NI

NASA Technical Memorandum 58231

(NASA-TM-58231) SOLAR POWER SATELLITE COST ESTIMATE (NASA) 169 p HC A08/MF A01 CSCL 22B

N81-16085

Unclas
G3/15 41257

Solar Power Satellite Cost Estimate

Ronald J. Harron and Richard C. Wadle

January 1981

NASA
National Aeronautics and
Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

NASA Technical Memorandum 58231

Solar Power Satellite Cost Estimate

Ronald J. Harron and Richard C. Wadle
Lyndon B. Johnson Space Center
Houston, Texas

NASA
National Aeronautics and
Space Administration

**Scientific and Technical
Information Branch**

1981

CONTENTS

PRECEDING PAGE BLANK NOT FILMED

TABLES

FIGURES

Figure		Page

Figure		Page

SUMMARY

This document presents a cost estimate in 1977 dollars for the solar power satellite based on the silicon cell design concept for a 60-satellite program (300 GW) installed over a 30-year period. The estimate is broken down by program phase and by system component.

There are five program phases: research, engineering verification, demonstration, investment, and production. The cost of the program through the first operational unit is estimated to be $102 billion and subsequent units are estimated to cost $11.5 billion each. The result is an average unit cost of $2,300/kW.

A single 5-GW SPS unit was broken down by system component for costing purposes. The components are tabulated in accordance with a work breakdown structure. The major elements in the work breakdown structure are the satellite, space construction, the transportation system, the ground receiving station, and system maintenance. Cost estimates were prepared and assembled using a variety of cost-estimating techniques including parametric cost models, the mature industry technique, delphi techniques, and learning curves. Each subsystem cost estimate includes references to supporting documentation for more detailed design description and more discussion of the actual estimate. Wherever sufficient information was available, nonrecurring costs and theoretical first unit costs are identified with particular subsystems.

The major cost elements of the solar power satellite system are the satellite ($5 billion), space construction ($1.1 billion), the transporation system ($2.8 billion), the ground receiving station ($2.2 billion), and program management ($0.4 billion), for a total unit cost of $11.5 billion.

INTRODUCTION

This document presents a complete cost scenario for the development, deployment, and operation of a solar power satellite (SPS) system. The scenario used provides cost data for each part of a defined evolutionary program. The data were developed from system definition studies conducted by the Boeing Aerospace Company under contract to NASA JSC from October 1978 to December 1979 and in-house efforts by NASA JSC. While there is no official U.S. Government cost estimate for an SPS, this preliminary cost information is useful for comparing alternatives, determining cost drivers, and identifying areas of high payoff potential. These cost studies are based on the silicon solar cell reference system as defined in the NASA/DOE Reference System Report (ref. 1). Costs are collected according to the work breakdown structure (WBS) shown in figure 1. Note that some WBS elements are omitted from figure 1 because they refer to components not used in the silicon reference system. The SPS reference system generates 5 GW of power at the the ground receiving station bus bar for each satellite. It uses silicon solar cells for energy collection, klystron amplifiers for d.c.-to-microwave power conversion, and an active control system for aiming the microwave beam at the receiving antenna (rectenna).

The purpose of this document is to present a breakdown of cost estimates for each program phase and a cumulative cost estimate for implementing the scenario. The scenario does not preclude other program possibilities. It merely represents a viable technical approach to implementing an SPS program.

The program is divided into five phases: research, engineering, verification, demonstration, investment, and production. The cost and schedule estimates for each phase of the program are given in figures 2 and 3 and are summarized in tables I through VI. All cost figures shown in this document are in 1977 dollars.

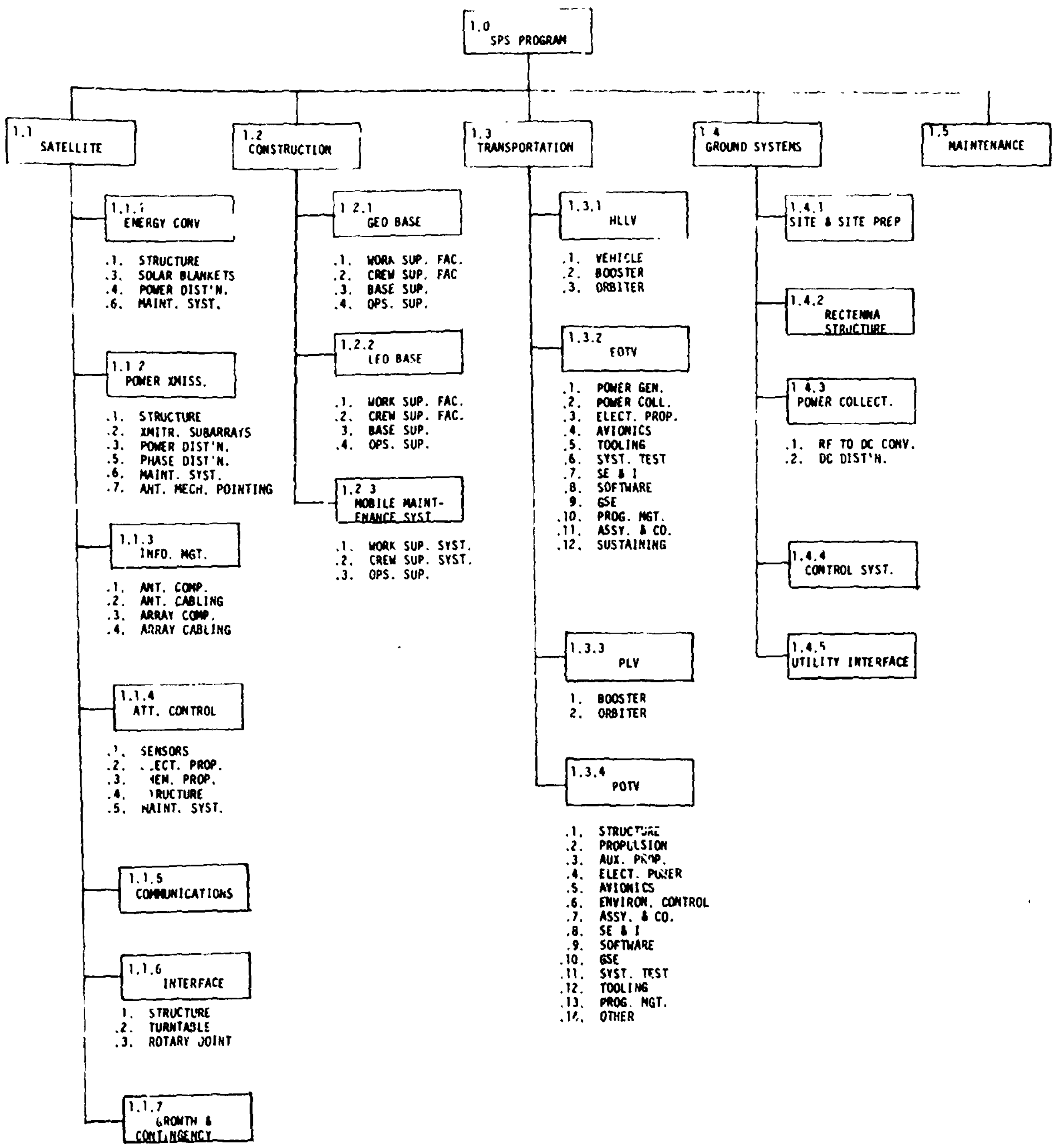
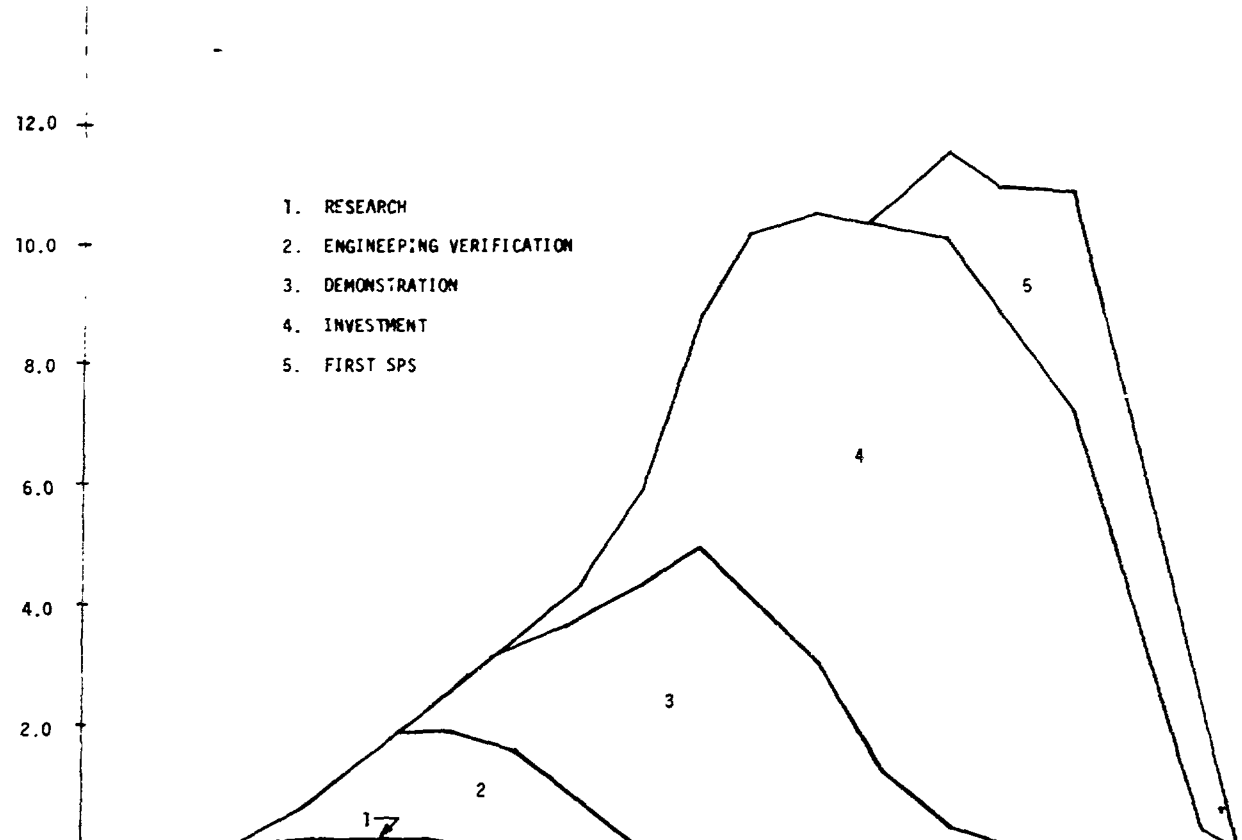


Figure 1.- SPS work breakdown structure.



YEAR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	TOTAL
RESEARCH PHASE	0	0	0	.03	.1	.1	.1	.04	0	0	0	0	0	0	0	0	0	0	0	0	.37
ENGINEERING VERIFICATION PHASE	0	0	0	.15	.5	1.2	1.9	1.9	1.5	.8	0	0	0	0	0	0	0	0	0	0	7.95
DEMONSTRATION PHASE	0	0	0	0	0	0		.7	1.7	2.9	4.1	4.9	4.1	2.9	1.2	.4	0	0	0	0	2[illegible].9
INVESTMENT PHASE	0	0	0	0	0	0	0	0	.1	.6	1.7	3.9	6.1	7.6	9.1	9.6	8.6	7.1	3.1	.2	57.7
FIRST SPS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.4	2.3	3.7	4.1	2.0	13.5
TOTAL	0	0	0	.18	.6	1.3	2.0	2.6	3.3	4.3	5.8	8.8	10.2	10.5	10.3	11.4	10.9	10.8	7.2	2.2	102

Figure 2.- Annual cost of SPS program by phase.

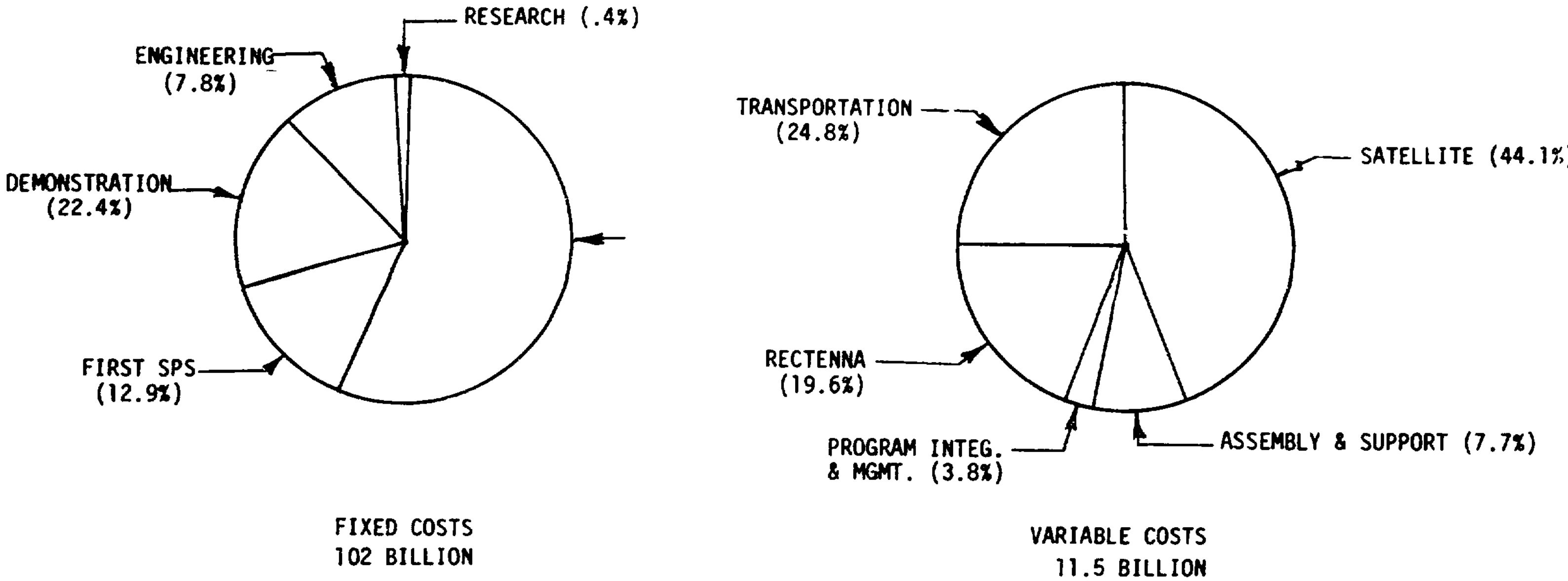


Figure 3.- SPS program fixed and variable costs.

TABLE I.- RESEARCH PHASE COST

	Category	Cost ($\$ \times 10^6$)
I	POWER GENERATION AND DISTRIBUTION	
	Solar Arrays	57
	Thermal Systems	9
	Power Distribution and Processing	13
II	POWER TRANSMISSION	
	Microwave Transmission	40
III	STRUCTURES AND CONTROL	
	Structures and Dynamics	5
	Materials	11
	Flight Controls	6
IV	SPACE CONSTRUCTION	25
V	SPACE TRANSPORTATION	20
VI	SYSTEM STUDIES	19
VII	RESEARCH FLIGHT TESTS	165
	TOTAL	370

TABLE II.- ENGINEERING VERIFICATION PHASE COST

Category	Description	Cost ($ × 10^6)
SPS-Related	Subsystems development and test	366
EVTA Hardware	Engineering verification test article: 1-megawatt array plus microwave and electric propulsion experiments	209
LEO Development Labs	Eight-man test and space support facility	2348
Manned OTV	All-propulsive or aerobraking OTV with 2- to 4-man capability	1243
Shuttle Flights	LEO development labs and MOTV support plus EVTA launch	869
Shuttle Booster	Liquid flyback booster for Shuttle	2856
Program Management and Integration	Integration, coordination, and management support to tie program elements together	61
	TOTAL	7952

TABLE III.- DEMONSTRATION PHASE COST

Category	Description	Cost ($ × 10^6)
Demonstrator DDT&E	Development of the demonstrator subsystems and integrated configuration	2 725
Pilot Production Facilities	Pilot lines for arrays, klystrons, power processors, etc.	400
Demonstrator	Hardware for demonstrator	2 541
Shuttle DDT&E and Fleet	Two boosters, two Orbiters, 25 external tanks, development of pod-type HLLV	2 959
Construction DDT&E	LEO base: 8-meter habitat and full work support facility (WSF) GEO base: habitat delta for shielding and 10% WSF	3 118
Construction Base Cost	LEO base: 4 habitats and full WSF GEO base: 1 habitat and 10% WSF	2 975
Space Operations	Four years' operations: construct bases and demonstrator	2 783
POTV DDT&E plus One Extra Unit	Personnel OTV with passenger module	1 727
EOTV DDT&E	Electric OTV development only (supports demo article)	1 775
Demonstrator Rectenna	8 x 11 km	1 757
Program Management and Integration		152
	TOTAL	22 912

TABLE IV.- INVESTMENT PHASE COST

Category	Description	Cost ($ × 10^6)
HLLV Development	Two-stage fully reusable	10 522
SPS DDT&E	Upgrading demo subsystems and integration of configuration	2 150
HLLV FLeet	Six boosters, seven Orbiters, tooling and GSE	6 072
EOTV Fleet	Thirty vehicles	5 963
Construction DDT&E	Delta DDT&E to upgrade bases to operational capability	4 261
Construction Base Buildup	Fabricate and launch base systems	12 935
Ground-Based SPS Facilities	Production factories	7 760
Space Systems Facilities	Launch and recovery site deltas plus special factories	7 283
Program Management and Integration		761
	TOTAL	57 707

TABLE V.- PRODUCTION PHASE (FIRST SPS COST)

Category	Description	Cost ($ × 10^6)
SPS Hardware	Flight hardware ready to ship	5 032
Space Transportation	All space transportation, hardware, and crew	3 645
First Year Full Base Operations	Crew salaries and spares and support	1 671
Rectenna	10 x 13 km	2 242
Mission Operations		17
Sustaining DDT&E	Development support to prototype	431
Program Management and Integration		431
	TOTAL FOR SPS #1	13 469

TABLE VI.- PRODUCTION PHASE
(AVERAGE SPS UNIT COST)

Category		Cost ($ × 10^6)	
SATELLITE			5 032
Power Collection		2 575	
Structure	390		
Rotary joint	88		
Solar cell blankets	1 729		
Power distribution	130		
Maintenance provisions	238		
Power Transmission		1 725	
Structure	22		
Attitude control	139		
Instrumentation/communication	71		
Transmitter subarrays	773		
Power distribution	282		
Maintenance provisions	438		
Cost Growth		730	
RECTENNA			2 208
Land		240	
Structure and Installation		304	
RF Assemblies and Ground Plane		929	
Distribution Buses		268	
Command and Control Center		61	
Power Processing and Grid Interface		674	
TRANSPORTATION			2 802
HLLV		1 954	
EOTV		575	
PLV		260	
POTV		13	
ASSEMBLY AND SUPPORT			1 075
PROGRAM MANAGEMENT AND INTEGRATION			430
UNIT COST PER PRODUCTION SPS			11 547

DEFINITION OF TERMS

Definition of Cost Categories

DDT&E costs: The design, development, test, and evaluation account includes all costs associated with the engineering and support required to translate the SPS performance specification into a detailed design. It includes the preparation of detailed drawings for hardware fabrication, assembly, and system integration. Also included are all required tests, both ground and flight, together with any test facilities required, and the costs related to test evaluation, data reduction, and design modification. Specifically not included in the DDT&E costs are the costs associated with the construction of production facilities and the launch and recovery facilities associated with the SPS transporation system. These costs are separately accounted so that they may be amortized over the SPS implementation scenario.

TFU cost: The theoretical first unit costs are those costs associated with the production of the first identifiable SPS system, subsystem, or element produced by the full-scale production process. It is a useful point of departure for the application of learning technique to determine average unit production costs. It includes costs after the completion of the DDT&E phase but before the initial operation of the first SPS.

Average unit cost: The average unit cost is the cost associated with the production of a typical SPS system, subsystem, or element. It is essentially the average cost of a unit produced to comply with implementation scenario. It includes all quality assurance costs, manufacturing costs, and production test costs associated with an ongoing program.

Definiton of Program Phases

Research phase: The research phase will address and resolve issues of environmental effects, technical practicality, and selection of cost-effective technologies and will develop a comparative assessment of benefits of the SPS relative to other energy options. It will be composed mainly of ground-based research, but certain flight projects are also required to complete the research phase.

This scenario treats only SPS hardware and software research and research on support technologies such as space operations. Environmental research will be conducted in parallel with the research described herein. Costs and schedules for environmental research are not reflected in this scenario.

Engineering verification phase: The engineering verification phase will bring the technology results of the research phase to a state of large-scale development readiness. Prototype subsystems will be developed and tested, as will prototype production and operations processes. The products of this phase will be specifications for the demonstration SPS and all its support systems, costs estimates for the demonstration and production SPS's and all support systems, costs estimates for the demonstration and production lines, and firm developement and risk management plans for this program phase.

The engineering verification test article concept is based on the following major requirements:

a. Test of a solar array similar to that planned for SPS at low Earth orbit (LEO), intermediate altitudes, and geosynchronous orbit (GEO)

b. Fabrication and test of a space structure large enough to demonstrate dynamic control by analysis

c. Test of scaled-down power transmission system at GEO

d. Test of electric propulsion systems at LEO, intermediate altitudes, and GEO to ascertain performance against plasma and magnetosphere interactions

Demonstration phase: The demonstration phase will produce and test a pilot plant SPS that delivers power to a commercial electric power network. The power delivered will be on the order of 100 to 200 MW.

Investment phase: At this point in the program, a commitment to create the industrial base to produce two 5-GW SPS's per year will be made. Examples include building ground-based factories to produce the solar cells and klystrons, and to develop the transportation fleet.

Production phase: The production phase begins with the installation of the first 5-GW SPS. Subsequently, SPS's will be installed at the rate of two per year until a total of 60 satellites are in place and operating. The first unit is slightly more costly than the average because it incurs some nonrecurring costs.

COST ESTIMATING METHODOLOGY

Virtually all the DDT&E and TFU transportation system costs were estimated using the parametric cost model (PCM) computer program developed by Boeing. This program requires both factual and judgmental input information. Factual input data include susbsystem descriptors such as the nature of the subsystem, its mass, volume, performance, and characteristics. Judgmental input data include the estimator's opinion of subsystem complexity and its newness (as opposed to an off-the-shelf design).

The PCM program then computes estimates of both DDT&E and TFU costs from a data bank of historical aircraft and aerospace parametric cost data. The PCM estimate of the TFU vehicle cost along with the number of vehicles to be produced to meet the requirements of the implementation scenario is used with the learning curve (see fig. 4 to obtain an estimate of the average unit cost).

Aircraft industry experience indicates that a learning curve factor of $\lambda = 0.85$ is applicable at the vehicle level. Experience with jet aircraft production indicates that this relationship holds true to the 1000th unit and beyond. Average unit costs were estimated at the vehicle level only and not at the subsystem level.

Many of the costs of SPS elements are strong functions of the quantity produced or, as in the case of the transportation system, the flight frequency. The implementation scenario used for estimating purposes is a total program of 32.5 years duration from first launch to the completion of the sixtieth 5-GW reference SPS. The following assumptions were made in the derivation of this scenario:

a. An initial 2-year period for the assembly of construction bases in both low Earth orbit and geosynchronous orbit and the fabrication of the Electric Orbit Transfer Vehicle (EOTV) fleet. Six months are devoted to the LEO construction base and 1.5 years to the fabrication of the EOTV fleet. The GEO base is completed at the end of the second year.

b. The first SPS requires 12 months' construction time and is completed at the end of the third year of the scenario.

c. 59 subsequent SPS's are completed at the rate of one every 6 months.

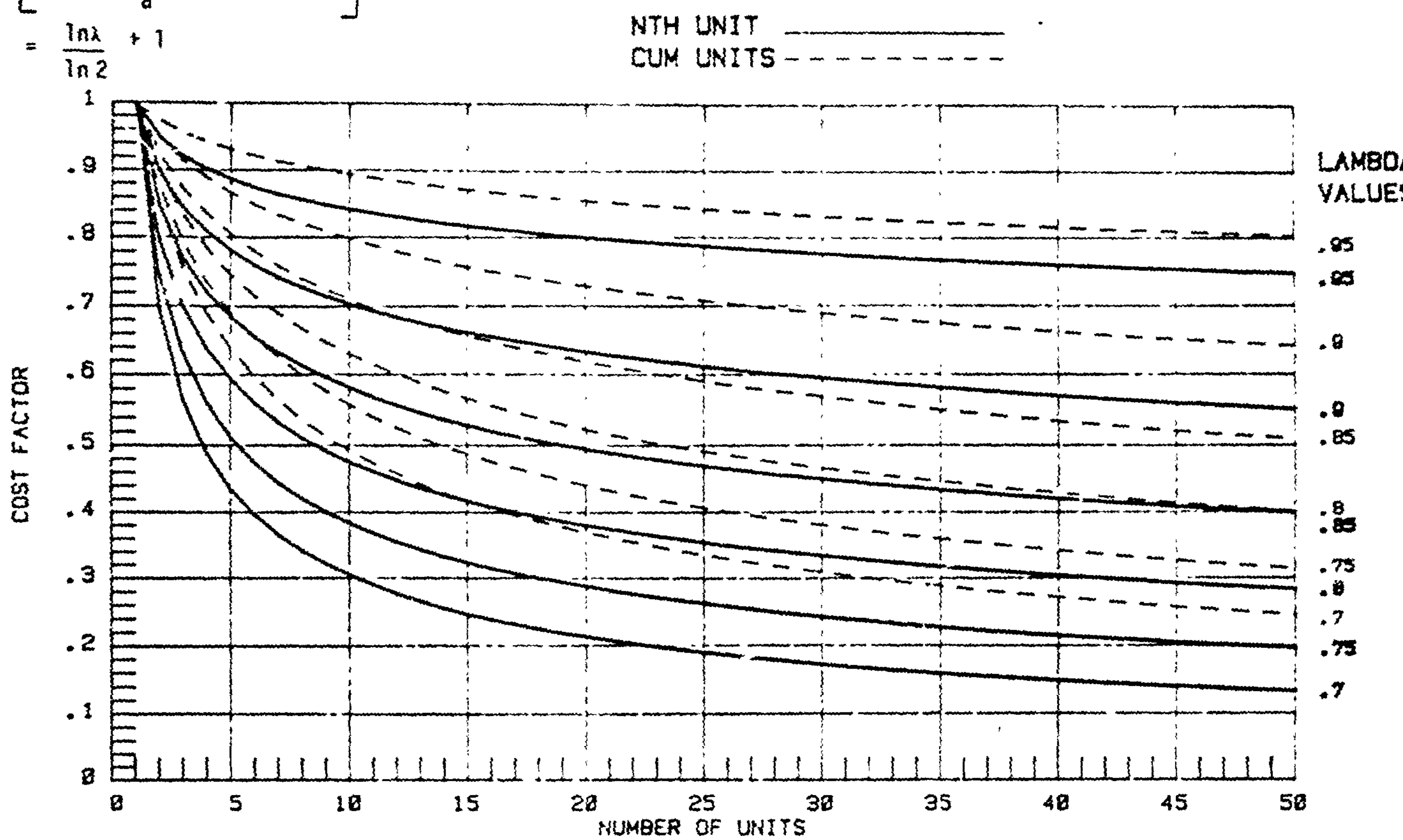
d. In space, crews are changed every 90 days.

All costs were computed in 1977 dollars. Launch facility costs are estimated as part of the ground systems cost and are not included in the transportation costs.

$$CF_{nth} = N^{\frac{\ln N}{\ln 2}}$$

$$CF_{cum} = \frac{1}{N}\left[\frac{(N + .05)^a - (1.5)^a}{a} + 1\right]$$

$$\text{where } a = \frac{\ln\lambda}{\ln 2} + 1$$



COST OF N UNITS = (TFU COST) X (NUMBER PRODUCED) X (CUMULATIVE COST FACTOR)

COST OF Nth UNIT = (TFU COST) X (Nth UNIT COST FACTOR)

Figure 4.- Learning curve factors.

SECTION 1 - SOLAR POWER SATELLITE

WBS 1.1 SOLAR POWER SATELLITE

Definition

The solar power satellite includes all functions required to receive sunlight, convert sunlight to electrical energy, conduct this energy to microwave transmitters, and transmit the energy to a ground station as a power beam.

Design Description

The solar power satellite consists of a silicon solar array photovoltaic energy conversion system supported by a truss structure, an attitude control system with attitude sensing and elctric thrusters, a power collection and distribution system to conduct the generated power to the energy conversion power transmitter interface, and a microwave power transmission system consisting of a phased array mounted on a two-tier structure (fig. 5). A more detailed description can be found in reference 2.

Cost

$\$5160 \times 10^6$/SPS including contingency growth (ref. 2). The cost estimate breakdown is shown in table VII. All figures have been rounded to the nearest million dollars.

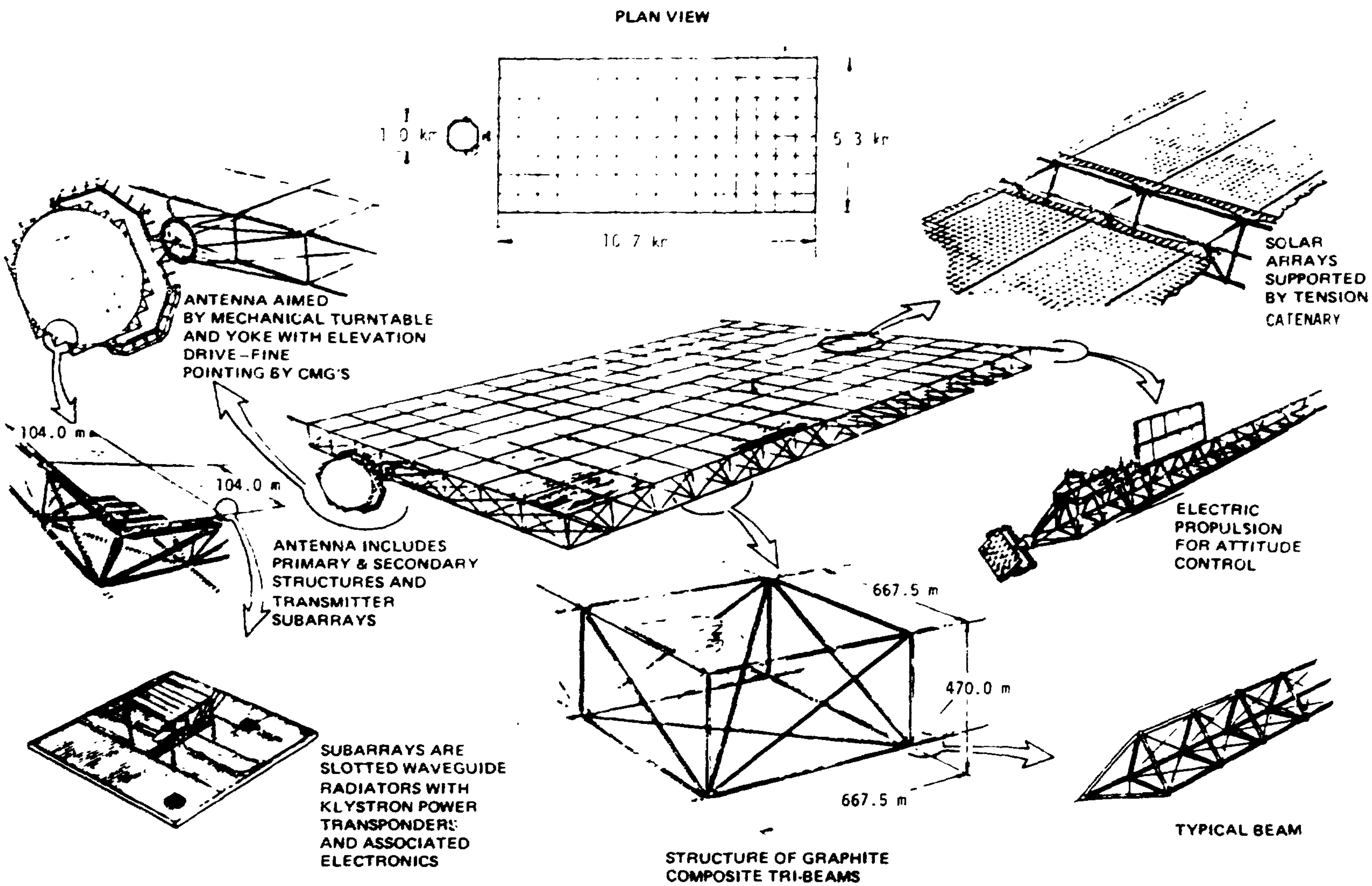


Figure 5.- Satellite.

TABLE VII.- SOLAR POWER SATELLITE
SUMMARY MASS AND COST ESTIMATE

WBS no.	Description	Mass M.T.	Nonrecurring costs including DDT&E $\$ \times 10^6$	TFU $\$ \times 10^6$	Avg. unit $\$ \times 10^6$
1.1	SPS	50 984			5 160
1.1.1	ENERGY CONVERSION	27 665			2 487
1.1.1.1	STRUCTURE	4 655	762	390	390
1.1.1.1.1	PRIMARY STRUCTURE	4 137	639	237	237
1.1.1.1.2	SECONDARY STRUCTURE	463	63	145	145
1.1.1.1.3	POWER DIST'N SUPPORT	55	60	7	7
1.1.1.3	SOLAR BLANKETS	21 145	5 031	1 729	1 729
1.1.1.3.1	SOLAR CELL PANELS	21 069		1 725	1 725
1.1.1.3.2	INTERBAY JUMPERS	76		3	3
1.1.1.4	POWER DISTRIBUTION	1 246	648	130	130
1.1.1.4.1	MAIN BUSES	1 090		77	77
1.1.1.4.2	AQUISITION BUSES	40		3	3
1.1.1.4.3	SWITCHGEAR	116		50	50
1.1.1.6	MAINTENANCE SYST	621			238
1.1.1.6.1	LASER ANNEALERS	178			203
1.1.1.6.2	DOCKING PORTS	4			6
1.1.1.6.3	TRACKS	439			29
1.1.2	POWER TRANSMISSION	13 629			1 538
1.1.2.1	STRUCTURE	324	526	22	22
1.1.2.1.1	PRIMARY STRUCTURE	154	497	11	11
1.1.2.1.2	SECONDARY STRUCTURE	171	29	11	11

TABLE VII (Continued)

WBS no.	Description	Mass M.T.	Nonrecurring costs including DDT&E $\$ \times 10^6$	TFU $\$ \times 10^6$	Avg. unit $\$ \times 10^6$
1.1.2.2	TRANSMITTER SUBARRAYS	10 389	2 766	774	774
1.1.2.2.1	KLYSTRONS	7 007	1 803	415	415
1.1.2.2.2	DIST'N WAVEGUIDE	434			29
1.1.2.2.3	RADIATING WAVEGUIDE	1903			126
1.1.2.2.5	WIRING HARNESS	91	6		2
1.1.2.2.6	CONTROL CIRCUITS	380	182	94	94
1.1.2.2.7	STRUCTURE	574			38
1.1.2.2.8	ASSEMBLY & CHECKOUT				70
1.1.2.3	POWER DIST'N & COND	2 539	1 357	282	282
1.1.2.3.1	CONDUCTORS	356			16
1.1.2.3.2	SWITCHGEAR	222			62
1.1.2.3.3	DC TO DC CONVERTERS	1 112			155
1.1.2.3.4	THERMAL CONTROL	536			45
1.1.2.3.5	ENERGY STORAGE	313	83	11	5
1.1.2.5	PHASE DISTRIBUTION	12	83	11	11
1.1.2.5.1	MASTER REF	< 1			1
1.1.2.5.2	SLAVE REPEATERS	1			9
1.1.2.5.3	CABLING	11			1
1.1.2.6	MAINTENANCE SYST	230			438
1.1.2.6.1	GANTRIES	91			254
1.1.2.6.2	DOCKING PORTS	17			23
1.1.2.6.3	CARGO HANDLING	5			4

TABLE VII (continued)

WBS no.	Description	Mass M.T.	Nonrecurring costs including DDT&E $\$ \times 10^6$	TFU $\$ \times 10^6$	Avg. unit $\$ \times 10^6$
1.1.2.6.4	CREW BUSES	30			62
1.1.2.6.5	COMPONENT XPORT	4			4
1.1.2.6.6	UNIDENTIFIED (20%)	29			56
1.1.2.6.7	TRACKS	54			36
1.1.2.7	ANTENNA MECH POINTING	134			121
1.1.2.7.1	CMG'S	128			119
1.1.2.7.2	STAR SCANNERS	< 1			1
1.1.2.7.3	INSTALLATION PROV	6			1
1.1.3	INFO MANAGEMENT	96	348		42
1.1.3.1	ANTENNA COMPUTERS	3			16
1.1.3.1.1	MAIN COMPUTERS	< 1			
1.1.3.1.2	SECTOR CONTROL	1			
1.1.3.1.3	AREA CONTROL	1			
1.1.3.1.4	RTU'S & INST	1			
1.1.3.2	ANTENNA CABLING	60			4
1.1.3.3	ARRAY COMPUTERS	2			11
1.1.3.4	ARRAY CABLING	31			11
1.1.4	ATTITUDE CONTROL	212	697		139
1.1.4.1	SENSOR SYSTEMS	1			
1.1.4.2	ELECTRIC PROPULSION	179			
1.1.4.2.1	THRUSTERS	6			
1.1.4.2.2	PROPELLANT	50			

TABLE VII (Concluded)

WBS no.	Description	Mass M.T.	Nonrecurring costs including DDT&E $\$ \times 10^6$	TFU $\$ \times 10^6$	Avg. unit $\$ \times 10^5$
1.1.4.2.3	PROPELLANT TANKS	4			
1.1.4.2.4	PROPELLANT FEED	1			
1.1.4.2.5	POWER PROCESSORS	112			
1.1.4.2.6	INSTALLATION PROV	6			
1.1.4.3	CHEMICAL PROPULSION	26			
1.1.4.4	STRUCTURE	6			
1.1.4.5	MAINTENANCE SYST	< 1			
1.1.5	COMMUNICATIONS	< 1	50		7
1.1.6	INTERFACE	236	651		88
1.1.6.1	STRUCTURE	175			23
1.1.6.2	TURNTABLE & DRIVE	38			40
1.1.6.3	ELECTRIC ROTARY JOINT	22			17
1.1.7	GROWTH & CONTINGENCY	9146			730

WBS 1.1.1. ENERGY CONVERSION

Definition

The energy conversion system includes the solar array support structure, solar blankets, power distribution, and maintenance provisions.

Design Description

The energy conversion system consists of a silicon solar array suspended trampoline-fashion in a hexahedral truss structure, and the power collection and distribution system required to conduct the generated power to the energy conversion/power transmitter interface.

Cost
$\$2487 \times 10^6$ (ref. 2)

WBS 1.1.1.1. SATELLITE STRUCTURE

Definition

The satellite structure includes all necessary members to support the solar blankets and other energy conversion subsystem hardware. It includes structural beams, beam couplers, cables, tensioning devices, and secondary structures.

