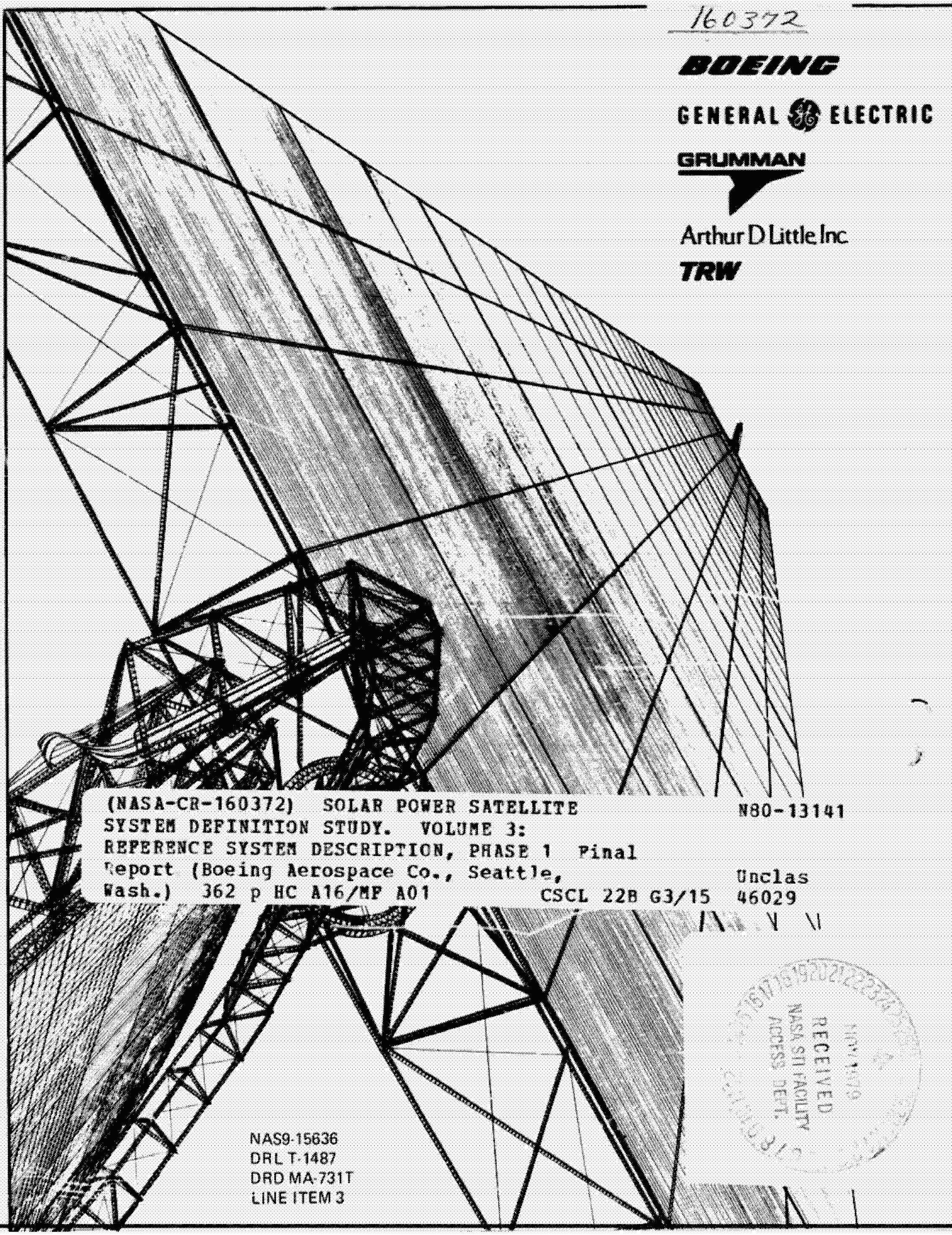
BOEING

Solar Power Satellite System Definition Study

Volume III
Phase I, Final Report
Reference System Description
D180-25037-3

NASA CR-
160372

BOEING
GENERAL ELECTRIC
GRUMMAN
Arthur D Little Inc
TRW



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Solar Power Satellite
System Definition Study
Conducted for the NASA Johnson Space Center
Under Contract NAS9-15636

Volume III
PHASE I, FINAL REPORT
Reference System Description
D180-25037-3

April 1, 1979

Approved By: [signature]
G. R. Woodcock
Study Manager

Boeing Aerospace Company
Ballistic Missiles and Space Division
P.O. Box 3999
Seattle, Washington 98124

FOREWORD

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

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

This report includes a total of seven volumes:

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

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

Key team members that contributed in the various disciplines were the following:

