP-SWITCHING STATION IS IN TURN FED BY FIVE 200 MW POWER SECTORS. EACH POWER SECTOR CONTAINS FIVE 40 MW BLOCKS. EACH CONVERTER STATION COLLECTS 40 MW DC POWER FROM PRIMARY RECTENNA UNITS AND INVERTS DC TO AC POWER.

RECTENNA POWER COLLECTION AND TRANSMISSION SYSTEM



GROUND POWER COLLECTION AND CONVERSION SYSTEM

EACH 40 MW POWER BLOCK CONSISTS OF FORTY 1 MW PRIMARY UNITS WITH OUTPUT VOLTAGE OF ± 2 kV. THE END OF EACH PRIMARY UNIT IS CONNECTED THROUGH DC CIRCUIT BREAKERS TO 2 kV DC CABLES RUNNING RADIALLY AS SHOWN IN THE DIAGRAM TO THE CONVERTER STATION. DC SMOOTHING REACTORS REDUCE THE RIPPLE CURRENTS.

SINCE THE RECTENNAS ARE CONSTANT POWER DEVICES AND THE DC/AC CONVERTER CAN IN NO WAY AFFECT POWER FLOW, THE CONTROL OF POWER BE APPLIED ON THE DC SIDE. THIS MEANS THAT EITHER THE RF LEVEL MUST BE CONTROLLED AT ITS SOURCE OR THE NUMBER OF RECTENNAS CONNECTED IN PARALLEL MUST BE VARIED. CIRCUIT BREAKERS PROVIDED FOR RECTENNA PROTECTION CAN ALSO BE USED TO ADD OR REMOVE UNITS IN ORDER TO CONTROL POWER, BUT NOT ON A CONTINUOUS BASIS.

IT IS RECOGNIZED THAT THE SPS SYSTEM WILL OPERATE AT CONSTANT POWER BUT POWER VARIATION IS NEEDED TO GET ON LINE AND TO GET OFF LINE FOR SUCH THINGS AS MODIFICATION OR MAINTENANCE. IT MAY BE THAT THE 20 MW POWER GROUPS ARE SMALL ENOUGH THAT THEY CAN BE PICKED UP OR DROPPED AS THE MINIMUM SIZE INCREMENT.

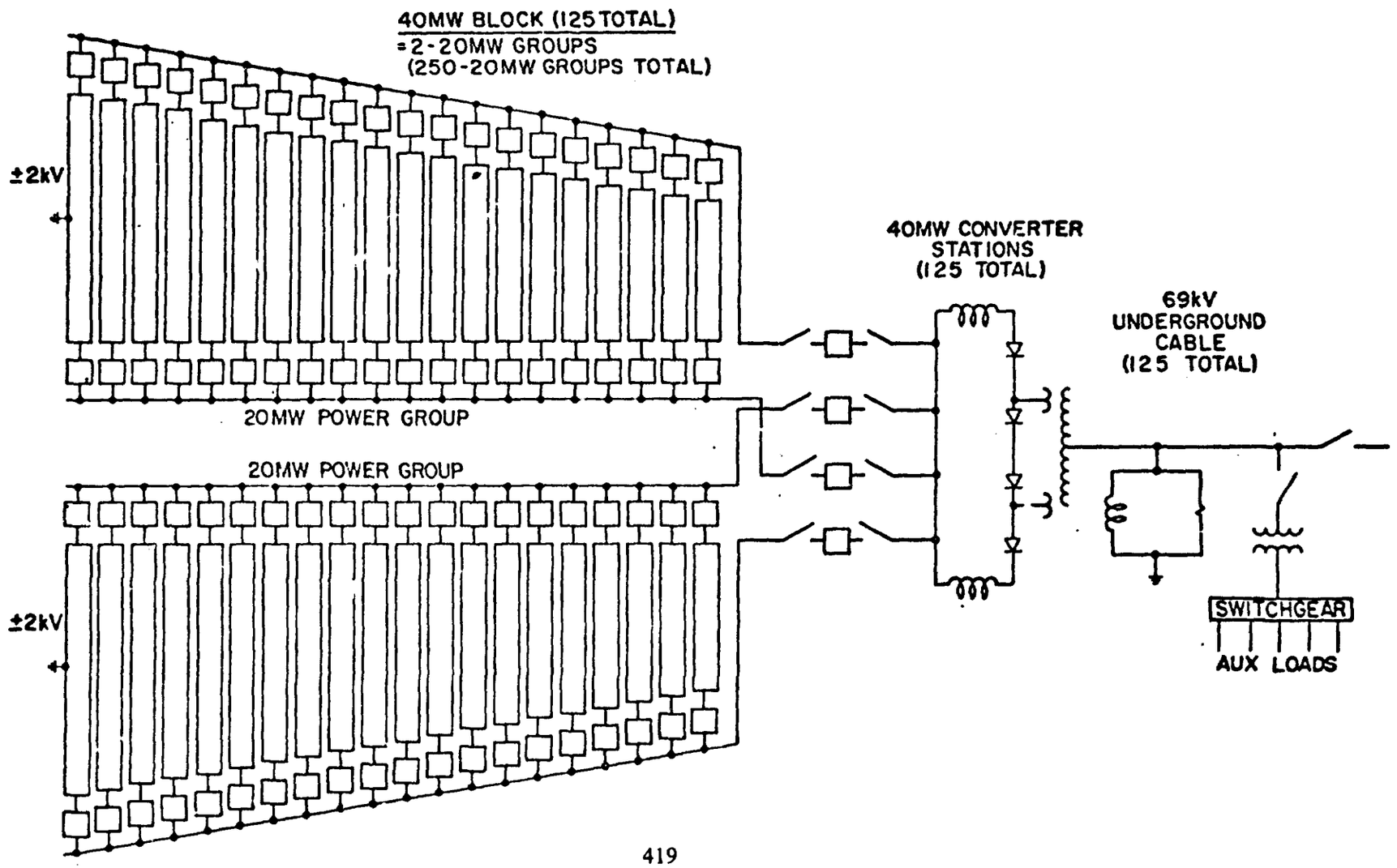
THE CONVERTER THYRISTOR BRIDGE CIRCUIT FEEDS ALTERNATING CURRENT TO THE CONVERTER TRANSFORMER WHICH STEPS THE VOLTAGE UP TO 69 kV AT 60 HZ.

FILTERS CONNECTED THE AC BUS ABSORB CURRENT HARMONICS GENERATED IN THE CONVERTER. THE AC WAVE SHAPE IS THEREBY KEPT WITHIN ACCEPTABLE HARMONIC CONTENT LIMITS FOR THE UTILITY GRID AND ASSOCIATED PLANT EQUIPMENT.

THE CONVERTER STATION OUTPUT, AT 69 kV AND A MAXIMUM CURRENT OF 400 AMPERES IS TRANSMITTED BY UNDERGROUND CABLE TO THE TRANSFORMER STATION.

THE CONVERTER STATION, ONCE COMMISSIONED, OPERATES AUTOMATICALLY. ALL SWITCHING, STARTUP AND SHUTDOWN ARE DIRECTED AND MONITORED BY A SMALL COMPUTER SYSTEM IN CONJUNCTION WITH OTHER CONVERTER AND STATION CONTROL EQUIPMENT.