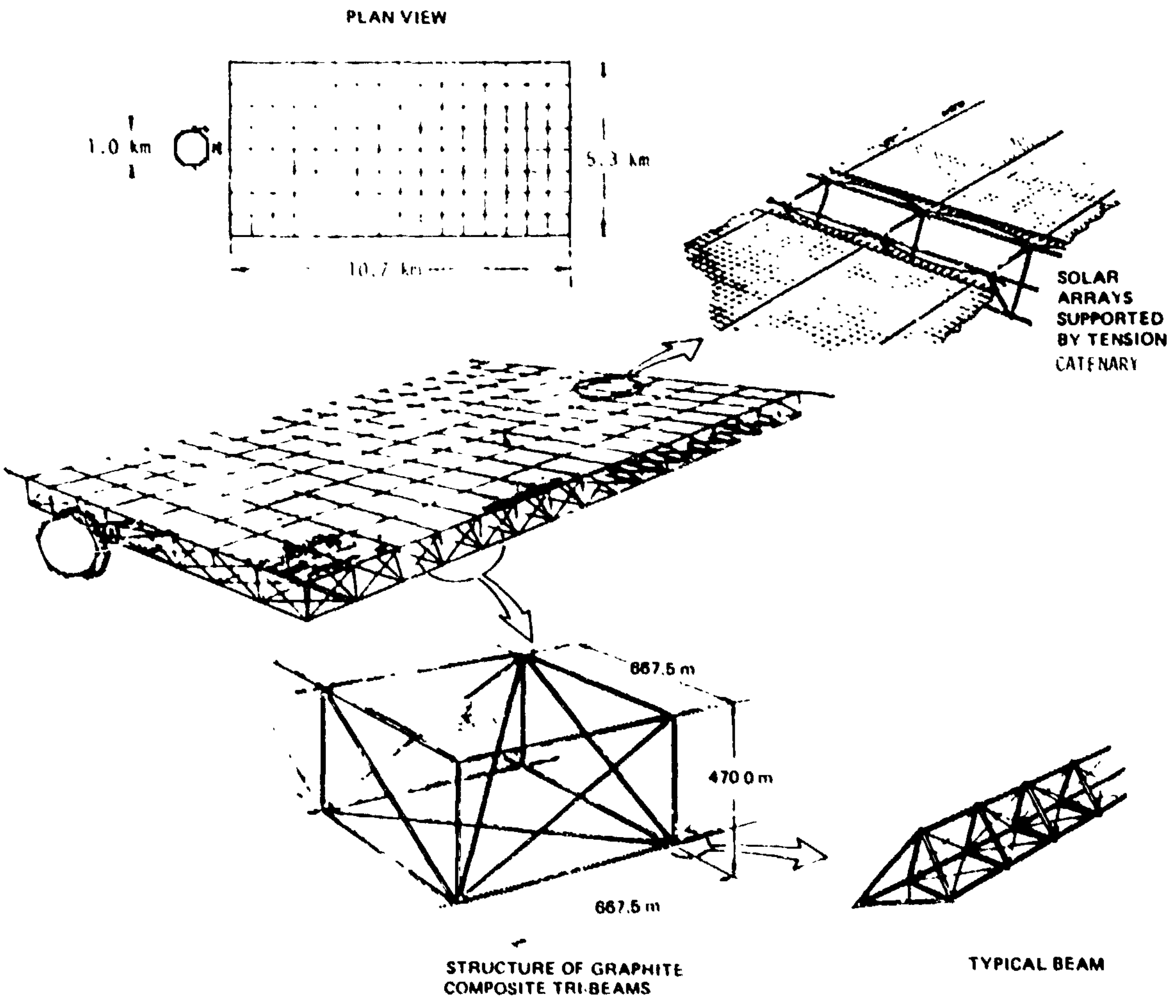


Figure 6.- SPS energy conversion.

Design Description

The energy conversion portion of the satellite is composed of 128 bays each 667.5 meters square by 470 meters in depth. The structure is 8 bays wide and 16 bays long. The main frame structure is a repeating hexahedral truss arrangement made up of two sizes of graphite composite tri-beams. The solar arrays are supported uni-axially using a catenary cable and uniform tension created by constant-force blanket tensioning springs at each blanket suport tape. The support for the power distribution main buses provides for thermal expansion at each vertical beam by using tension support ties from the buses to the main structure. Support provisions are included for ancillary subsystems mounted on the energy conversion structure.
OST

Cost

Production cost, \$390 10^6/SPS (ref. 2). Design and development, \$567 $\times 10^6$. Test and demonstration, \$77.6 $\times 10^6$.

WBS 1.1.1.1.1. PRIMARY STRUCTURE

Definition

The primary structure includes all of the members required to support the solar blankets. It includes the structural beams and beam couplers and required interfaces between the primary structure and the attachment points of the energy conversion subsystems.

Design Description

The main frame structure is a repeating hexahedral (box) truss arrangement made up of two sizes of graphite composite tri-beam (see fig. 7). The heavier 12.5-m beams support the uni-anxial solar array tensioning loads. The lighter 7.5-m beams are used in all other locations. Characteristics of the beams are shown below:

ITEM	TYPE A UPPER SURFACE LONGITUDINAL BEAM	TYPE B BEAM USED IN ALL OTHER LOCATIONS
SECTION	CLOSED	OPEN
Ref. side length	38 cm	38 cm
Mat'l. thickness	0.86 mm	0.71 mm
BEAM WIDTH	12.7 m	7.5 m
BATTEN SPACING	15.0 m	12.7 m
CRITICAL LOAD	17 480 N	7090 N
MASS/LENGTH	7.48 kg/m	4.11 kg/m

The satellite is composed of 128 square bays, 667.5 meters on a side and 470 meters deep (see fig. 8). The bays are arranged 8 wide by 16 long to provide an aspect ratio of two.

The energy conversion structure provides the strength required to tension the solar array blankets and decouple array blanket vibrational modes from control-system-induced excitation. It also provides the overall stiffness required to ensure control system stability. A hexahedral planar truss was chosen over tetrahedral and pentahedral options as the basic structural configuration offering the best compromise for strength, stiffness, and manufacturing ease. Space-fabricated beams of triangular cross section were selected for the basic structural elements of the truss for structural efficiency and to take advantage of existing designs for space-based beam fabrication machinery.

Graphite composite materials were selected for the beams to provide thermal stability and a high stiffness-to-mass ratio.

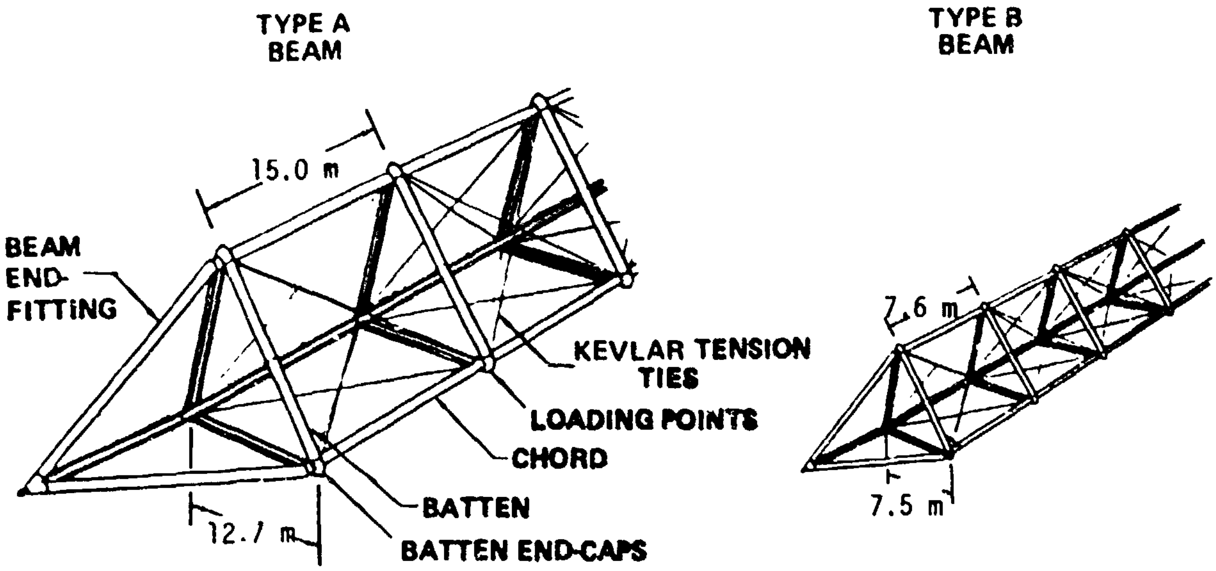


Figure 7.- SPS beam configurations.

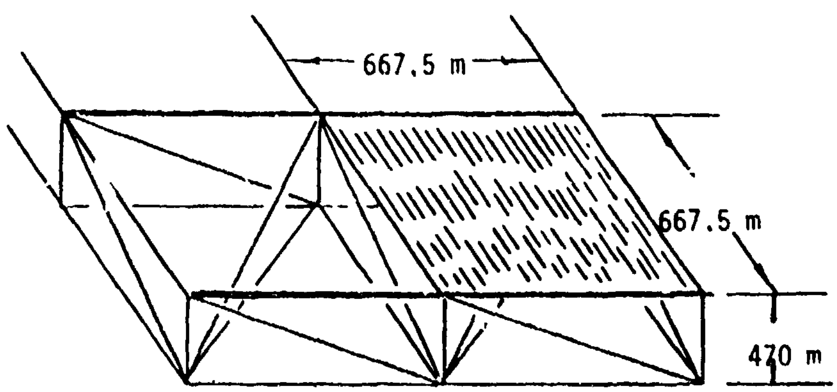


Figure 8.- SPS structural bay configuration.

Cost	$\$ \times 10^6$
Research	14.5
Engineering verification	26.1
Demonstration	77.1
Investment	521
Production	237 /SPS

WBS 1.1.1.1.2 SECONDARY STRUCTURE

Definition

The secondary structure includes all the hardware necessary to support the solar array, trampoline-fashion, within the structural bay. It includes cabling and tensioning devices attached between major structural beams and the solar array blanket segments.

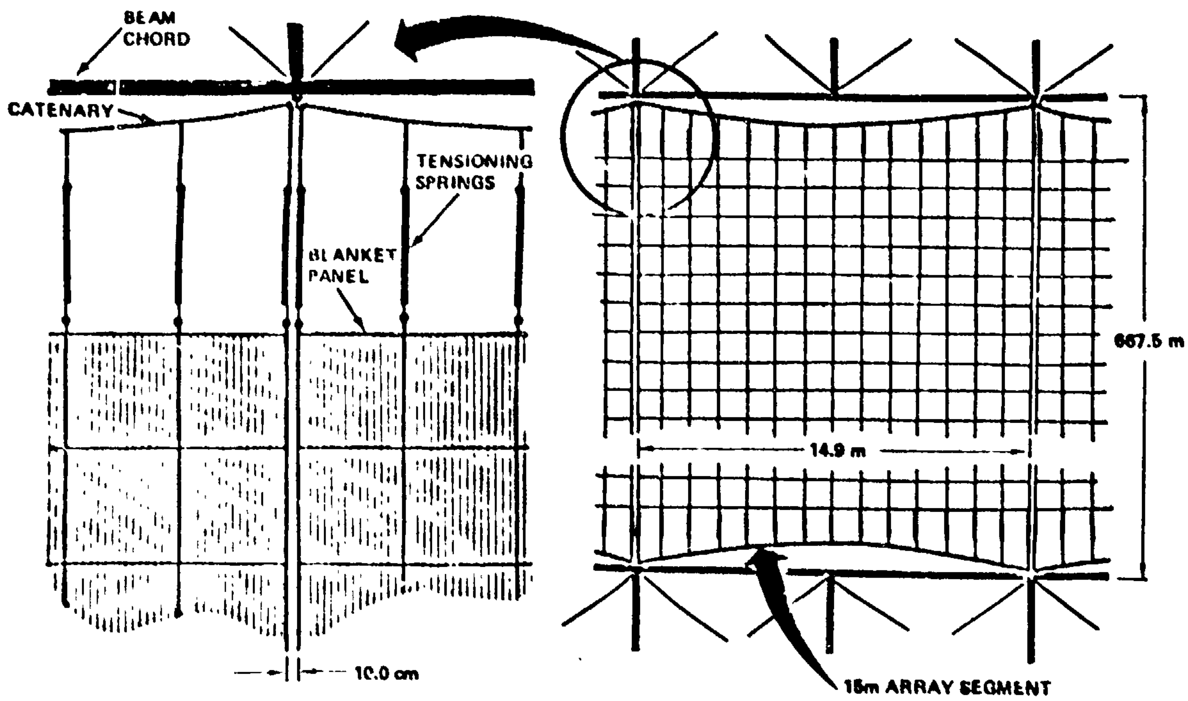


Figure 9.- SPS secondary structure.

Design Description

The method of supporting the solar blanket within the primary structural bays provides a uniform tension to the end of each solar array segment by the use of constant-force blanket tensioning springs at each blanket support tape. These springs are also attached to a catenary cable that is then attached to the primary structure upper surface beams at 15-m intervals. The springs are in compression, for better reliablility, and exert a uni-axial force of approximately 4.1 N to each blanket support tape.

The solar array blankets, attached to the sunfacing side of the structural bays, will experience significant temperature changes in going from unocculted to occulted conditions and vice versa (ref. 3, pp. 113-114). To accommodate any length changes that might occur in the solar array blanket during these temperature excursions, the blanket support selected was a catenary system that is compatible both with the major structural beams and the array blanket segments.

Cost (ref. 2)	$\$ \times 10^6$
Research	Included in space construction
Engineering verification	20.4
Demonstration	21.7
Investment	20.4
Production	145.2/SPS

WBW 1.1.1.1.3 POWER DISTRIBUTION SUPPORT

Definition

Power distribution support includes all of the hardware necessary to support the main power buses and the power acquisition buses.

Design Description

The support structure for the power distribution buses includes flex loops in the bus material at each vertical beam to allow for thermally induced length changes in bay length increments. The tension support ties from the buses to the main structure are preloaded to keep the natural frequency of the power bus system higher than that of the satellite. The tension/cable system selected, in addition to providing tension to compensate for thermal expansion, also tries to counteract the magnetic forces (caused by interconductor- and intraconductor-current-induced magnetic fields and the Earth's magnetic field) acting on the conductors. Additional strongbacks are used to maintain conductor positions between tension ties. Pallets are also provided to support the switchgear.

The bus support subsystem must

a. Provide a natural frequency substantially higher than the satellite.

b. Accommodate thermal expansion without applying large loads to the main satellite structure.

c. Maintain conductor spacing.

d. Be lightweight.

e. Have low ground fabrication cost.

f. Be easy to assemble in orbit, using mostly automated methods.

Trade-off studies conducted to satisfy these requirements led to the final selection of the main bus configuration shown in figure 10. This veiw shows several bays near the slipring end of the satellite, where there are 20 parallel buses. The three-point spring/cable ties to the main structure are shown, and the tension ties to reach the bus magnetic repulsion forces can be seen.

Cost (ref. 2)	$ \$ \times 10^6 $
Research	- - -
Engineering verification	22.9
Demonstration	13.7
Investment	22.9
Production	7.1/SPS

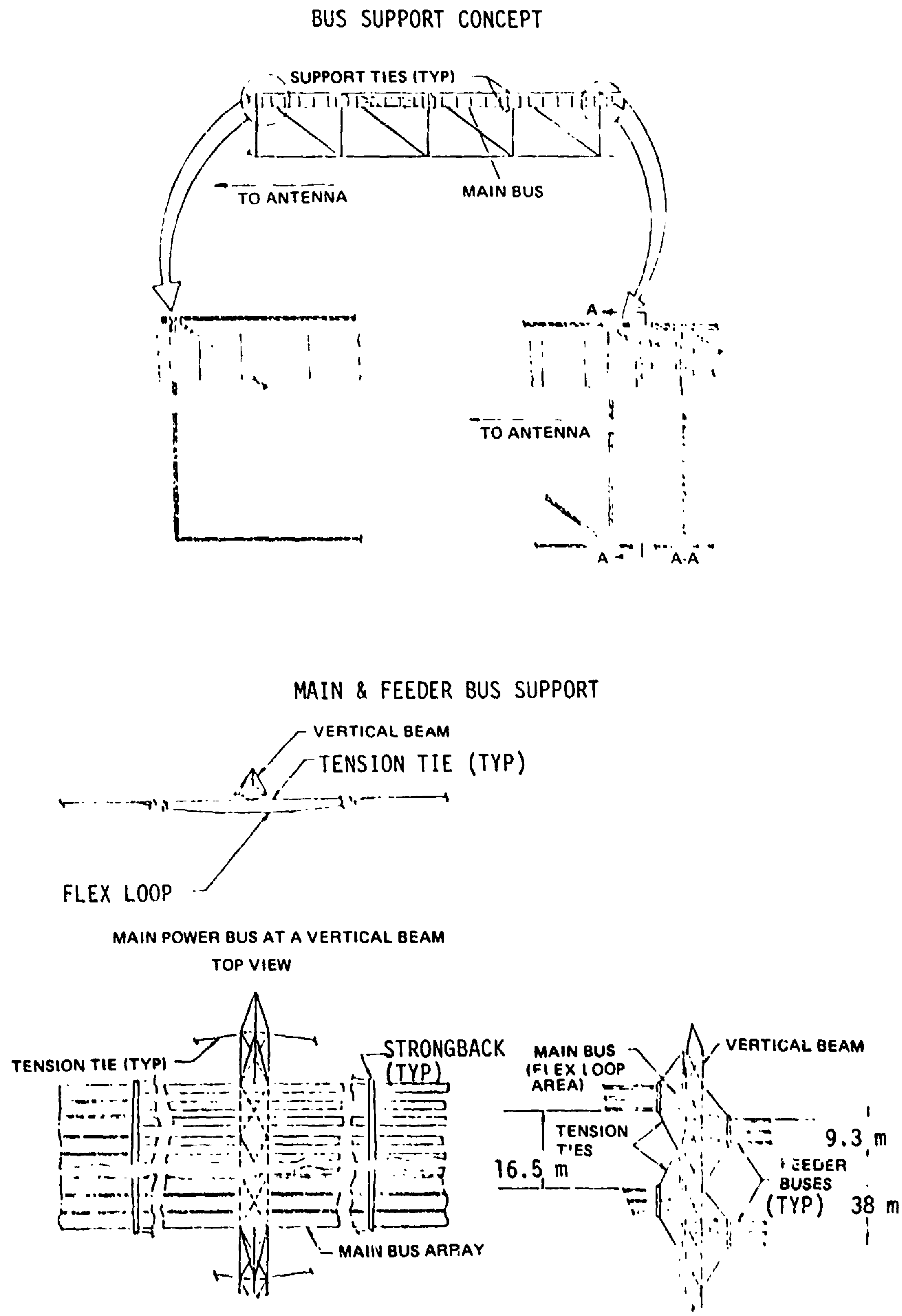


Figure 10.- SPS power distribution support.

WBS 1.1.1.3 SOLAR BLANKETS

Definition

The solar blankets convert solar energy to electrical energy and provide power to the power distribution and conditioning buses. This element includes the photovoltaic conversion cells, coverplates, substrates, electrical interconnects, and any integral attachment points. Excluded are tools and support equipment required for deployment and tensioning.

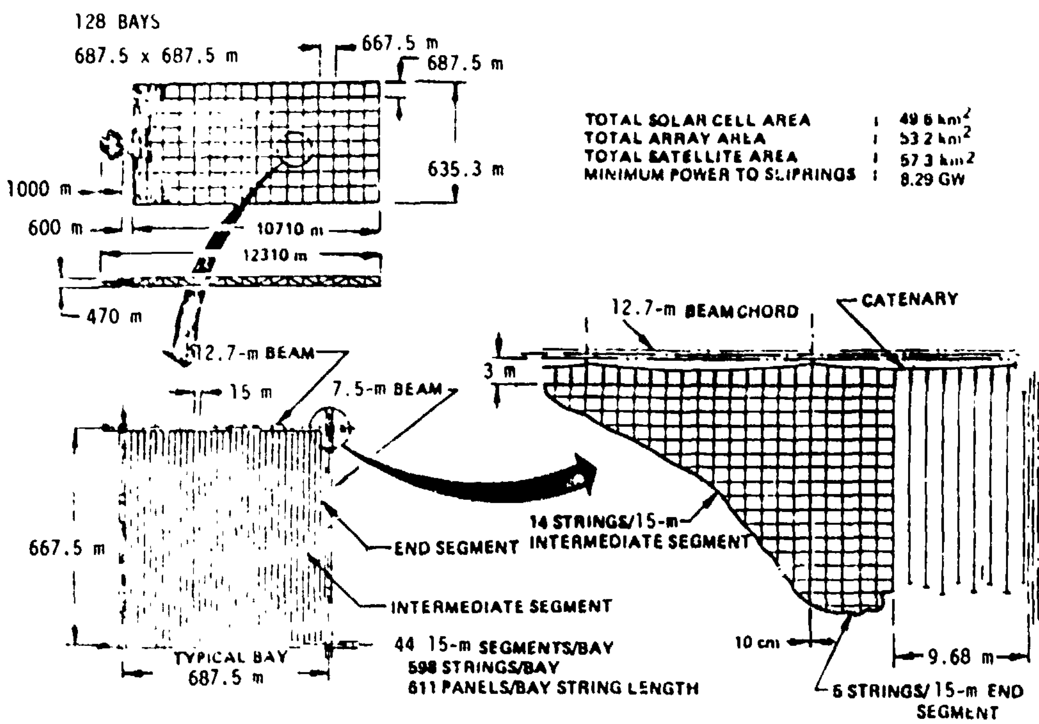


Figure 11.- Solar blankets.

Design Description

The solar array blankets provide for the conversion of solar energy into electrical energy and deliver the electrical power to the power distribution system in the voltage range of 42 to 44 kV. To generate this voltage, cell strings are connected in series. Jumper cabling is used to connect cell strings between satellite bays. Jumper cables are #12 insulated aluminum conductors. Fifty-μm thick silicon solar cells were selected as the basic energy conversion devices.

Cost (ref. 2)	$\$ \times 10^6$
Research	56.6
Engineering verification	35.7
Demonstration	591.3
Investment	4347.8
Production	1729/ SPS

WBS 1.1.1.3.1 SOLAR CELL PANELS

Definition

The solar cell panels are the hardware necessary to convert solar energy to electrical energy. This element includes the photovoltaic conversion cells, coverplates, substrates, electrical interconnects, and the attachment provisions for the catenary blanket suspension system.

Design Description

The basic energy coversion device is a 50 µm thick, 6.48-cm by 7.44-cm silicon solar cell with a textured surface to reduce reflectance. The cover is 75 µm thick, cerium-doped borosilicate glass which is electrostatically bonded to the solar cell. The substrate is 50 µm thick glass which is electrostatically bonded to the back of the cell. The cell is designed with both p and n junctions brought to the back of the cell. The interconnects are 12.5 µm thick, silver-plated copper. Complete panels are assembled by welding together module-to-module interconnections.

The basic panel adopted for design studies has a matrix of 222 solar cells, each 6.48 cm by 7.44 cm, connected in groups of 14 cells in parallel by 16 cells in series. Spacings between cells and edge spacings are shown in figure 12. Tabs are brought out at two edges of the panel for electrically connecting panels in series. Cells within the panel are interconnected by conducting elements printed on the glass substrate. Shadowing protection in provided by redundant shunting diodes at the panel level.

Panels are assembled to form larger elements of the solar array. The interconnecting tabs of one panel are welded to the tabs of the next panel in the string and then the interconnections are covered with a tape that also carries structural tension between panels. The 0.5-cm spacing between panels provides room for the welding electrodes, and also permits reasonable tolerances in the large sheet of 75-µm glass that covers the cells and the 50-µm sheets of substrate glass.

The panels are jointed in a matrix that is 14.9 meters wide by 656 meters long to form blanket segments. After assembly, the segment is accordion folded, at panel intersections, into a compact package for transport to the LEO assembly station.

Provisions are made for connection of the blanket segments with interbay jumpers to form power sectors. Conductor strips will be used to join strings and welding strips to join blanket segments. The conductor strips have a bossed section to connect with interbay jumpers.

The tapes at the end of blanket segments are extended and have attachment rings to connect to the tensioning springs of the catenary support system.

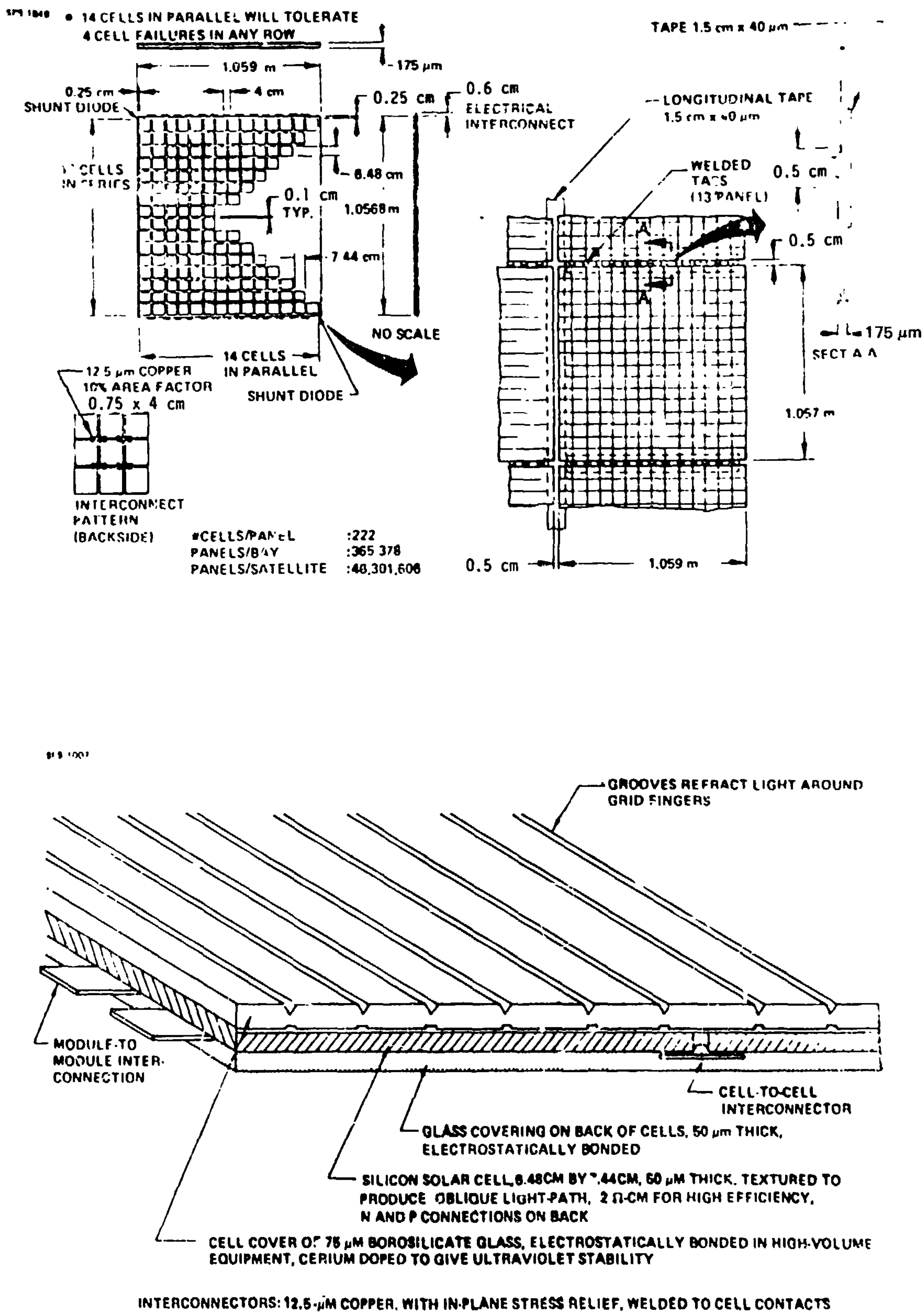


Figure 12.- Solar cell panels.

Important panel requirements were these:

a. The panel components and processes should be compatible with thermal annealing at 500°C. Annealing is required to compensate for radiation-induced solar cell degradation.

b. Presence of charge-exchange plasma during ion engine operation may necessitate insulating the electrical conductors on the panel.

c. The panel design should be appropriate for the high-speed automatic assembly of the 93 million identical panels required for each satellite.

d. Low weight and low cost are important.

Cost

1725×10^6/SPS, estimated by the mature industry method. $35/m^2 (ref. 2).

WBS 1.1.1.3.2 INTERBAY JUMPERS

Definition

Interbay jumpers provide for interbay pcwer distribution within a power sector and for connection to the acquisition buses of the power distribution system.

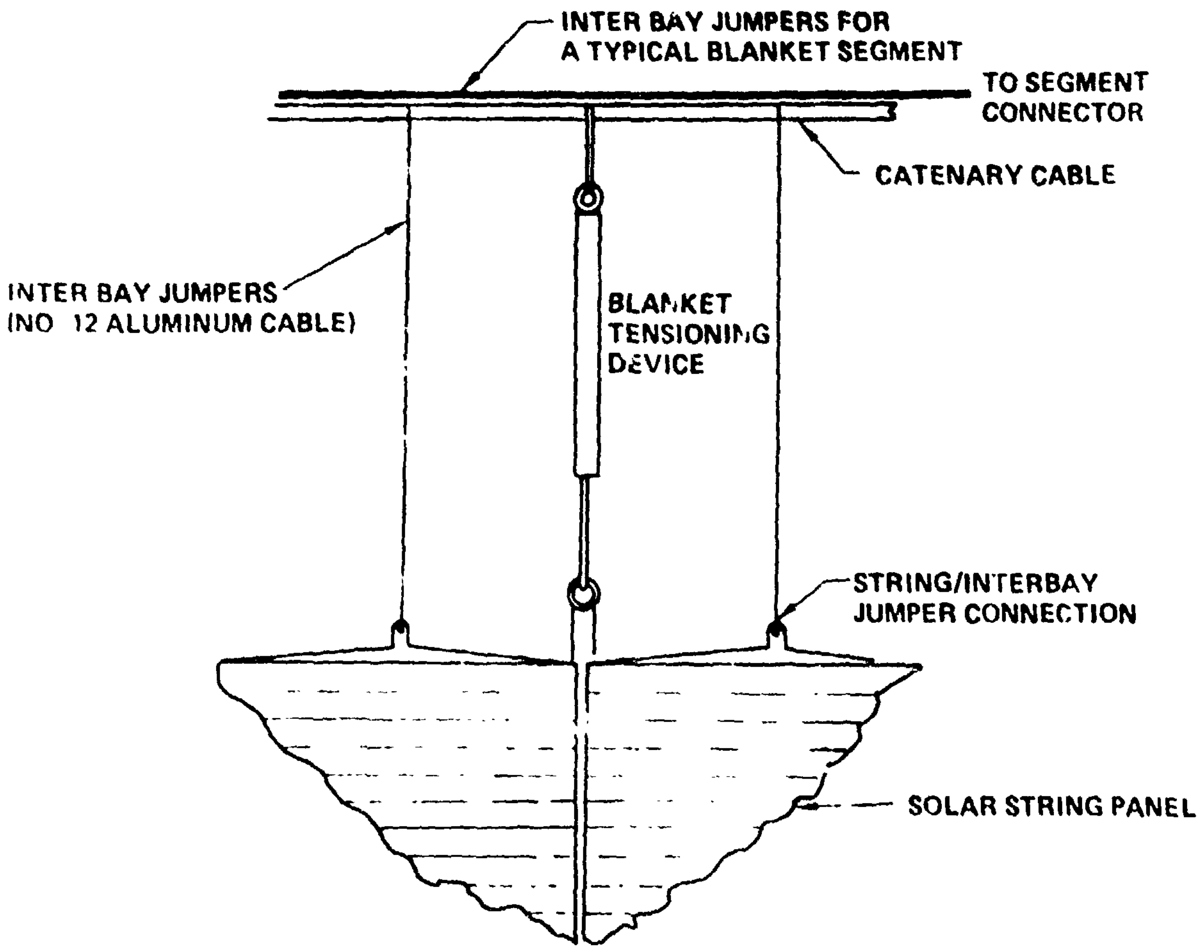


Figure 13.- SPS interbay jumpers.

Design Description

The interbay jumpers are #12 aluminum cable. One-blanket-segment jumpers are collected and run along the catenary cable to an end connector. This end connector is joined with the next bay's jumper and connection in the beam frame-work near the catenary support joint. This method was chosen as the simplest construction/maintenance scheme that would provide the necessary function.

Cost

$\$3.3 \times 10^6$/SPS (ref. 2)

WBS 1.1.1.4 POWER DISTRIBUTION

Definition

The power distribution element includes the power conductors, switchgear, and conditioning equipment required to transfer power from the solar blanket to the interfacing susbsytems. Also included are electrical cables and harnesses required to distribute power to equipment located on the energy conversion structure. Excluded are data buses which are included in the information management and control subsystem (WBS 1.1.3).

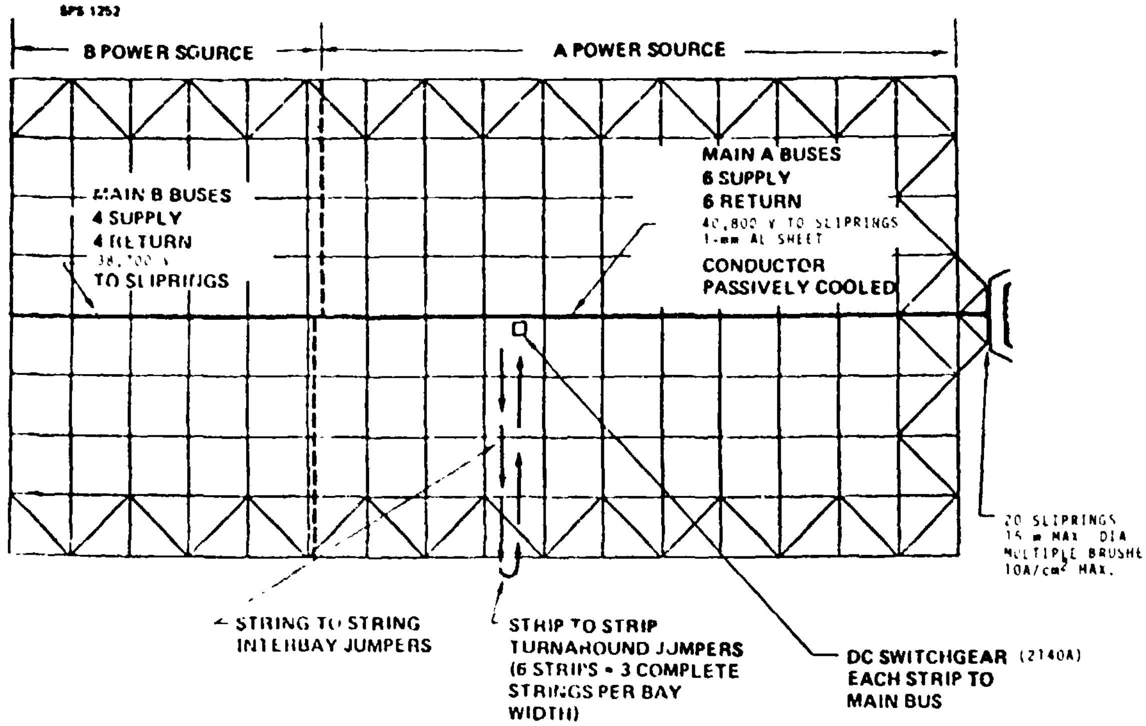
Design Description

An overall SPS functional diagram is shown in figure 14. The power distribution system for the energy conversion portion of the SPS is divided into two power areas (power sources A and B). Six main power buses (positive and return) are used to route power from the power source A portion of the array and four main power buses (positive and return) are used from power source B. The B power source is located farther from the microwave power transmission antenna. The main power buses are aluminum sheets, 1-mm thick, the width of which is proportional to the current flowing through them. The solar arrray is divided into 96 power sectors. At each sector, power is fed to the main distribution switchgear for power system control and operation. The switchgear includes both d.c. circuit breakers and disconnect switches. Acquisition buses are used to collect power from the solar cell strings and to route the current flow to the switchgear. Acquisition buses are triangular-shaped, 1-mm thick, sheet conductors whose width increases as each additional solar cell string is connected. Maximum width occurs at the point where the power feeder to the switchgear is attached.

Four power processors are installed on the energy conversion portion of the SPS to provide power to housekeeping systems installed thereon. Some energy storage is also provided.

Cost	$\$ \times 10^6$
Research	- -
Engineering verification	34.8
Demonstration	306.6
Investment	306.6
Production	130.3/SPS

SPS 1252



Power Distribution Concept

SPS 2021

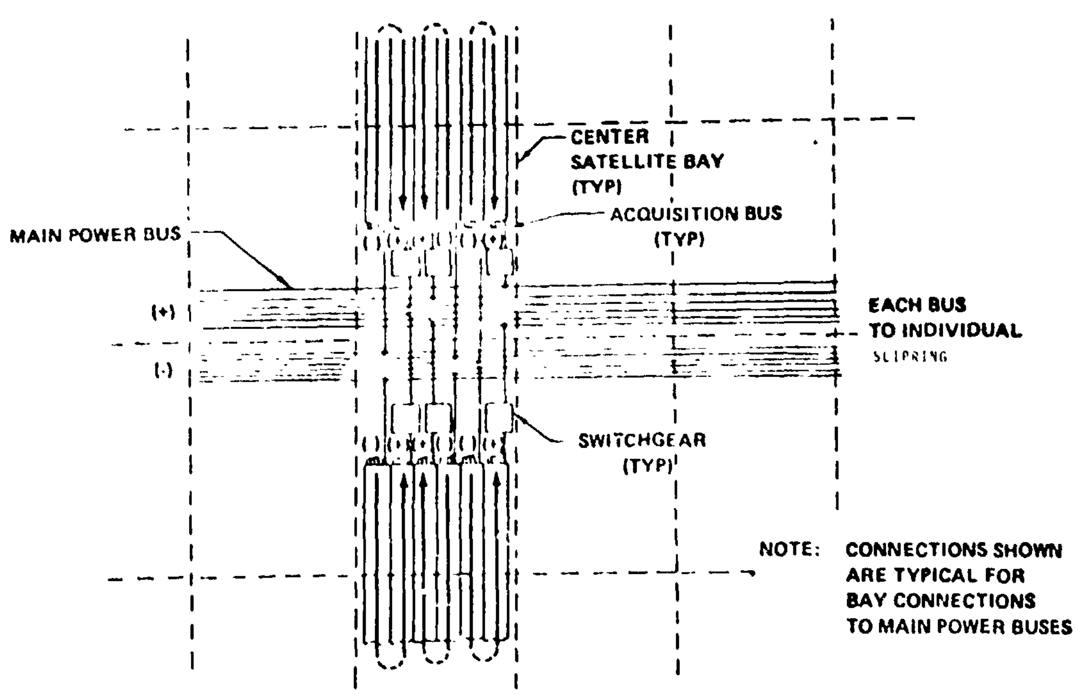


Figure 14.- SPS power distribution system.

WBS 1.1.1.4.1 MAIN BUSES

Definition

The main buses are the power conductors required to transfer power from the power sector switchgear connections to the interface system power distribution elements.

Design Description

The main power buses are 1-mm thick, conductor grade aluminum sheets. The width of the sheets is proportional to the bus current. There are a total of 20 main power buses: power source A - 6 positive and 6 return; power source B - 4 positive and 4 return. The maximum width of an A power bus is 3.58 meters. The maximum width of a B power bus is 2.54 meters. See figure 15.

Cost

$\$77 \times 10^6$/SPS, estimated using the Boeing PCM Program (ref. 2, p. 36).