Subject	JSC-Management Team	Contractor Team
Structures	Bob Reed	Rich Reinert (Boeing) A. Alberi (Grumman)
Power Distribution	R. Kennedy; M.E. Woods	J. Gewin
Power Transmission	R.H. Dietz	Erv Nalos
RF-DC Conversion	L. Leopold	E. Nalos
Phase Control	J. Seyl	W. Lund
Fiber Optic Phase Distribution	J. Seyl	G.E. Miller
Solid State Design	L. Leopold	G.W. Fitzsimmons B.R. Sperber
Array Analysis	Dr. D. Arndt	S. Rathjen
Information & Communications	R.H. Dietz, J. Kelley	Tom Walter (TRW)
Space Construction Operations	L. Jenkins	K. Miller (Boeing) R. McCaffrey (Grumman) R. Romanelli (Grumman)
Space Transportation	H. Davis E. Crum	Eldon Davis
Ground Receiving Station		R. Andryczyk (GE)
Siting	H. Roberts	D. Gregory (Boeing)
Power Collection	R.H. Dietz	P. Foldes (GE)
Grid Interface	L. Monford	B. Kaupang (GE)
Constuction	H. Roberts	J. Chestik (GE)
Mission Ops & Control	B. Wolfer	E. Davis (Boeing) K. Miller (Boeing) R. Crisman (TRW)
Industrial Infrastructure	J. Poradek	P. Chapman (A.D. Little)

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1.0 INTRODUCTION

1.0.1 DOCUMENT PURPOSE AND ORGANIZATION

This document provides a concise system description for the baseline solar power satellite (SPS), silicon option, developed by Phase I of the systems definition study, contract NAS9-15636. This represents a revision and update to an earlier document of the same title, Boeing Document D180-24071-1, issued at the conclusion of a prior systems definition study, contract NAS9-15196.

The principal system configuration changes relative to the earlier study were as follows:

1. SPS power rating was reduced to 5,000 megawatts ground output in conformance with the DOE/NASA baseline;
2. Shadowing protection was added to the solar blankets;
3. The solar array support structure was revised to increase redundancy;
4. Power distribution was changed from a three-bus to a multiple-bus configuration to reduce potential fault currents;
5. The rectenna structure was revised to reduce construction cost;
6. The space operations approach was revised to use of electric orbit transfer vehicles and construction at geosynchronous orbit, in conformance with the DOE/NASA baseline;
7. The space construction base was revised to a 4-bay end-builder to enhance productivity.

The baseline changes were the result of system trade studies and analyses, presented in the comparison volume to this system description, D180-25037-2.

Certain elements of this system description have been adopted directly from the earlier document without revision except a change in WBS number as necessary to reflect the current NASA work breakdown structure.

The document is organized in accordance with the new work breakdown structure shown in Figure 1.0-1. Prior to the system description, a brief historical background is given.