GROUND POWER COLLECTION AND CONVERSION SYSTEM



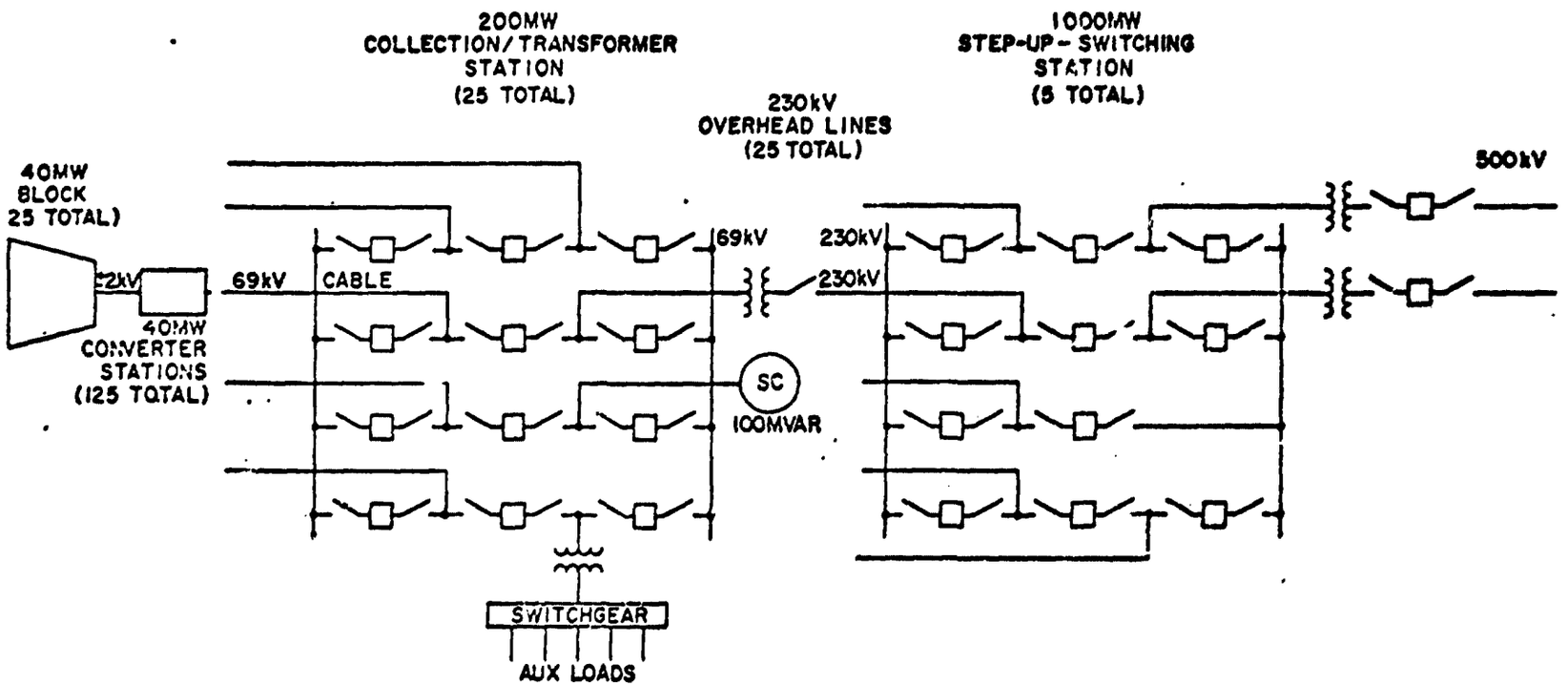
GROUND POWER COLLECTION AND TRANSMISSION SYSTEM

ONE LINE DIAGRAM

THE COLLECTION/TRANSFORMER STATION GATHERS THE POWER OUTPUT OF 5 CONVERTER STATIONS, CONNECTS THESE CIRCUITS INTO A RELIABLE SWITCHING ARRANGEMENT, AND TRANSFORMS THE AC POWER FROM 69 kV UP TO 230 kV. THIS IS DONE BY PHYSICALLY AND ELECTRICALLY ARRANGING AND CONNECTING STANDARD ELECTRICAL EQUIPMENT I TO THE DESIRED CONFIGURATION. THE ELECTRICAL CONFIGURATION PROVIDES RELIABILITY BY A "BREAKER AND A HALF" SCHEME 69 kV SWITCHYARD. A SINGLE CONTINGENCY OUTAGE CAN BE SUSTAINED IN THE 69 kV SWITCHYARD WITHOUT LOSS OF POWER OUTPUT CAPABILITY. TO PROVIDE COMPENSATION FOR THE INHERENT LAGGING POWER FACTOR CHARACTERISTICS OF THE CONVERTER VALVE AND TRANSFORMER EQUIPMENT ONE 100 MVAR SYNCHRONOUS CONDENSER IS CONNECTED TO THE 69 kV BUS. THE SYNCHRONOUS CONDENSER RATING IS CHOSEN TO ALLOW SYNCHRONOUS CONDENSER MAINTENANCE ON ADJACENT COLLECTION/TRANSFORMER STATIONS WITHOUT CURTAILING POWER OUTPUT.

THE STEP-UP SWITCHING STATION RECEIVES THE OUTPUT FROM FIVE COLLECTION/TRANSFORMER STATIONS AT 230 kV AND TRANSFORMS THE VOLTAGE TO 500 kV. THE "BREAKER AND A HALF" SCHEME EMPLOYED CAN SUSTAIN ANY SINGLE CONTINGENCY 500 kV SWITCHYARD FAULT WITHOUT REDUCTION IN STATION OUTPUT. THE SELECTION OF THE VOLTAGE LEVEL FOR THE ULTIMATE BULK POWER TRANSMISSION INTERFACE WITH THE UTILITY GRID AS WELL AS THE POSSIBILITY OF INTERCONNECTING TWO OR MORE OF THE 1000 MW SWITCHING STATIONS TOGETHER SHOULD BE OPTIMIZED BASED ON DETAILED INFORMATION ABOUT THE CONNECTING UTILITY SYSTEM. THE SOLUTION SHOWN IS ONE OF SEVERAL POSSIBLE.

GROUND POWER COLLECTION AND TRANSMISSION SYSTEM



RECTENNA POWER CONDITIONING ANALYSIS

FAILURE CHARACTERISTICS FOR SYSTEM ELEMENTS

THE FAILURE CHARACTERISTICS FOR THE ELEMENTS IN THE RECTENNA POWER COLLECTION AND TRANSMISSION SYSTEM MAY BE DEVELOPED FROM ELECTRIC UTILITY INDUSTRY STATISTICS. THE FAILURE RATES SHOWN ARE IN TERMS OF FAILURES PER YEAR AND THE MEDIAN REPAIR TIME ASSUMES A SUFFICIENT SUPPLY OF SPARE PARTS AND AVAILABLE MAINTENANCE PERSONNEL. THE FAILURE RATES FOR THE DC CIRCUIT BREAKERS AND THE CONVERTER STATION ARE SOMEWHAT CONSERVATIVE. THE COMPONENTS ASSUMED USED IN THE DESIGN OF THESE DEVICES ARE CURRENT TECHNOLOGY EQUIPMENT, WHILE THE DETAILED DESIGN MUST BE DEVELOPED.