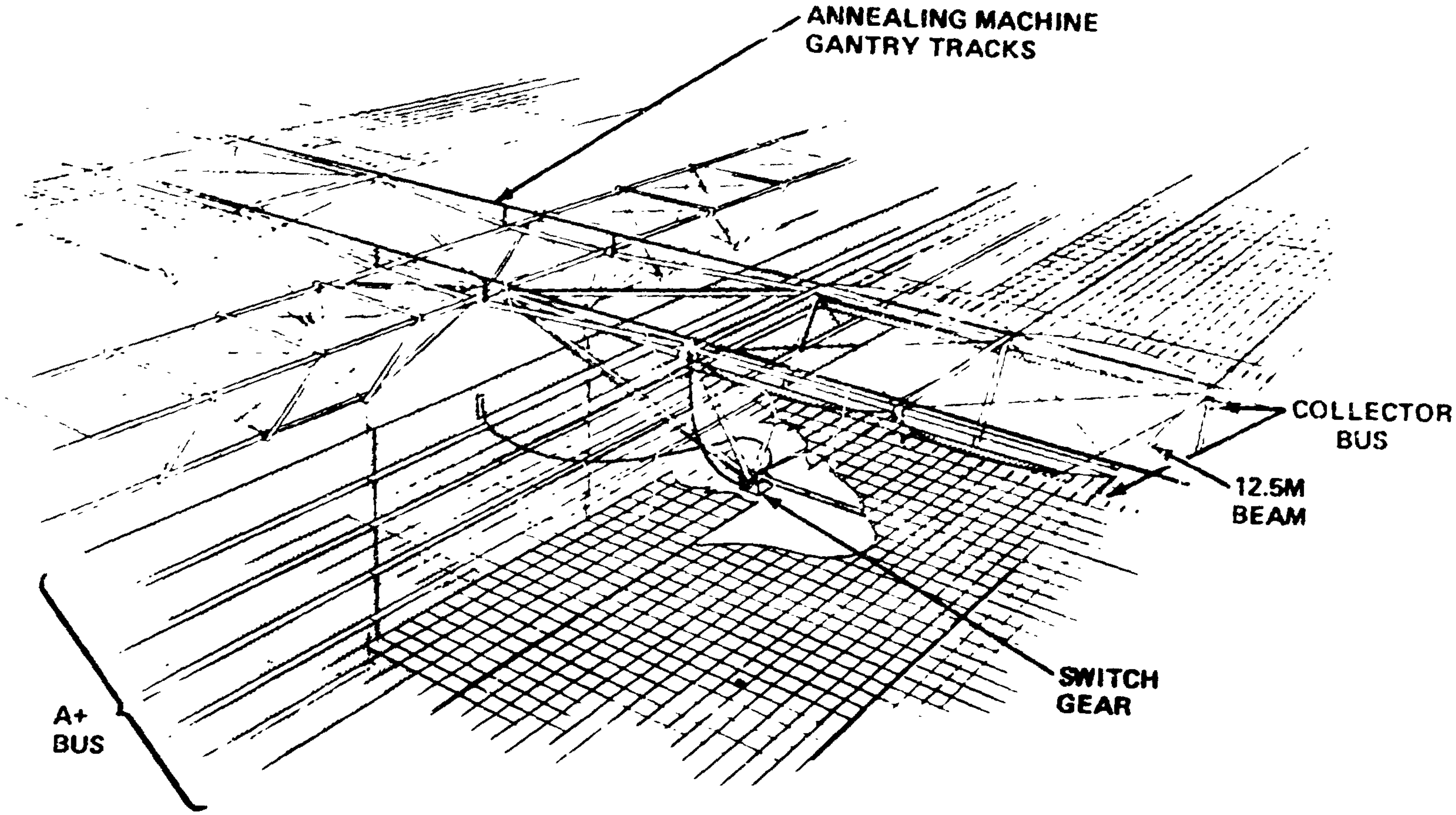


Figure 15.- SPS main power buses.

WBS 1.1.1.4.2 ACQUISITION BUSES

Definition

The acquisition buses are the conductors required to collect power from the solar cell string and route it to the power sector switchgear installation.

Design Description

An acquisition bus is a 1-mm thick, triangular-shaped, aluminum conductor. Its length is approximately 110 m and its maximum width is 41.5 cm. Provisions are included for attaching the cell strings to the bus.

The formation of high voltage in the solar array is accomplished by connecting approximately 78 000 sets of solar cells in series. The strings must traverse four bays and then return across the same four bays. The purpose of the acquisition buses is to provide a current path between cell strings at the end of the fourth bay (farthest from the switchgear) and to collect the current from the cell strings at the end of the first bay (nearest the switchgear) for subsequent connection to the switchgear on the positive end and to the return bus on the negative end of the power sector. See figure 16.

Cost

$\$3 \times 10^6$/SPS, estimated using the Boeing PCM program.

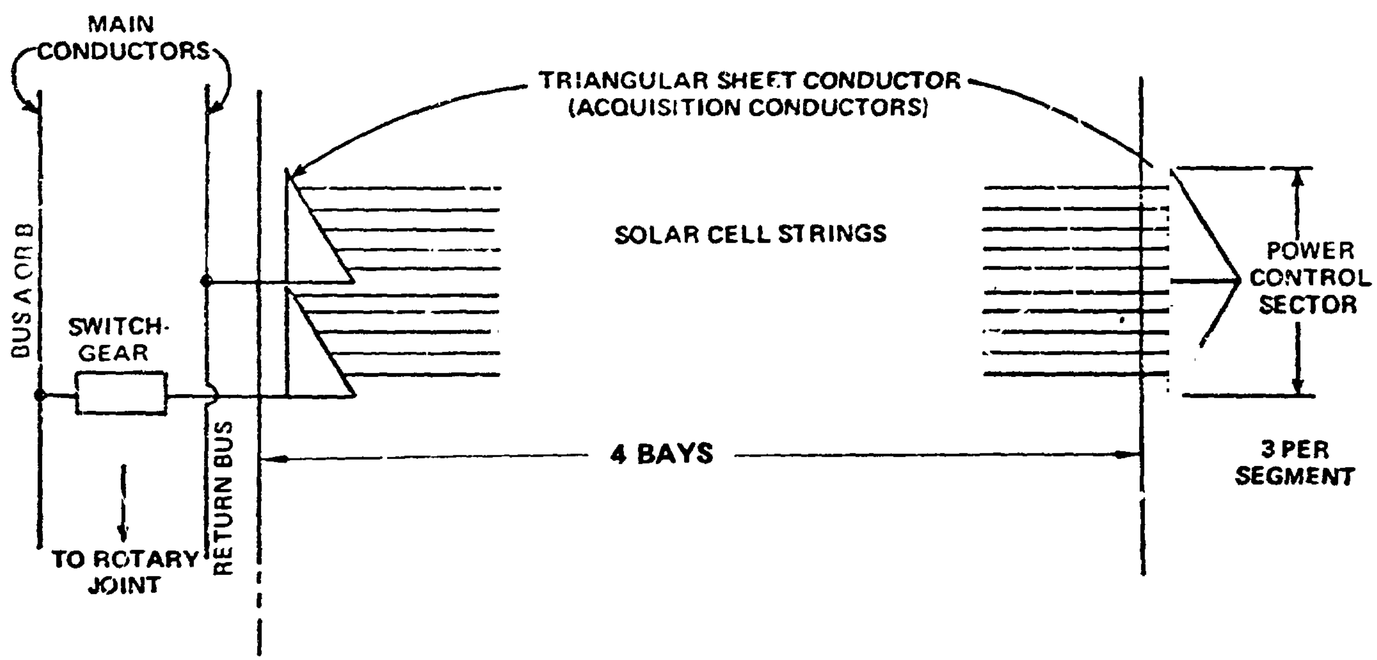


Figure 16.- SPS acquisition buses.

WBS 1.1.1.4.3 SWITCHGEAR

Definition

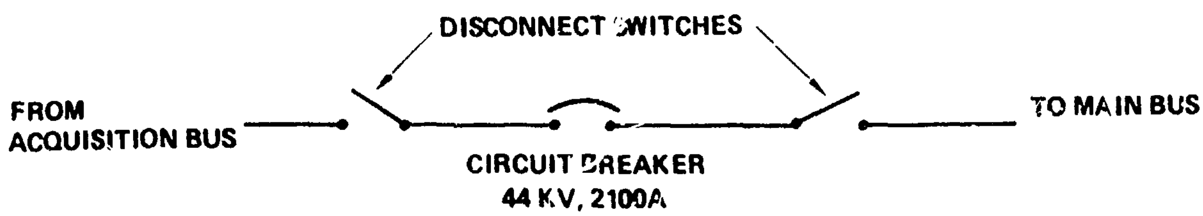
The switchgear includes the circuit breakers (required for power system operation and control), the disconnect switches, (required for isolation for maintenance or repair of the energy conversion portion of the main power distribution), and the control system.

Design Description

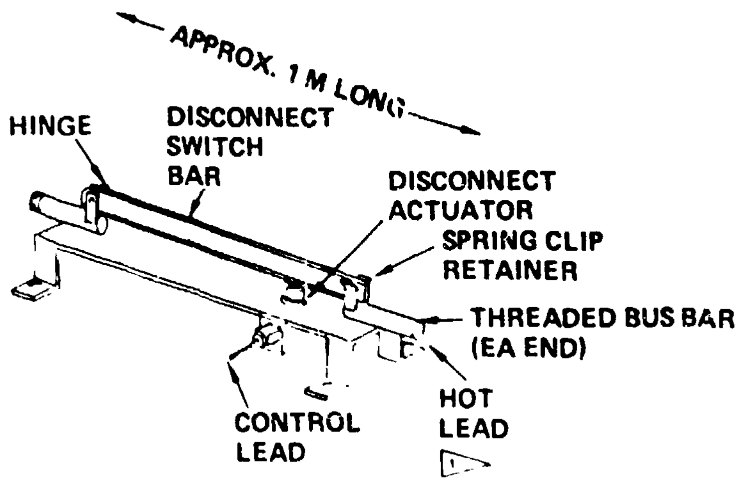
The circuit breakers are of the vacuum type with nominal ratings of 44 000 V and 2 100 A. They include circuits for undervoltage, overvoltage, overcurrent, and reverse current detection and operation. Transducers for sensing sector current and voltage are also included. The disconnect switches contain provisions for remote operation as well as local. They are to be operated only when no current is flowing. See figure 17.

Cost

$\$50 \times 10^6$/SPS, estimated using the Boeing PCM program.



Simplified Switchgear Schematic
(Typical 96 Places)



Disconnect Switch

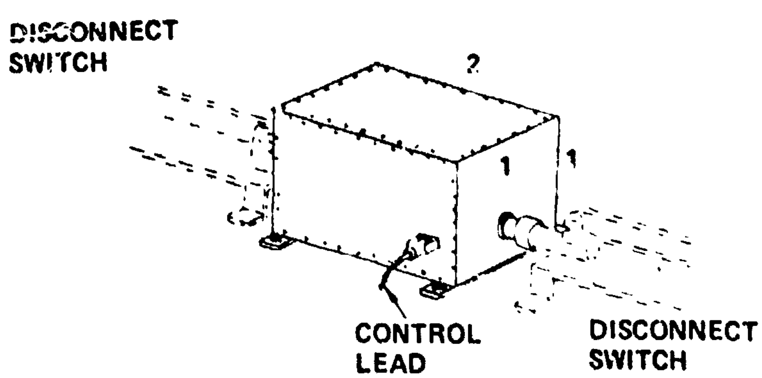


Figure 17.- SPS switchgear.

WBS 1.1.1.6 MAINTENANCE SYSTEM

Definition

The maintenance system includes maintenance access provisions and solar array annealing hardware.

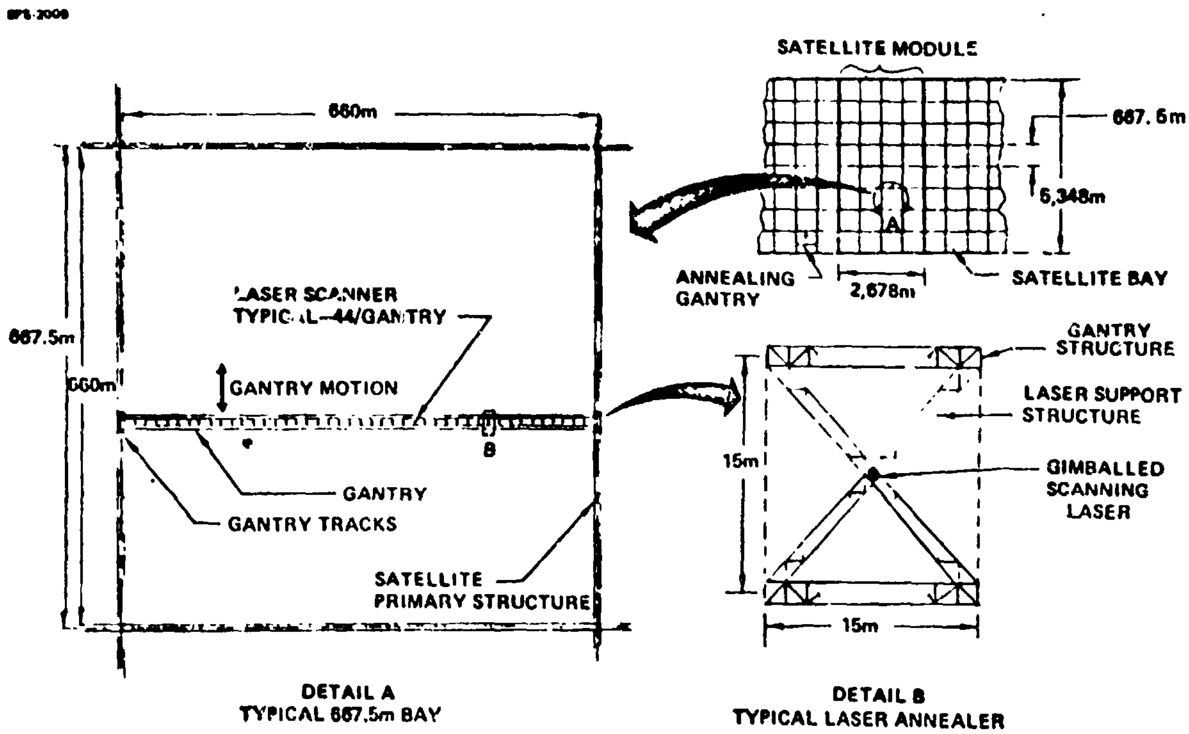


Figure 18.- Laser annealing concept.

Design Description

This section describes the built-in energy conversion system maintenance equipment to accomplish the maintenance operations given in WBS 1.2.3.3.

The main power buses are suspended on a cable-support system below the upper surface of the solar collector. These buses are not accessible by a cherrypicker mounted on the annealing machine gantry for two reasons: (1) a cherrypicker could not find a clear path through the structural beams (there are cable stays in the beams) and there is no room between the ends of the solar arrays and the beams, and (2) the main bus stack could be as tall as 60 meters. Consequently, the main buses and the switchgear assemblies must be accessed from below the solar array.

Figure 19 illustrates the main bus access concept. A track beam is required to parallel the main buses. The track beam is tied into the parallel SPS structural beam to provide torsional rigidity. Each of the legs of this track system would have a carriage attached to which a flying cherrypicker would dock.

The basis for the maintenance access provisions is given in Section 13 of the Operations and Systems Synthesis document (ref. 4).

The annealing gantry with its equipment, shown in figures 20, 21, and 22, includes the following:

a. Gantry structure that spans one bay, 667.5m.

b. Wheel and drive system for moving about the array on the track network.

c. Laser unit. This includes a set of CO_2 electric discharge lasers, scanning optics, power processors, thermal control equipment, motive equipment for moving along the gantry, and a docking port for a flying cherrypicker.

d. Solar array atop the gantry to power the lasers. This array precludes the need to obtain power from the SPS array.

e. Power busing to deliver array power to the annealer system.

Cost (ref. 2, p. 44) $\$ \times 10^6$

Research		Included in solar blanket research
Engineering verification		66.3
Demonstration		319.3
Investment		152.3
Production		
1.1.1.6.1	Annealers	
	Gantry	9.6
	Array	2.4
	Busing	1.1
	Laser power supply	24.3
	Thermal control	45.7
	Lasers	82.2
	Contingency	38
		203.3
1.1.1.6.2	Docking ports	5.7
1.1.1.6.3	Tracks	29
		238/SPS

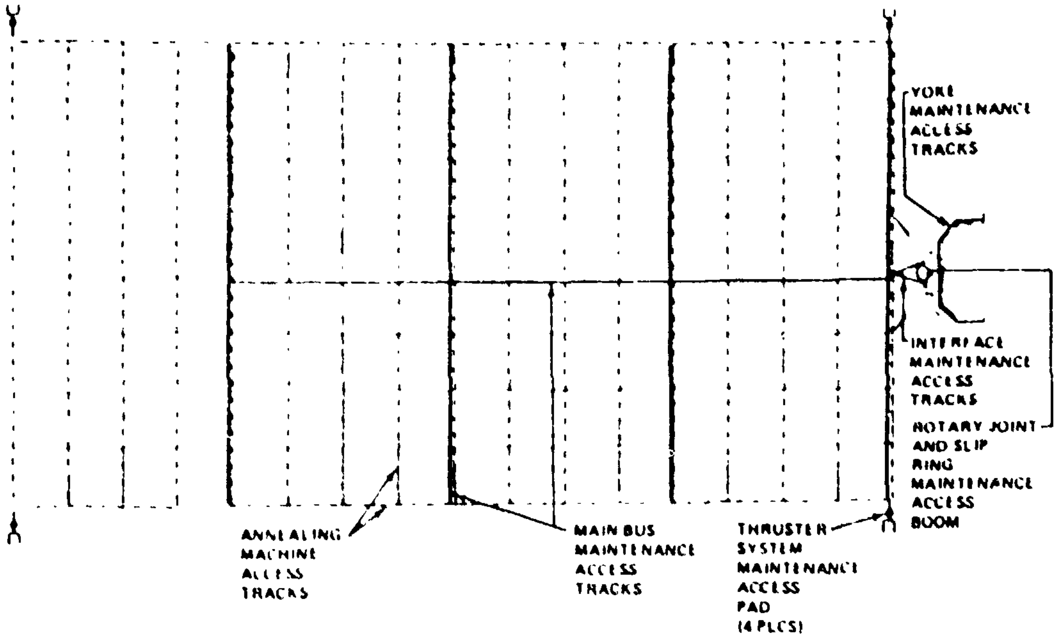


Figure 19.- SPS maintenance access system.

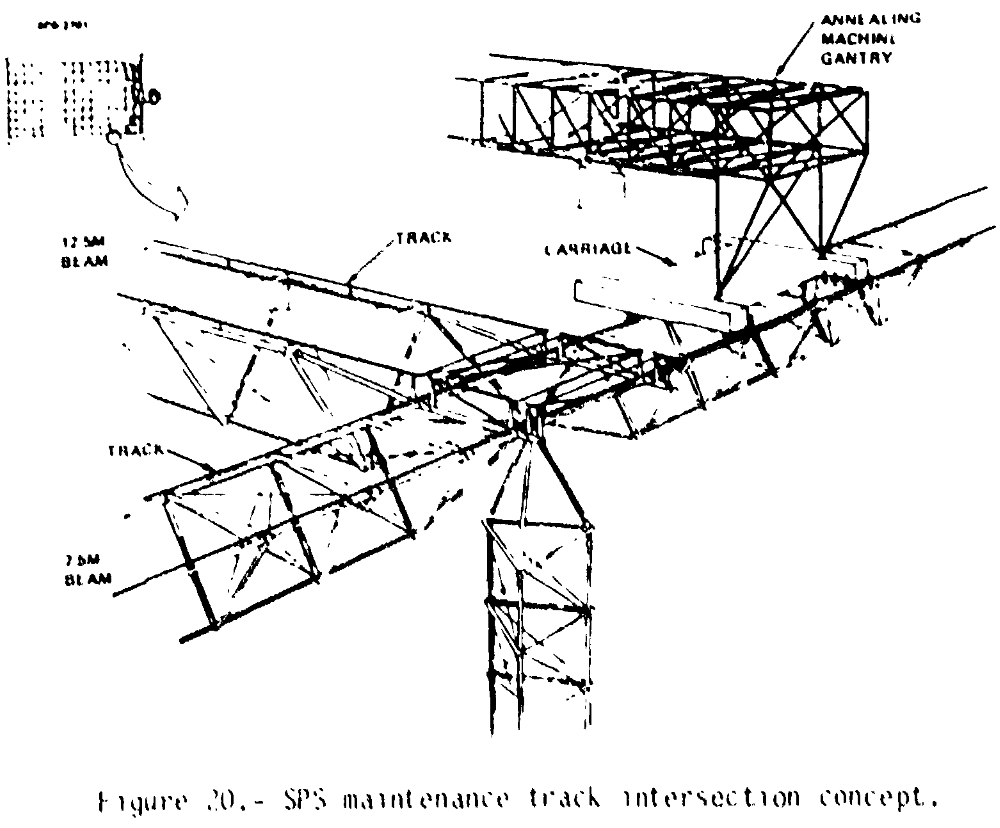


Figure 20.- SPS maintenance track intersection concept.

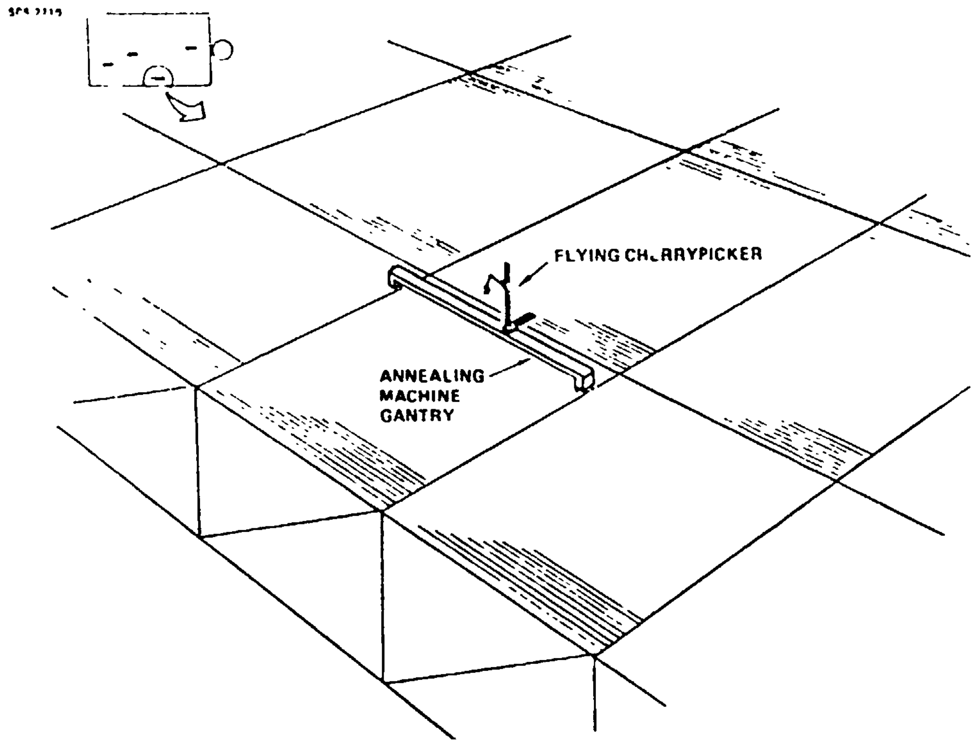


Figure 21.- Solar array top surface maintenance access system.

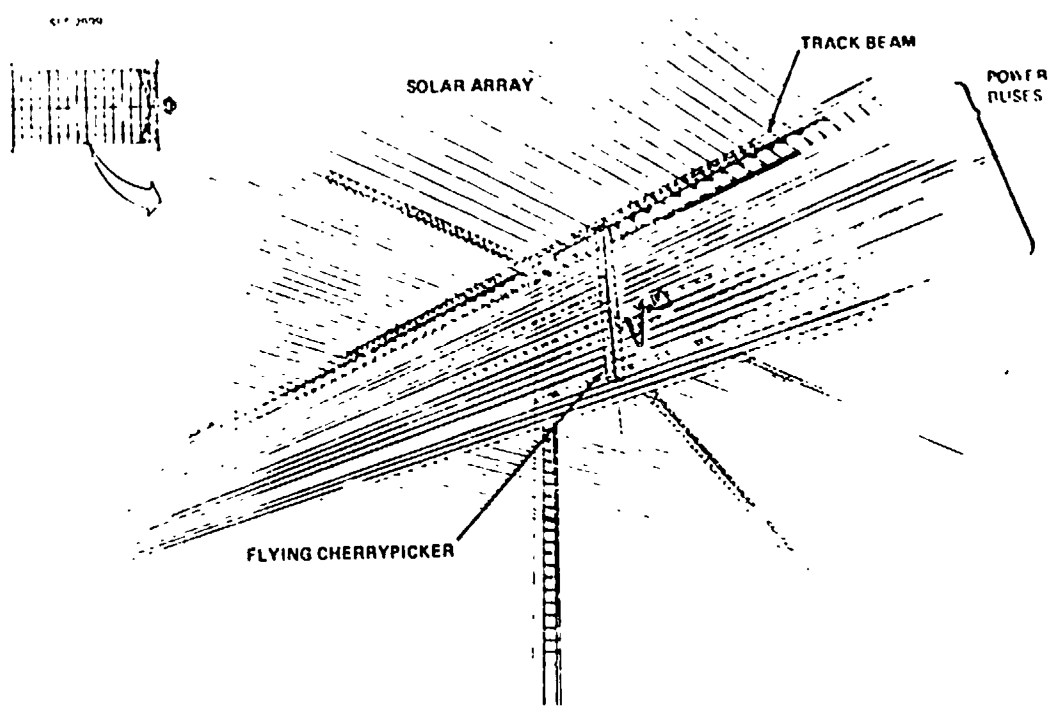


Figure 22.- Main bus maintenance access system.

WBS 1.1.2 MICROWAVE POWER TRANSMISSION SYSTEM

Definition

The microwave power transmission system (MPTS) includes all elements needed to convert d.c. electric power to microwave power at 2.45 GHz and to direct this power in the form of a coherent beam to the receiving antenna on Earth. The major subelements are

1.1.2.1 Structure
1.1.2.2 Subarrays
1.1.2.3 Power Conditioning and Distribution
1.1.2.4 Reference Phase Distribution
1.1.2.5 Thermal Control (allocated to the other subsystem elements; no mass or cost is attributed to this element)
1.1.2.6 Maintenance Equipment
1.1.2.7 Antenna Mechanical Pointing

Also mounted physically on the antenna but not included in this WBS element are portions of

1.1.3 Information Management and Control
1.1.5 Communications

Design Description

The power transmitter is a large, planar, phased array made up of subarrays mounted on a two-tier (primary and secondary) structure. Each of the 7220 subarrays includes from 4 to 36 klystron power amplifiers and associated control electronics. The quantized variation in the number of klystrons per subarray, and hence power density, provides an approximation of a 9.54-dB truncated Gaussian power illumination taper. This taper reduces sidelobe intensity about 7 dB (factor of 5) below the levels projected for a constant illumination and improves aperture-to-aperture beam efficiency.

The subarrays are supported by the secondary structure, which is in turn supported by the primary structure. DC power from the solar array is fed to the subarrays through power processing and protective switchgear. About 15 percent of the power is processed to alternate voltages and regulated as necessary. The remainder is provided directly to the klystrons. All power is connected through interrupters and disconnect switches for fault isolation.

The reference phase distribution system distributes a coherent reference clock signal to all subarrays. This signal and the uplink (pilot) signal are phase-conjugated at each klystron power amplifier to provide low level RF drive signals of the correct phase. These signals are amplified to about 5 watts by solid-state preamplifiers and fed to each klystron; the klystron RF power output is approximately 70 kW each.

The antenna mechanical pointing includes star sensors and control moment gyros (CMG's) that aim the antenna toward its ground station to an accuracy of about one minute of arc. Computation is provided by the information management and control system; ground commands to correct residual aiming errors can be input through the communications system if necessary. Continuous desaturation of the CMG's is provided by a feedback loop that commands the antenna turntable drive. Low-pass filters and a compliant antenna mechanical suspension permit the CMG's to retain fine pointing control authority.

The antenna maintenance equipment includes crew provisions and mobility systems to support periodic removal and replacement of failed equipment.

Cost

The transmitter cost estimate is the sum of element estimates and is $\$1538 \times 10^6$. Cost details are given in element descriptions in the following pages (ref. 2).

WBS 1.1.2.1.1 SPS TRANSMITTER PRIMARY STRUCTURE

Definition

The primary structure is the main structure that provides overall shape and form to the transmitter.

Design Description

The primary structure is a pentahedral truss made up of 1.5-meter tri-beams (fig. 23) fabricated in space by a beam machine. Feedstock for the beam machine is a graphite filamentary composite thermoplastic material shipped from Earth in roll and/or nested form. The beam elements are protected with thermal control and ultraviolet screen coatings and by selective multilayer insulation in the area where transmitter heat creates a temperature that would otherwise exeed the capability of the material. Beam sections are terminated in centroidal fittings with mechanical attachments that include joint-slop takeup provisions to maximize structure rigidity.

Cost	$ $\times 10^6$
Research	- -
Engineering verification	17.4
Demonstration	250.9
Investment	228.7
Production	11 /SPS

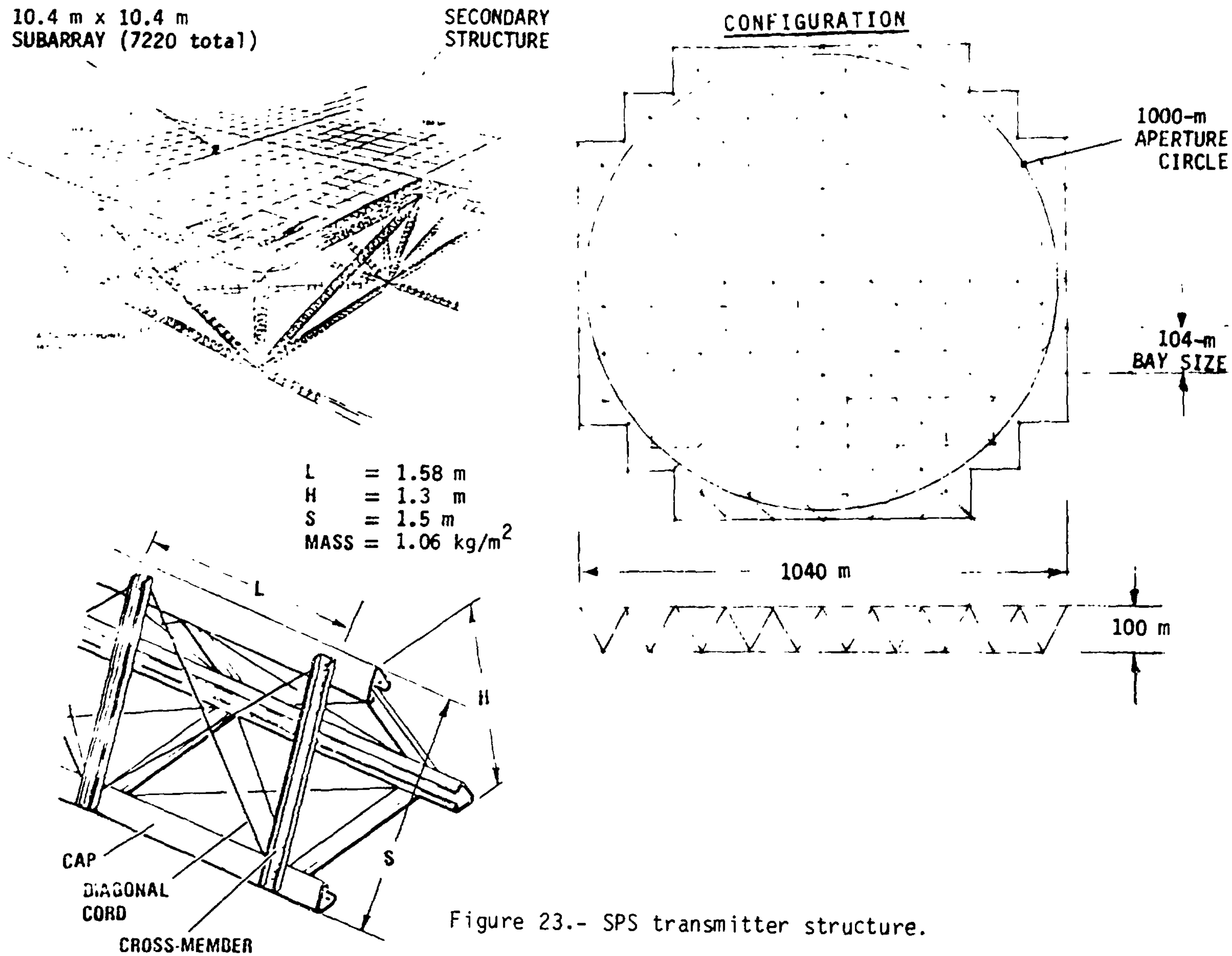


Figure 23.- SPS transmitter structure.

WBS 1.1.2.1.2 SPS TRANSMITTER SECONDARY STRUCTURE

Definition

The secondary structure includes all members necessary to support the transmitter subarrays and other power transmission subsystems on the primary structure.

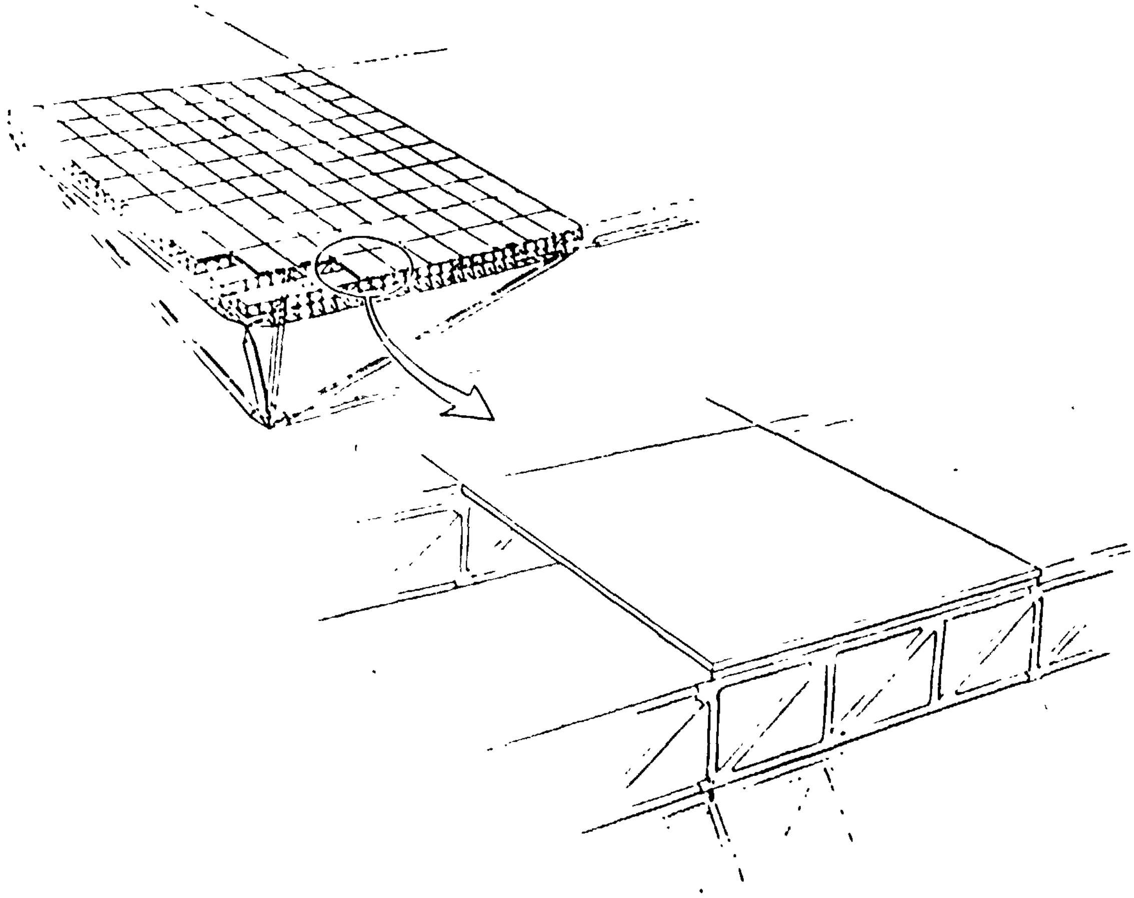


Figure 24.- Transmitter secondary structure.

ORIGINAL PAGE IS
OF POOR QUALITY

Design Description

The secondary structure is a bridge on the MPTS primary structure and provides the base for mounting the transmitter subarrays, each of which is installed on a three-point mount. The basic element of the secondary structure is a 10.4-m beam, 2.5 m in depth, space-fabricated from graphite composite materials. The secondary structure is continuous around the perimeter of the antenna. The member spacing is the width of one subarray in one direction and twice that in the other direction.

Cost

Research	- Carried under array structure
Engineering verification	- EVTA does not require a secondary structure
Demonstration	- $\$17.9 \times 10^6$ DDT&E plus $\$11.3 \times 10^6$ for flight hardware
Investment	- None
Production	- Feedstock costed at $66/kg (this will be a high-temperature composite for a total per SPS of $\$11.3 \times 10^6$)

WBS 1.1.2.2 - TRANSMITTER SUBARAYS

Definition

The transmitter subarrays include all installed elements as well as the structure and waveguides that form the basic subarray configuration.

Design Description

The subarrays are basic power-radiating elements of the transmitter. There are 10 types of subarrays corresponding to the 10 power intensity levels of the transmitter illumination taper. These 10 types use the same equipment, but the arrangement and number of elements vary with the number of klystrons.

The klystrons, control circuits, and wiring harness are described on lower level description sheets. The radiating waveguides, distribution waveguides, and structure are an integral production unit and are described at this level.

Thicknesses are as follows: radiating waveguide faces - 0.4 mm; Stick dividers - 0.6 mm; distribution waveguide - 0.8 mm. Other dimensions are shown in figure 25.

Each subarray includes 120 radiating waveguide "sticks" each a total of 60 wavelengths long. The sticks geometry is selected so that the stick wavelength is twice the stick width, yielding a subarray 10.43 m square. The arrangement of klystrons and RF power distribution waveguides is selected to minimize continuous stick length, subject to the constraint that each stick be an integral number of wavelengths. Sheets within the sticks set the length of each radiating element.

All of the subarray configurations are schematized in figure 25. All geometries except the 4 by 4 employ a split klystron output to cut active stick length in half. This cannot be done for the 4 by 4 configuration because 60 is not evenly divisible by 8.

The subarray distribution and radiating waveguides are assumed to be fabricated from graphite/metal (aluminum) matrix composites. The structure members are a high-temperature graphite/plastic matrix composite. Solid-state components are mounted on the radiating waveguide assembly under multilayer insulation so that the radiating waveguide serves as a cold plate. In addition, thermal insulation is used to force the klystron heat rejection sytem to radiate only out the back face of the antenna, reducing the temperature of the solid-state components.

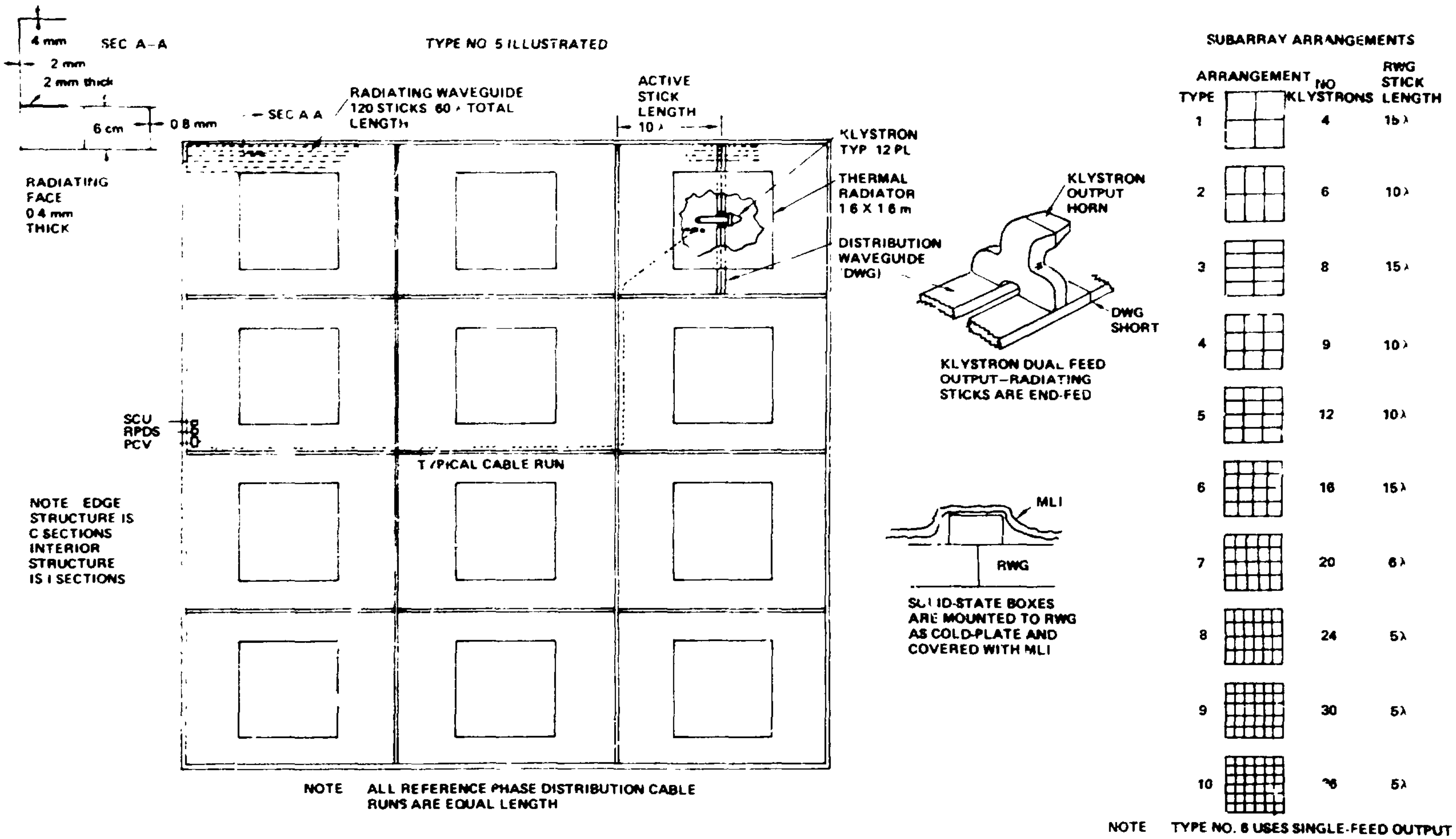


Figure 25.- Transmitter subarrays.