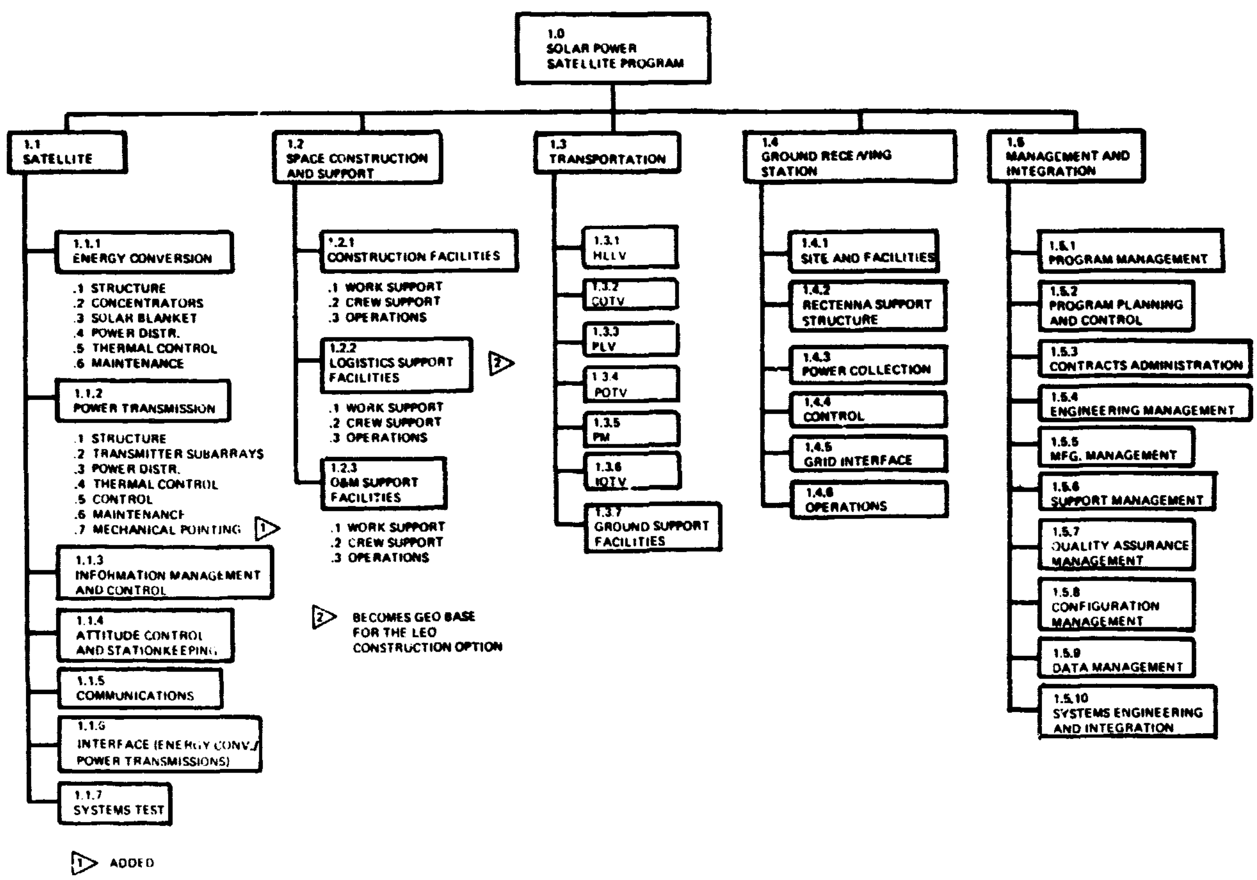

Figure 1.0-1. Work Breakdown Structure for SPS

1.0.2 HISTORY

Solar power has long been recognized as an ideal source of energy for mankind. It is naturally available and plentiful, does not disturb the environment, e.g., by creation of wastes, and is itself free.

About ten years ago, a way of utilizing solar energy to generate electricity on a 24-hour continuous basis was proposed by Peter Glaser of A.D. Little. His proposal was to place the solar collectors in space, where they can collect sunlight continuously, can readily be aimed at the sun, and where very large collector areas can be obtained with relatively little investment in material resources. Energy collected by these solar power satellites (SPS's) would be transmitted to Earth by electromagnetic means. The original Glaser proposal, and most of the subsequent studies, have assumed the use of radio frequency systems in the microwave frequency range. Recently, the possibility of laser beaming has also been recognized.

The solar power satellite principle is illustrated in Figure 1.0-2. In a geostationary orbit 36,000 km above the Earth's equator, each SPS would be illuminated by sunlight over 99% of the time and in continuous line-of-sight contact with its ground receiving station. Electrical power produced on the satellite by photovoltaic or heat engine conversion of the sunlight would be converted to electromagnetic energy at high efficiency, and formed into a narrow beam precisely aimed at the SPS ground stations. The ground station receiving antennas would reconvert the energy into electricity for distribution. Solar power satellites are intended to serve as producers of baseload electricity for utility service. SPS's are seen not as a substitute for other solar energy options, but as a complement that would allow solar energy to more completely serve humanity's energy needs

Dr. Glaser's original proposal was published in 1968 in Science magazine. In 1971 and 1972 a small contractor study team was formed including Arthur D. Little, Grumman, Raytheon and Spectrolab. This team was awarded a study contract through the NASA Lewis Research Center to investigate basic technical feasibility of the SPS concept. The conclusions of that study were that the system is technically feasible and could provide baseload electricity from solar power for use on Earth. Additional studies and experiments, partly funded by NASA over the period 1973 to 1975, established the

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- Satellites are positioned in high-intensity, nearly continuous sunshine; unaffected by night and weather, they provide baseload electricity.
- Hundreds of satellites can be installed above equator over Pacific Ocean.