RECTENNA POWER CONDITIONING ANALYSIS

FAILURE CHARACTERISTICS FOR SYSTEM ELEMENTS

EQUIPMENT	FAILURE RATE PER YEAR	MEDIAN REPAIR TIME HOURS/FAILURE
DC CIRCUIT BREAKERS	.2	8
CONVERTER STATION	.33	10
SWITCHING STATION (PER BREAKER)	.00063	13
TRANSFORMER	.0041	219
AC CIRCUIT BREAKER	.0176	4
SYNCHRONOUS CONDENSER	.5	112

FAILURE MODE AND EFFECTS ANALYSIS

PRELIMINARY LISTING OF ELECTRICAL FAULTS, SYSTEM PROTECTION AND POWER LOSS

THE DEVELOPMENT OF THE FAILURE MODES AND EFFECTS FOR THE GROUND POWER COLLECTION AND TRANSMISSION SYSTEM IS CURRENTLY IN THE PHASE OF DETERMINING THE VARIOUS EVENTS OR FAILURES THAT MAY OCCUR AND THE PROTECTIVE SCHEMES AVAILABLE TO MINIMIZE THE POWER LOSS. THE AREA OF GREATEST CONCERN AT THE MOMENT IS THE OPERATION OF THE 1 MW DC CIRCUIT BREAKERS DURING DC GROUND FAULTS AS WELL AS THE "CROWBAR" EVENTS INTERNAL TO THE 1 MW PRIMARY UNITS.

TO BE CAPABLE OF PROTECTING FOR THESE SITUATIONS, WHILE ALLOWING AN AUTOMATIC RESUMPTION OF POWER COLLECTION AFTER A BREAKER TRIP IT APPEARS THAT THESE BREAKERS WILL BE OF SOLID STATE DESIGN TO PREVENT FEED-IN FROM THE OTHER PRIMARY UNITS DURING FAULTS, AND MECHANICAL BREAKERS FOR ISOLATION.

OTHER GROUND FAULTS IN THE DC COLLECTION SYSTEM WOULD LIKELY BE CABLE TERMINATION FAULTS, AND ALL THE DC CIRCUIT BREAKERS WOULD TRIP A TOTAL OF 20 MW. THE 69 kV CIRCUIT BREAKERS WOULD PROTECT FOR CONVERTER FAULTS, 69 kV SWITCHYARD FAULTS, AND SYNCHRONOUS CONDENSER FAULTS.

LIGHTNING STROKES TO THE OVERHEAD TRANSMISSION SYSTEM COULD CAUSE POWER INTERRUPTIONS FROM 40 TO 1000 MW FOR ABOUT 30 CYCLES WHEN UTILIZING FAST RECLOSING CIRCUIT BREAKERS. A TYPICAL FREQUENCY OF LIGHTNING STROKES COULD BE ABOUT FOUR PER 100 MILES PER YEAR.

FAILURE MODE AND EFFECTS ANALYSIS

PRELIMINARY LISTING OF ELECTRICAL FAULTS,
SYSTEM PROTECTION AND POWER LOSS

EVENT/FAILURE	PROTECTION	POWER LOSS MW
DC GROUND FAULT WITHIN 1 MW PRIMARY UNIT	DC CIRCUIT BREAKER	1
"CROWBAR" EVENTS WITHIN 1 MW PRIMARY UNIT	DC CIRCUIT BREAKER	1
DC GROUND FAULT EXTERNAL	DC CIRCUIT BREAKERS	20
CONVERTER FAILURE 69 kV SYSTEM FAULT	69 kV BREAKERS	0 - 40
SYNCHRONOUS CONDENSER FAULT	69 kV BREAKERS	0
LIGHTNING STROKES (30 CYCLES OUTAGE/FAULT)	CIRCUIT BREAKERS W/FAST RECLOSING	40 - 1000

KEY RESULTS AT THE END OF PHASE I

THE KEY RESULTS AVAILABLE AT THE END OF PHASE I FOR INPUTS TO THE MORE COMPREHENSIVE UTILITY SYSTEM OPERATIONAL INTEGRATION WORK TO BE PERFORMED IN PHASE II WOULD BE:

1. A DISCUSSION OF UTILITY SYSTEM PARAMETERS INFLUENCING THE CHOICE OF THE RECTENNA OUTPUT VOLTAGE LEVELS AND OF AC OR DC LONG RANGE TRANSMISSION. THE SELECTED SITE LOCATION AND THE SPECIFIC UTILITY SYSTEM STUDIED WOULD BE IMPORTANT INPUTS TO THIS DECISION.

2. BY THE HELP OF PROBABILITY MATHEMATICS, OUTAGE PROBABILITY MODELS WILL BE DEVELOPED FOR THE RECTENNA SUBSYSTEMS AND THEN MERGED TO OBTAIN AN APPROXIMATE PROBABILITY MODEL FOR RECTENNA FORCED OUTAGES.

3. RECTENNA ELEMENT SCHEDULED MAINTENANCE REQUIREMENTS WILL BE DEVELOPED FOR INPUTS TO THE OVERALL MAINTENANCE PLAN.

KEY RESULTS AT THE END OF PHASE I

- CONSIDERATIONS FOR SPS POWER INTEGRATION
- PROBABILITY MODEL FOR RECTENNA FORCED OUTAGES
- RECTENNA SCHEDULED MAINTENANCE REQUIREMENTS

MISSION/SYSTEM CONTROL

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INTRODUCTION

A set of preliminary tasks were performed during Phase I in order to prepare for a more detailed evaluation of mission operations command and control during Phase II. The options developed during Phase I will be evaluated and a baseline concept selected for use in preparing cost and technical development assessments.

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INTRODUCTION

PHASE I TASKS

- DEVELOP A REPRESENTATIVE MISSION OPERATIONS COMMAND AND CONTROL (C&C) CONCEPT
- PREPARE A SET OF OPTIONS TO THAT CONCEPT
- DEFINE THE CRITERIA WHICH WILL BE USED TO EVALUATE THESE OPTIONS IN PHASE II

PHASE II TASKS

- EVALUATE THE PHASE I OPTIONS AND SELECT BASELINE MISSION OPERATIONS COMMAND AND CONTROL CONCEPT
- DEVELOP CANDIDATE SOLUTION TO EQUIPMENT, FACILITIES, SOFTWARE AND PERSONNEL NEEDS
- PREPARE TECHNICAL DEVELOPMENT AND COST ASSESSMENTS

SPS SYSTEM MAJOR ELEMENTS REQUIRING COMMAND, CONTROL AND TRACKING

This figure illustrates the major elements of the system which either require or provide command and control during mission operations. The functions of each of these elements and their interrelationships during all mission operations were analyzed to determine the mission operations C&C functions required.