Cost

Estimated using the Boeing PCM and mature industry techniques.

	$\$ \times 10^6$
Research	93.4
Engineering verification	60.6
Demonstration	874.8
Investment	1 891.3
Production	

1.1.2.2.1	Klystrons	414.8
1.1.2.2.2	Distribution	28.7
1.1.2.2.3	Radiating waveguides	126.1
1.1.2.2.4	Wiring harness	1.6
1.1.2.2.5	Control circuits	93.9
1.1.2.2.6	Structure	38.3
1.1.2.2.7	Assembly and checkout	70.4
		773.8/SPS

Note: 1.1.2.2.4 was reserved for thermal control, which was not separately costed but rather included in each subsystem.

WBS 1.1.2.2.1 KLYSTRON MODULE

Definition

The klystron module includes all the hardware and control circuits for the klystron RF amplifiers: the cathode subassembly, the RF circuit (body), the collector, the output wave guide and window (if required), and the solenoid for beam focusing. The module includes a solid-state preamplifier, a throughphase stabilizatin unit and the klystron thermal control system. External instrumentation and monitor circuits (both d.c. and RF) are also included.

Design Description

The basic klystron operates at 42 kV with 45-50 dB gain using a compact, efficient (82%-85%) solenoid wound-on-body design approach with conservative design parameters (0.15 A/cm^2 cathode loading) to achieve long life. The five-stage depressed collector design provides an overall d.c.-RF conversion efficiency of 85 percent. The layout of the basic klystron building block module is shown in figure 26. The six-cavity design, with a second harmonic bunching cavity for shortlength and high efficiency, features a dual output waveguide with 35 kW in each arm. The thermal control system is used to cool the output gap, the depressed collector, and the solenoid, to a design temperature of 300°C on the body and 500°C on the collector. The driver for the final klystron power amplifier provides an output of about 3 watts CW for a 45 dB output amplifier saturated gain. It is driven directly from phase regeneration circuitry at a power level of about a milliwatt. The driver is a multistage transistor amplifier with up to 10 dB gain per stage at this frequency. Phase correction functions will be performed at low drive levels. Also shown in the configuration sketch are the thermal control system and a circuit block diagram. The klystron power amplifier receives reference signals at 490 MHz from the local phase control receiver and at 980 MHz from the phase distribution system. The downlink baseband of 2450 MHz is synthesized from these two signals.

Cost

Detailed estimate made for the research phase. Boeing used for DDT&E and production estimates.

	$\$ \times 10^6$
Research	5.0
Engineering verification (including basic DDT&E)	34.0
Demonstration	463.5
Investment	1300
Production @$4087 per klystron	414.8/SPS

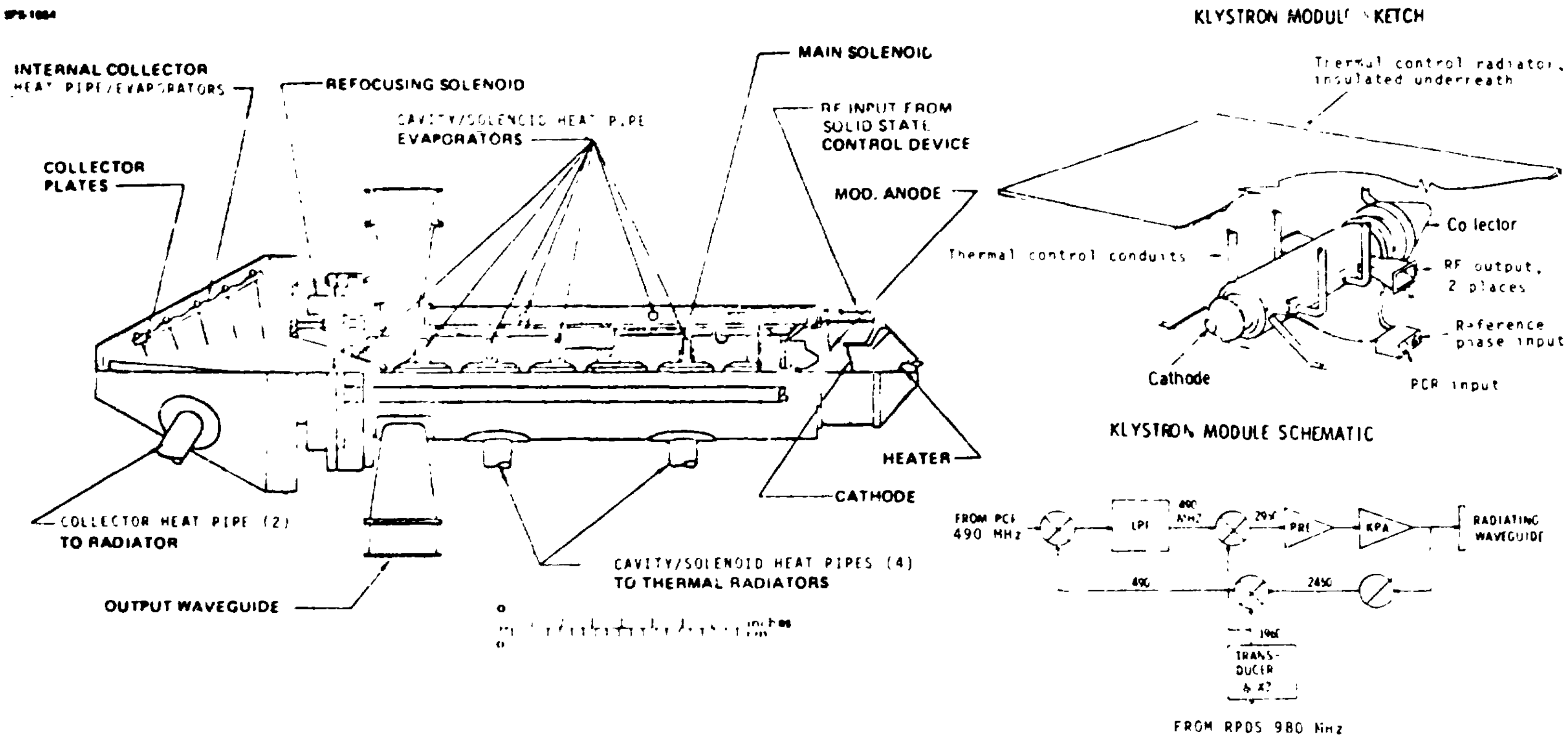


Figure 26.- Klystron module.

WBS 1.1.2.2.2 DISTRIBUTION WAVEGUIDES

WBS 1.1.2.2.3 RADIATING WAVEGUIDES

These two items were analyzed as a part of the subarray itself. The radiating waveguides, distribution waveguides, and subarray structure are designed as an integral unit. For cost data, see WBS 1.1.2.2.

WBS 1.1.2.2.5 SUBARRAY WIRING HARNESS

Definition

The subarray wiring harness consists of all electrical and optical wiring harnesses on the subarray.

Design Description

Function	Type	Length, m	Number	Unit/Mass, kg/M
980-MHz RPSR-PCR & BSPU	Optic	12	1 per klystron	.025
490-MHz PCR-BSPU	Optic	0.5	1 per klystron	.05
Klystron power	Electric (d.c.)	7 (avg)	1 per klystron	.05
12-V to klystron-associated control	Electric (d.c.)	7 (avg)	1 per klystron	.01
12-V to RPSR & SCU	Electric (d.c.)	1	2 per subarray	.01
Data, SCU to klystron-associated units	Shielded data bus	7 (avg)	1 per klystron	.01
Data to PCU & RPSR	Shielded	1	2 per subarray	.01

Routing of these is depicted under control circuits.

The power cabling is normal design practice. Data busing on the subarray will use shielded twisted pairs. Low-level RF distribution is fiber optic to avoid electromagnetic interference. The 12-m cables are of equal length to minimize phase error.

Cost

Research

Included in breadboarding tasks at subarray level

Engineering verification

Design and development	$467 000
Ground test units	$645 000
Flight test units	$645 000
Support to flight test	$435 000

Demonstration

Delta DDT&E	$1.113 million (first production unit and 80% learning)
Demo units @ $5 200	$2.3 million

Investment

None

Production

Mass production in automated wire shops assumed to reach cost of $17.4/kg for a total of $1.58 million per SPS

WBS 1.1.2.2.6 SUBARRAY CONTROL CIRCUITS

Definition

The subarray control circuits include:

a. Phase control receiver (PCR's)
b. Klystron-level remote terminal units (RTU's)
c. Reference phase slave repeater units (RPSR's)
d. Subarray (microprocessor) control units (SCU's)
e. Power control units (PCU's)
f. Bandspread synthesizer and preamp units (BSPU's)

Wiring harnesses are a separate WBS entry.

Design Description

The subsystem-level wiring diagram (figure 27) describes this system element. The phase control receivers receive the uplink signal through uplink antenna apertures included in the subarray as receiving antennas that do not interrupt the continuity of the downlink aperture.

The reference phase is provided to the PCR's and RPSR's via fiber optics. These units provide IF signals to the klystron modules, which provide phase conjugation to generate the downlink baseband signal.

The remote terminal units and subarray microprocessor control units provide all command and data handling functions at the subarray level. As an example, if arcing occurs in a klystron, these control units provide a clamp signal to the modulating anode of the klystron and a cutoff signal to the power control unit. These latter units control the circuit breaker functions as necessary for arc protection for the klystrons.

The subarray control circuits include those control functions most logically applied at the subarray level. These include

a. Phase control reception at the klystron level
b. Receipt and distribution of the reference phase
c. System status data handling and command functions
d. Power electronics terminal switching

The subarray is a self-contained unit that requires as inputs only a phase control uplink signal (from Earth), a reference phase, and d.c. electric power.

The control circuit design includes an adaptation of a spread-spectrum retrodirective phase control system.

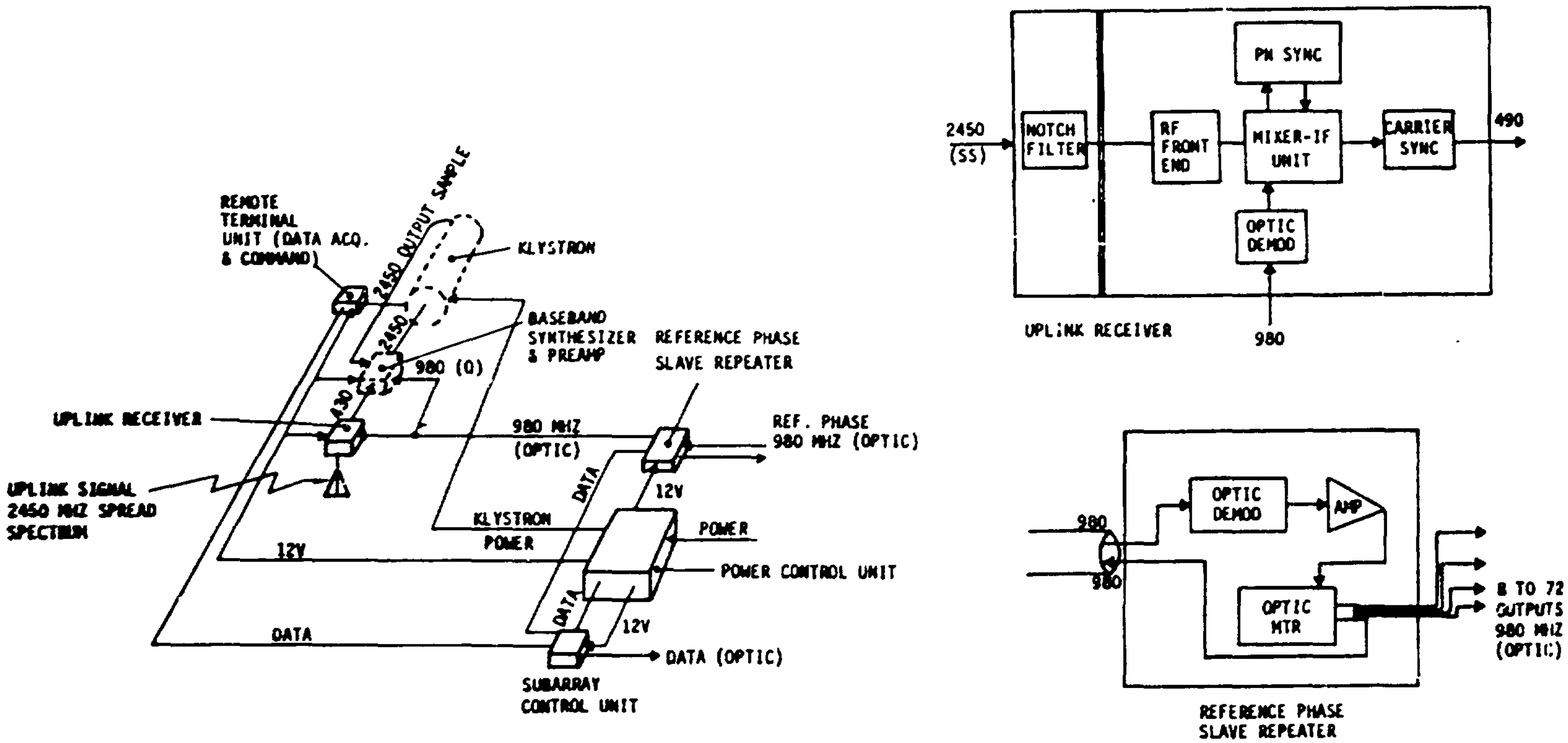


Figure 27.- Subarray control circuits.

Cost	$\$ \times 10^6$
Ground-based research	4.7
Flight research	75.3
Engineering verification (including basic DDT&E)	10.5
Demonstration	26.1
Investment	65.4
Production	93.9/SPS

WBS 1.1.2.3 MPTS POWER DISTRIBUTION AND CONDITIONING

Definition

MPTS power distribution and conditioning includes the power conductors, switchgear, and conditioning equipment required to transfer power from the interface subsystem to the subarray wiring harnesses and to any other power-consuming equipment located on the microwave power transmission structure.

Design Description

The MPTS power distribution system provides power transmission, conditioning, control, and energy storage for all elements mounted on the antenna side of the rotary joint (see fig. 28). The antenna is divided into 228 power control sectors, each of which provides power to approximately 440 klystrons. The klystrons require power at nine different voltage levels. Two of the klystrons' depressed collectors require most of the supplied power and are supplied directly from dedicated portions of the satellite power generation system. The rest of the klystron power and the power required for other power-consuming equipment mounted on the power transmission structure is provided by d.c.-d.c. converters. Switchgear is provided for power control and fault protection. System disconnect switches are provided for equipment isolation for maintenance purposes.

Aluminum sheet conductors are used for power transmission from the interface subsystem to the power sector control substations and are routed along structural elements on the antenna primary structure farthest from the radiating waveguides. Round aluminium conductors provide power transmission from the substations to the antenna RF subarrays. Flexible connections are used to route power across the elevation joint between the antenna yoke and the antenna. Each power sector substation includes the required d.c.-d.c. converter, switchgear, disconnects, and energy storage.

Cost

	$\$ \times 10^6$
Research	13.2
Engineering verification	36.2
Demonstration	645.7
Investment	661.8
Production	281.8/SPS

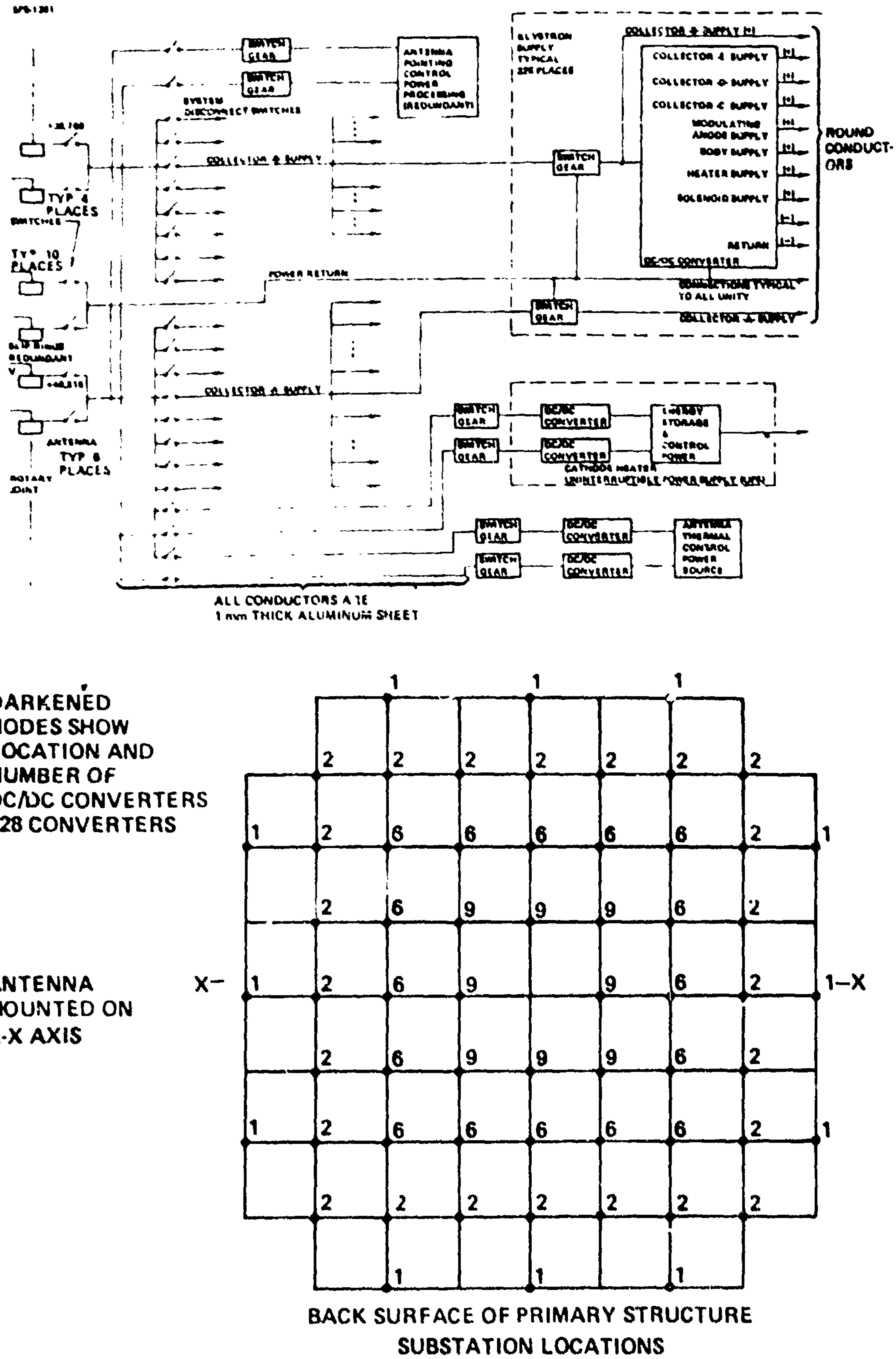


Figure 28.- MPTS power distribution.

WBS 1.1.2.3.1 CONDUCTORS

Definition

This element consists of the power conductors that are required to conduct power from the interface subsystem to the subarray wiring and to any other power-consuming elements mounted on the power transmission system structure.

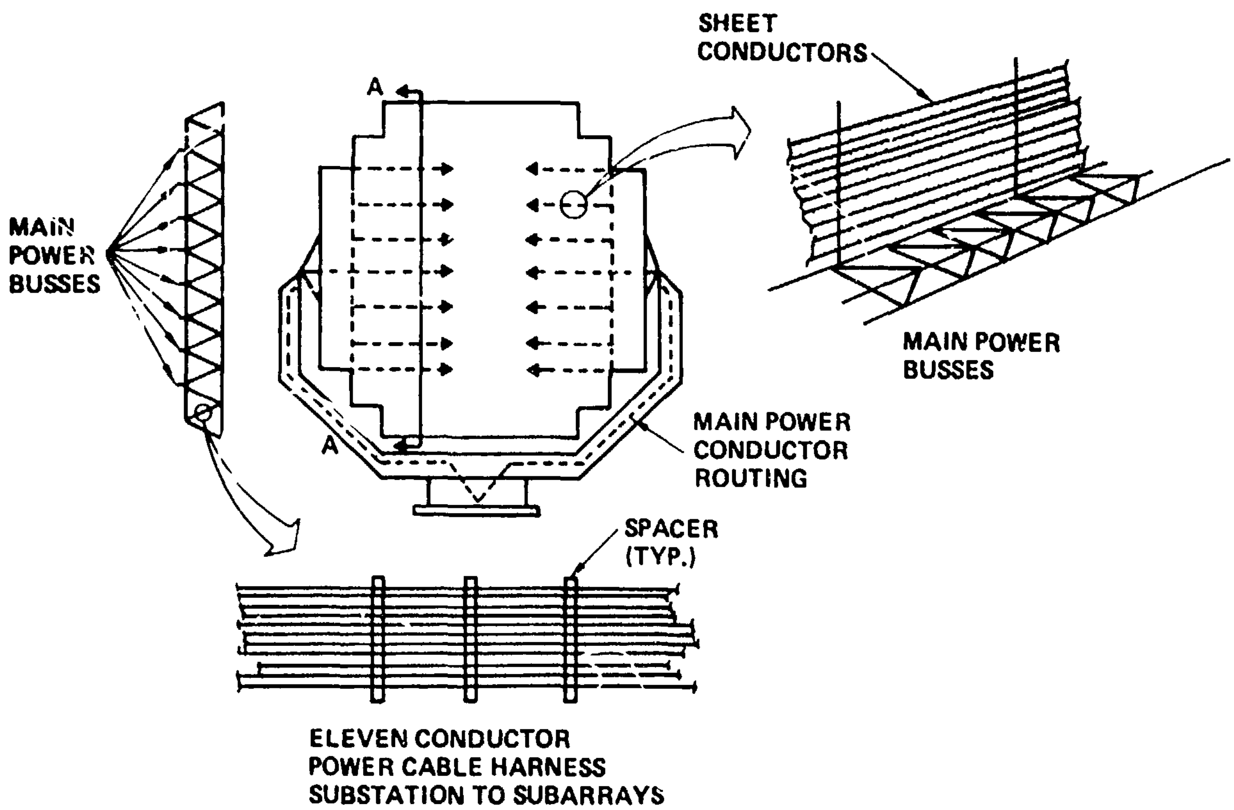


Figure 29.- DC conductors.

Design Description

Two types of power conductors are used in the MPTS power distribution system. The conductors from the rotary joint slipring assembly to the power sector substations are 1-mm thick aluminum sheets. The conductors between the substations and the subarrays are round aluminum conductors. The conductors between the d.c.-d.c. converters and power-consuming equipment other than subarrays mounted on the antenna are also circular aluminum conductors. All conductors are uninsulated and the surface emissivity is assumed to be 0.9.

Cost

$\$16 \times 10^6$/SPS estimated using the Boeing PCM program.

WBS 1.1.2.3.2. SWITCHGEAR

Definition

The switchgear includes the circuit breakers and disconnect switches required for power control, fault protection, and circuit isolation.

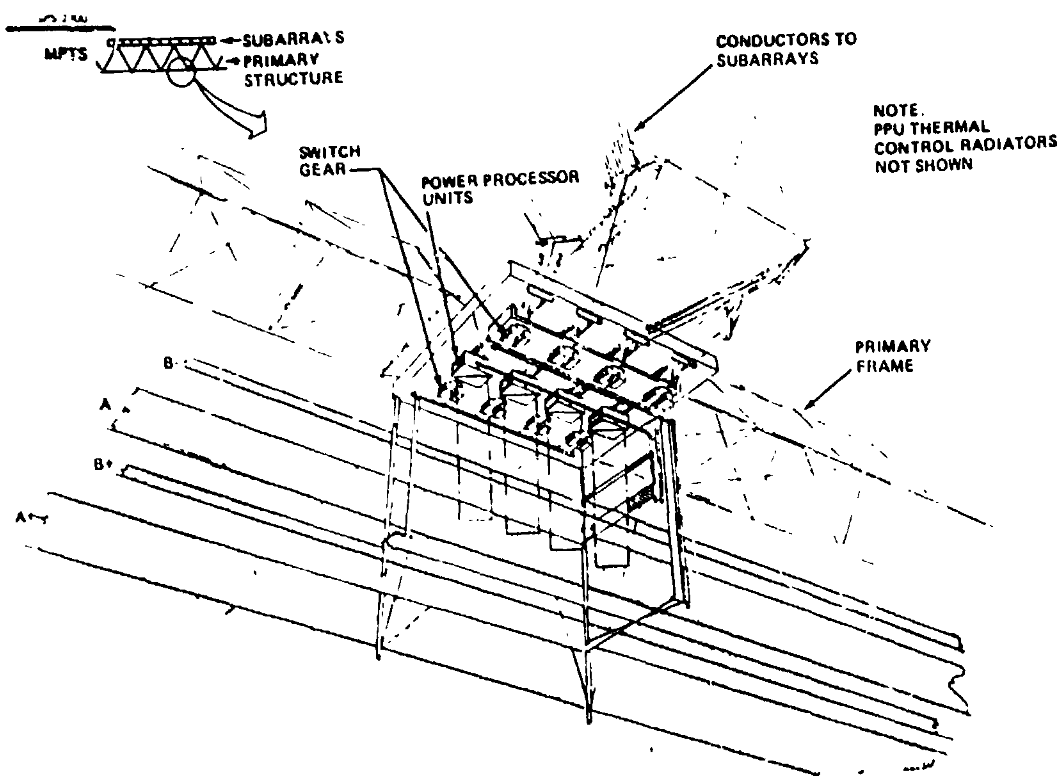


Figure 30.- MPTS switchgear.

Design Description

The switchgear for the MPTS power distribution system consists of vacuum circuit breakers with associated communication circuitry. The switchgear for both the power sources is as follows:

Power source	Voltage	Current	Quantity
A	40.8 kV	620 A	456
B	38.7 kV	290 A	456

Redundant switchgear is provided at each location to improve system reliability and reduce power loss due to failures. System disconnect switches are provided at the input of each set of redundant circuit breakers. Disconnect switches are opened only when no current is flowing and are used only for isolation and not for fault protection. The switchgear is mounted at the power sector substations.

Cost

$\$62 \times 10^6$/SPS (ref. 5).

WBS 1.1.2.3.3 DC-DC CONVERTER

Definition

This element consists of the MPTS antenna-mounted d.c.-d.c. converters that supply any power processing required for power-consuming equipment mounted on the MPTS antenna structure.

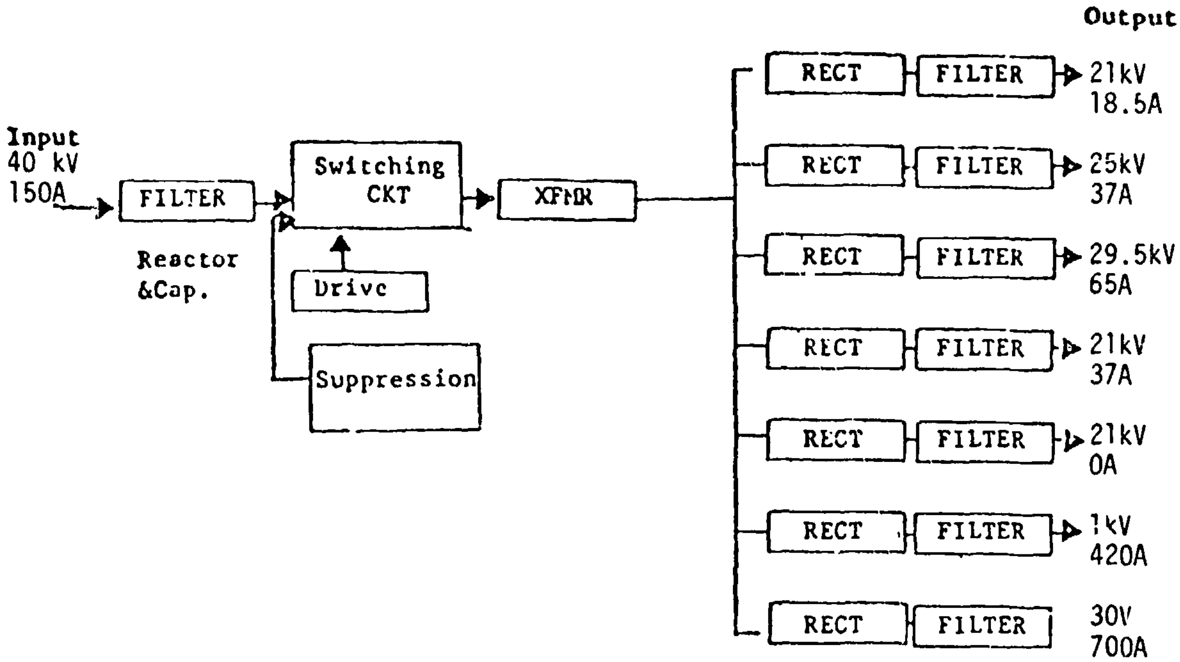


Figure 31.- DC-DC converter block diagram.

Design Description

The MPTS power control and distribution subsystem provides conditioned power for all MPTS elements. The five-depressed-collector klystron requires conditioned power on all inputs except the two collectors that are powered directly from SPS Collector A and Collector B supplies. The power conditioning subsystem to provide these voltages is diagramed in figure 31. The estimated input power to each d.c.-d.c. converter is about 5400 kW. The particular switching circuit device has not yet been selected, but an analysis has shown that a switching speed of 20 kHz with SCR's or power transistors can yield a d.c.-d.c. conversion efficiency of about 95 percent.

Cost

$\$155.1 \times 10^6$/SPS (ref. 5).

WBS 1.1.2.3.4 PROCESSOR THERMAL CONTROL

Definition

Processor thermal control includes the hardware required to collect and dissipate the waste heat from the power-processing equipment installed on the MPTS structure.

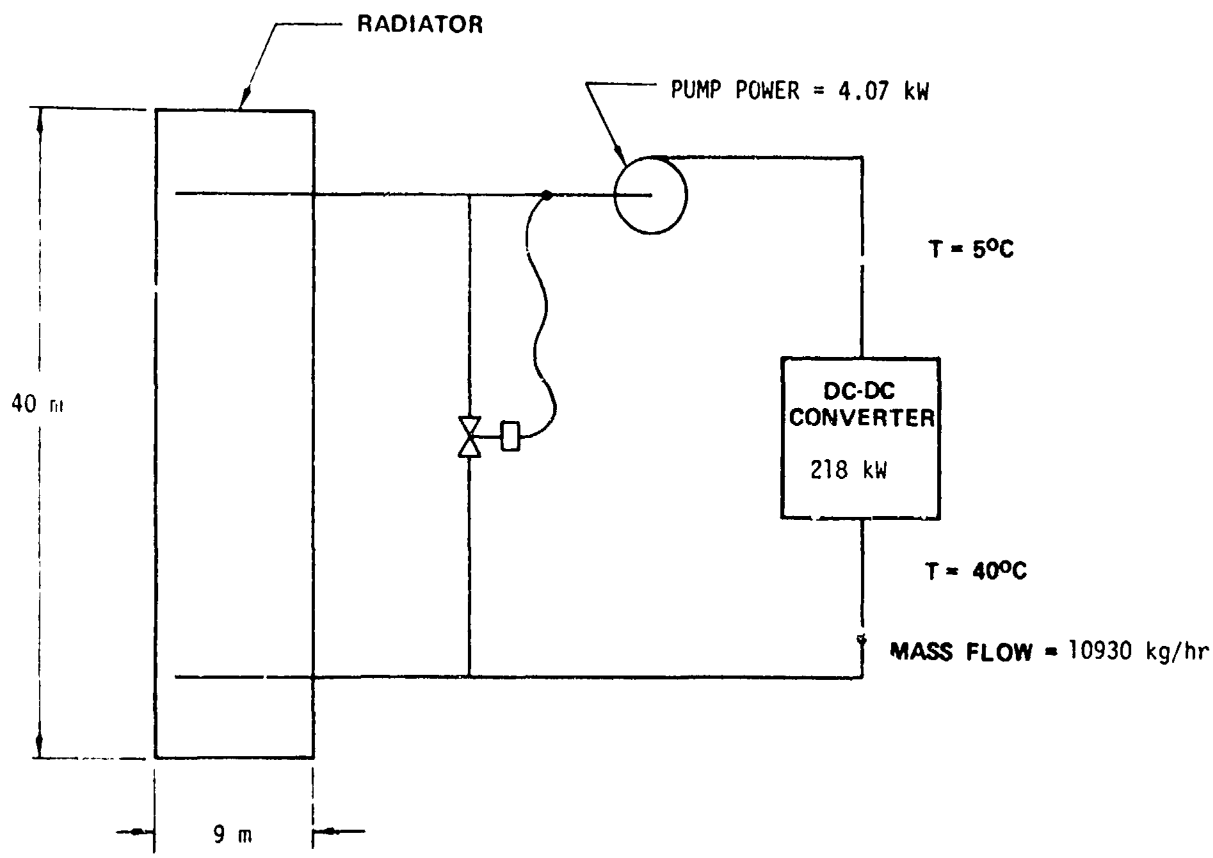


Figure 32.- Power processor thermal control.

Design Description

The basic system is composed of a heat exchanger, pump, thermal control/bypass valve, and thermal radiator. The heat exchanger uses finned heat pipes, with the condenser sections in contact with the working fluid of the active loop. The evaporator section is in the power converters for better heat rejection from the more sensitive solid-state components. The fluid pump was sized at 4.1 kW. The power consumption of all the processor thermal control systems was estimated at 928 kW.

Cost

$\$45 \times 10^6$/SPS, estimated using the Boeing PCM program.

WBS 1.1.2.3.5 ENERGY STORAGE

Definition

This element consists of the equipment required to store the energy needed to run the equipment installed on the MPTS antenna structure during periods of occultation.

Design Description

The MPTS energy storage subsystem consists of nickel-hydrogen batteries installed at each power sector substation. The energy storage subsystem provides power to keep the klystron heaters on during occultation and to provide power to critical systems during this period.

Cost

The energy storage system theoretical first unit cost is $328 000. This estimate is for one of the 234 batteries on an SPS. (This estimate includes cell interconnects, charging equipment conditioners, and regulators.) The TFU estimate was obtained using the Boeing parametric cost model. The battery has a mass of 1300 kg and a rating of 52 kWh. Using a 70-percent learning curve, the unit battery cost drops to $19 800 after 234 have been made. This reduction results in a total cost per SPS of $4.6 million.

WBS 1.1.2.5 REFERENCE PHASE DISTRIBUTION SYSTEM

Definition

The reference phase distribution system includes all the elements involved in receiving the reference phase signal and distributing it to the subarray, except for the cabling, which is a separate WBS item.

Design Description

Transmitting antenna coordinates are denoted by (X, Y) where X is the direction parallel to the elevation axis of the antenna/yoke system and Y is perpendicular to X (see fig. 33). The direction of power transmission, Z, is the cross product X × Y. The direction -Y is toward the solar array. The point (0, 0) is at the center of the antenna array. Subarrays are numbered by their count from the array center in the fashion (X, Y).

For purposes of reference phase distribution, the transmitting antenna is divided into 20 sectors. Each sector is in turn divided into 20 groups with 19 subarrays each (see fig. 34).

Three level-one reference phase receivers on subarrays (-5, -2), (5, -2), and (-1, 5) each receive the derived spread-spectrum reference phase signal from the pilot beam transmitter on the ground, demodulate it to the 980 MHz IF frequency, and transmit it to all 20 level-two reference phase slave repeater units via actively delay-compensated two-way fiber optic cable links (see fig. 35).

Each level-two reference phase slave repeater unit receives all three level-one input phase signals and selects from among them by automatic gain control (AGC) signal-level weighted averaging (if they are all coherent with each other) or by two-out-of-three voting logic (if they are incoherent). The resulting signal is then transmitted to 19 equivalent level-three reference phase slave repeater units via actively delay-compensated two-way fiber optic links with doubly redundant electronics but nonredundant fibers.

The level-three (sector group) reference phase slave repeater units take the AGC weighted average of the input signal if the two inputs are coherent and select the input with correct operating characteristics if they are incoherent. After amplification, the signal is distributed to the level-four reference phase slave repeater units that constitute the input to the 19 subarrays in their group via a single two-way fiber optic link.

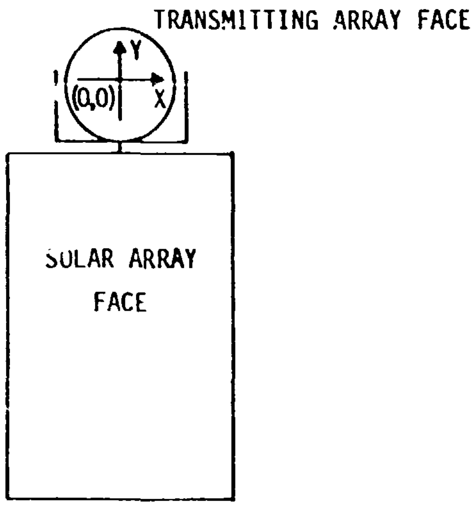


Figure 33.- MPTS coordinate system.

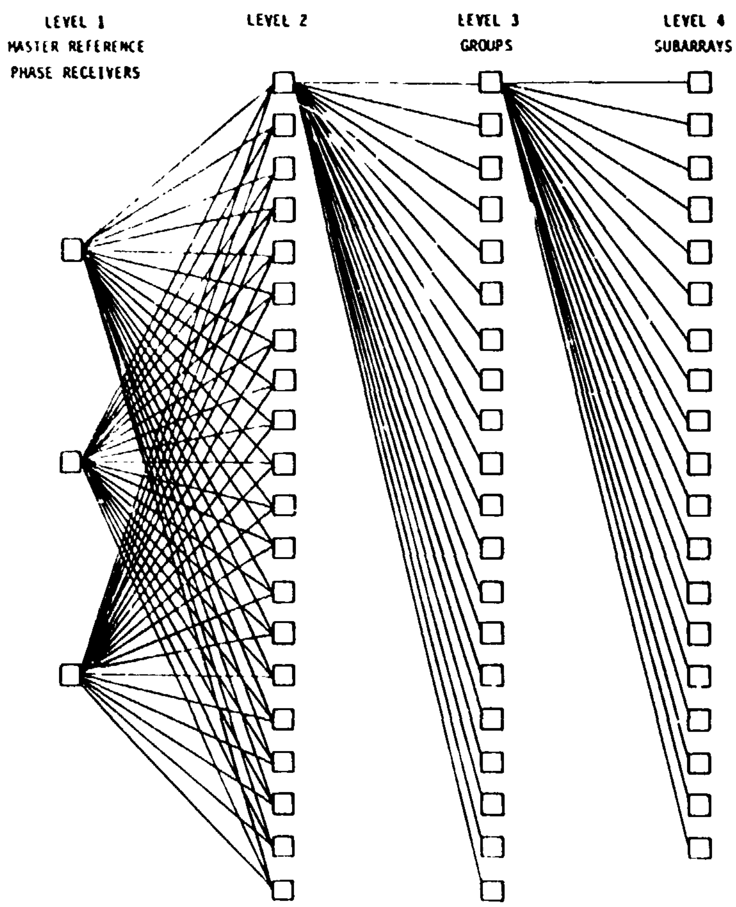


Figure 34.- Reference phase distribution tree structure.

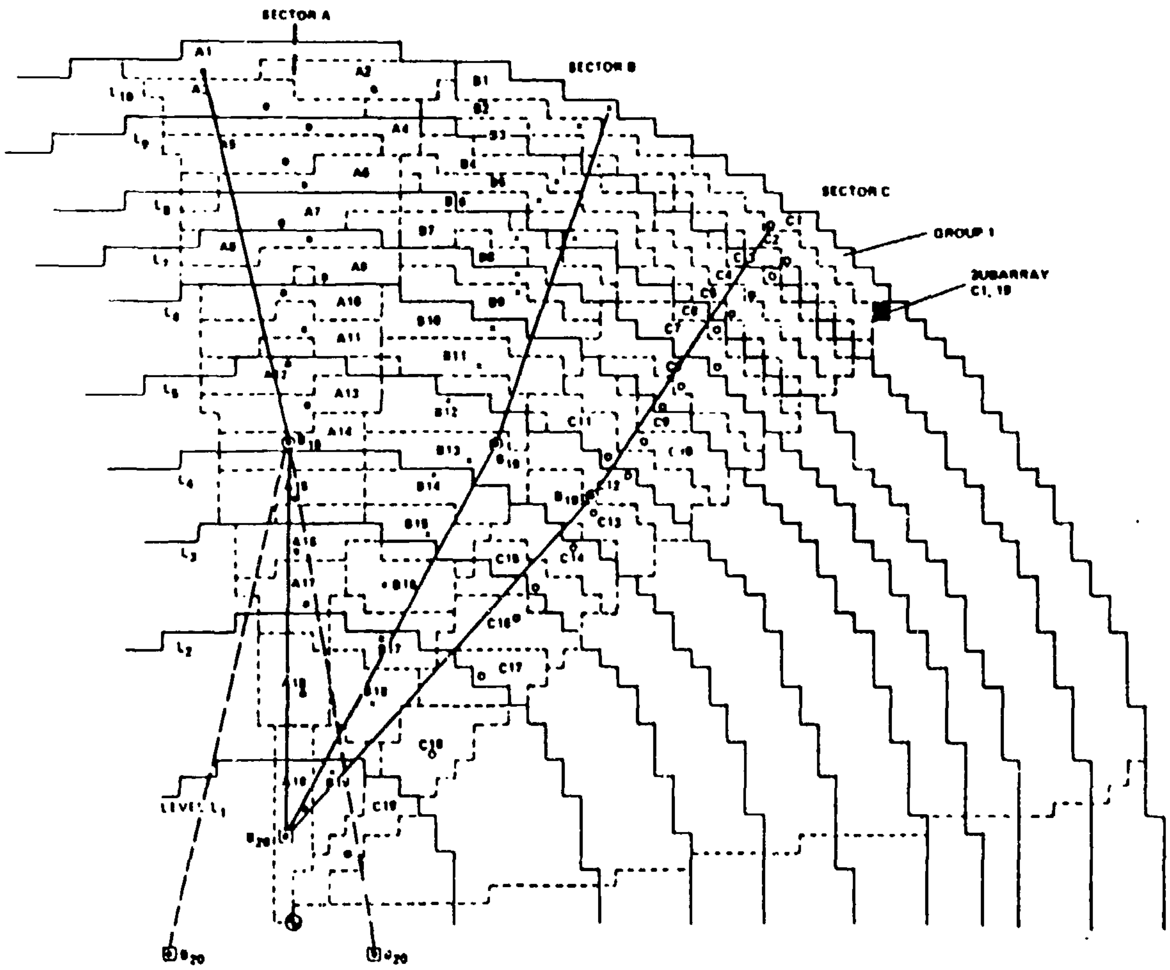


Figure 35.- Location of phase repeater stations of sectors and groups.

The reference phase receivers deconvolute basic satellite control commands from the spread-spectrum reference signal as part of the receiving process. These commands are superimposed on the fiber optic reference phase signals to the slave units and may override normal modes of operation. Any level-one reference phase signal may be explicitly ignored or enabled as the true reference phase signal for level-two slave units by explicit ground command, even though normal operating mode is to take the AGC weighted average.

Similarly, level-two reference phase signal channels may be explicitly selected or disabled in an override of the normal automatic selection mode.

Cost (ref. 3 p. 83)	$\$ \times 10^6$
Research	Included under subarray control circuits
Engineering verification	24.2
Demonstration	35.0
Investment	24.3
Production	
1.1.2.5.1 Master reference receivers	1.1
1.1.2.5.2 Slave repeaters	8.7
1.1.2.5.3 Cabling	1.1
	\$10.9/SPS

WBS 1.1.2.6 MAINTENANCE SYSTEMS

Definition

This element consists of the built-in MPTS maintenance equipment that is used by the visiting maintenance crew.

Design Description

The MPTS maintenance operations require maintenance equipment to operate on both faces of the antenna.

Antenna Front-Face Maintenance Provisions - The level of replacement selected for the radiating surface of the MPTS is that of the klystron tube module plus its thermal control system as shown in figure 36. Actual removal of the tube module involves access through holes in the radiator to reach the distribution waveguide attachment bracket that secures the module to the distribution waveguide. Once this attachment is released, the module can be removed.

The selected klystron tube module replacement concept uses vertical access through the cubic secondary structure, which is attached to the A-frame primary structure.

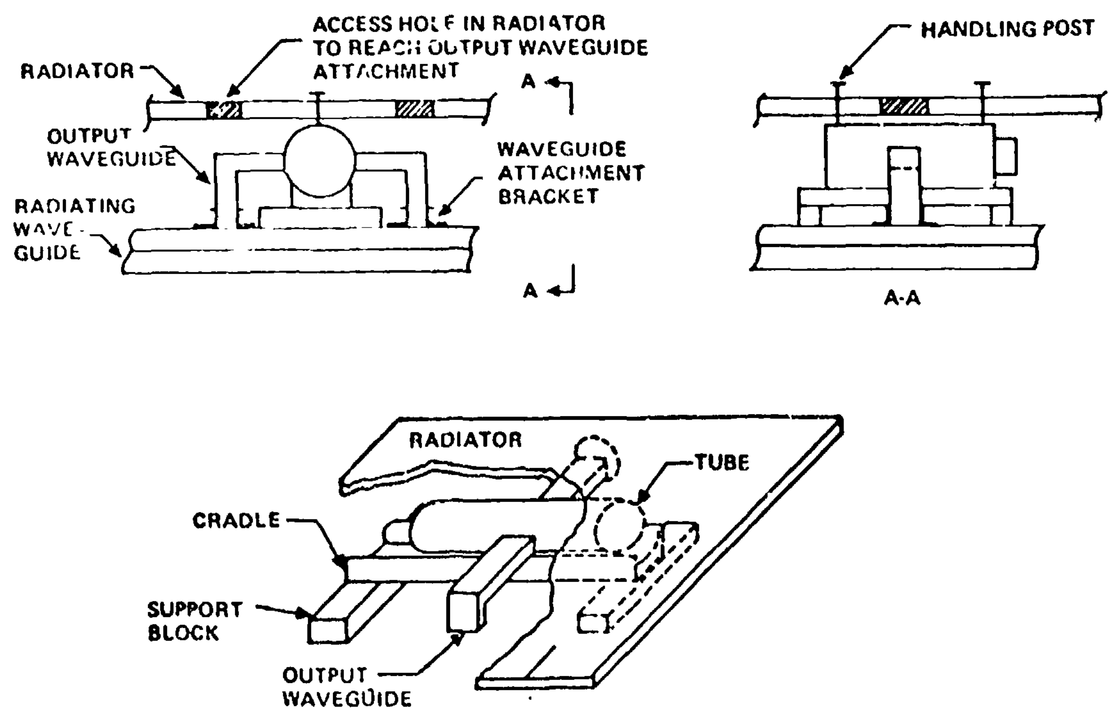


Figure 36.- Level of replacement.

The overall concept is illustrated in figure 37. The primary structure is an A-frame design forming ridges that allow free unobstructed movement of the maintenance gantry moving horizontally across the antenna.

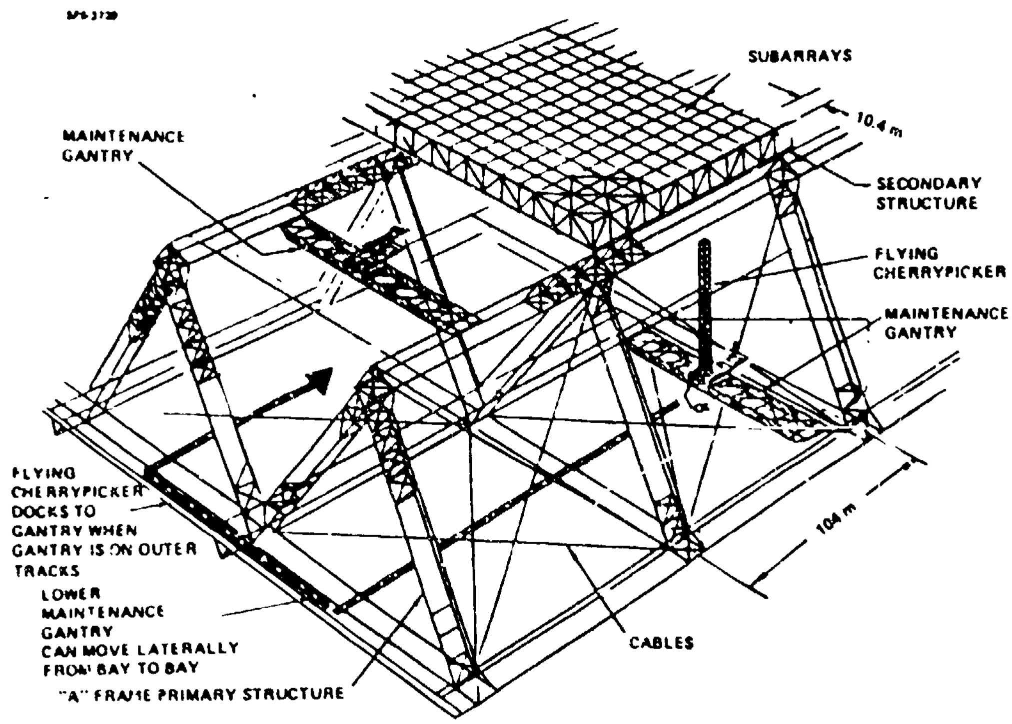


Figure 37.- Maintenance gantries.

The antenna will have a total of ten channels in which maintenance gantries can be mounted (see fig. 38). Attached to each of the gantries are the maintenance vehicles, which reach up through the secondary structure to reach the failed klystron tubes, as shown in figure 39.

Additional detail of the cubic secondary structure and the maintenance vehicle is presented in figure 40, with a maintenance vehicle shown moving along in the direction of the channel. The gantry itself is designed to transport all of the spare klystron tubes necessary for a given shift. The maintenance vehicle consists of a hinged boom and a two-person crew cabin with manipulators. A small klystron rack is also attached to the boom to eliminate the need for the manipulators to reach back down to the gantry for each tube that must be replaced. In the case of a 36-tube subarray, as many as three tubes may require replacement.

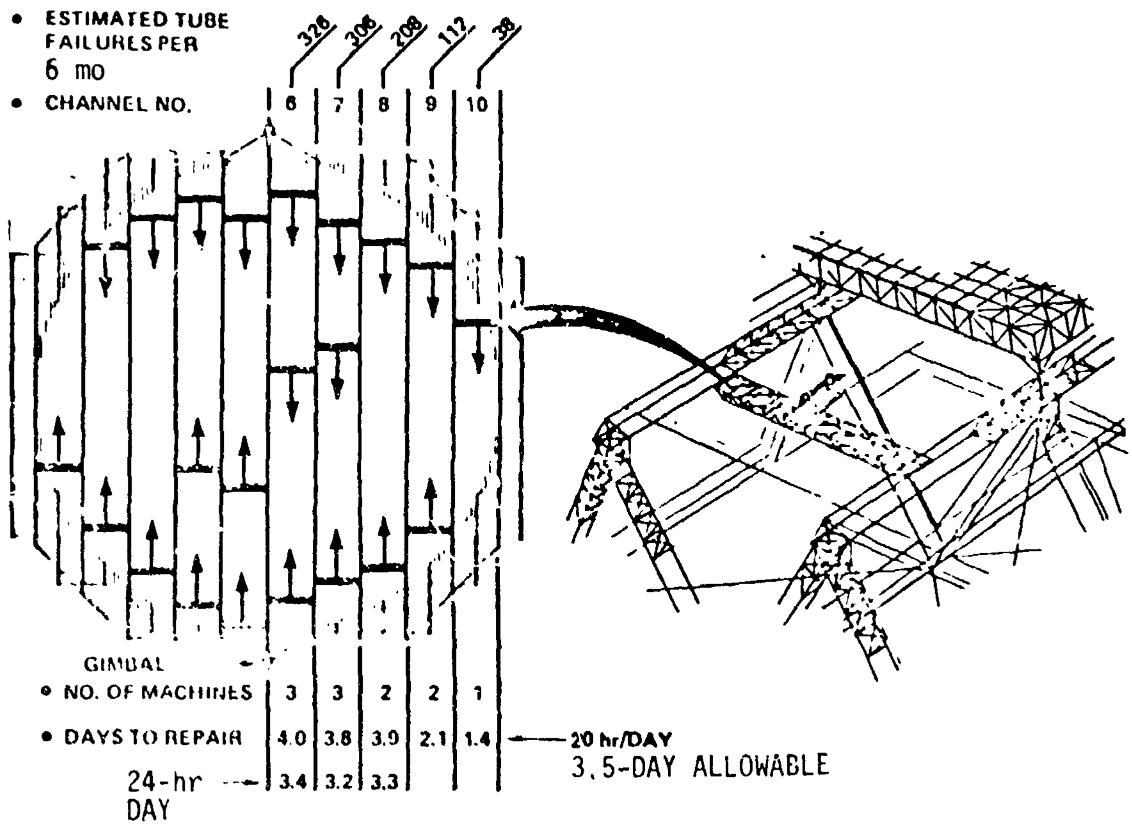


Figure 38.- Antenna maintenance system installation.

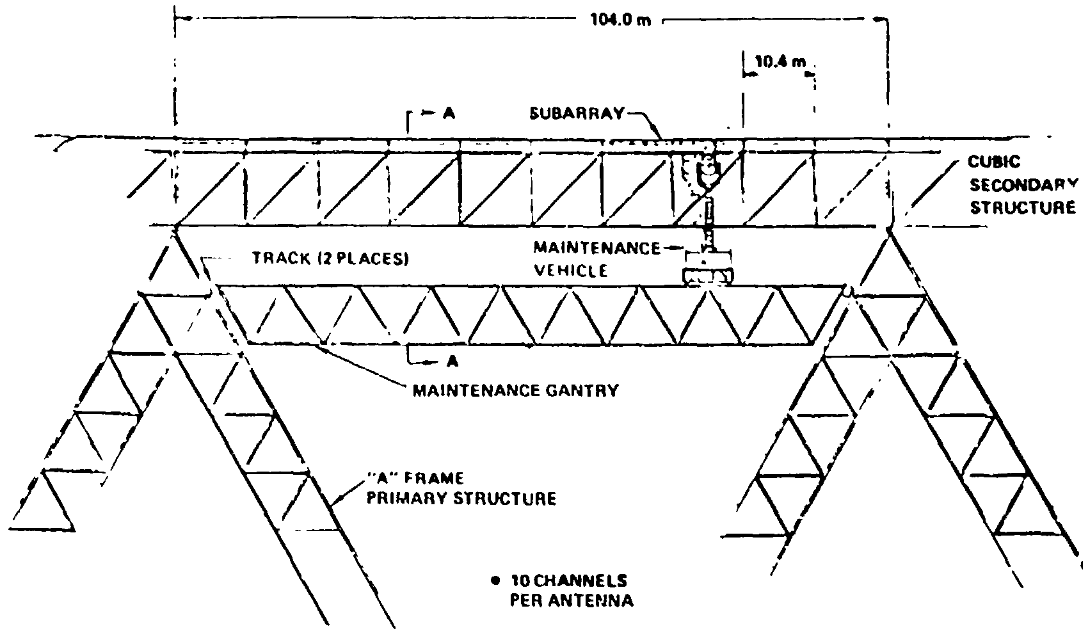


Figure 39.- Vertical access for tube maintenance.

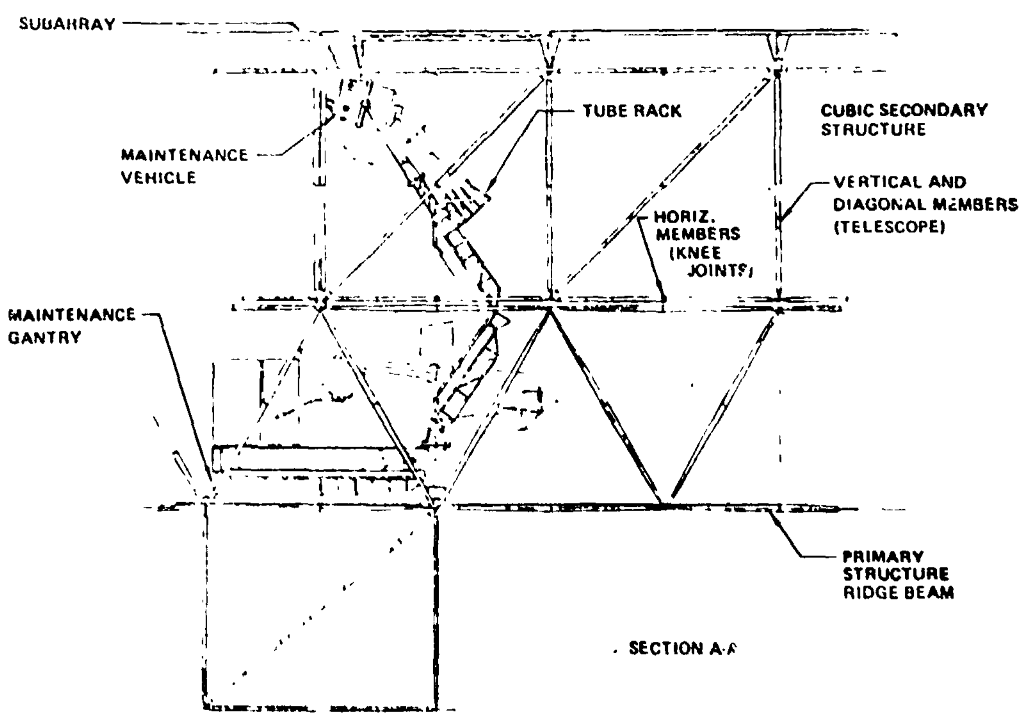


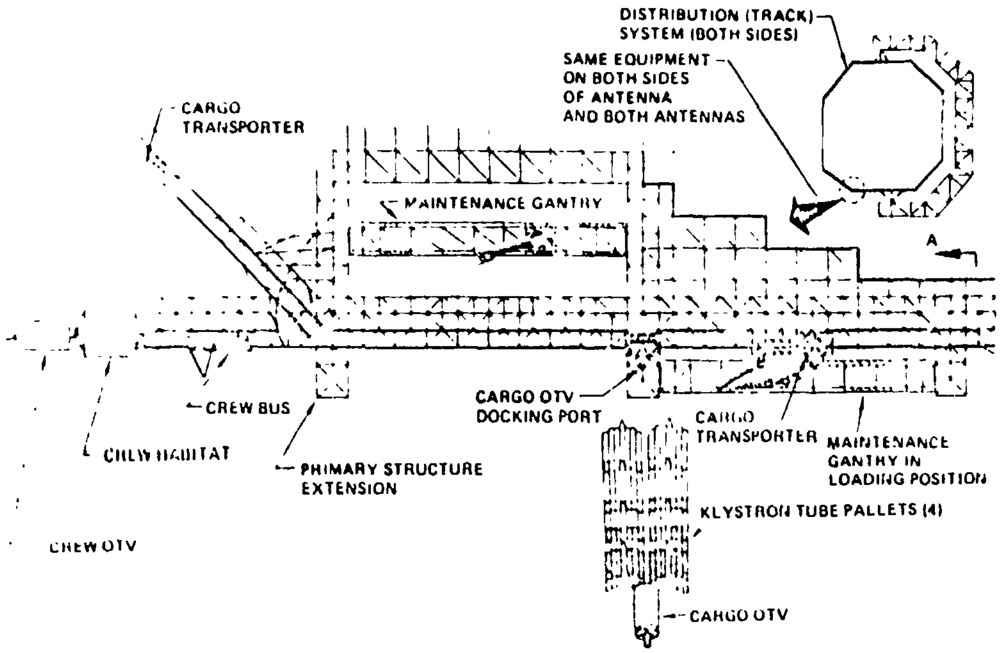
Figure 40.- Vertical access maintenance vehicle.

The phase control system and some of the power distribution system elements are also accessed and replaced using the gantry/cherrypicker systems.

To enable the docking of the various maintenance system elements and to transfer cargo around the antenna, the antenna structure has been designed to incorporate a cargo distribution system and has structural additions to allow maintenance gantries to be positioned so they can be accessed and supplied with new klystron tube modules. In figure 41, the systems are shown as they relate to one side of one antenna. Since two crews work on each satellite, these systems are present on both side of the antenna.

The actual distribution of the cargo around the antenna is accomplished through use of cargo transporters operating on the track system on two sides of the antenna. The cargo transporter system consists of three separate units attached together to form a "train." The middle unit is a control unit that has a crew cabin, power systems, and a crane/manipulator that moves the cargo between the train and the maintenance gantries. Units on either side of the control unit are essentially trailers that carry either new klystron tube modules or those that have failed and been removed. The train moves down to each gantry and delivers to it the number of klystron tubes required in that particular antenna channel during one shift or one day of operation, depending on the channel.

Antenna Back Surface and Mid-Plane Maintenance Provisions - On the antenna back surface, the main power buses will be routed to electrical substations located at various primary structure nodal points. The maintenance access system selected for this application is illustrated in figure 37. Only one of these gantry/cherrypicker systems is warranted by the expected failure rates of the components located on the antenna back face. This system is also employed to replace the power conductors that are routed between the substations and the secondary structure.



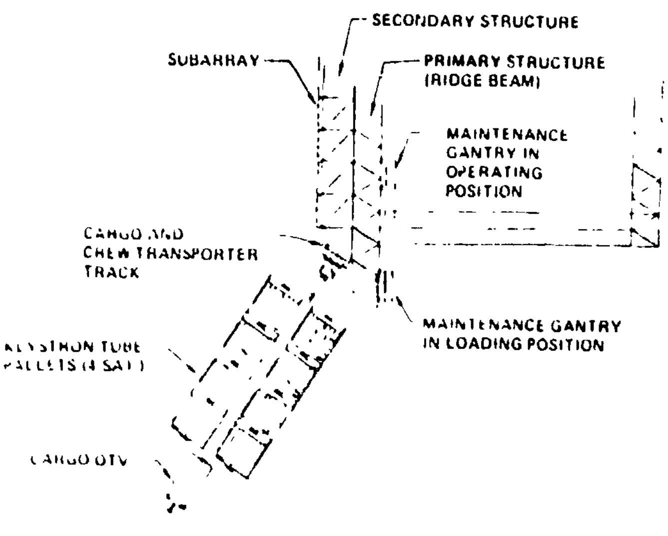


Figure 41.- Antenna maintenance systems.

Cost		$\$ \times 10^6$
Research		Covered under space construction
Engineering verification		--
Demonstration		
DDT&E	138.8	
Demo unit		
8 gantries	6.9	
8 MRWS's	141.2	
24 docking ports	16.7	
1 crew bus	44.3	
1 transporter	1.5	
1 cargo handler	3.2	
Tracks	35.7	
		388.3
Investment		--
Production		438.2

PRODUCTION DETAILS

Item	TFU cost ($\$ \times 10^6$)	#rqd.	Prod. unit cost ($\$ \times 10^6$)	Cost per SPS ($\$ \times 10^6$)
Gantry	0.9	22	0.4296	9.5
MRWS	25.2	22	11.1	244.1
Docking port	.9	66	.2548	23.4
Crew bus	44.3	2	31.0	62.1
Component transport	1.5	4	1.1	4.3
Cargo handling cherrypicker	3.2	2	1.8	3.7
Growth and contingency (16% of above items)				55.5
Tracks @ $66/kg				35.7
				438.2

WBS 1.1.2.7 ANTENNA MECHANICAL POINTING

Definition

The antenna mechanical pointing subsystem consists of control moment gyros located on the power transmission structure and used to accomplish mechanical pointing of the antenna transmitting face toward the Earth receiving antenna. Subarray pointing or positioning provisions are included in the subarray WBS 1.1.2.2.

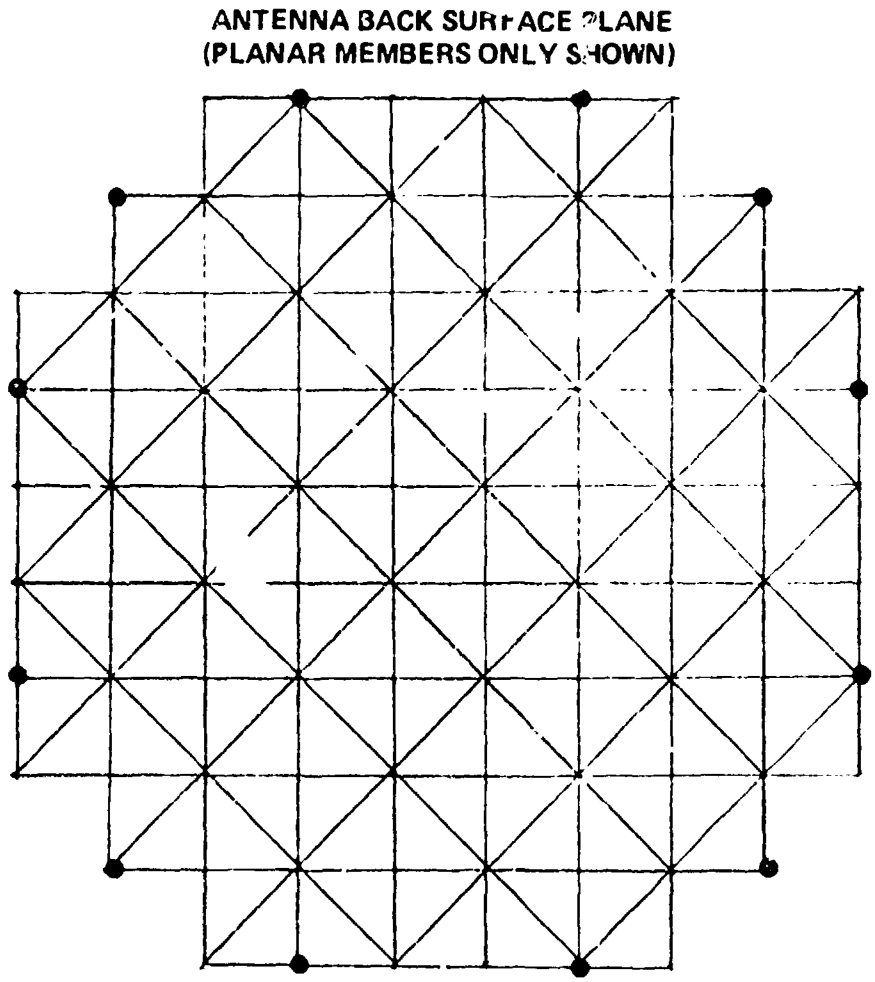


Figure 42.- Antenna mechanical pointing CMG installation locations.

Design Description

The MPTS attitude control system provides fine control of antenna mechanical aiming. Control moment gyros (CMG's) are used to generate torques required for this fine control. Control of the CMG's is accomplished using the signals derived from pointing errors determined by the phase control system. Rough pointing to acquire the phase control signal is accomplished using star scanners to control the CMG's.

The CMG's are located on the back side of the primary structure and are 12 in number for each transmitting antenna. A feedback loop from the antenna attitude control system to the SPS mechanical rotary joint allows the rotary joint to apply torque to the antenna to continuously desaturate the antenna CMG's. This torque is supplied through a highly compliant mechanical joint so that the natural frequency of the antenna in its mechanical supports is below the control frequency bands for the CMG's controlling the antenna attitude.

Cost	$\$ \times 10^6$
Research	
Sensors	0.93
CMG design	.28
Wheels, bearings, motors	.70
Other actuators	.53
	2.4
Engineering verification	
EVTA (with smaller, state-of-the-art wheels)	9
Lab work on test hardware for larger wheels	13
	22
Demonstration	
DDT&E	464
3 prototypes	271
	735
Investment	--
Production @ $10.1 million/unit	121/SPS

C-2

WBS 1.1.3 INFORMATION MANAGEMENT AND CONTROL

Definition

The information management and control system (IMCS) includes all computers and centralized and decentralized data processing required for overall onboard management of the satellite configuration operation, flight control, and power transmission systems.

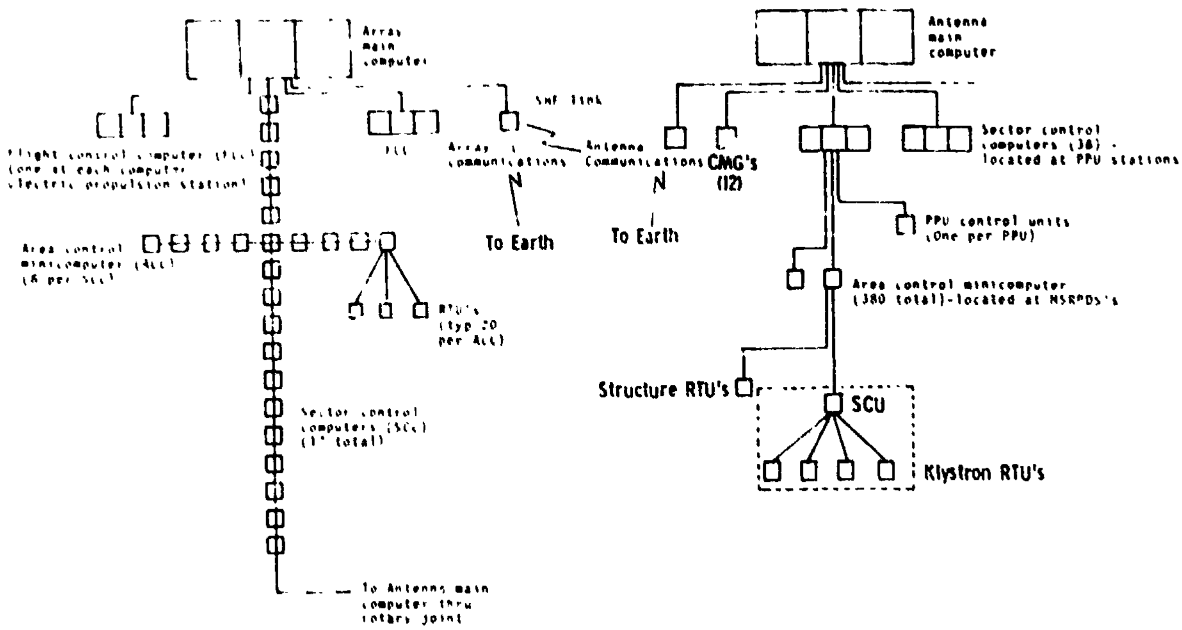


Figure 43.- Information management block diagram.

Design Description

The central processor unit (CPU) manages data traffic to and from the ground, formats telemetry for transmission, and checks commands for bit errors. Other functions of the CPU include the storage of commands for operating and testing the data subsystem in the absence of ground control and the control of telemetry data storage for later transmission. Critical computers are triply redundant and cross-strapped.

Each tier monitors operation of the tier below, instigates checks on subordinate units, and establishes priority for upward communication. The lowest tier links the IMCS to other systems through sensor readings, digital data transfers, and command outputs. An upper tier may also override a command by a lower tier in order to restore operation or diagnose apparent failures if its information on the status of the remote technical unit (RTU) involved (or information from another RTU) warrants such action.

Fiber optics were selected for harnesses because such a system is of lighter weight, is more fault tolerant (because it is a nonconductor, it does not propagate faults), has a wide-band multiplexing capability, is inherently immune to EMI and arc discharges, and requires raw materials that are in ready supply and inexpensive. It is recognized, however, that a considerable amount of development in fiber optics will be required.

A code format containing a clock has been selected because the long distances over which the data must be transmitted not only make synchronization with a separate clock signal very difficult but also result in an appreciable increase in complexity and cost.

Cost	$\$ \times 10^6$
Research	5.9
Engineering verification	21.7
Demonstration	320.3
Investment	--
Production	41.7/SPS

WBS 1.1.4 ATTITUDE CONTROL AND STATIONKEEPING

Definition

Attitude control and stationkeeping includes the components required to orient and maintain the satellite's position and attitude in geosynchronous orbit. Included are sensors, reaction wheels, and chemical and electric propulsion hardware and propellants.

Design Description

The attitude control system includes an attitude sensing system and an electric propulsion system with four installations, one at each corner of the SPS energy conversion system. A typical corner installation is illustrated in figure 44. The attitude control system includes thrusters, power processors, structure, propellant feed and control systems, and instrumentation and control. Chemical propulsion is provided for control during equinoctial occultations or unexpected loss of electric power.

The method of collector control makes use of multiple thrusters providing a total force equal to the solar pressure. Individual thrusters are modulated above or below their bias level to provide the control torques needed to offset gravity-gradient disturbance torques. In essence, there is no additional propellant penalty for collector attitude control. Single-axis (pitch) rigid body control only is shown. Thruster location will be at the nodal points of one of the lower modes to minimize excitation of that particular flexible mode. Active damping of other modes will be achieved by superimposing additional thrust modulation signals on the attitude control thrust level commands. These signals are derived from the outputs of multiple rate sensors which are processed to isolate the rigid-body and lower-bending-mode components of motion.

Thrusters include the primary electric thrusters for maintenance of attitude control and auxiliary chemical thrusters required to establish attitude control when electric power is not generated by the SPS. The electric thrusters are 120 cm diameter ion thrusters operated on argon as primary propellant. Approximately 50 000 kg per year is required, as established by the need to eliminate orbit perturbations introduced by solar pressure. All other flight control can be accomplished by modulation of the solar pressure counterthrust. The chemical propulsion system employs liquid hydrogen and liquid oxygen. The propellant containers are spherical aluminum tanks located near each thruster installation and are sized to hold a 1-year propellant supply plus a 20-percent margin. The oxygen and hydrogen tankage includes 20 000 kg of maneuvering reserve propellants in addition to the normal control propellant.

The propellant feedlines are uninsulated aluminum lines. Propellant pressure is controlled to the pressure required for the thrusters by regulators. A shutoff valve is included in each line to each thruster so that any malfunctioning thruster can be isolated from propellant feed. The feedlines include flexible elements and gimbals to cross the thruster panel gimbal joint. Electric thrust control is provided by startup and

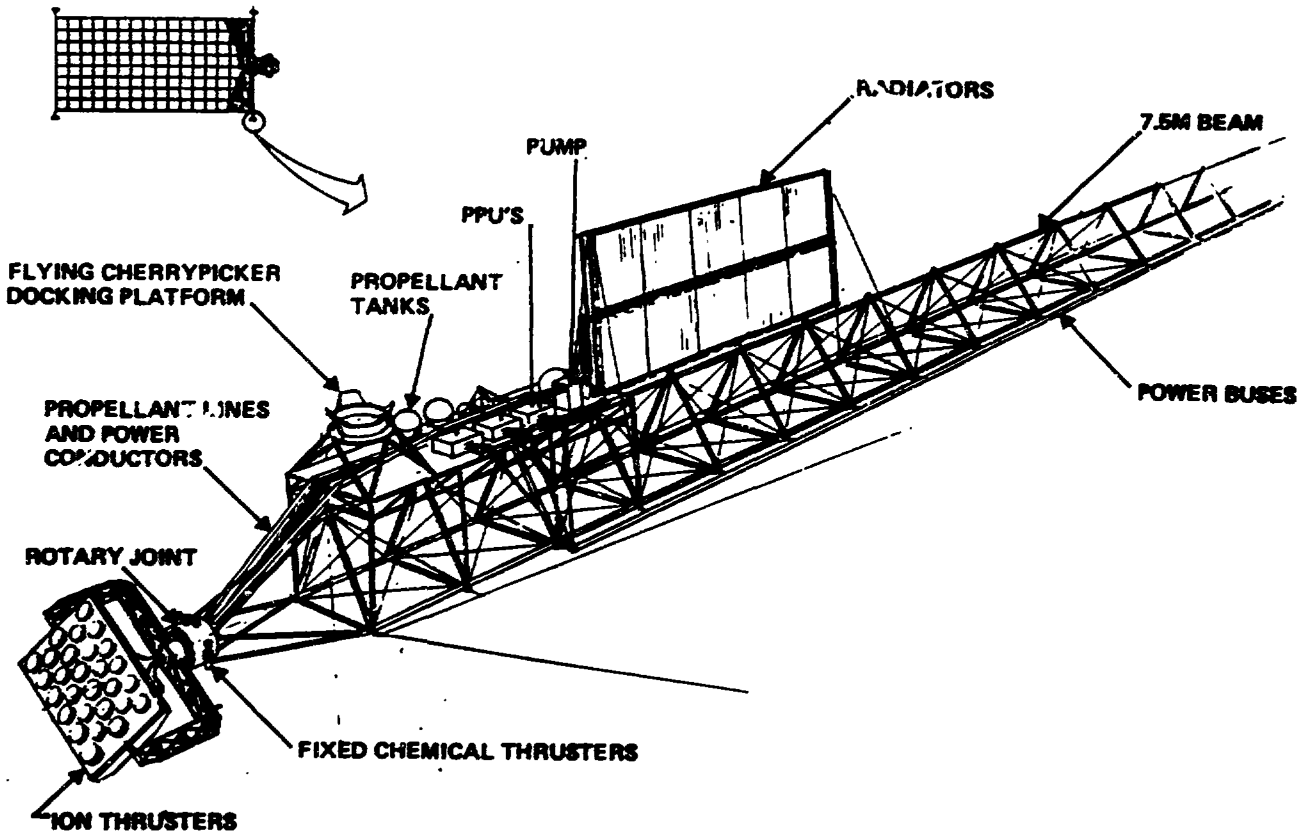


Figure 44.- SPS attitude control system.

shutdown of individual thrusters. Oxygen/hydrogen thruster control is provided by operating the thrusters in pulse mode.

The structure consists of a cable-stayed 7.5-m beam with the necessary support structure for system installations. The gimbal system is a two-axis, motor-driven, slow-rate gimbal system whose commands are derived from the instrumentation and control system.

The power processors are solid-state and convert the 40 000 V from the SPS to lower voltage required by thrusters and other subsystems.

<u>Cost</u>	$\$ \times 10^6$
Research	--
Engineering verification	51.3
Demonstration	429.6
Investment	215.7
Production	139.1/SPS

WBS 1.1.4.5 MAINTENANCE SYSTEM

Definition

The maintenance system consists of the flying cherrypicker docking platform on the attitude control system.

Design Description

The satellite attitude control system is a complex of electric and chemical thrusters, propellant tanks, power processors, and thermal control system components located on the tip of beams that extend outboard of the satellite body. To access these components, a flying cherrypicker docking platform is located on the complex as shown in figure 44.

Cost

The cost for this WBS element was not independently estimated but rather included in the next higher WBS level.

WBS 1.1.5 COMMUNICATIONS

Definition

The communications element consists of the hardware to transmit and receive intelligence among the various SPS elements. This includes communication of both data and voice between the SPS and the control center as well as among the various cargo and personnel vehicles. Excluded is intravehicular and intrasatellite communications.