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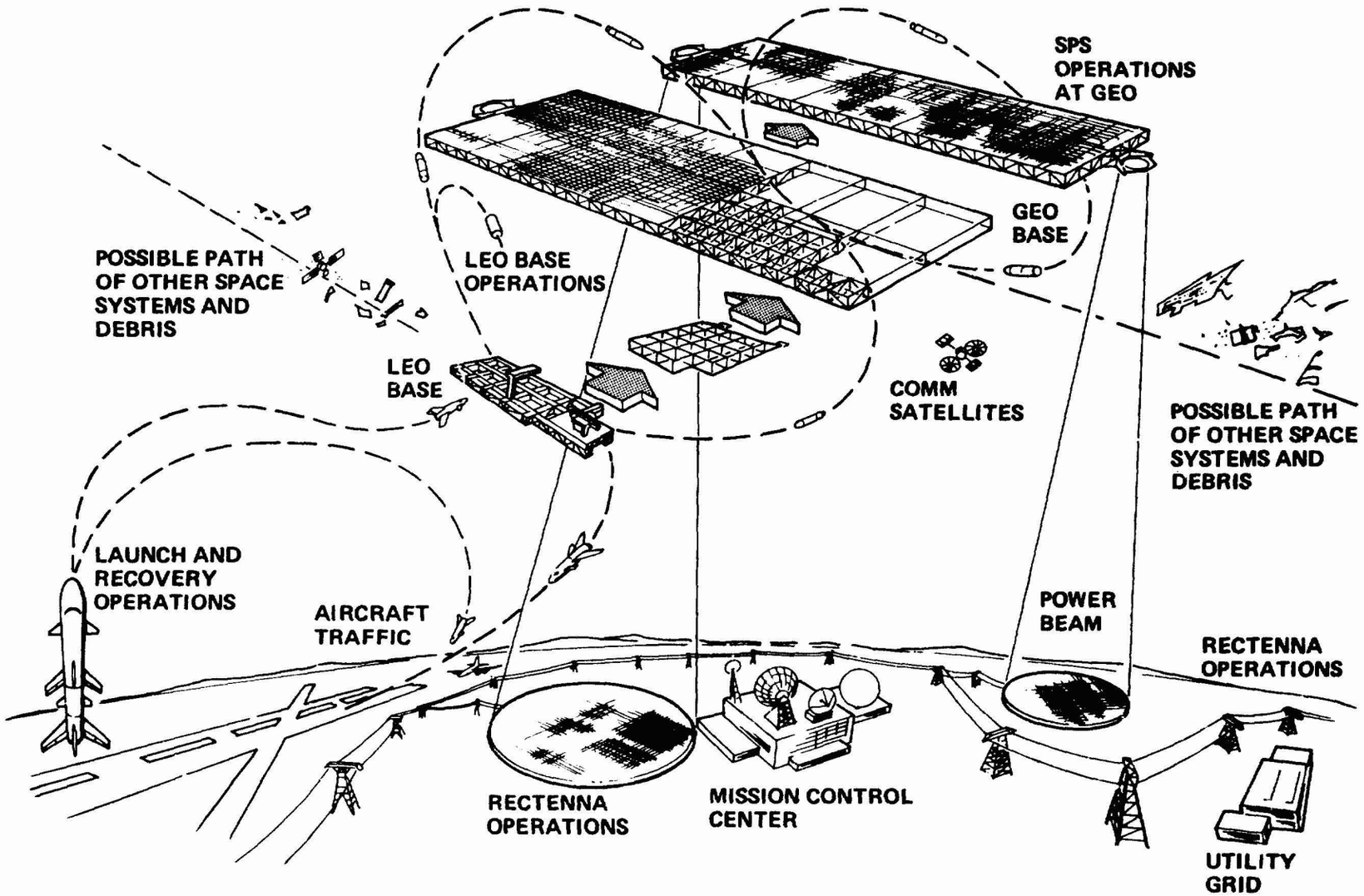
SPS SYSTEM MAJOR ELEMENTS REQUIRING COMMAND, CONTROL AND TRACKING



DEFINITIONS

In order to assure a common basis for communication in the discussion of the somewhat complex subject, a definition of some of the principal terms have been prepared. Throughout this portion of the presentation the abbreviation "C&C" is used for the term command and control.

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DEFINITIONS

- MISSION OPERATIONS – OPERATIONS OF ALL ORBITAL ELEMENTS OF THE SPS SYSTEM INCLUDING THE TRANSPORTATION VEHICLES WHICH TRAVEL AMONG THESE ELEMENTS

- MISSION OPERATION COMMAND AND CONTROL – THE COMMAND AND CONTROL OF MISSION OPERATIONS. THIS INCLUDES THE RECEPTION AND INTERPRETATION OF STATUS DATA (PREDOMINANTLY TELEMETRY DATA) TO DETERMINE ANY NECESSARY COMMANDS AND THE IMPLEMENTATION OF THESE COMMANDS. ORBITAL AND TRAJECTORY TRACKING IS ALSO INCLUDED IN THIS TASK

- COMMAND AND CONTROL CENTERS – CENTERS WHICH HAVE BEEN DELEGATED AUTHORITY FOR COMMAND AND CONTROL OF SELECTED MISSION OPERATIONS

- MISSION CONTROL CENTER (MCC) – THE COMMAND AND CONTROL CENTER WHICH HAS CENTRAL COMMAND AND CONTROL AUTHORITY FOR MISSION OPERATIONS

COMMAND AND CONTROL FUNCTIONS REQUIRED DURING MISSION OPERATIONS

This figure summarizes an analysis which was made of all mission operations to determine the C&C functions required during each operation. Also as a part of this analysis a determination was made as to where the responsibility should reside for each function identified. The criteria used for assignment of responsibility were:

a) Place the responsibility in a control center in the local system element which can most readily provide the technical expertise, obtain the necessary information and perform the required communication with the system elements involved. For example, C&C of HLLV or OTV docking at an orbital base is assigned to that base since it has the necessary status information as well as direct control of the docking equipment on the base. Also, communication with the crew of the docking vehicle is conducted over a relatively short range.

b) To the extent possible provide control autonomy to local system elements.

c) A third criterion was to group responsibility for those control functions which do not lend themselves to local control into a central control (Mission Control Center, MCC). An example is midcourse control of transportation vehicles. In this case no local system element is involved and the status information must be obtained by relatively long range r.f. communication. The MCC will be provided with the personnel, information and communication capability to perform the assigned functions.

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COMMAND AND CONTROL FUNCTIONS REQUIRED DURING MISSION OPERATIONS

SYSTEM ELEMENT	LOCAL COMMAND AND CONTROL CENTERS AND FUNCTIONS	MISSION CONTROL CENTER FUNCTIONS
LAUNCH AND RECOVERY SITE – HLLV AND PLV	LAUNCH AND RECOVERY C&C CENTER – PREPARE AND LAUNCH VEHICLES, PAYLOADS AND CREW – LANDING AND/OR RECOVERY	– LAUNCH AND RANGE COORDINATION – MIDCOURSE CONTROL TO LEO – BOOSTER STAGE SEPARATION AND CONTROL
LEO BASE – HLLV AND PLV – OTV – SPS MODULES-IN-TRANSIT (SMIT)	LEO BASE C&C CENTER – BASE AND SPS MODULE CONSTRUCTION MANAGEMENT – HLLV; PLV; OTV – DOCKING AND UNLOADING – PREPARE AND LAUNCH VEHICLES, PAYLOADS, CREWS – SMIT – LAUNCH PREPARATION AND LAUNCH	– HLLV; PLV; OTV – RENDEZVOUS COORDINATION – LAUNCH COORDINATION – MIDCOURSE CONTROL – OTV BOOSTER SEPARATION AND CONTROL – SMIT – LAUNCH COORDINATION – MIDCOURSE CONTROL – LEO BASE – TRACKING, STATIONKEEPING, CONTINGENCY RESOLUTION
GEO BASE – OTV – SMIT – SPS – MAINTENANCE VEHICLES	GEO BASE C&C CENTER – BASE AND SPS CONSTRUCTION MANAGEMENT – OTV – DOCKING AND UNLOADING – PREPARE AND LAUNCH VEHICLES, PAYLOADS AND CREWS – SMIT – RENDEZVOUS AND BERTHING – SPS – MAINTENANCE OPERATIONS – MAINTENANCE VEHICLES – PREPARE AND LAUNCH VEHICLES, CREWS AND PAYLOADS – DOCKING AND UNLOADING	– OTV; MAINTENANCE VEHICLES – RENDEZVOUS COORDINATION – LAUNCH COORDINATION – MIDCOURSE CONTROL – SMIT – RENDEZVOUS COORDINATION – SPS – ACTIVATION AND COORDINATION – MAINTENANCE COORDINATION – GEO BASE – TRACKING, STATIONKEEPING, CONTINGENCY RESOLUTION
OPERATIONAL SPS	RECTENNA C&C CENTER – MONITOR SPS POWER PERFORMANCE	– C&C, TRACKING, STATIONKEEPING – POWER SUBSYSTEM C&C – ECLIPSE SCHEDULES/ANTENNA POINTING – MAINTENANCE VEHICLES DOCKING AND LAUNCH
COMMUNICATIONS SATELLITES		– C&C, TRACKING, STATIONKEEPING

COMMAND AND CONTROL CENTERS

As the result of the analysis of mission operations these five C&C centers were established. The first four are located in local system segments, the fifth (the MCC) is an independent center dedicated to C&C. This center will have the central authority for mission operations. The other centers will interface and coordinate with this center when they are commanding and controlling local mission operations for which they have been assigned authority.