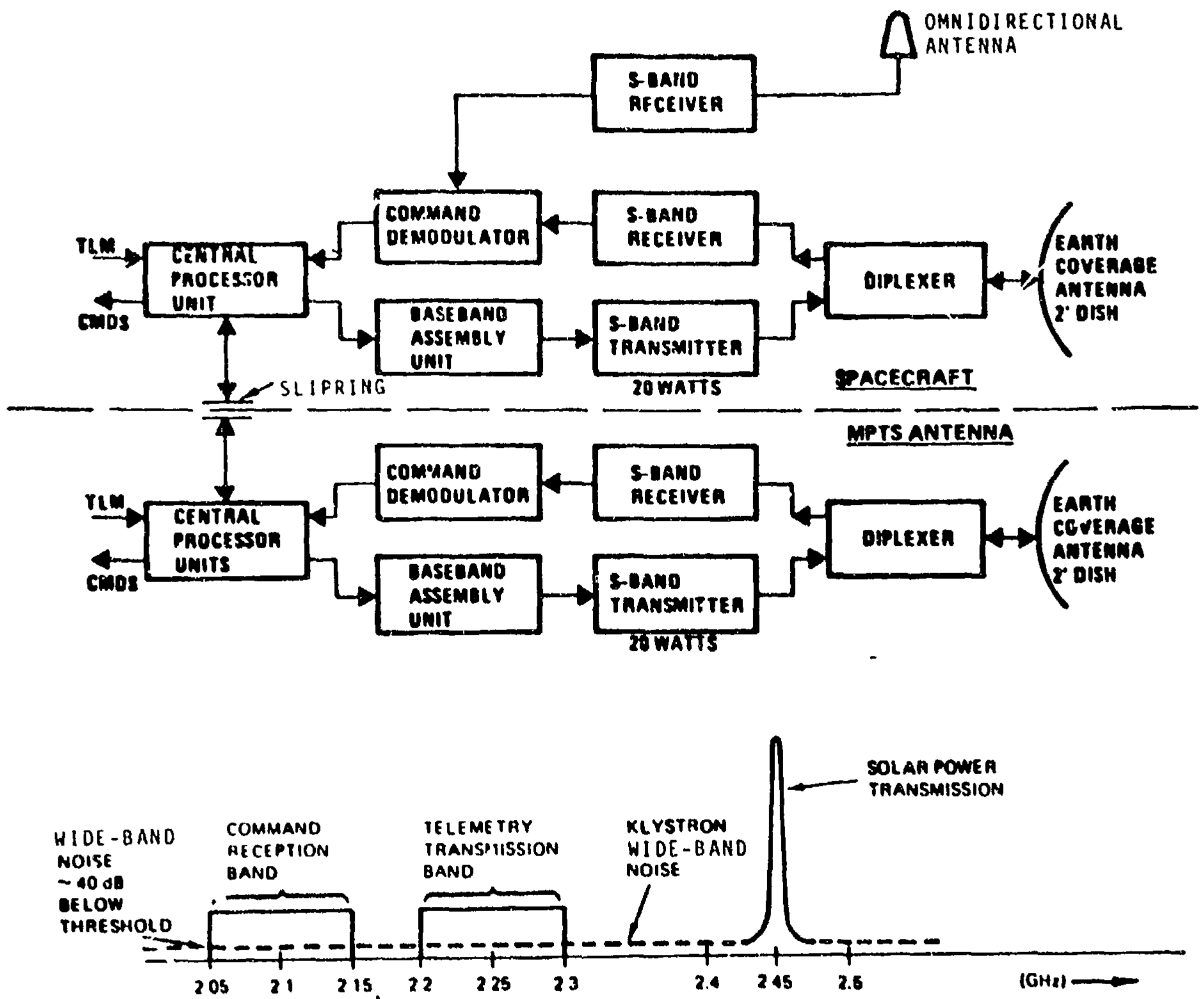


Figure 45.- SPS communication system.

Design Description

The communication system configuration consists of a spacecraft system and an MPTS antenna system which have a limited data link by the data bus through the sliprings. The IMC system is such tha' a rate of approximately 1 megabit/sec is required for both the command uplink and the telemetry downlink. Each subsystem has a 2-ft parabolic antenna providing an Earth coverage gain of 18 dB at S-band frequency. An omnidirectional antenna is located on the spacecraft to provide for command reception in the event of a major error in spacecraft attitude control. The configuration with a 20-W transmitter will transmit up to 20 Mbps and receive up to 10 Mbps.

With the proposed frequency plan, uplink command information will be received by the satellite in the 2.050 to 2.150 GHz band. Telemetry data will be transmitted in the 2.200 to 2.300 GHz band.

Cost	$\$ \times 10^6$
Research	--
Engineering verification	15.7
Demonstration	24.0
Investment	10.4
Production	7.0/SPS

WBS 1.1.6 INTERFACE (ENERGY CONVERSION/POWER TRANSMISSION)

Definition

The SPS has a movable interface between the energy conversion system and the power transmission system as shown in figure 46. A 360° rotary joint and an antenna elevation mechanism are required to maintain proper alinement of the transmitter with the ground receiving station. Included are structure, mechanism, power distribution, thermal control, and maintenance hardware.

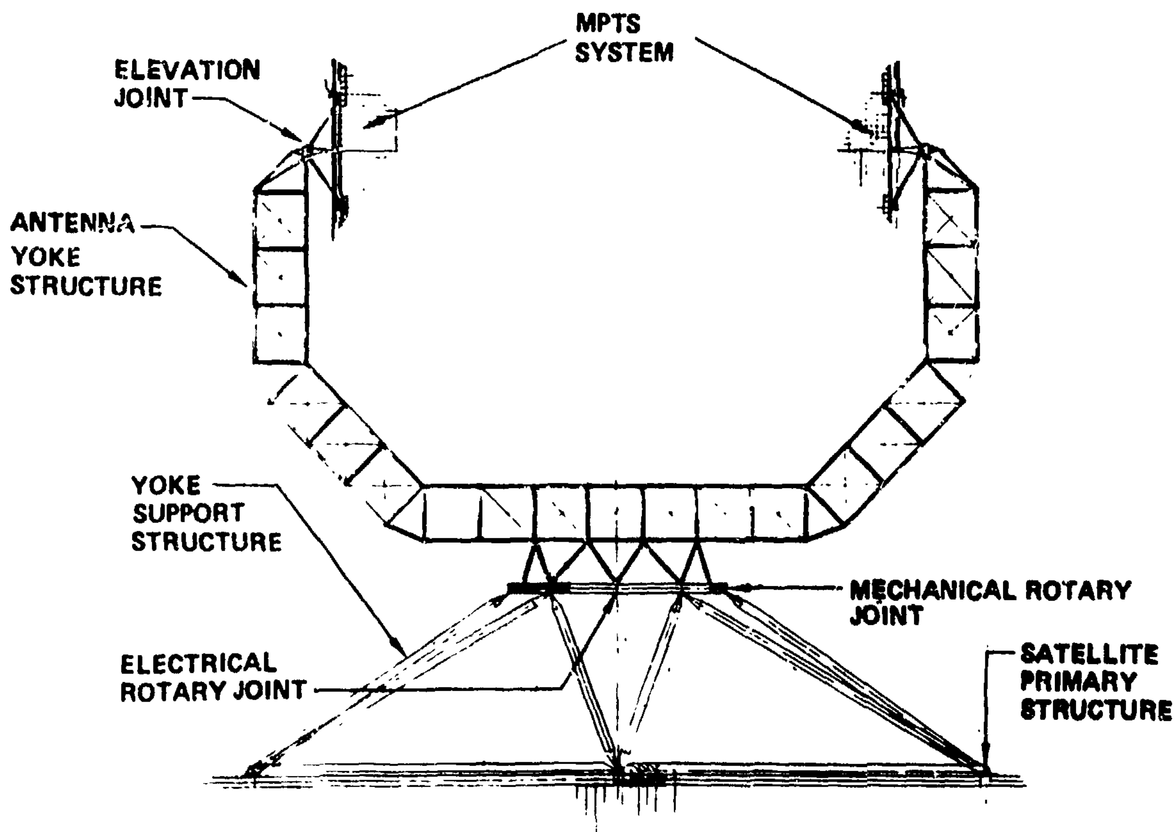


Figure 46.- SPS interface.

Design Description

The interface element is composed of the yoke support structure, which provides for transition from the modular energy conversion structure to the support structure for the circular mechanical drive ring and the electrical slipring assembly; the mechanical turntable; the electrical rotary joint; the antenna yoke structure; and the antenna elevation joint. All structural members used in the yoke support structure are 12.7-m beams. The antenna yoke structure is a 135-m truss constructed using 7.5-m beams with Kevlar tension cables. The mechanical rotary joint is a 350 m diameter drive ring with 12 roller drive assemblies and 36 idler assemblies. The electrical slipring assembly is 16 m in diameter and contains 20 sliprings.

Cost	$\$ \times 10^6$
Research	--
Engineering verification	17.4
Demonstration	269.5
Investment	364
Production	88 /SPS

WBS 1.1.6.1 STRUCTURE

Definition

WBS element 1.1.6.1 includes all members necessary to provide a mechanical interface between the primary structures of the energy conversion system and the power transmission system. It includes beams, beam couplers, cables, tensioning devices, and secondary structures. Excluded are elements of the drive assembly, which are included in WBS 1.1.6.2 (Turntable).

Design Description

The structural members used between the energy conversion structure, the mechanical rotary joint, and the octagonal structure that supports the mechanical and electrical rotary joint are 12.7-m beams. All beams used in the antenna yoke structure are 7.5-m beams. Tension cables used in the yoke structure are Kevlar and are 6.3 mm in diameter.

Cost

The cost for this WBS element was not independently estimated but rather included in the next higher WBS level.

WBS 1.1.6.2 TURNTABLE

Definition

WBS element 1.1.6.2 includes the components required to rotate and elevate the power transmission system. Included are the drive ring, bearings, gear drives, and drive motors.

Design Description

The mechanical drive ring provides 360° rotation between the energy conversion and the power transmission portion of the SPS. The mechanical rotary joint is composed of two segmented circular beams (one on the satellite side and one on the yoke side). Each circular beam is attached at eight points (every 45°) to its adjacent support structure. The inner and outer base chords of each circular beam are adjacent to each other. Between each set of base chords, a drive ring and roller assembly is attached to provide relative movement between the satellite and the MPTS system. The antenna yoke attaches to its circular beam in a method similar to that described for the yoke support structure. Elevation control is provided at each of the two yoke-to-antenna gimbal attachment points.

Cost

The cost for this WBS element was not independently estimated but rather included in the next higher WBS level.

WBS 1.1.6.3 ELECTRICAL ROTARY JOINT

Definition

The electrical rotary joint provides for the transfer of electrical power through the interface. The element includes sliprings, brush assemblies, feeders, and insulation. It excludes main power buses.

Design Description

The multiple bus system selected for SPS power distribution requires a multiple slipring electrical rotary joint to transfer power between the power generation and power transmission portions of the SPS. Twenty sliprings accomplish power transfer for the 10 pairs of power buses. Coin silver (90 percent silver and 10 percent copper) was selected for the slipring material and silver molybdenum disulfide with 3 percent graphite was selected for the brushes. The characteristics of this combination yield low brush/slipring voltage drops. The design uses a brush current density of 20 A/cm^2, resulting in only about 40 kW of power being dissipated in the rotary joint. Brush assemblies are designed for symmetrical loading of the slipring because of brush preload. Insulators for brush assemblies, sliprings, and feeders are alumina.

Cost

The cost for this WBS element was not independently estimated but rather included in the next higher WBS level.

WBS 1.1.7 GROWTH AND CONTINGENCY

For contingency purposes, a growth of 22 percent in the total satellite mass from the estimated mass was assumed. It was further assumed that this mass growth would occur in satellite systems costing less than the average. The satellite cost growth was therefore estimated at 17 percent or 5 percent less than the mass growth. (See reference 2.)

SECTION 2 - CONSTRUCTION

WBS 1.2 SPACE CONSTRUCTION AND SUPPORT

Definition

Space construction and support includes all hardware and activities required to assemble, check out, operate, and maintain the satellite system. Included are space stations, construction facilities and equipment, and manpower operations.

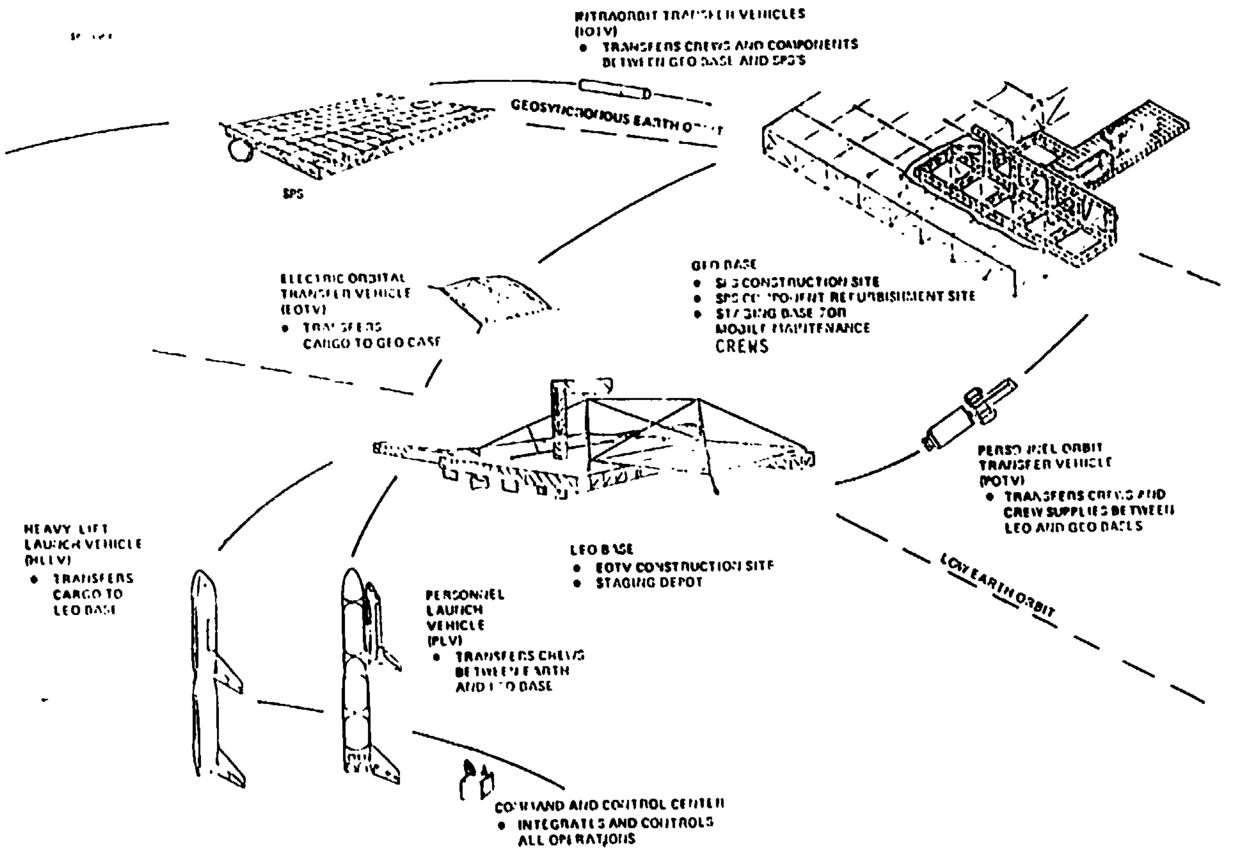


Figure 47.- SPS construction operations diagram.

Design Description

The baseline construction concept entails constructing a 5-GW photovoltaic SPS at geosynchronous orbit (GEO) using Electric Orbit Transfer Vehicles (EOTV's) to haul cargo between a low Earth orbit (LEO) base and a GEO base.

Cargo is delivered to the LEO base by Heavy Lift Launch Vehicles (HLLV's). There would be eight HLLV flights every week. Seventy-five crewmembers would be transferred between Earth and the LEO base by the Personnel Launch Vehicle (PLV) 14 times every 90 days.

The LEO base is used to construct the EOTV's and is also used as a staging depot for transferring cargo and crews to GEO. During EOTV construction operations, there would be about 200 people at the LEO base. During the ongoing cargo-handling phase, there would be about 135 people.

Cargo is transferred between the LEO base and the GEO base in approximately 180 days using the EOTV's. Crews and crew supplies are transferred to the GEO base in approximately 6 hours using chemical (LO_2/LH_2) Personnel Orbit Transfer Vehicles (POTV's).

The SPS's are constructed at GEO using a four-bay-wide end-builder construction base. The GEO construction base can construct one 5-GW SPS in approximately 6 months employing a crew of approximately 400 people.

The GEO base is also used as a place to refurbish failed SPS hardware and is the home base of the maintenance crews and mobile maintenance systems that travel to operational SPS's.

The baseline space construction and support system is designed to construct two 5-GW SPS's per year and eight EOTV's per year.

Cost

The cost estimate breakdown is shown in table VIII.

TABLE VIII.- SPACE CONSTRUCTION AND SUPPORT
SUMMARY MASS AND COST ESTIMATE

WBS no.	Description	Mass M.T.	Nonrecurring costs including DDT&E $\$ \times 10^6$	Avg. unit $\$ \times 10^6$
1.2	Space Construction			
1.2.1	GEO Base	6656	3318	7833
1.2.1.1	Work Support Facility	5028	868	3108
1.2.1.1.1	Structure	2927	93	293
1.2.1.1.2	Construction Equipment	460	344	1565
1.2.1.1.3	Cargo Handling Equipment	399	180	374
1.2.1.1.4	Subassembly Factories	38	47	281
1.2.1.1.5	Test Facilities	20	22	148
1.2.1.1.6	Vehicle Maintenance Facility	3	--	8
1.2.1.1.7	SPS Maintenance Support Facility	63.5	128	211
1.2.1.1.8	Base Subsystems	938	52	280
1.2.1.1.9	Base Facilities	242	--	158
1.2.1.1.10	Command and Control	1	2	1
1.2.1.2	Crew Support Facility	1628	592	2221
1.2.1.2.1	Crew Quarters	1215	197	1672
1.2.1.2.2	Work Modules	413	395	549
1.2.1.3	Base Support		1857	2504
1.2.1.4	Annual Operational Support	1125		1128
1.2.2	LEO Base	1832	4356	2973
1.2.2.1	Work Support Facility	1023	1317	1136
1.2.2.1.1	Structure	380	126.4	38
1.2.2.1.2	Construction Equipment	266	365	507

TABLE VIII.- (Concluded)

WBS no.	Description	Mass M.T.	Nonrecurring costs including DDT&E $\$ \times 10^6$	Avg. unit $\$ \times 10^6$
1.2.2.1.3	Cargo Handling Equipment	165	450	298
1.2.2.1.4	Subassembly Factories	10	47	3.5
1.2.2.1.5	Test Facilities	0	0	0
1.2.2.1.6	Transportation Support	73	224	138
1.2.2.1.7	Base Maintenance	49	--	54
1.2.2.1.8	Base Subsystems	70	102	55
1.2.2.1.9	Command and Control System	10	2	44
1.2.2.2	Crew Support Facility	809	1975	1304
1.2.2.3	Base Support		1060	534
1.2.2.4	Annual Operational Support	534		543
1.2.3	Mobile Maintenance System	522	--	371
1.2.3.1	Work Support Systems	269	--	56
1.2.3.1.1	Klystron Pallet Assembly			9
1.2.3.1.2	Flying Cherrypicker			31
1.2.3.1.3	Free-Flyer			16
1.2.3.2	Crew Support Systems	253		315
1.2.3.2.1	Crew Module			302
1.2.3.2.2	Crew Supply Module			13
1.2.3.3	Annual Operational Support	104		103

The construction cost per SPS is determined by allocating to each SPS one-sixtieth of the facilities cost and one-half of the annual support cost. These figures are consistent with a 60-SPS program constructed at the rate of two SPS's per year.

Facilities	$\$ \times 10^6$				$\$ \times 10^6$
GEO base	7833	÷	60	=	131
LEO base	2973	÷	60	=	50
Mobile maintenance system	371	÷	60	=	6
					187

Operations					
GEO base	1128	÷	2	=	564
LEO base	543	÷	2	=	272
Mobile maintenance system	103	÷	2	=	52
					888

Total construction cost per SPS....................1075

WBS 1.2.1 GEO BASE

Definition

The GEO base includes the facilities, equipment, and operations required to assemble and check out the satellite system. Included are fabrication and assembly facilities, cargo depots, and operations.

Design Description

Construction of the 5-GW reference satellite takes place in GEO. Consequently, the personnel needed to activate the four-bay end-builder construction base must travel first by means of the Personnel Launch Vehicle (PLV) to LEO and finally by means of a Personnel Orbit Transfer Vehicle (POTV) from LEO to GEO.

The four-bay end builder assembles the SPS satellite in two successive passes as shown by the construction sequence illustrated in figure 47. During the first pass, the GEO construction base builds a 4-bay-wide strip 16 bays long. Construction of the satellite antenna is performed in parallel. When one-half of the satellite energy conversion system has been assembled, the base is indexed to the side and then back along the edge of the satellite. The base is realined with the end frame of the satellite to start the second construction pass. The remaining four-bay-wide strip is attached directly to the assembled satellite as the base moves toward the other end. Large Electric Orbit Transfer Vehicles (EOTV's) will deliver SPS materials and components throughout the assembly process. GEO base crews will also be rotated as needed. The satellite antenna is completed in parallel with the construction of the 8- by 16-bay energy conversion system. At the end of the second pass, the base is indexed sideward to mate the antenna with the centerline of the energy conversion system. Following the final test and checkout, the GEO base will be separated from the satellite and transferred to the next SPS construction location.

The GEO base is also the location of SPS component refurbishment facilities and is a staging base for mobile maintenance crews and transport vehicles.

Cost

See table VIII for cost and mass data.

WBS 1.2.2 LEO BASE

Definition

The LEO base includes the hardware, software, and operations required in LEO to support the construction, operation, and maintenance of the satellite system. Included are crew life support facilities, cargo and propellant depots, and vehicle-servicing facilities necessary for the receipt, storage, and transfer of cargo and personnel destined for a construction base or operational satellite located in GEO. This element also includes the hardware, software, and operations required to construct EOTV's.

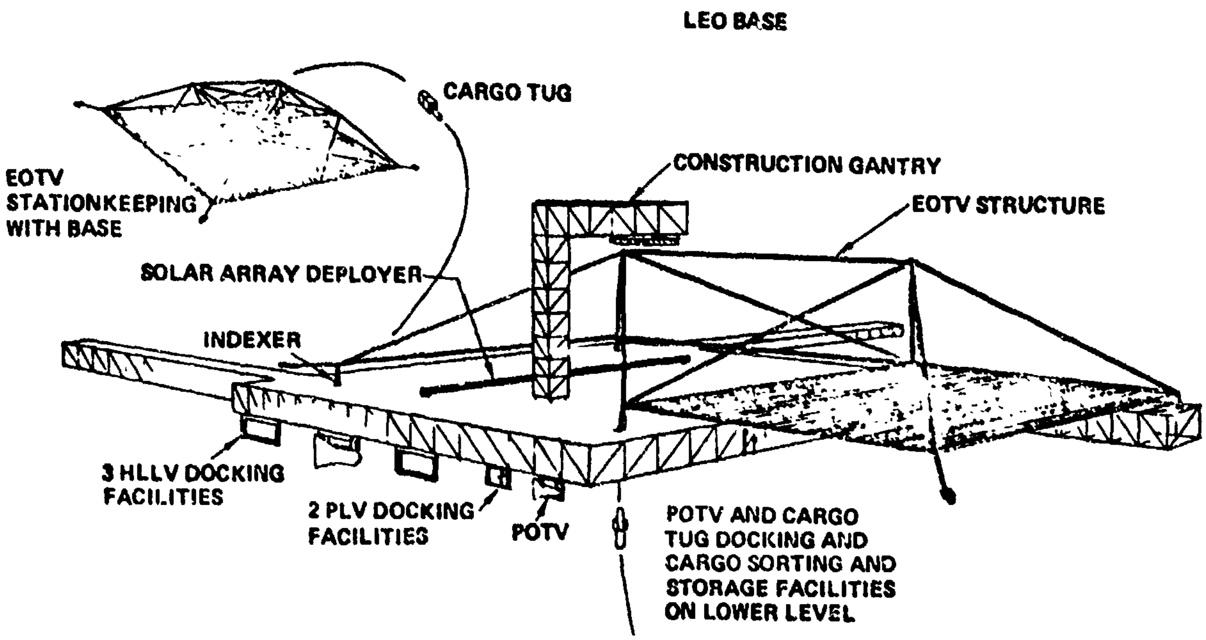


Figure 48.- LEO base.

Design Description

The LEO base is shown in figure 48. It is used to construct EOTV's and it serves as a staging depot for cargo and crews destined for GEO.

The base gets its planform configuration from the requirements imposed by EOTV construction operations. The main deck size is approximately the size of one EOTV bay. The outriggers make it possible to index the EOTV structure in one-bay increments in three different directions during the construction process. The construction gantry and an assortment of construction equipment operate from the upper surface of the base.

The LEO base serves as a staging depot for cargo being transferred from Heavy Lift Launch Vehicles (HLLV's) to EOTV's. The EOTV's will stationkeep with the LEO base during the cargo transfer operations conducted by cargo tugs.

The LEO base also serves as a staging depot for the crews on their way between Earth and the GEO base. This requires transient crew quarters and the docking facilities and support equipment for the Earth-to-LEO crew vehicles (PLV's) and the interorbit crew transfer vehicles (POTV's).

Cost

See table VIII for cost and mass data.

WBS 1.2.3 MOBILE MAINTENANCE SYSTEM

Definition

Mobile maintenance systems are flown between the GEO base and operational satellites. Included are the mobile work support systems, crew support systems, and maintenance operations at the satellite. Other SPS maintenance-related elements and operations are described in WBS 1.1.1.6 (Energy Conversion Maintenance System) and WBS 1.1.2.6 (Power Transmission Maintenance System).

Design Description

The mobile maintenance work support and crew support elements are shown in figure 49. The mobile maintenance systems will be based at the GEO base between maintenance sorties. These system elements will shuttle between satellites and the GEO base.

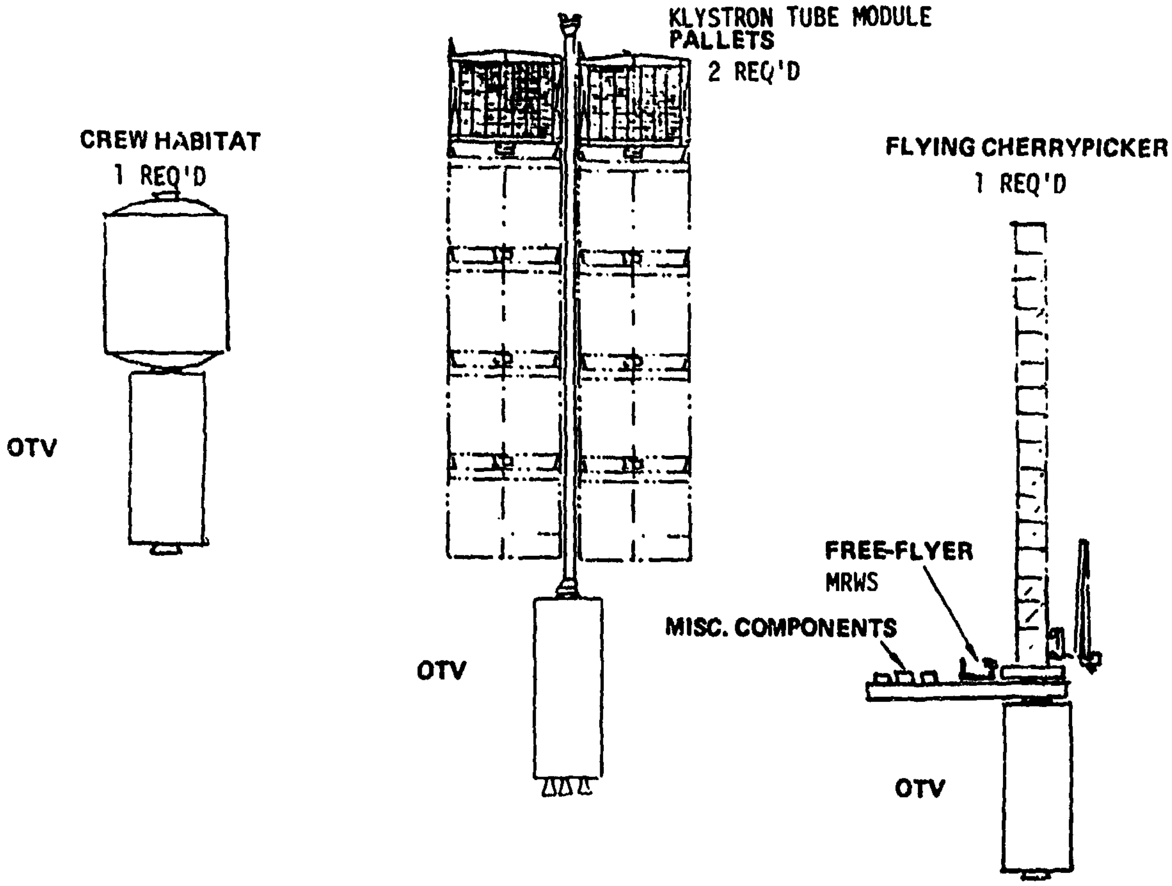


Figure 49.- Mobile maintenance support system.

SECTION 3 - TRANSPORTATION SYSTEM

WBS 1.3 TRANSPORTATION SYSTEM

Definition

The transportation system includes all the vehicles and operations necessary to construct, operate, and maintain the SPS system. Specifically, it consists of four vehicles: the Heavy Lift Launch Vehicle (HLLV) for the transportation of cargo to LEO; the Electric Orbit Transfer Vehicle (EOTV) for the transportation of cargo from LEO to GEO; the Personnel Launch Vehicle (PLV) for transportation of personnel to LEO; and the Personnel Orbit Transfer Vehicle (POTV) for transportation of personnel from LEO to GEO.

Design Description

There are six payload types requiring transportation. These are the SPS itself, the LEO construction base, the GEO construction base, the EOTV and POTV vehicles with their propellants, and the maintenance-related payloads. The mass associated with each of these payload types is listed in table IX.

From these payload requirements, the number of flights required to implement and support the 60-SPS scenario was derived. In table X, the cargo payloads to be carried from LEO to GEO by the EOTV during the 33-year scenario are shown. From this information, the EOTV flights required were computed and are presented in figure 50. The mass transported by the EOTV must also be transported to LEO by the HLLV, so the EOTV payloads are also listed in table XI, where the HLLV payloads are totaled.

Figure 51 shows the number of people required at GEO and LEO to construct the satellites and maintain the system for the 33 years of the scenario. From this information, the numbers of PLV and POTV flights required were computed and the results are shown in figures 52 and 53.

From the numbers of flights by the EOTV, POTV, and PLV, the mass to be transported by the HLLV was computed and is listed in table XI. The HLLV flights required were then determined and are summarized in figure 54.

Figure 55 presents the required number of each type of vehicle. These quantities were computed by dividing the number of flights required by the expected vehicle life.

The estimated annual effort required to operate and maintain the transportation system is summarized in table XII.

TABLE IX.- PAYLOAD CHARACTERISTICS

	Mass (metric tons)
SPS	
Satellite	50 984
Allowance for breakage (2%)	1 020
Total per satellite	52 004
LEO BASE	
Base	1 603
Crew facilities, supplies/yr	313
Work facilities, supplies/yr	72
GEO BASE	
Base	4 800
Crew facilities, supplies/yr	568
Work facilities, supplies/yr	683
EOTV	
Vehicle	1 462
Propellant/flight	515
Refurbishment/flight	40
POTV	
Stage	14
Propellant/flight(up/down)	200/185
Refurbishment/flight	0.1
Personnel module	53
SPS MAINTENANCE	
SPS supplies/satellite/yr	236
Crew & work facilities/20 satellites	1 154
Crew & work supplies/yr/20 satellites	206
POTV maintenance sortie propellant/satellite/yr	25

TABLE X.- EOTV PAYLOADS TO GEO FOR CONSTRUCTION

[All mass in metric tons]

Year	Sat. qty.	SPS	GEO base	GEO base supplies	Tug propellant	POTV propellant	Total EOTV payload
1		--	2400	127	48	740	3 315
2		--	2400	455	63	1480	4 398
3		26 002		796	296	2590	29 684
4	2	78 006		1251	851	4070	84 178
5	4	104 008		1251	1147	4070	110 476
6	6	104 008		1251	1151	4070	110 480
7	8	104 008		1251	1161	4070	110 490
8	10	104 008		1251	1170	4070	110 499
9	12	104 008		1251	1180	4070	110 509
10	14	104 008		1251	1195	4070	110 524
11	16	104 008		1251	1199	4070	110 528
12	18	104 008		1251	1210	4070	110 539
13	20	104 008		1251	1224	4070	110 553
23	40	104 008		1251	1300	4070	110 629
33	60	104 008		1251	1406	4070	110 735

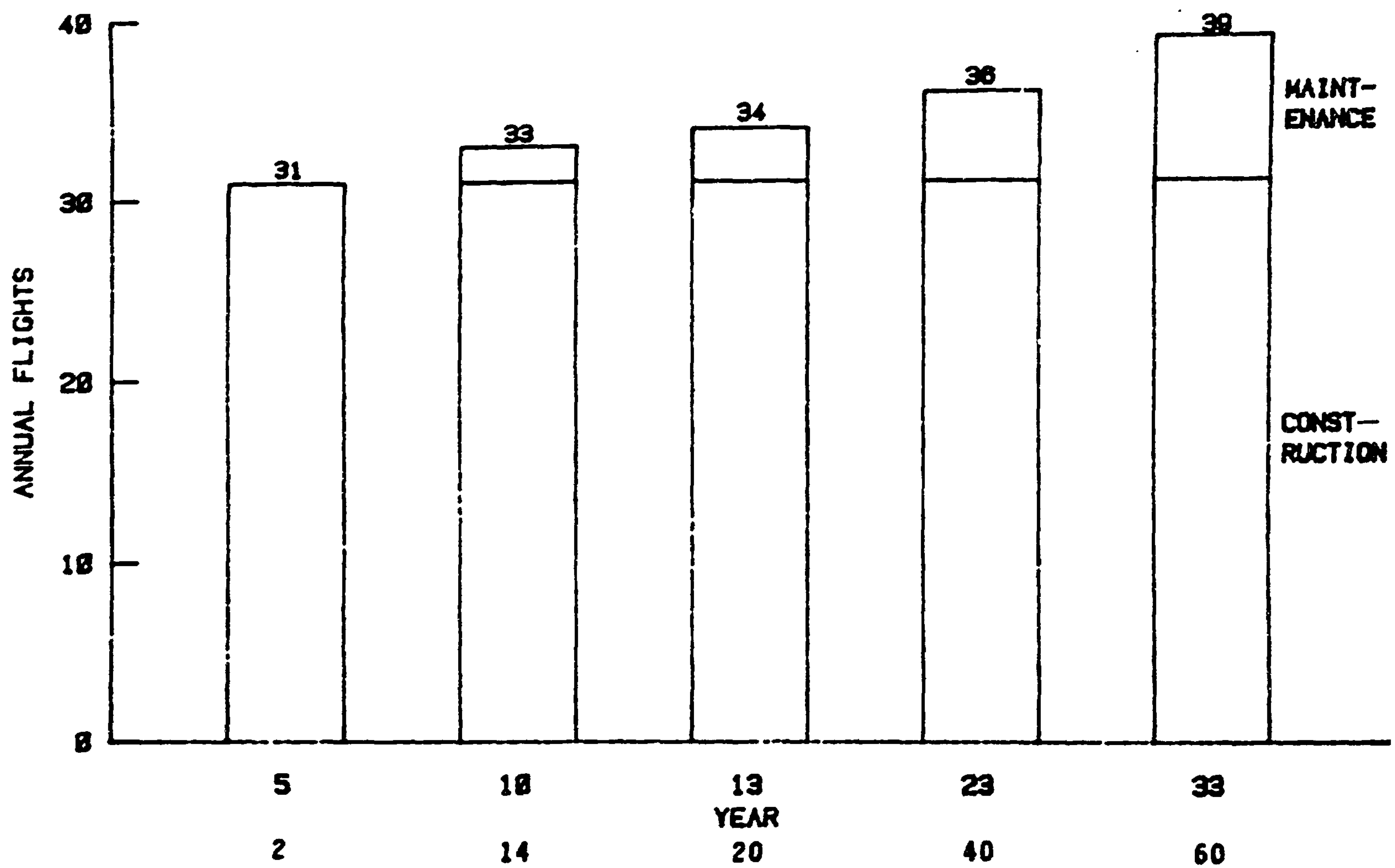


Figure 50.- EOTV flights.

TABLE XI.- HLLV PAYLOADS TO LEO

[All mass in metric tons]

Year	Sat. qty.	LEO base supplies	EOTV fleet Const.	EOTV fleet Maint.	EOTV payloads Const.	EOTV payloads Maint.	POTV fleet Const.	POTV fleet Maint.	POTV payloads Const.	POTV payloads Maint.	Total HLLV payload
1	-	555	9 280	--	2 575	--	1554	--	123	--	14 087
2	--	785	9 450	--	2 918	--	3080	--	238	--	16 471
3	--	785	13 405	--	27 094	--	5390	--	476	--	47 150
4	2	725	17 607	226	80 108	916	8470	770	748	69	109 639
5	4	725	18 807	1744	106 406	838	8484	834	794	115	138 747
6	6	725	17 345	396	106 410	1 310	8470	1 640	748	136	137 180
7	8	725	17 345	622	106 420	2 107	8484	2 460	794	204	139 161
8	10	725	17 345	678	106 429	2 292	8470	3 280	748	272	140 239
9	12	725	17 345	847	106 439	2 764	8484	4 114	794	386	141 898
10	14	785	29 041	1017	106 454	3 561	8470	4 920	748	408	155 404
11	16	785	29 041	1130	106 458	3 746	8484	5 754	794	476	156 668
12	18	785	27 579	4167	106 468	4 218	8470	6 569	748	544	159 548
13	20	725	17 345	1469	106 481	5 245	8484	7 374	794	658	148 575
23	40	725	17 345	2769	106 559	10 133	8470	14 824	748	1224	162 797
33	60	725	17 345	4294	106 665	15 357	4570	23 780	748	1972	175 456

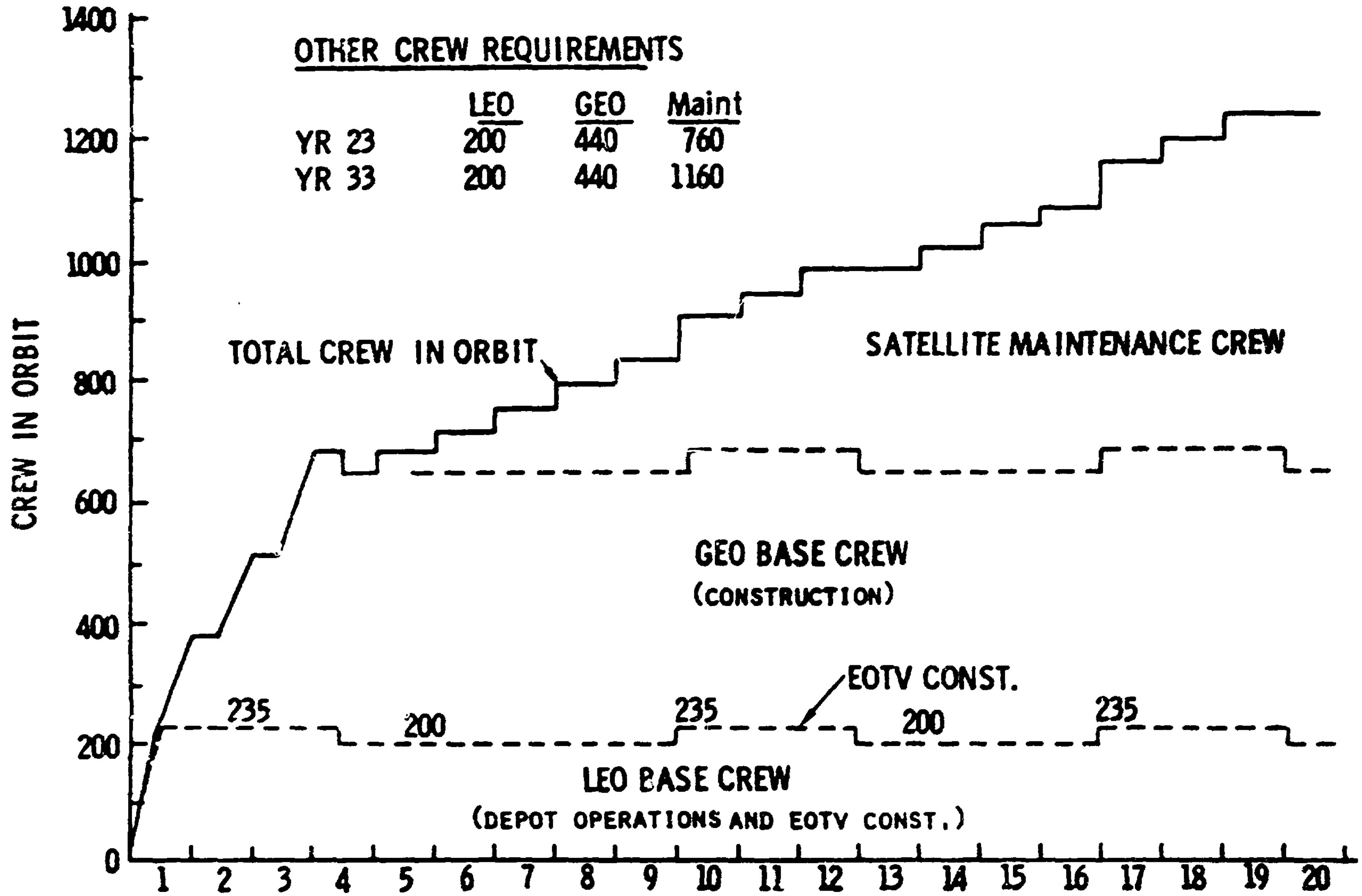


Figure 51.- Crew in orbit.