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COMMAND AND CONTROL CENTERS

1. LAUNCH AND RECOVERY COMMAND AND CONTROL CENTER
2. LEO BASE COMMAND AND CONTROL CENTER
3. GEO BASE COMMAND AND CONTROL CENTER
4. RECTENNA COMMAND AND CONTROL CENTER
5. MISSION CONTROL CENTER

CATEGORIES OF C&C FUNCTIONS ASSIGNED TO MISSION CONTROL CENTER

A large number of diverse C&C functions were assigned to the Mission Control Center as a result of the analysis of mission operations. These functions were reviewed with the objective of organizing and categorizing them in order to make efficient use of resources. The functions were divided into the six categories shown by grouping together those functions having similar requirements for the following resources; type of information required, technical expertise, equipment and software.

Four of these categories (i.e., Transportation Vehicle C&C, SMIT C&C, Operational SPS C&C, and Communication Satellite C&C) each require the information, expertise, etc. to operate space vehicles. However, the space vehicles are so widely different (i.e., attitude control, propulsion, power, etc.) that specially trained crews, widely different software and unique procedures will be required. Hence separate categories were established.

Space Traffic Control has the responsibility to insure that the movements of all space vehicles and other space elements are coordinated and controlled such that they do not interfere with each other or with other space traffic and are not impacted by space debris or meteors. This requires tracking information plus personnel and software capable of projecting this information into future traffic situations.

Orbital Base C&C - It is anticipated that the orbital bases will be autonomous, however, the Mission Control Center may be called upon to perform tracking, stationkeeping and repositioning in either primary or back-up mode.

The size of the circles indicates a preliminary estimate of the relative magnitude of the effort required for accomplishing the tasks in each category. Similarly the thickness of the arrows indicates the magnitude of the interface between each category.

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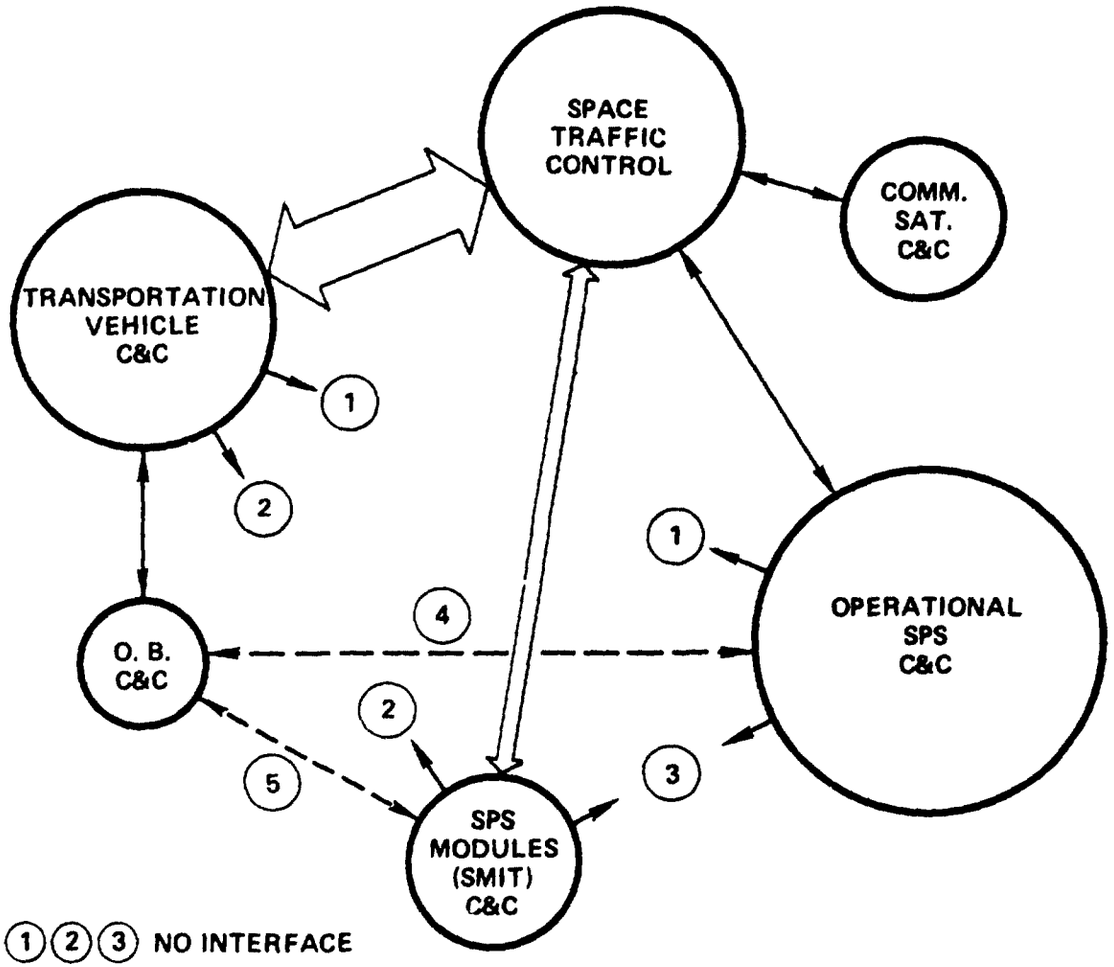
CATEGORIES OF C&C FUNCTIONS ASSIGNED TO MISSION CONTROL CENTER



(1)(2)(3) NO INTERFACE

(4) ONLY INTERFACE IS LAUNCH OF COMPLETED SPS FROM GEO

(5) ONLY INTERFACE IS LAUNCH OF MODULE FROM LEO AND DOCKING OF MODULE AT GEO

C&C CENTER RELATIONSHIPS TO MAJOR SYSTEM ELEMENTS AND TO EACH OTHER

This figure is a graphical presentation of the results of the mission operations C&C analysis. The shaded circles indicate the four C&C centers which are collocated with major system elements. The six categories of Mission Control Center C&C are shown by the cross-hatched circles. The clear circles and arrows indicate system elements which do not have collocated C&C centers. The annotated small arrows indicate the principal interfaces which exist. Space Traffic Control will interface with all other control centers and system elements, however, these interfaces are not shown in order to simplify the figure.

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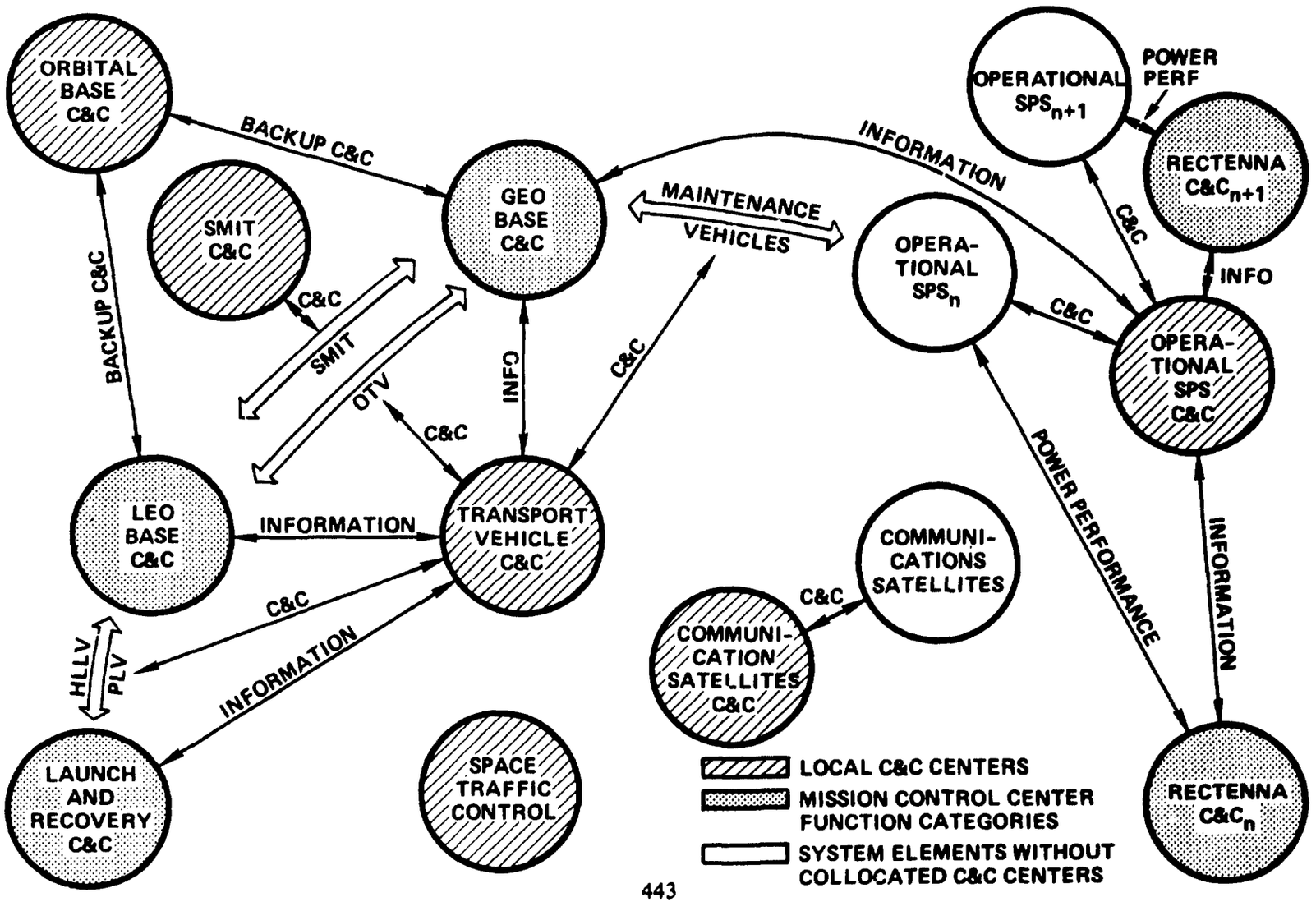
C&C CENTER RELATIONSHIPS TO MAJOR SYSTEM ELEMENTS AND TO EACH OTHER



MISSION OPERATIONS C&C OPTION CATEGORIES

The selected concept of a system for command and control of mission operations consists of:

1) The five C&C centers previously identified which include the Mission Control Center
2) Assignment of C&C functions to each of these centers as previously defined
3) A Mission Control Center consisting of two facilities which would be separated geographically
   a) One facility which includes Transportation Vehicle C&C and Space Traffic C&C functional categories
   b) Another facility which includes Orbital Base C&C, SPS Modules-in-transit (SMIT) C&C and Communication Satellite C&C

   The reason for two facilities is that in the event of a catastrophic event (such as hurricane, flood, earthquake) which would cause loss of power or a majority of the capability at one location, a back-up capability would exist. In addition, it is anticipated that the magnitude of MCC operations will become large enough, due to the numbers and types of vehicles involved, that two facilities will be required.

A large number of options to this concept have been considered. This figure shows the major categories of these options. These options will be evaluated in detail in Phase II using criteria which have been defined in this Phase.

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OPTIONS TO MISSION OPERATIONS C&C CONCEPT

OPTION	EXAMPLE	ADVANTAGES	DISADVANTAGES
ESTABLISH MORE OR FEWER C&C CONTROL CENTERS THAN FIVE IN THIS CONCEPT	EACH RECTENNA IS TOTAL C&C CENTER FOR AN SPS	RECTENNA IS IMMEDIATELY AWARE OF EITHER SPS OR GRID POWER PROBLEMS, CAN REACT SWIFTLY	LARGE NUMBER OF C&C CREWS AND EQUIPMENT REQUIRED
ASSIGN RESPONSIBILITIES DIFFERENTLY AMONG THE FIVE CONTROL CENTERS	OPERATIONAL BASES COMPLETELY AUTONOMOUS. NO C&C CAPABILITY FROM MCC	REDUCED COST OF MCC BY ELIMINATING ONE CATEGORY OF FUNCTIONS	NO CONTINGENCY RESOLUTION CAPABILITY IN EVENT OF PROBLEMS WITHIN THE BASE
GROUP RESPONSIBILITIES DIFFERENTILY THAN SIX C&C CATEGORIES IN MCC	CREATE C&C CENTER FOR EACH TYPE OF TRANSPORTATION VEHICLE	EACH TYPE OF VEHICLE IS QUITE DIFFERENT. MAY GET BETTER C&C OF EACH TYPE	MAY NOT BE ABLE TO COMBINE USE OF PERSONNEL AND EQUIPMENT AS EFFECTIVELY ESPECIALLY IN BACKUP MODES
PUT MCC IN MORE OR FEWER FACILITIES (GEOGRAPHIC LOCATIONS) THAN TWO IN THIS CONCEPT	PROVIDE THREE MCC FACILITIES	PROVIDES GREATER POTENTIAL FOR REDUNDANCY, HENCE RELIABILITY	HIGHER COST

Rectenna Siting Investigation

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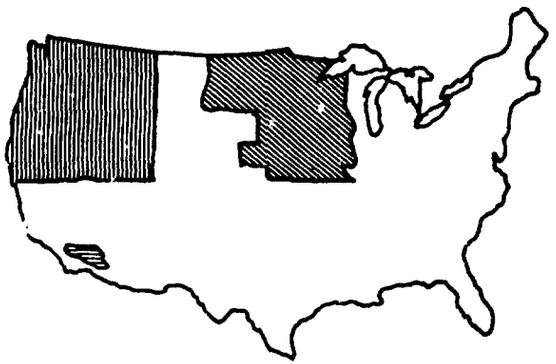
SITING GROUND RULES

Data exchange agreements were developed between three utility regions and this study. This enabled us to acquire more specific information as to utility needs for power generation and distribution in these areas, and to add some realism to the questions of rectenna siting and grid integration. The geographical areas served by these three utilities are illustrated on the accompanying map.

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

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

SPS-2312

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.

SITING CONCLUSIONS

It is quite unlikely that more detailed investigation would rule out many of the sites potentially identified in this preliminary analysis. Even if half of the sites identified were later ruled out, however, siting of adequate capacity to meet the needs of utilities in these regions appears to be possible.