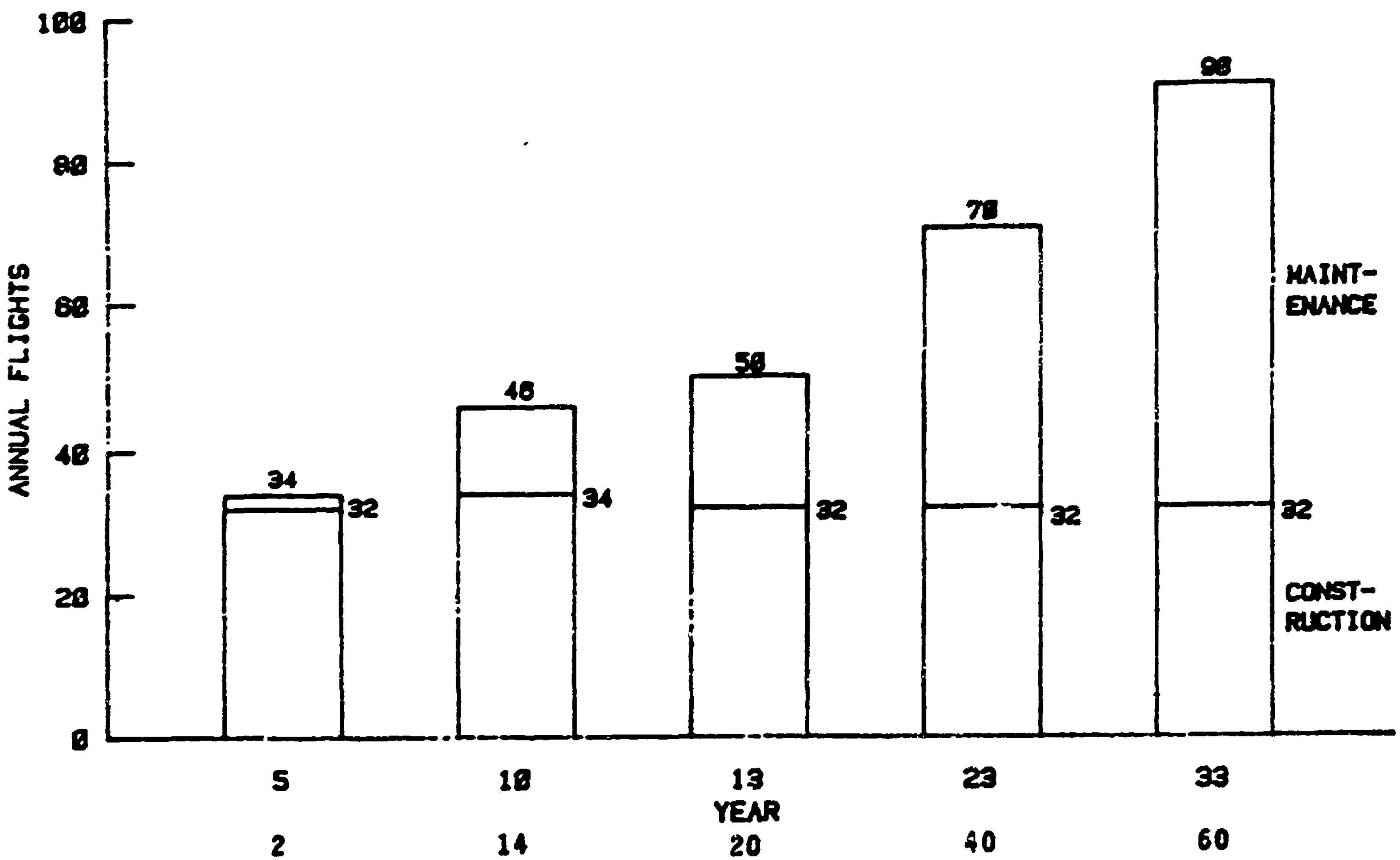


Figure 52.- PLV flights.

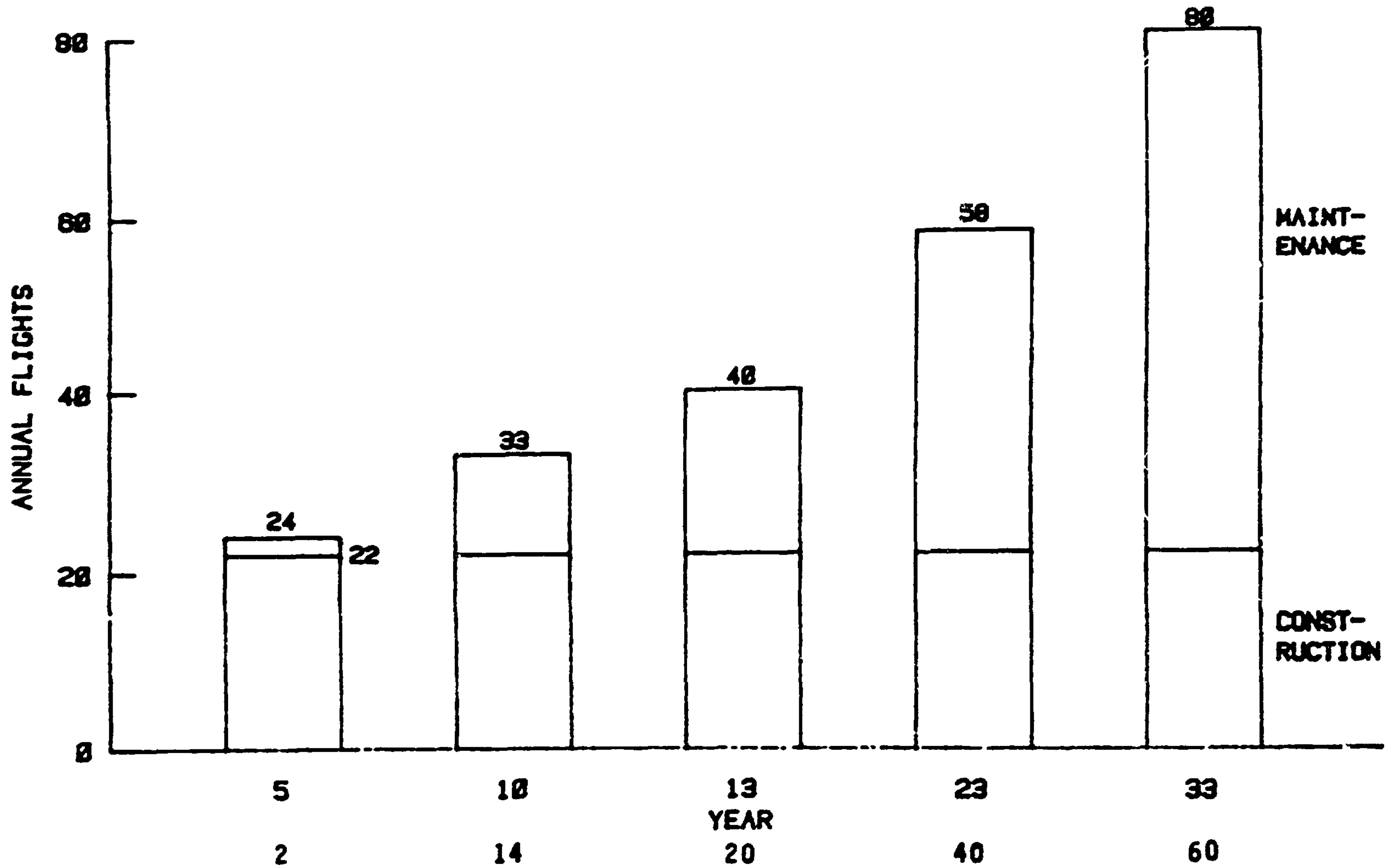


Figure 53.- POTV flights.

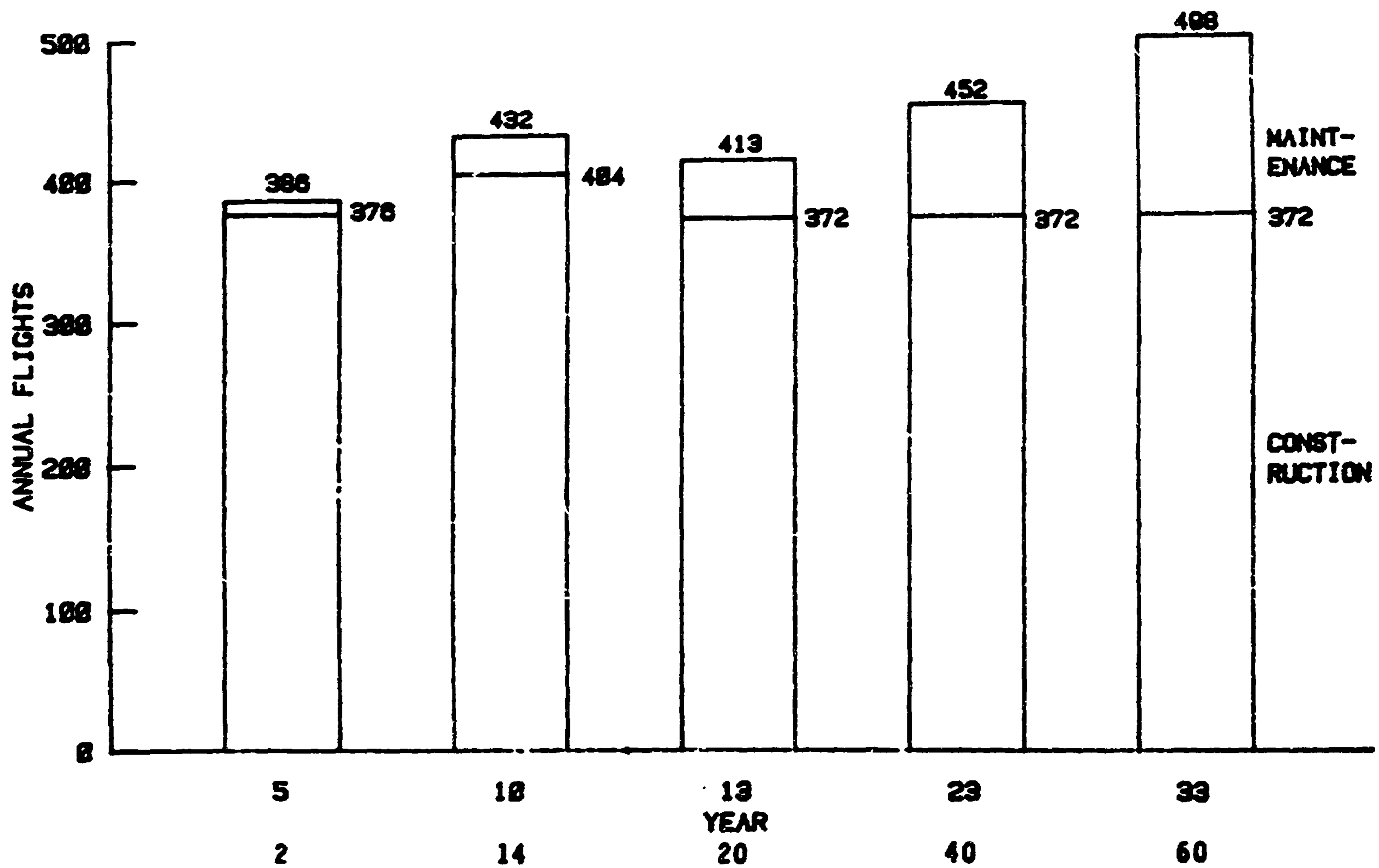


Figure 54.- HLLV flights.

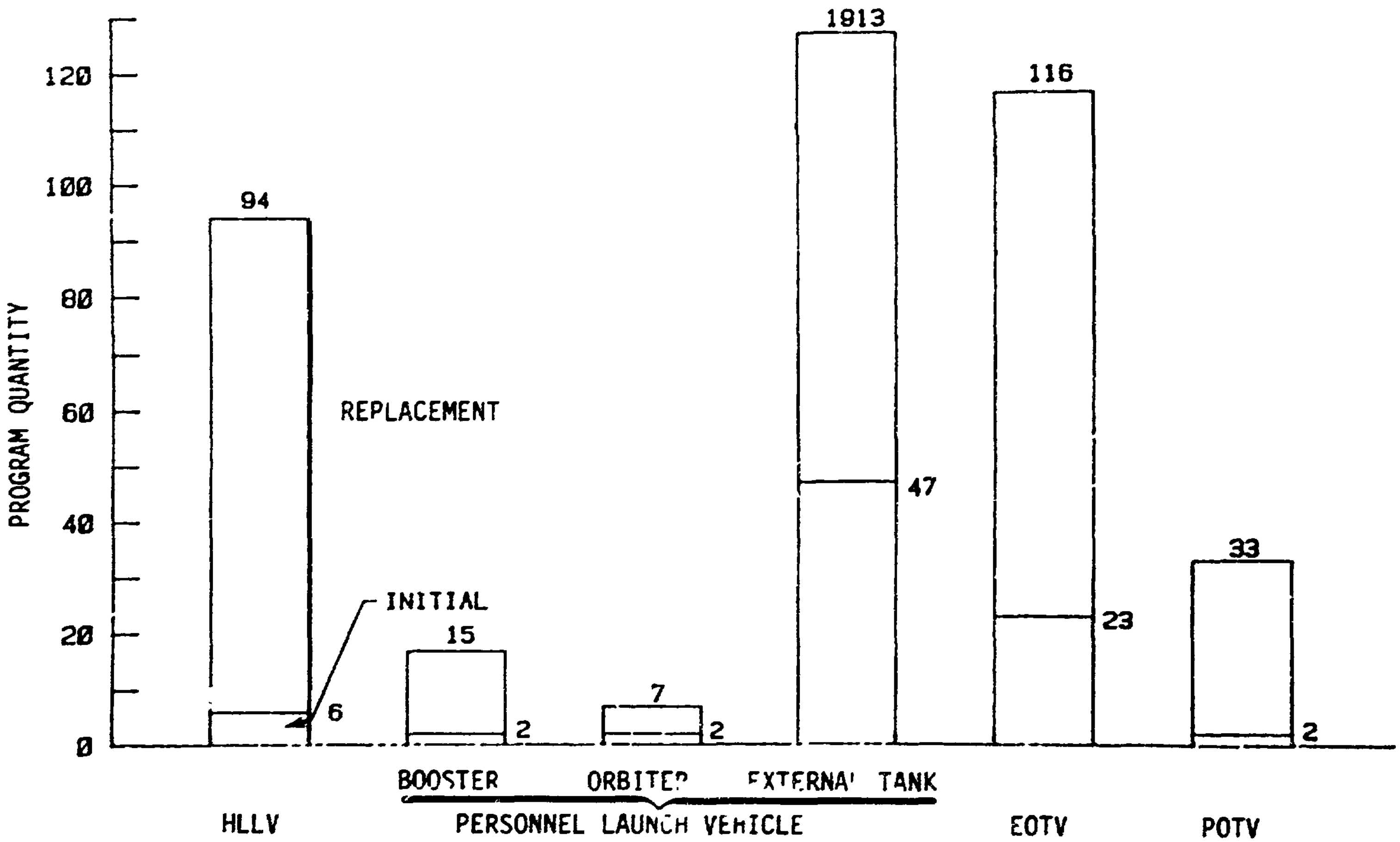


Figure 55.- Transportation vehicle quantities.

TABLE XII.- GROUND OPERATIONS AND SYSTEM MAINTENANCE

WBS	Facility	Total annual man-hours Operations	Maintenance
1.3.7	Ground Support Facilities	[a]5 174 832	[b]7 676 714
1.3.7.1	Launch Facilities		
1.3.7.1.1	HLLV Launch Facilities	476 800	862 500
1.3.7.1.2	PLV Launch Facilities	79 196	133 616
1.3.7.2	Recovery Facilities		
1.3.7.2.1	Landing Site[e]	145 920	218 880
1.3.7.2.2	HLLV Orbiter and Payload Processing Facility	906 400	1 359 600
1.3.7.2.3	HLLV Booster Processing Facility	492 800	739 200
1.3.7.2.4	Engine Maintenance Facility	(c)	(c)
1.3.7.2.5	Hypergolic Maintenance Facility	(c)	(c)
1.3.7.2.6	Passenger Offloading Facility	2 400	3 360
1.3.7.2.7	PLV Booster Processing Facility	67 520	101 280
1.3.7.2.8	PLV Orbiter Processing Facility	75 656	1 134 984
1.3.7.2.9	Vertical Assembly Building	35 840	36 854
1.3.7.2.10	Mobile Launch Platform	(d)	(d)
1.3.7.3	Fuel Facilities[e]	727 080	823 440
1.3.7.4	Logistic Support	1 314 000	1 971 000
1.3.7.5	Operations[e]	851 280	292 000

[a]Total Annual Operations Man-Hours = 2 587 Man-Years
[b]Total Annual Maintenance Man-Hours = 3 838 Man-Years
[c]Included in 1.3.7.2.2 and 1.3.7.2.3
[d]Included in 1.3.7.1.2
[e]The HLLV and PLV portions of these items total as follows:

	Operations	Maintenance
HLLV-Related Man-Hours	4 710 500	6 075 700
HLLV-Related Cost	$188 million	$243 million ($40/man-hr)
PLV-Related Man-Hours	464 300	1 601 000
PLV-Related Cost	$18 million	$64 million ($40/man-hr)

Cost

The cost per flight (in millions of dollars) for each vehicle type is estimated as follows:

HLLV	10.1
EOTV	40.7
PLV	10.7
POTV	1.3

These per-flight estimates result in an overall transportation cost per SPS of $2.8 billion (see table XIII).

TABLE XIII.- TOTAL TRANSPORTATION COST SUMMARY

DDT&E costs	$\$ \times 10^6$
Heavy Lift Launch Vehicle	11 202
Electric Orbit Transfer Vehicle	2 247
Personnel Launch Vehicle	2 616
Personnel Orbit Transfer Vehicle	1 012
Total Transportation DDT&E	$17 077

Average Transportation Cost per SPS			$\$ \times 10^6$
HLLV	$\frac{\$10.1 \text{ million/flt} \times 11\ 606 \text{ flts}}{60 \text{ SPS's}}$	=	1 954/SPS
EOTV	$\frac{\$40.7 \text{ million/flt} \times 847 \text{ flts}}{60 \text{ SPS's}}$	=	575/SPS
PLV	$\frac{\$10.7 \text{ million/flt} \times 1458 \text{ flts}}{60 \text{ SPS's}}$	=	260/SPS
POTV	$\frac{\$1.3 \text{ million/flt} \times 587 \text{ flts}}{60 \text{ SPS's}}$	=	12.7/SPS
Total Transportation Cost per SPS			2 802/SPS

WBS 1.3.1 HEAVY LIFT LAUNCH VEHICLE

Definition

The Heavy Lift Launch Vehicle (HLLV) is a vehicle used to transport all SPS hardware and construction, maintenance, and support equipment to low Earth orbit.

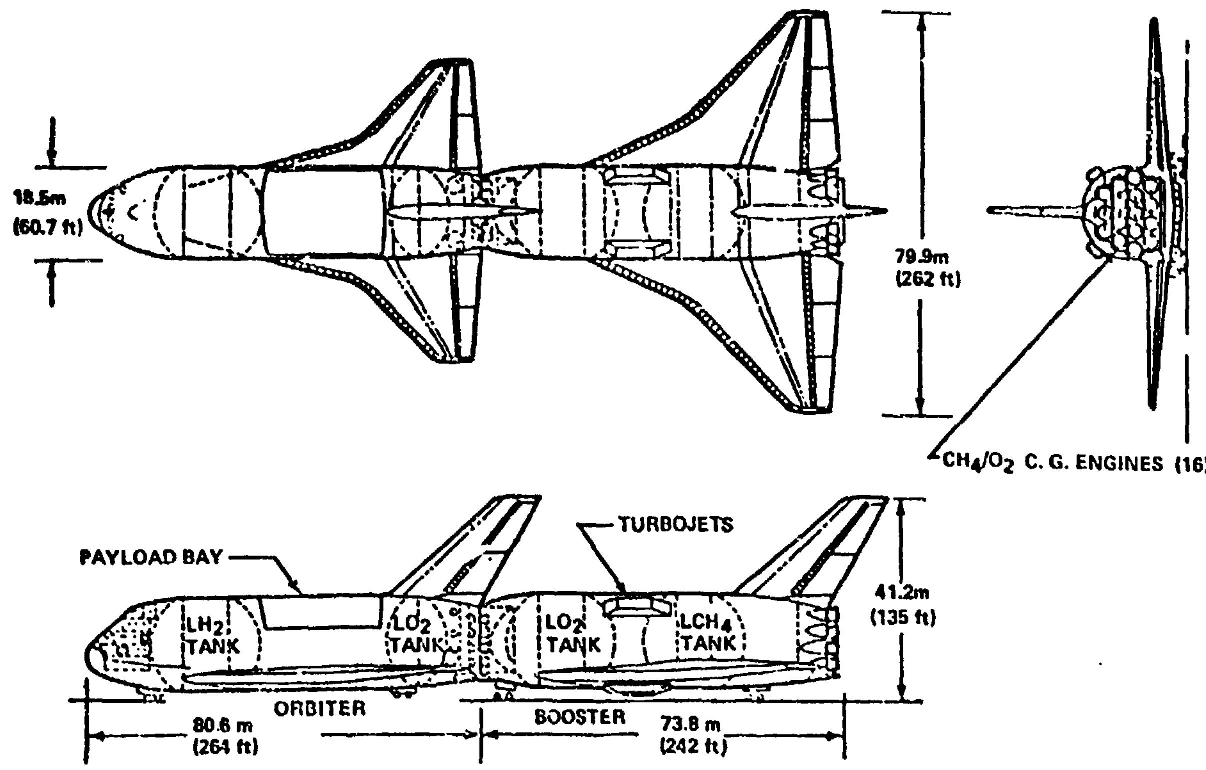


Figure 56.- The HLLV.

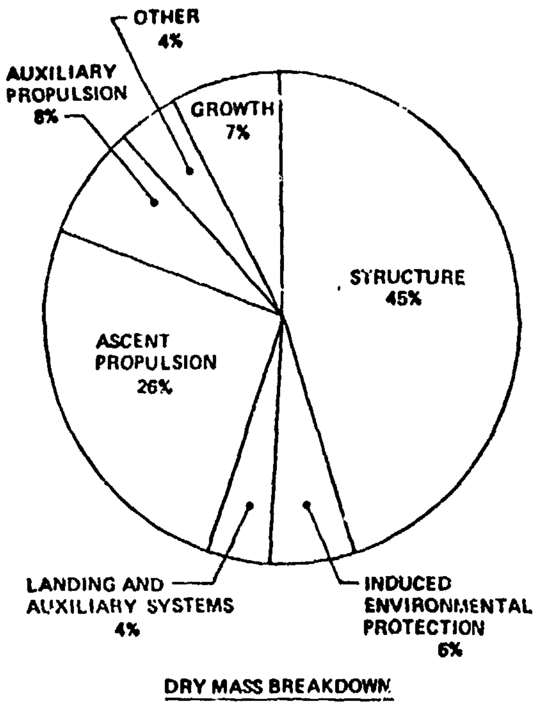
Design Description

The HLLV is a two-stage, winged, fully reusable vehicle. The series burn concept uses 16 LCH_4/LO_2 engines on the booster stage and 14 SSME's on the Orbiter. The booster engines employ a gas generator cycle to generate a vacuum thrust of 9.8×10^6 newtons each. The SSME's provide 2.1×10^6 newtons each. An RP1/air propulsion system has been provided on the booster for flyback capability to simplify operations. Heat sink thermal protection is used for the booster, and the Shuttle reusable surface insulation is used on the Orbiter. The HLLV has a gross payload of 424 M.T. and a net payload of 374 M.T. The vehicle has an inert weight of 1413 M.T. and has an estimated life of 300 missions. Propellant requirements are 1709 M.T. LCH_4, 329 M.T. LH_2, 7103 M.T. LO_2, and 85 M.T RP1 per flight. Turnaround time is estimated to be 97 hours for the booster and 127 hours for the Orbiter. An HLLV mass breakdown is shown in figure 57. A more detailed vehicle description can be found in reference 6, pp. 255-267 and 272-277.

Cost

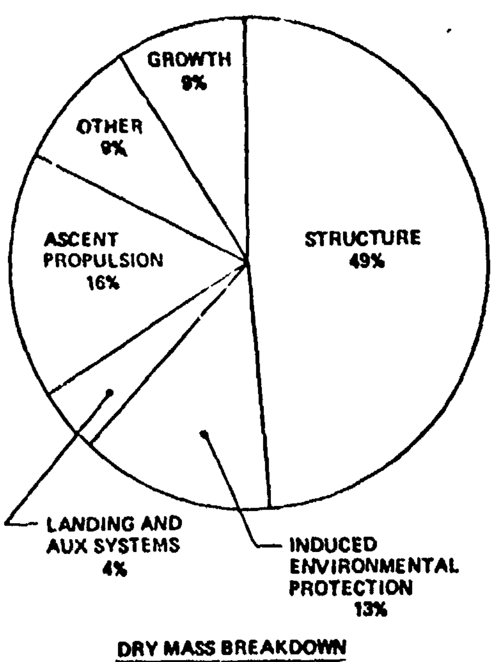
See table XIV for cost estimates for the design, development, test, and evaluation (DDT&E), theoretical first unit (TFU), and average unit of the various elements of the Heavy Lift Launch Vehicle. See table XV for the cost per HLLV flight.

Booster Mass Statement



	MASS, kg
STRUCTURE	360 800
INDUCED ENVIRONMENTAL PROTECTION	46 400
LANDING AND AUXILIARY SYSTEMS	34 600
ASCENT PROPULSION	204 600
AUXILIARY PROPULSION	60 600
PRIME POWER	4 300
ELECTRICAL CONVERSION AND DISTRIBUTION	4 200
HYDRAULIC CONVERSION AND DISTRIBUTION	10 900
SURFACE CONTROLS	10 300
AVIONICS	1 600
ENVIRONMENTAL CONTROL	200
GROWTH	58 600
DRY MASS =	798 900
RESIDUALS AND RESERVES	49 800
LANDING MASS =	848 700
LOSSES DURING FLYBACK	86 200
START FLYBACK MASS =	932 900
ENTRY IN-FLIGHT LOSSES	3 700
START ENTRY MASS =	936 600
IN-FLIGHT LOSSES PRIOR TO ENTRY	27 000
STAGING MASS =	963 600
THRUST DECAY PROPELLANT	14 500
INERT MASS =	978 100

Orbiter Mass Statement



	MASS, kg
STRUCTURE	182 900
INDUCED ENVIRONMENTAL PROTECTION	48 300
LANDING AND AUX SYSTEMS	15 800
ASCENT PROPULSION	60 800
AUXILIARY PROPULSION	9 500
PRIME POWER	2 500
ELECTRICAL CONVERSION AND DISTRIBUTION	4 800
HYDRAULIC CONVERSION AND DISTRIBUTION	3 600
SURFACE CONTROLS	6 800
AVIONICS	2 400
ECLS AND PERSONNEL PROVISIONS	2 900
GROWTH	32 900
DRY MASS =	373 200
PERSONNEL AND PAYLOAD ACCOMMODATIONS	4 100
RESIDUAL AND RESERVES	14 500
LANDING MASS =	391 800
ENTRY IN-FLIGHT LOSSES	3 400
START ENTRY MASS =	395 200
IN-FLIGHT LOSSES PRIOR TO ENTRY	39 900
INERT MASS =	435 100

Figure 57.- HLLV mass statement.

TABLE XIV.- HEAVY LIFT LAUNCH VEHICLE SUMMARY COST ESTIMATE

[All costs in millions of dollars]

WBS no.	Description	DDT&E	TFU	Avg. unit
1.3	SPACE TRANSPORTATION			
1.3.1	HEAVY LIFT LAUNCH VEHICLE			
1.3.1.1	VEHICLE	11 202	1748	595
1.3.1.2	BOOSTER STAGE	6 528	984	335
1.3.1.2.1	STRUCTURES	550	169	
1.3.1.2.2	INDUCED ENVIRON. PROTEC.	15	6	
1.3.1.2.3	LANDING & AUXILIARY SYST.	193	110	
1.3.1.2.4	ASCENT PROPULSION	803	199	
1.3.1.2.5	FLYBACK PROPULSION	235	107	
1.3.1.2.6	OTHER BOOSTER SYSTEMS	156	134	
1.3.1.2.7	BOOSTER SYSTEMS TEST	3 294	0	
1.3.1.2.8	BOOSTER GSE	315	153	
1.3.1.2.9	TOOLING	397	0	
1.3.1.2.10	SOFTWARE	27	0	
1.3.1.2.11	PROG. INT. & MGT.	162	44	
1.3.1.2.12	GSE SUBSYSTEMS	306	0	
1.3.1.2.13	ASSEMBLY & CHECKOUT	--	61	
1.3.1.2.14	BOOSTER SE&I	75		
1.3.1.3	ORBITER STAGE	4 674	764	260
1.3.1.3.1	STRUCTURES	325	104	
1.3.1.3.2	INDUCED ENVIRON. PROTEC.	164	65	
1.3.1.3.3	LANDING & AUX. SYST.	92	56	
1.3.1.3.4	ASCENT PROPULSION	41	182	
1.3.1.3.5	AUXILIARY PROPULSION	280	24	
1.3.1.3.6	OTHER ORBITER SYSTEMS	212	137	
1.3.1.3.7	ORBITER SYSTEMS TEST	2 569	--	
1.3.1.3.8	ORBITER GSE	258	119	
1.3.1.3.9	TOOLING	273	--	
1.3.1.3.10	SOFTWARE	24		
1.3.1.3.11	PROG. INT. & MGT.	133	33	
1.3.1.3.12	GSE SUBSYSTEMS	237	--	
1.3.1.3.13	ASSEMBLY & CHECKOUT	--	46	
1.3.1.3.14	ORBITER SE&I	65	--	

TABLE XV.- HLLV - COST PER FLIGHT

		Cost ($\$ \times 10^3$)
HARDWARE:		
$\frac{\$595 \text{ million per vehicle}}{300 \text{ flights per vehicle}}$	=	1 980
PROPELLANT:		
H_2 346 M.T. @ $1.53/kg	=	530
O_2 7458 M.T. @ $0.037/kg	=	276
CH_4 1794 M.T. @ $0.385/kg*	=	700
RP1 87 M.T. @ $0.374/kg*	=	73
REPLENISHMENT AND REFURBISHMENT:		
Stage 1		
Ascent engines		1 002
Air-breathing engines		6
All other		870
Stage 2		
Ascent engines		930
Maneuvering engines		6
All other		780
GROUND OPERATIONS		628
TOOLING		235
MANPOWER		2 138
TOTAL COST PER FLIGHT		10 100 ($10.1 million)

*Costs for fuel are from Boeing's alternate aircraft fuels study, assuming CH_4 from coal and RP1 from shale.

WBS 1.3.2 ELECTRIC ORBIT TRANSFER VEHICLE

Definition

The cargo orbit transfer vehicle is used to transport satellite components, maintenance hardware, and selected crew and base support supplies from LEO to GEO. This vehicle uses electric propulsion and is called the Electric Orbit Transfer Vehicle (EOTV).

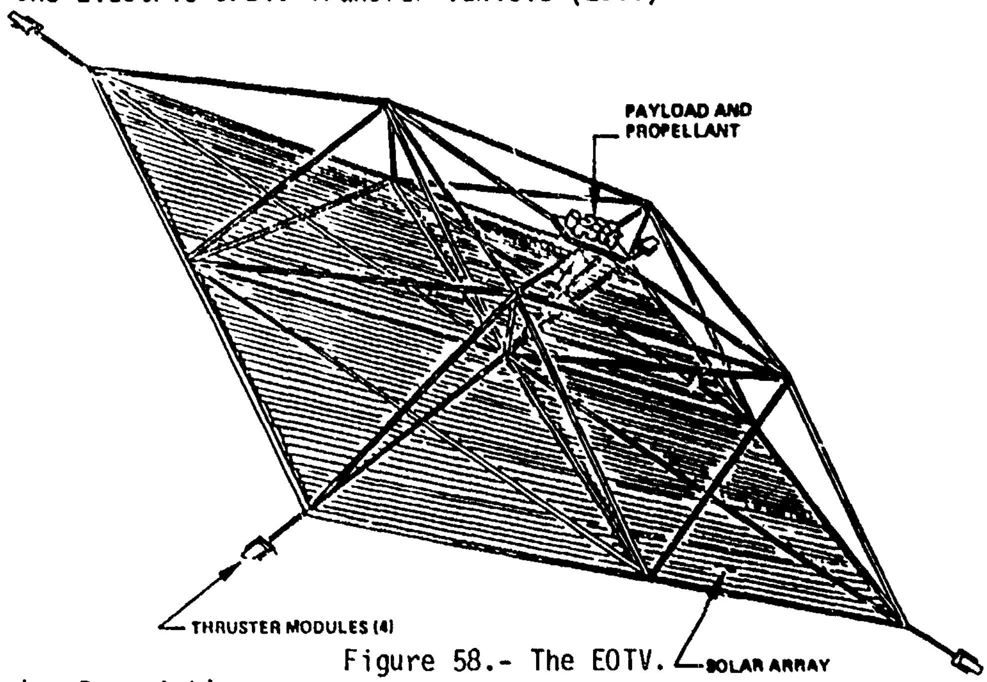


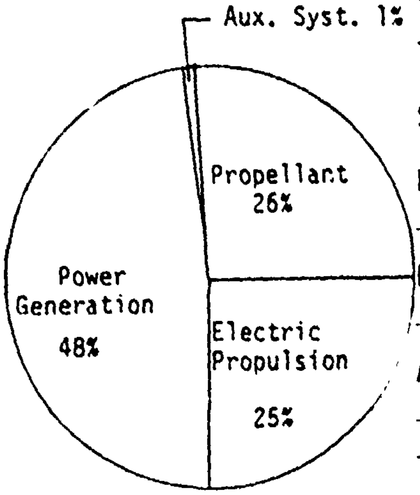
Figure 58.- The EOTV.

Design Description

The EOTV configuration for cargo transportation is shown in figure 58. The vehicle is sized to deliver 4000 M.T. to GEO and return 200 M.T. from GEO, with an up-trip time of 180 days and a down-trip time of 40 days. Propulsion is provided by 1156 120-cm diameter ion thrusters with an Isp of 8000 seconds. The thrusters use an argon propellant and are powered by a 1 km by 1.5 km silicon solar collector. Solid-state power processors are used to compensate for wide swings in power and voltage caused by occultation, radiation damage, and thermal effects. The vehicle is designed for 10 round trip flights and the payload size was chosen to be compatible with 10 HLLV flights. An EOTV mass breakdown is shown in figure 59. Additional detail may be found in reference 6, pp. 278-293.

Cost

Table XVI presents the summary cost estimate for the Electric Orbit Transfer Vehicle. Table XVII presents the cost per EOTV flight.



Item	Mass, kg
Solar Array - Silicon	780 000
Structure	122 000
Power Distribution	42 000
Energy Storage	7 000
Power Generation and Distribution Subtotal	951 000
Thrusters	79 000
Power Conditioning	219 000
Thermal Control	88 000
Structures and Mechanisms	61 000
Propellant Feed	49 000
Electric Propulsion Subtotal	496 000
Auxiliary Systems Subtotal	15 000
Total Dry Weight	1 462 000
Propellant	
Argon	469 000
Hydrogen	6 600
Oxygen	39 400
Start Burn Mass	1 977 000

Figure 59.- EOTV mass statement.

TABLE XVI.- ELECTRIC ORBIT TRANSFER VEHICLE
SUMMARY COST ESTIMATE

[All costs in millions of dollars]

WBS no.	Description	DDT&E	TFU	Avg. unit
1.3.2	ELECTRIC ORBIT TRANSFER VEHICLE (EOTV)	2 247	2 126	283.6
1.3.2.1	POWER GENERATION SYSTEM	.4	917	
1.3.2.2	POWER COLLECTION & DIST.	10.5	7	
1.3.2.3	ELECTRIC PROPULSION SYST.	89.1	777	
1.3.2.4	AVIONICS	19.9	14	
1.3.2.5	TOOLING	858.5	--	
1.3.2.6	SYSTEMS TEST	1 164.1	--	
1.3.2.7	SE&I	12	--	
1.3.2.8	SOFTWARE	18.3	--	
1.3.2.9	GSE	23.1	228	
1.3.2.10	PROG. INT. & MGT.	51.3	75	
1.3.2.11	ASSEMBLY & CHECKOUT	--	96	
1.3.2.12	SUSTAINING ENGINEERING		12	

TABLE XVII.- EOTV - PER FLIGHT COST

	Cost ($ × 10^3)
HARDWARE:	
$\frac{\$283.6 \text{ million per vehicle}}{10 \text{ flights per vehicle}} = \frac{283,600K}{10}$	≈ 28 400
PROPELLANT:	
Argon 494 M.T. @ $1/kg	494
O_2 37.8 M.T. @ $0.037/kg	1
H_2 9.5 M.T. @ $1.53/kg	14
REFURBISHMENT	11 300
PROGRAM SUPPORT	500
TOTAL COST PER FLIGHT	40 709 ($40.7 million)

WBS 1.3.3 PERSONNEL LAUNCH VEHICLE

Definition

The Personnel Launch Vehicle (PLV) is used to transport personnel and priority cargo to low Earth orbit.

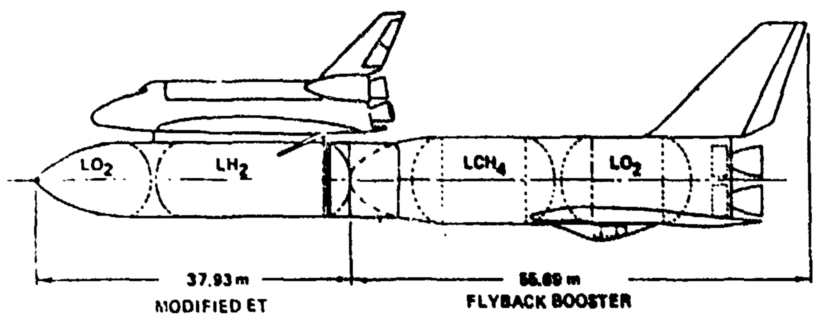


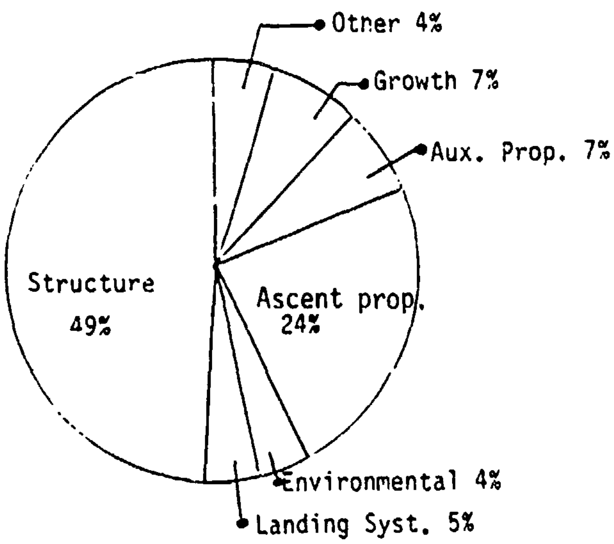
Figure 60.- The PLV.