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

RECOMMENDATIONS

Recommendations for continued siting analysis are summarized on the facing page.

Recommendations

1) CONTINUE ANALYSIS WITH FINE SCALE MAPS (7.5 MINUTE) TO SEARCH OUT SITING PROBLEMS AND DERIVE DATA FOR GENERAL ELECTRIC'S RECTENNA TASK.

- AVERAGE SLOPES
- SOIL TYPES
- DRAINAGE CHARACTERISTICS

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

3) 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.

Technology Advancement Planning

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OVERALL SPS DEVELOPMENT

A number of studies have been conducted attempting to identify the developmental evolution needed to advance from the present paper study stage to achievement of operational solar power satellites. These studies have varied substantially in detailed scenarios and content, but all have generally tended to agree on the four major program steps indicated on the facing page. The schematic of the program shows neither clearly defined beginnings nor ends to any of the sets or any overall schedule. The potential for significant overlap between the phases is also indicated. It is quite likely that information-gathering phases such as system definition and evaluation, and technology research and advancement, will have no clearly-defined end points. When these activities have reached sufficient maturity to initiate technology verification or developmental phases they will continue to explore more advanced concepts and technology.

Overall SPS Development

SYSTEM DEFINITION
& EVALUATION

TECHNOLOGY RESEARCH
& ADVANCEMENT (LABORATORY AND HIGH-PRIORITY SHUTTLE FLIGHTS)

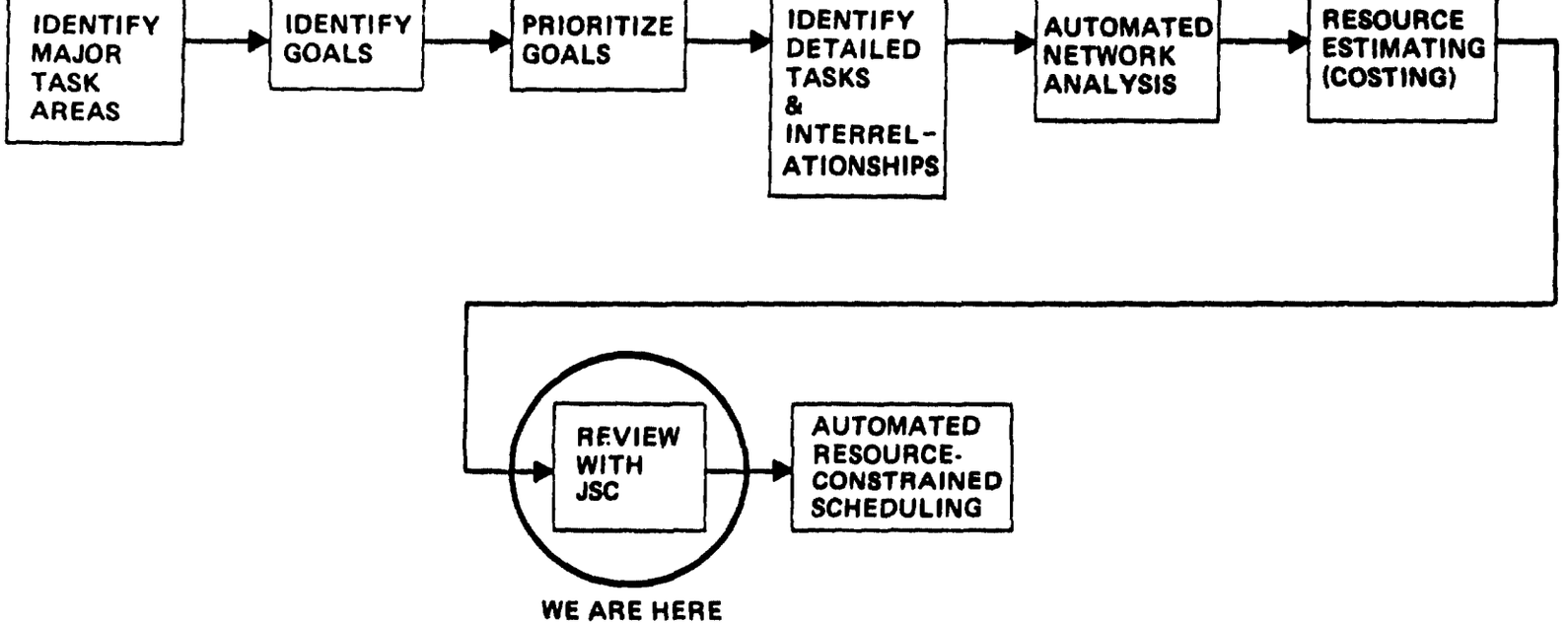
TECHNOLOGY
VERIFICATION (FLIGHT PROJECTS)

SPS DEVELOPMENT
AND COMMERCIALIZATION

PLANNING PROCESS

The planning process described here is presently being applied to the technology advancement planning area. The first pass through the process has reached the point indicated. This is viewed as a continuing iterative process with each succeeding iteration improving upon the definition and rationality of the plan being evolved. We expect to provide status memoranda of the evolving plan for review by JSC and others at regular intervals so that the final planning document from this contract on this subject will be a data product representing a reasonable consensus regarding technology advancement.

Planning Process



TECHNOLOGY ADVANCEMENT PLANNING

The technology advancement plan presently being prepared covers the ten areas indicated on the facing page. In general the plan allows for multiple technology paths, converging upon selections of technology only after laboratory verification and assessment of the alternatives is accomplished.

Technology Advancement Planning

DETAILED PLAN COVERS TEN AREAS

- PHOTOVOLTAICS
- THERMAL SYSTEMS
- POWER TRANSMISSION
- SPACE STRUCTURES
- MATERIALS & PROCESSES
- FLIGHT CONTROLS
- SPACE CONSTRUCTION
- SPACE TRANSPORTATION
- POWER DISTRIBUTION
- SPACE ENVIRONMENT EFFECTS

MULTIPLE PATHS IN MOST AREAS, e.g.,

SILICON →
GALLIUM ARSENIDE → SELECT
OTHER →

TECHNOLOGY ADVANCEMENT PLAN AUTOMATED SCHEDULING EXAMPLE

An automated system called Project-II is being utilized for this analysis. It provides automated network scheduling, resources and cost analysis. Program schedules can be adjusted to fit within budget limits and observe priorities of task. The example shown here is a fragment of the present schedule plan for SPS solar array development.

Technology Advancement Plan Automated Scheduling Example

SPS-2331

BOEING

SOLAR POWER SATELLITE

RUN DATE 12OCT78 1755HRS — W O R K I N G S C H E D U L E — PROJECT START 8JAN79

PROJECT TADO TECHNOLOGY ADVANCEMENT PROGRAM — BASE COMPLETION 27SEP90

CODE 1 SOLAR ARRAYS — SORT CODES 12 — PAGE 1

NODE=0/FC /...1979..../...1980..../...1981..../...1982..../...1983..../1984.