Design Description

The PLV is a derivative of the Space Shuttle system. The vehicle consists of a winged, liquid-propellant, flyback booster that uses four O_2/CH_4 engines similar to the HLLV booster engines, a smaller version of the Shuttle external tank, and the Space Shuttle Orbiter. The payload to LEO is 89 M.T., compatible with the 80-person payload of the POTV. The vehicle has a design life of 200 flights. The choice of the Space Shuttle Orbiter as part of the PLV minimizes the DDT&E costs and permits the average unit cost to be based on a known cost rather than an estimate. A PLV mass breakdown is shown in figure 61.

Cost

Tables XVIII and XIX present the PLV summary cost estimate and cost per flight.



FLYBACK BOOSTER MASS SUMMARY

Item	Mass, kg
Wing	31,940
Tail	4,930
Body	68,490
Induced Environ. Protection	9,050
Landing and Aux. Systems	9,710
Propulsion - Ascent	51,320
Propulsion - RCS	960
Propulsion - Flyback	13,800
Prime Power	1,190
Elec. Conv. and Distribution	960
Hyd. Conv. and Distribution	4,230
Surface Controls	2,020
Avionics	1,450
Environmental Control	210
Growth Allowance	16,200
Dry Mass	(216,460)
Residuals and Reserves	12,700
Landing Mass	(229,160)
Flyback Fuel	26,260
In-flight Losses	3,900
Inert Mass	(259,320)

EXTERNAL TANK (ET) MASS SUMMARY

Element	Mass, kg
Structures	21,146
Thermal Protection	1,631
Propulsion & Mech. System	1,710
Electrical System	66
Orbiter Attachment	1,492
Change Uncertainty	686
ET Inert Mass	26,731
Unusables	1,530
ET MECO Mass	28,261

Figure 61.- PLV mass statement.

TABLE XVIII.- PERSONNEL LAUNCH VEHICLE

SUMMARY COST ESTIMATE

[All costs in millions of dollars]

WBS no.	Description	DDT&E	TFU	Avg. unit
1.3.3	PERSONNEL LAUNCH VEHICLE	2616	790	673
1.3.3.1	BOOSTER STAGE	2616	240	123
1.3.3.1.1	STRUCTURES	--	--	
1.3.3.1.2	INDUCED ENVIRON. PROTEC.	--	--	
1.3.3.1.3	LANDING & AUX. SYSTEMS	--	--	
1.3.3.1.4	ASCENT PROPULSION	--	--	
1.3.3.1.5	FLYBACK PROPULSION	--	--	
1.3.3.1.6	OTHER BOOSTER SYSTEMS	60	15	
1.3.3.1.7	PROGRAM INT. & MGT.	77	18	
1.3.3.2	ORBITER STAGE	--	550	550
1.3.3.2.1	STRUCTURES			
1.3.3.2.2	INDUCED ENVIRON. PROTECT.			
1.3.3.2.3	LANDING & AUX. SYSTEMS			
1.3.3.2.4	ASCENT PROPULSION			
1.3.3.2.5	OMS PROPULSION			
1.3.3.2.6	OTHER ORBITER SYSTEMS			

TABLE XIX.- PLV - COST PER FLIGHT

		Cost ($ × 10^3)
HARDWARE:		
$\frac{\$670 \text{ million per vehicle}}{200 \text{ flights per vehicle}}$	=	3 350
External tank (expendable)	=	3 200
PROPELLANT:		
O_2 1685 M.T. @ $0.037/kg		62
CH_4 432 M.T. @ $0.39/kg		169
H_2 82 M.T. @ $1.53/kg		125
REFURBISHMENT AND REPLENISHMENT		263
GROUND OPERATIONS		517
TOOLING		116
MANPOWER		2 300
PROGRAM SUPPORT		623
TOTAL COST PER FLIGHT		10 700 ($10.7 million)

WBS 1.3.4 PERSONNEL ORBIT TRANSFER VEHICLE

The Personnel Orbit Transfer Vehicle (POTV) is designed to transport crews, priority crew supplies, and priority cargo from LEO to GEO. The POTV is also used to transfer crews from the GEO base to an SPS for maintenance.

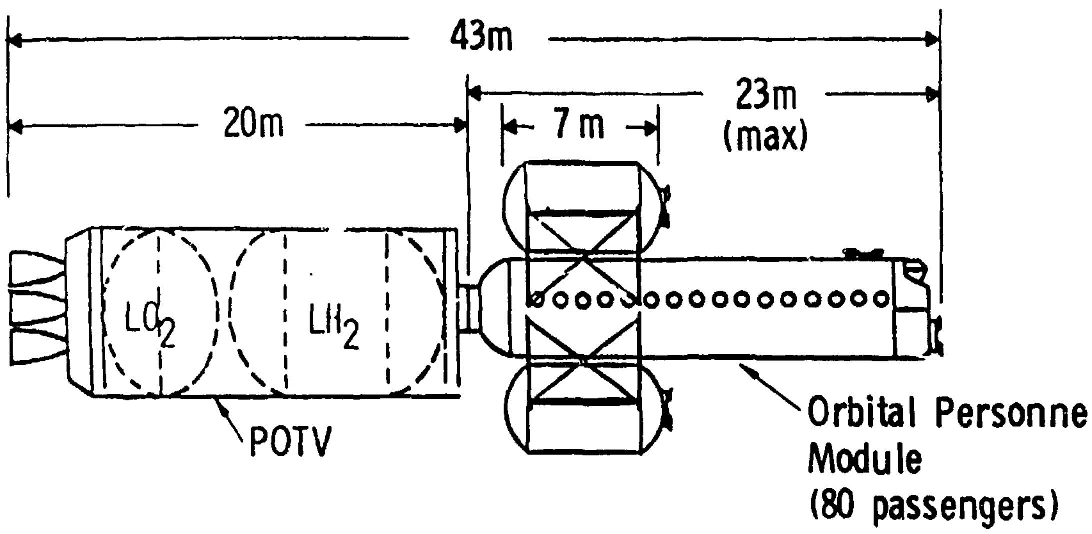


Figure 62.- The POTV.

Design Description

The POTV is a single-stage, LO_2/LH_2-propelled vehicle that can transport 90 M.T. of payload from LEO to GEO with a turnaround time of 5 days. This includes transit time, refueling time, and crew rotation time. The payload is sufficient to delivery 80 GEO workers and crew supplies for 6600 work days. The vehicle has a design life of 50 round trip flights. Refueling is accomplished at GEO with propellant delivered by the EOTV. Five 88-kN thrust, staged combustion engines are used for main propulsion. These engines have an I_{sp} of 470 seconds. Auxiliary engines with an I_{sp} of 375 seconds are used for attitude control and for low delta-V maneuvers and docking. Electric power is provided by Space-Shuttle-type fuel cells.

Cost

Tables XX and XXI present the POTV summary cost estimate and per-flight cost.

Item	Mass, kg
Structures and Mechanisms	6 900
Main Propulsion	2 500
Auxiliary Propulsion	500
Avionics	300
Electric Power System	450
Thermal Control	1 030
Contingency (15%)	1 750
	13 430
Total Propellant and Fuel-Cell Fuel	203 000
Total Start Burn Mass	216 500

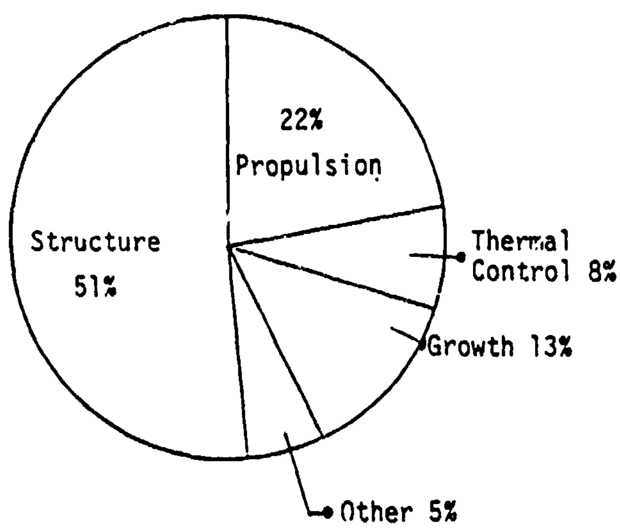


Figure 63.- POTV mass statement.

TABLE XX.- PERSONNEL ORBIT TRANSFER VEHICLE

SUMMARY COST ESTIMATE

[All costs in millions of dollars]

WBS no.	Description	DDT&E	TFU	Avg. unit
1.3.4	PERSONNEL ORBIT TRANSFER VEHICLE (POTV)	1012	100	44
1.3.4.1	STRUCTURES	39	15	
1.3.4.2	PROPULSION	381	19	
1.3.4.3	AUXILIARY PROPULSION	5	6	
1.3.4.4	ELECTRIC POWER	16	4	
1.3.4.5	AVIONICS	45	8	
1.3.4.6	THERMAL/ENVIRON. CONTROL	23	1	
1.3.4.7	ASSEMRLY & CHECKOUT		6	
1.3.4.8	SE&I	22	--	
1.3.4.9	SOFTWARE	26	--	
1.3.4.10	GSE	48	21	
1.3.4.11	SYSTEMS TEST	198	--	
1.3.4.12	TOOLING	14	7	
1.3.4.13	PROG. INT. & MGT.	83	7	
1.3.4.14	OTHER	112	6	

TABLE XXI.- POTV - COST PER FLIGHT

		Cost ($ × 10^3)
HARDWARE:		
$\frac{\$44 \text{ million per vehicle}}{50 \text{ flights per vehicle}}$	=	880
PROPELLANT:		
O_2 179 M.T. @ $0.037/kg		7
H_2 31 M.T. @ $1.53/kg		48
REFURBISHMENT AND REPLENISHMENT:		
Engines		68
Other		3
TOOLING		3
GROUND SUPPORT EQUIPMENT		11
MISCELLANEOUS		289
TOTAL COST PER FLIGHT		1309 ($1.3 million)

SECTION 4 - GROUND RECEIVING STATION

WBS 1.4 GROUND RECEIVING STATION

Definition

The SPS ground receiving stations include all functions required to receive the power beams, convert them to grid-compatible electric power, and provide ground control for beam formation, aiming, and power.

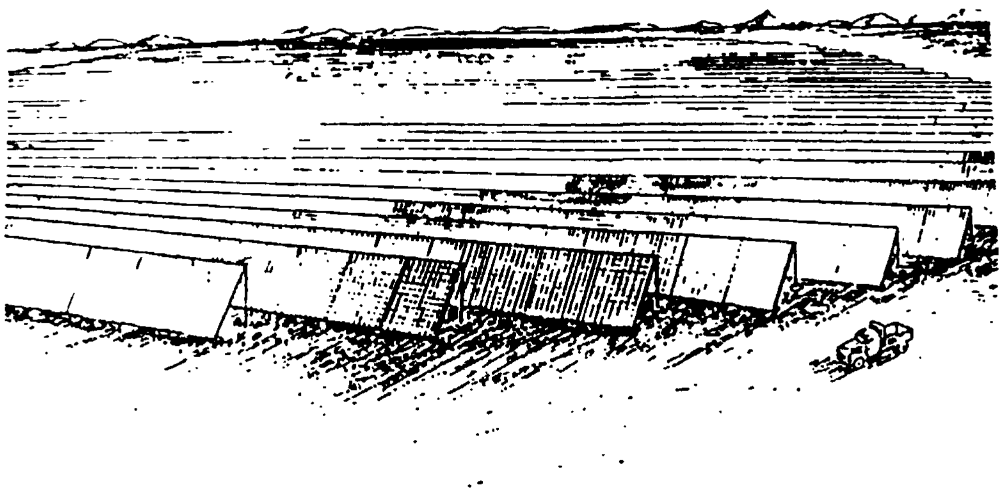


Figure 64.- The ground receiving station.

Design Description

The rectenna, which receives and rectifies the downlink power beam, has half-wave dipoles feeding Schottky barrier diodes. Two-stage low-pass filters between the dipoles and the diodes suppress harmonic generation and provide impedance matching. The sites were sized and the panels tilted for a 35° latitude location. The structure is supported by concrete beams and footings. The rectenna is designed for a peak input power of 23 mW/cm^2 and includes a buffer zone to assure that the maximum microwave beam power at any off-site location is less than 0.1 mW/cm^2. The ground station has an overall efficiency - microwave energy to a.c. on the grid - of 76 percent. A more detailed description can be found in reference 5.

Cost

\$2 208 × 10^6 (ref. 6).

TABLE XXII.- GROUND STATION SUMMARY COST ESTIMATE PER SPS

WBS no.	Description	$ \times 10^6$
1.4	Ground Receiving Station	2208
1.4.1	Site and Site Preparation	240
1.4.2	Rectenna Primary Structure	304
1.4.3	Power Collection	929
1.4.3.1	RF-DC Conversion	661
1.4.3.2	DC Distribution	268
1.4.4	Control System	61
1.4.5	Utility Interface	674

WBS 1.4.1 SITE AND SITE PREPARATION

Definition

WBS 1.4.1 includes the land area for the ground receiving station and all site preparation.

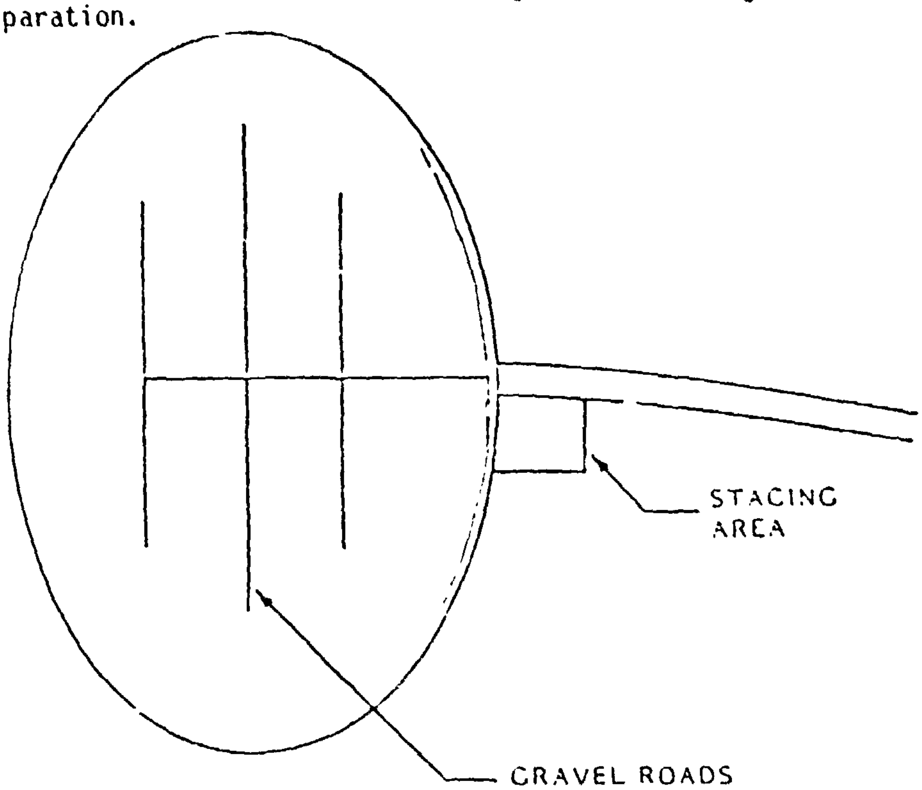


Figure 65.- Rectenna site and facilities.

Design Description

The land area required was assumed to be an ellipse sufficient to intercept the microwave beam down to a power level of 0.1 mW/cm^2 at a latitude of 35^o. This is an ellipse whose major axis is 18.7 km and whose minor axis is 13.8 km, for an area of 200 km^2 (50 000 acres). Of this, the buffer zone, an area of non-uniform width in which there are no elements but the power density is above 0.1 mW/cm^2, is 94 km^2 (23 000 acres). This area may be planted in grass or forest, as appropriate. (See reference 7.)

Cost

Raw land is estimated at $2500 per acre. Site preparation is also estimated at $2500 per acre. Engineering costs for site preparation were included in this number. DDT&E costs were assumed to be zero, and the TFU cost was considered to be the same as the average cost.

WBS 1.4.2 RECTENNA PRIMARY STRUCTURE

Definition

WBS 1.4.2 includes all support structure for the active rectenna elements.

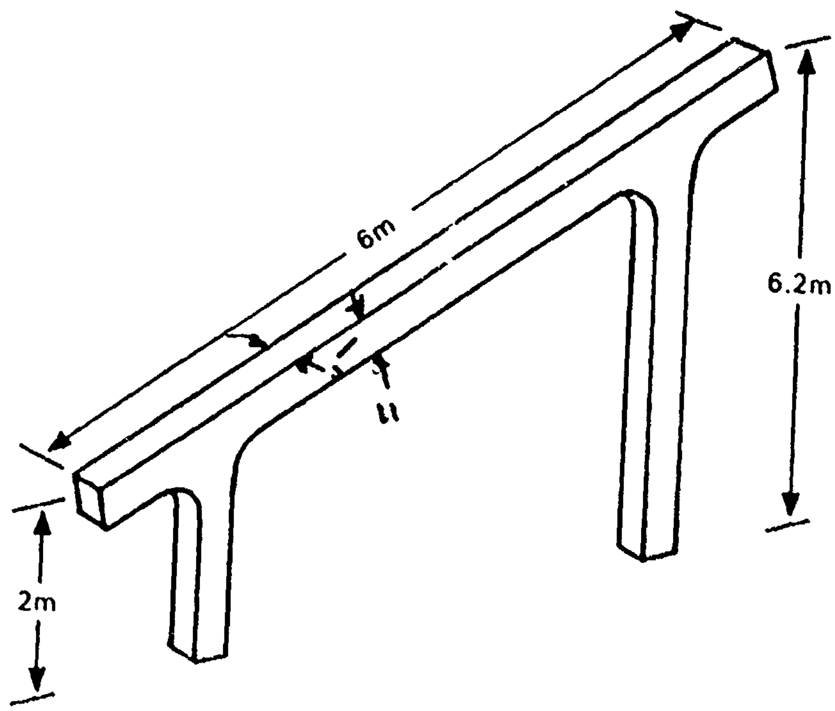


Figure 66.- Rectenna support structure.

Design Description

Concrete was chosen for the structural support because it costs substantially less than an equivalent steel structure. The structure was designed to withstand a 46 m/sec wind at an elevation of 10 m. The number of structures of the type illustrated required per 5-GW rectenna is 3 715 050 (ref. 5, pp. 4-19).

Cost

Structural material costs are estimated by a materials-takeoff process to be $48.5 per element. Including foundation concrete, the total materials cost is estimated to be $183 million. The highly automated installation process is estimated to cost $24.6 million for labor and $64 million for equipment. Freight charges to the site are estimated at $32.2 million, making a total for primary structure and foundation of $304 million (ref. 5, pp. 4-53, and 4-56).

WBS 1.4.3 POWER COLLECTION

WBS 1.4.3.1 RF-DC CONVERSION

Definition

WBS 1.4.3.1 includes the hardware elements used to convert microwave energy into direct current.

Design Description

The rectenna concept utilizes a weatherproof matched dipole configuration, shown in figure 67. All materials required are readily available and of low cost. The mechanical design is amenable to highly automated production. Using rectenna construction methods proven in tests by the Jet Propulsion Lab and Raytheon, an efficient two-plane design has been developed. An actual section, shown in figure 68, has been evaluated in RF tests. The metal shield is used to provide environmental protection as well as to prevent direct radiation of harmonic power. Also, the d.c. converting bus forms part of the filter and RF rectification circuit.

The two-plane design consists of the active receiving elements and a reflecting screen, or ground plane. The reflecting plane need only be a metallic mesh with suitable spacing relative to the wavelength. Refer to figure 67 for the form and location of the ground plane. A mesh allows passage of the wind, rain, and snow so structural loading is reduced.

The foreplane contains the half-wave dipoles, the input wave filters, the rectification circuit, the smoothing capacitance, and the d.c. power collection and busing function. Figure 69 shows the electrical format of the foreplane. Figure 68 shows a section of foreplane construction as defined in figure 69 with the addition of a shield. The foreplane shown in figure 68 has been thoroughly checked out electrically and found to be equal in efficiency to that of the three-plane construction. Figure 67 shows how the foreplane can be integrated with the reflecting screen to form the major portion of the rectenna structure. It has been found that the metal shield placed over the active portion of the rectenna to shield it from the environment and to prevent direct radiation of harmonic power from the rectifier circuit can function very satisfactorily as the horizontal load-bearing member of the rectenna.

The dipoles are formed of aluminum wire. There are approximately 7.654×10^9 dipole assemblies per rectenna.

Cost

The cost for the RF-d.c. conversion system was based on 4-cent diodes ($298 million), $349 million for steel, and $14 million for integration and assembly, resulting in a total of $661 million (ref. 6, p. 312).

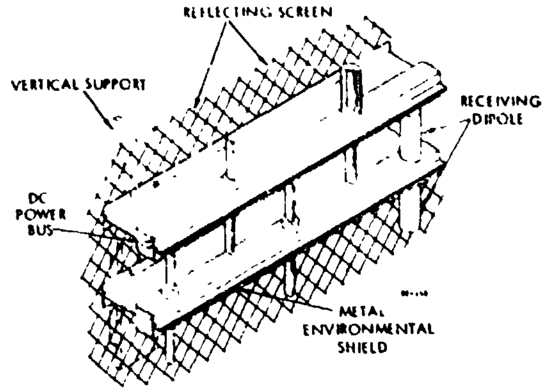


Figure 67.- Two-plane rectenna construction consisting of a reflecting screen or ground plane and a foreplane which contains the dipole antenna, wave filters, diode rectifiers, and bus bars - all protected from the environment by a metal shield.

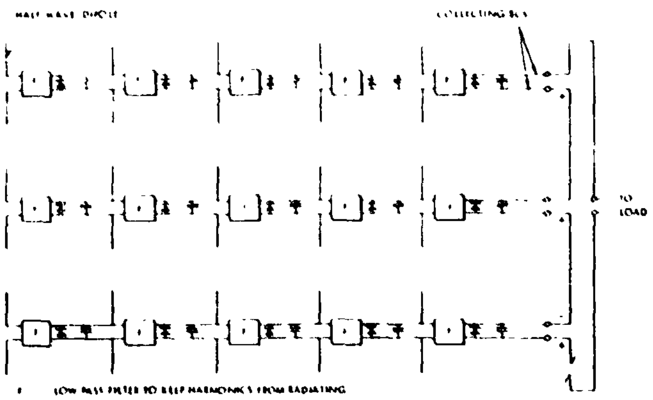


Figure 68.- Completed rectenna foreplane assembly consisting of a metallic shield and a core assembly of five rectenna elements. This section has been substituted for a section of three-level construction and found to perform as well.

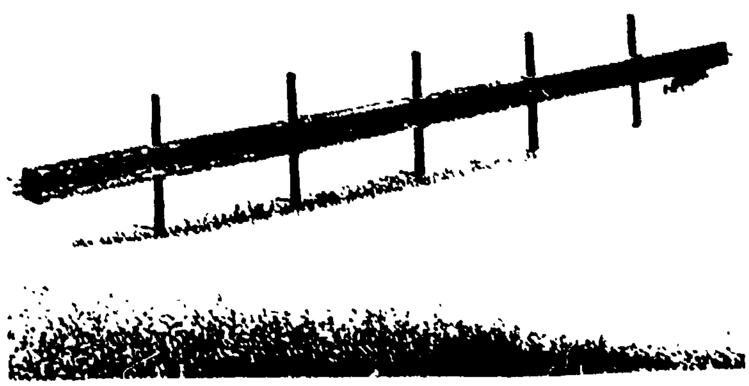


Figure 69.- Schematic of the foreplane of the two-plane rectenna showing the arrangement of half-wave dipoles, input filters, and Schottky carrier rectifying diodes. Two-wire transmission lines are used both for microwave circuits and for carrying out the d.c. power collected by the array.

WBS 1.4.3.2 DC DISTRIBUTION SYSTEM

Definition

The d.c. distribution system includes all conductor and switching equipment necessary to collect the d.c. power produced by the RF-d.c. converters and conduct it to the d.c.-a.c. converters.

Design Description

To develop the details of the rectenna power collection network, the aperture area is divided into 10 approximately elliptical rings. The d.c. power collecting scheme distinguishes the following assemblies:

Dipole
Array
Panel
Unit
Group

These assemblies can be connected in a number of ways. Two particular configurations were analyzed in some detail. In the first, the so-called "low voltage" design, the network is connected so that the line voltages remain within a nominal ±3.25 kV range.

In the second, the so-called "low current" design, the network current remains below 300A, but the range of the voltage increases to ±23 kV. For safety and reliability reasons, the first design was selected as the baseline. However, this design results in a rectenna configuration that is 10 to 20 percent more expensive than the low current design because of the larger conductor quantities necessary.

It is assumed that the basic receiving element of the rectenna is an electrical dipole in the front of a perfectly reflecting element or ground plane. The dipole assembly also contains a filtering and matching circuit to match the dipole, when it is placed in an infinite array of dipoles, to the incoming wave with a -20 dB or better reflection coefficient.

Because of the power density variation over the rectenna aperture, a single type of radiating element and a single type of rectifier cannot provide optimum conversion efficiency. Either a number of radiating element types or a number of diode types must be provided. Presently a single diode type is assumed and it is operated with four different types of antenna elements. It is assumed that, like the dipole element already described, these antenna elements are formed by using the basic dipoles in arrays of 2, 4, or 8. The corresponding assemblies will be called type 1, 2, 3, or 4 receiving elements or arrays. The array formation requires 2-, 4-, and 8-way power combiners, which can be simple printed circuits.

From the dipole or array assemblies, panels are formed. It is assumed that the panel is the smallest assembly unit. The panel area is 10 m^2, with a north-south dimension of 3 m and an east-west dimension of

3.33 m. Figure 70 shows a typical panel assembly in the center of the rectenna. Since it is assumed that all panels are the same size, 7.67 million panels are required in the rectenna. There are four different types of panels, corresponding to the four different types of receiving arrays. Although the dipoles and diodes are identical for all panels, the combining-matching-filtering circuits and the diode wiring are of four types.

From the panels, unit assemblies are formed. The units are nominally composed of 1000 panels, and the N-S dimension of a unit is always 32 × 3.662 m = 117.184 m (i.e., there are always 32 rows of panels in the N-S dimension). The assembly layout limits the number of unit types to seven.

The last assembly which is formed to handle d.c. power is called a "group" and brings the power output into the 5- to 10-MW range. To keep the voltage levels relatively low, the groups are formed from the units by parallel connections only.

The power from the units is brought to the group centers, where the d.c.-to-a.c. inverters are located.

Only one iteration was made for the selection of conductor sizes and the system was not optimized. A relatively small increase in conductor weight could reduce the losses from the panels (about 4300 metric tons of aluminum could reduce panel losses by 50 percent); however, increasing the conductor size increases fabrication problems and might rule out the use of printed conductors.

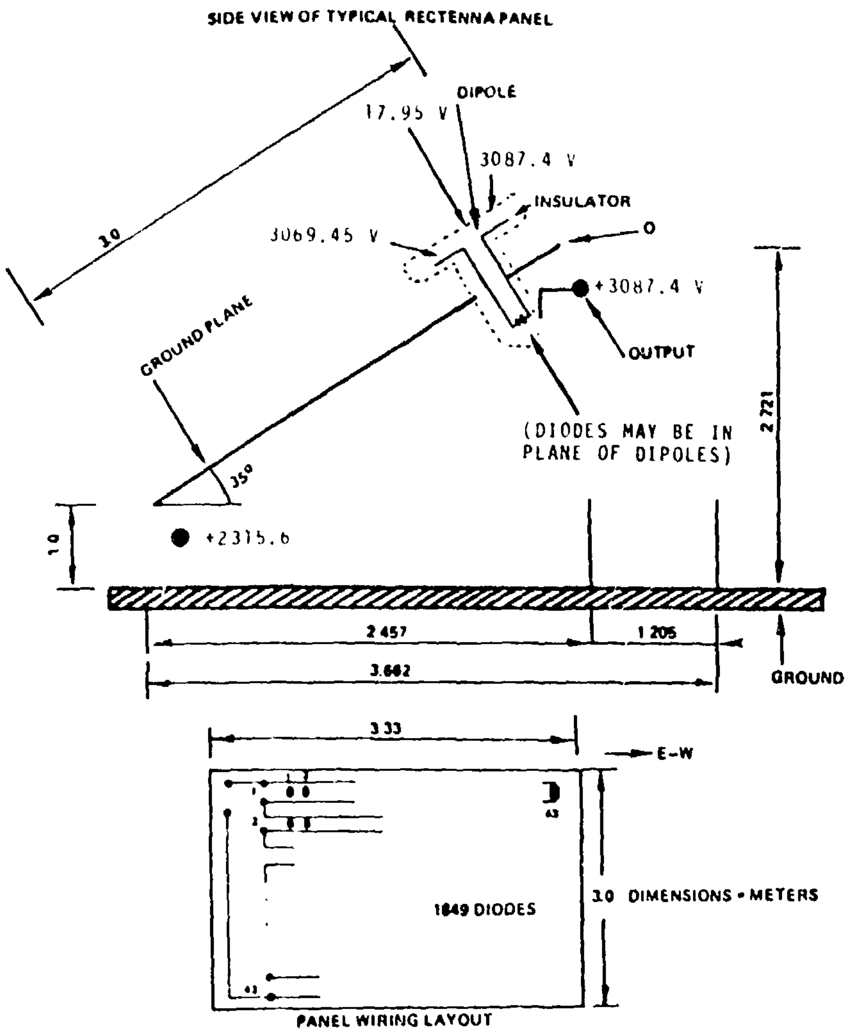


Figure 70.- The d.c. power collection system.

Cost

The d.c. power distribution system is estimated to cost $268 million. This estimate is based on the use of 165 000 metric tons of aluminum conductors (ref. 6, p. 312).

WBS 1.4.4 CONTROL SYSTEM

Definition

WBS 1.4.4 consists of the hardware elements used for the uplink phase control system.

Design Description

Phase control of the SPS transmitter is provided by an uplink transmitter at the center of the rectenna. This uplink system employs the spread-spectrum coding technique defined by W. L. Lindsey of Lincom for JSC under separate contract.

Other control is provided through the communications system described under WBS 1.1.5.

Cost

$\$61 \times 10^6$ (ref. 2, p. 308).

WBS 1.4.5 UTILITY INTERFACE

Definition

The utility interface consists of the hardware that is used to convert d.c. power to a.c. power and to interface with the a.c. power grid.

Design Description

The selection of the layout for the interface between the individual d.c.-a.c. inverters and the power grid is based on the bulk power levels of the d.c.-a.c. inverters as well as on the needs of the bulk power transmission system. In the baseline design, the d.c. output from the dipoles is collected into 40-MW d.c.-a.c. inverter stations (see fig. 71). The 40-MW inverter station output is transmitted by underground cable to 200-MW transformer stations, where the voltage is stepped up to 230 kV, then collected in 1000-MW groups and transformed to 500 kV for interface with the bulk transmission system. The switchyards are shown arranged as reliable "breaker and a half" schemes, where single contingency outages may be sustained without loss of power 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 should be optimized on the basis of detailed information about the receiving utility system.

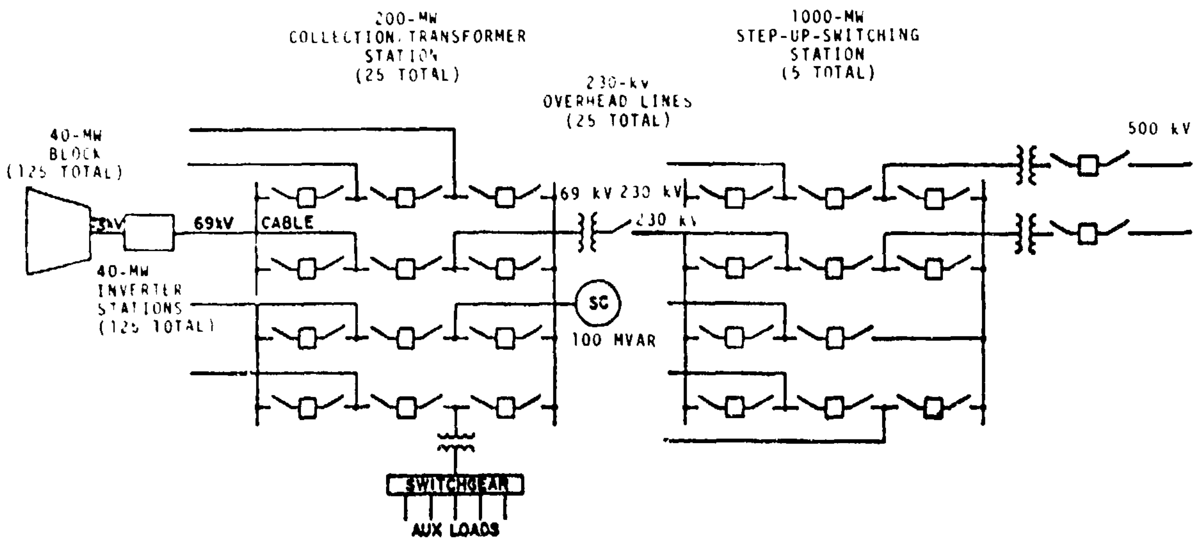


Figure 71.- Utility interface.

Figure 72 shows the proposed arrangement, using a total of six 500-kV circuits, four of which are assumed to be directed to a single load area with the remaining two circuits directed to two additional load areas. It is anticipated that any two of the six circuits could be removed from service without reduction of the rectenna output. The remaining four circuits, together with the normal utility transmission interconnections, should be capable of carrying the 5000-MW output required. In other words, the system shown could handle either a line maintenance outage plus the sudden fault loss of a second circuit or the sudden loss of two circuits alone. Additional circuits would, of course, provide the ability to handle additional multiple contingency situations.

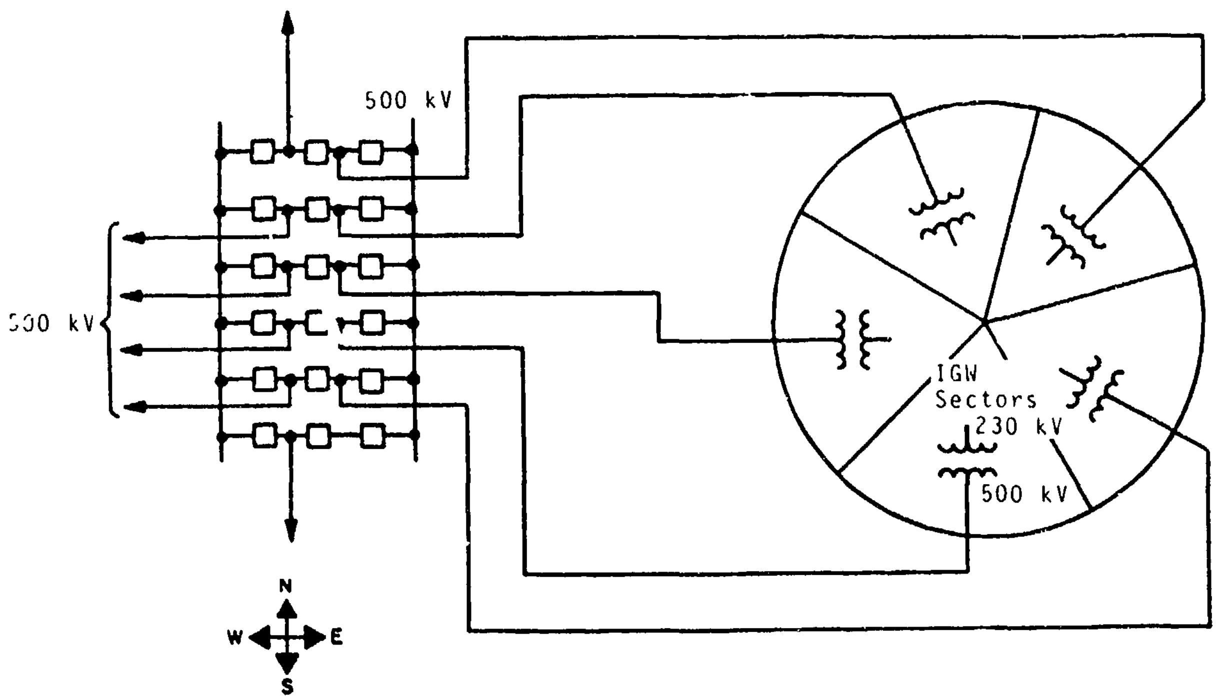


Figure 72.- Utility interface substation.

Cost

$674 × 10[6] estimated by General Electric on contract to Boeing (ref. 5, pp. 2-25).

SECTION 5 - MAINTENANCE

WBS 1.5 MAINTENANCE

Definition

Maintenance includes all those items for which maintenance requirements have been identified. Some maintenance cost has been identified with each of the major SPS subsystems.

Description and Cost

The identified maintenance requirements and their associated costs are summarized in table XXIII. The cost is expressed as an annual expense in millions of dollars and, at the major subsystem level, in mills per kilowatt-hour. The mills/kWh figure was computed from the annual expense using the following relationship:

$$\text{mills/kWh} = \frac{\text{annual expense}}{5 \times 10^6 \times 0.9 \times 8760}$$

This expression assumes a plant factor of 0.9.

The maintenance cost associated with the transportation system is included as a transportation system cost. The cost shown in table XXIII is the cost associated with bringing people and materials to the SPS for maintenance purposes. Similarly, the construction maintenance cost shown is for that portion of the LEO and GEO base maintenance which is directly related to satellite maintenance activities.

TABLE XXIII.- MAINTENANCE SUMMARY COST ESTIMATE

WBS no.	Description	Annual cost, $ $\times 10^6$	Rate, mills/kWh
1.5	SPS	203	5.15
1.5.1	Satellite	39.2	1.0
1.5.1.1	Klystron Maintenance	10.0	
1.5.1.2	DC-DC Converter Maintenance	14.5	
1.5.1.3	Other Satellite Maintenance	14.7	
1.5.2	Space Construction	3.9	.01
1.5.3	Transportation	119.2	3.0
1.5.3.1	Personnel	81.0	
1.5.3.2	Materials	38.2	
1.5.4	Ground Receiving Station	14	0.36
1.5.4.1	Maintenance Power System (13 000 man-hr/yr)	4.7	
1.5.4.2	Panel Replacement (6000 man-hr/yr)	2.1	
1.5.4.3	Security (20 000 man-hr/yr)	7.2	
1.5.5	Contingency	19.2	0.56
1.5.6	Management and Integration	7.5	0.22

CONCLUSIONS

On the basis of the estimating procedures and methodology used, it is concluded that an SPS program can be started with an initial outlay of $102 billion. This amount covers a research phase, an engineering verification phase, a demonstration phase, investment, and procurement of the first operational SPS. Subsequent SPS units can be installed at a rate of two per year for $11.4 billion each.

For the average SPS, the $11.4 billion cost is distributed as follows:

Satellite	44%
Construction and assembly	9%
Transportation	25%
Ground systems	19%
Program management	3%

These figures are all in 1977 dollars. Appropriate inflation multipliers must be used to convert these figures to current year dollars.

REFERENCES

1. Satellite Power System: Concept Development and Evaluation Program - Reference System Report. DOE/ER-0023, published jointly by the U.S. Department of Energy and the National Aeronautics and Space Administration, Oct. 1978 (Jan. 1979).

2. Solar Power Satellite System Definition Study: Volume II, Phase II Final Report - Reference System Description. D180-25461-2, Boeing Aerospace Company (NASA Contract NAS9-15636), Nov. 1979.

3. Solar Power Satellite System Definition Study: Part 1 Volume II - System Requirements and Energy Conversion Options. D180-20689-2, Boeing Aerospace Company (NASA Contract NAS9-15196), July 1977.

4. Solar Power Satellite System Definition Study: Volume III, Phase II Final Report - Operations and Systems Synthesis. D180-25461-3, Boeing Aerospace Company (NASA Contract NAS9-15636), Nov. 1979.

5. Solar Power Satellite System Definition Study: Part 4, Phase 1 Final Report. General Electric Space Division for Boeing Aerospace Company under NASA Contract NAS9-15636, Apr. 1979.

6. Solar Power Satellite System Definition Study: Volume III, Phase I Final Report - Reference System Description. D180-25037-3, Boeing Aerospace Company (NASA Contract NAS9-15636), Apr. 1979.

7. Solar Power Satellite System Definition Study: Part III - Preferred Concept System Definition. D180-24071-1, Boeing Aerospace Company (NASA Contract NAS9-15196), Mar. 1978.