ACTIVITY DESCRIPTION	NODE
SOLAR ARRAYS-START	10000004
START	10000009
DEVELOP THIN EFFICIENT SOLAR CELLS-START	11000017
DEV ANAL & TEST SILICON CELLS-START	11010016
DEVELOP CELL IMPROVEMENTS	11010115
ANALYZE INTEGRATION INTO THIN CELL BLANKET	11010215
INTEGRATE IMPROVEMENTS INTO THIN CELL	11010315
CHARACTERIZE CELL PERFORMANCE	11010415
CHARACTERIZE RADIATION DEGRADATION	11010519
DEVELOP HIGH VOLUME PRODUCTION PROCESS	11010614
CHARACTERIZE PROD CELL PERFORMANCE	11010715
DEV ANAL & TEST GALLIUM ARSENIDE CELLS-START	11020015
DEV GAAS CELL ON SUITABLE SUBSTRATE	11020115
CHARACTERIZE CELL PERFORMANCE	11020215
CHARACTERIZE CELL RADIATION DEGRADATION	11020315
DEVELOP HIGH VOLUME PRODUCTION PROCESS	11020415
CHARACTERIZE PROD CELL PERFORMANCE	11020515
EXPLORE ALTERNATIVE CELL TECHNOLOGIES	11030014
SELECT CELL TECHNOLOGY	11040019
DEVELOP SOLAR BLANKET TECHNOLOGY-START	12000017
DEVELOP SILICON BLANKET-START	12010016
DEVELOP SILICON COVER/SUBSTRATE	12010115
DEVELOP ELECTRICAL INTEGRATION	12010216
DEVELOP ANNEALING PROCESS	

POTENTIAL SPS PRECURSORY ELEMENTS

Earlier studies have conceived a number of SPS developmental systems. Several of the more recent ideas are pictorialized here. These range from a large power module designed to provide up to 300 kilowatts of electric power to large space payloads, to a so-called SPS commercial demonstrator. Each of these is visualized to serve a somewhat different need. The developmental test article would demonstrate construction of a large structural article, deployment of lightweight high voltage solar arrays, operation of a rotary joint, and operation of high power transmitter subarray. The proof-of-concept and productivity article would, in addition, demonstrate construction and maintenance procedures more nearly like those that would ultimately be used for SPS construction and maintenance. Finally, the commercial demonstrator would employ actual SPS elements such as transmitter subarrays and solar arrays, on a sufficiently large scale to acquire statistical information on failure rates and maintenance cost. Still larger articles such as a 500 to 1000 megawatt SPS prototype have been proposed by earlier studies. Finally, the initial full size SPS will be a prototype. Whereas earlier investigations had presumed that the full-size prototype SPS would be a 5,000 to 10,000 megawatt system, more recent information suggests that it should be a 2,500 megawatt system.

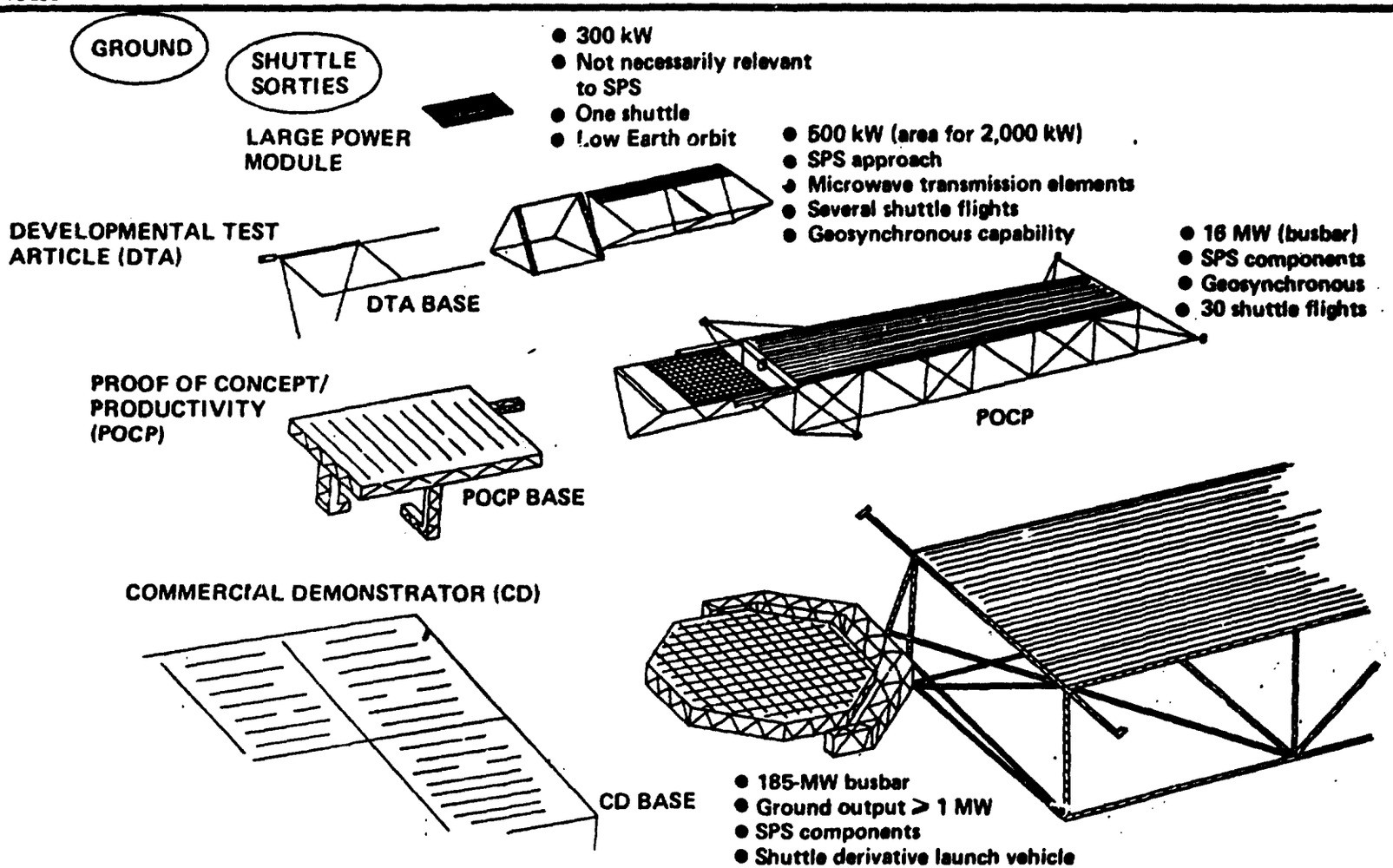
Questions of SPS developmental article configuration include questions of the support systems used to accomplish these demonstrations, especially the transportation and construction systems. The smaller articles in this illustration could be constructed using the space shuttle as transportation vehicle and construction support base. The commercial demonstrator would require a shuttle-derived heavy lift vehicle and probably some sort of permanently habitable construction base.

Although some logic can be stated for each of these articles, it is not pratical to think of constructing all of them. The question yet to be answered is which of these (or which other concepts) are really necessary to establish an adequate level of confidence to proceed with a true prototype SPS.

BOEING SPS

Potential SPS Precursory Elements

78-292



SPS DEVELOPMENT

This list summarizes the status of the SPS development program analysis task.

SPS Development

- OVERALL FOUR-STEP PROGRAM STRUCTURE IDENTIFIED
- TECHNOLOGY ADVANCEMENT GOALS, OPTIONS, SEQUENCES, AND TASK BECOMING CLEAR
- PRESENT TECHNOLOGY ADVANCEMENT PLAN INCLUDES SOME GROUND-BASED DEVELOPMENT ACTIVITIES; DISTINCTION NEEDED
- THREE TO FIVE SHUTTLE FLIGHT MISSIONS NEEDED TO
  - EXPLORE CRITICAL TECHNOLOGY ISSUES
  - ENSURE SUCCESS OF LATER FLIGHT PROJECTS
- NATURE OF NEEDED MAJOR FLIGHT PROJECTS NOT YET CLEAR
- RELATIONSHIP TO SPS DEVELOPMENT NOT YET CLEAR