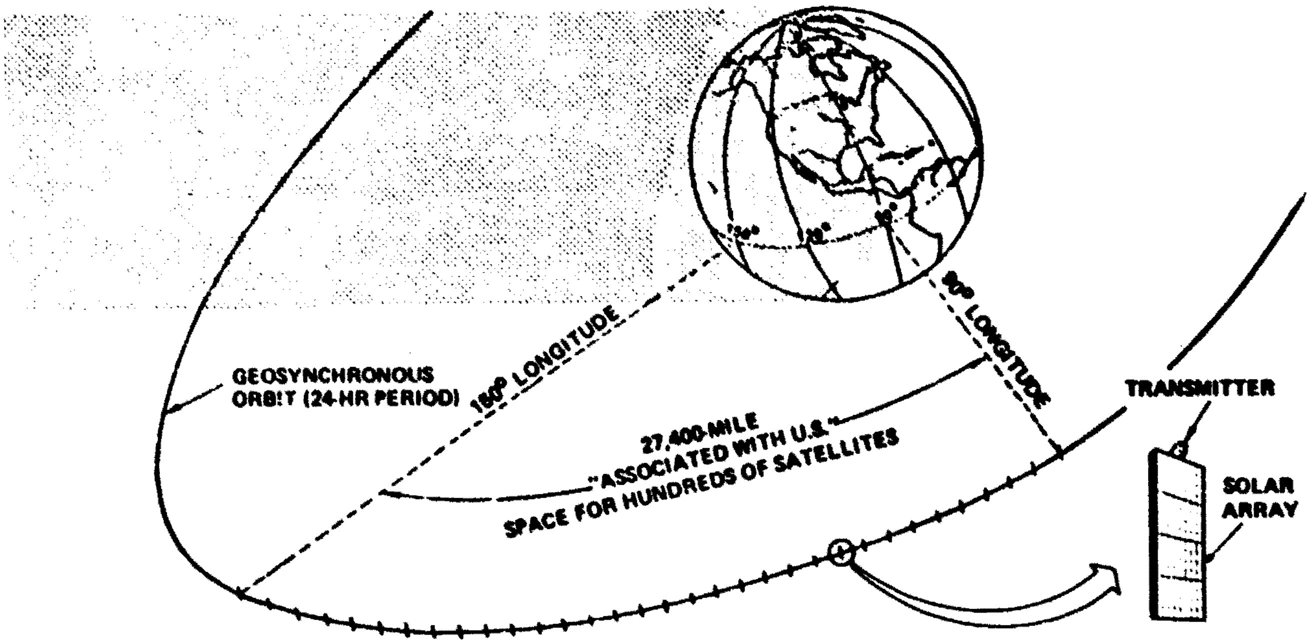


Figure 1.0-2 Solar Power Satellites: The Principle

feasibility of efficient energy transmission at microwave frequencies. In 1975 a demonstration conducted at JPL transmitted more than 30 kilowatts over a distance greater than a mile with a reception and conversion efficiency of 82 percent.

In the 1975 to 1977 time period, NASA conducted a technical assessment of SPS and began inhouse studies at the Johnson and Marshall Space Center. The Department of Energy conducted its own assessment; SPS was discussed in congressional hearings. The activities led to development of an SPS Development and Evaluation Program Plan jointly sponsored by DOE and NASA. The principal milestones in this plan are:

Reference System Definition Report, Oct. 1978 (Complete)
Preliminary Program Recommendations, May 1979
Updated Program Recommendations, Jan. 1980
Final Program Recommendations, June 1980

(Also during this period, NASA-funded space transportation system studies indicated that the high traffic volumes required to support an SPS program could lead to cost reductions far below those projected for the space shuttle. The potential for such cost reductions was seen as significant to the economic practicality of SPS.)

As a result, plans were formulated by NASA to conduct solar power satellite system definition studies in 1977 in order to support the first milestone of the DOE/NASA evaluation plan. These would increase by roughly an order of magnitude the degree of depth of design and cost definition for SPS systems. One such study was awarded to Boeing through the Johnson Space Center; the other study was awarded to Rockwell through the Marshall Space Flight Center. These studies created reference system designs including the solar power satellites, ground receiving stations, space transportation systems, space construction systems and other support systems. The results indicated that SPS's could be built by the year 2000 with a likelihood of economic benefit. The principal findings of these studies might be summarized as follows:

1. Examination of energy conversion options led to a preference for silicon photovoltaics in the Boeing study, and gallium arsenide photovoltaics in the Rockwell study. (Both studies suggested thermal engine SPS designs as a hedge against the possibility that expected cost reductions in photovoltaics mass production might not be achieved.) The silicon photovoltaic system offers less risk with a more

mature technology but an energy conversion system roughly 40 percent more massive than gallium arsenide.

2. Analyses of the power transmission system confirmed the basic feasibility indicated by the earlier studies and detailed microwave link error analysis confirmed attainability of adequate efficiencies. Integrated power transmission system conceptual designs were developed considering RF, electrical, mechanical, and thermal factors.

3. Space transportation system were designed to accomplish the SPS transportation operations at acceptable cost.

4. Space construction approaches and cosntruction base designs were developed for construction of 10,000 megawatt SPS's in geosynchronous orbit at a rate of approximately 1 per year.

The principal system elements from that study were the point of departure for the current study. The preferred SPS defined by Boeing is illustrated in Figures 1.0-3 through 1.0-8.

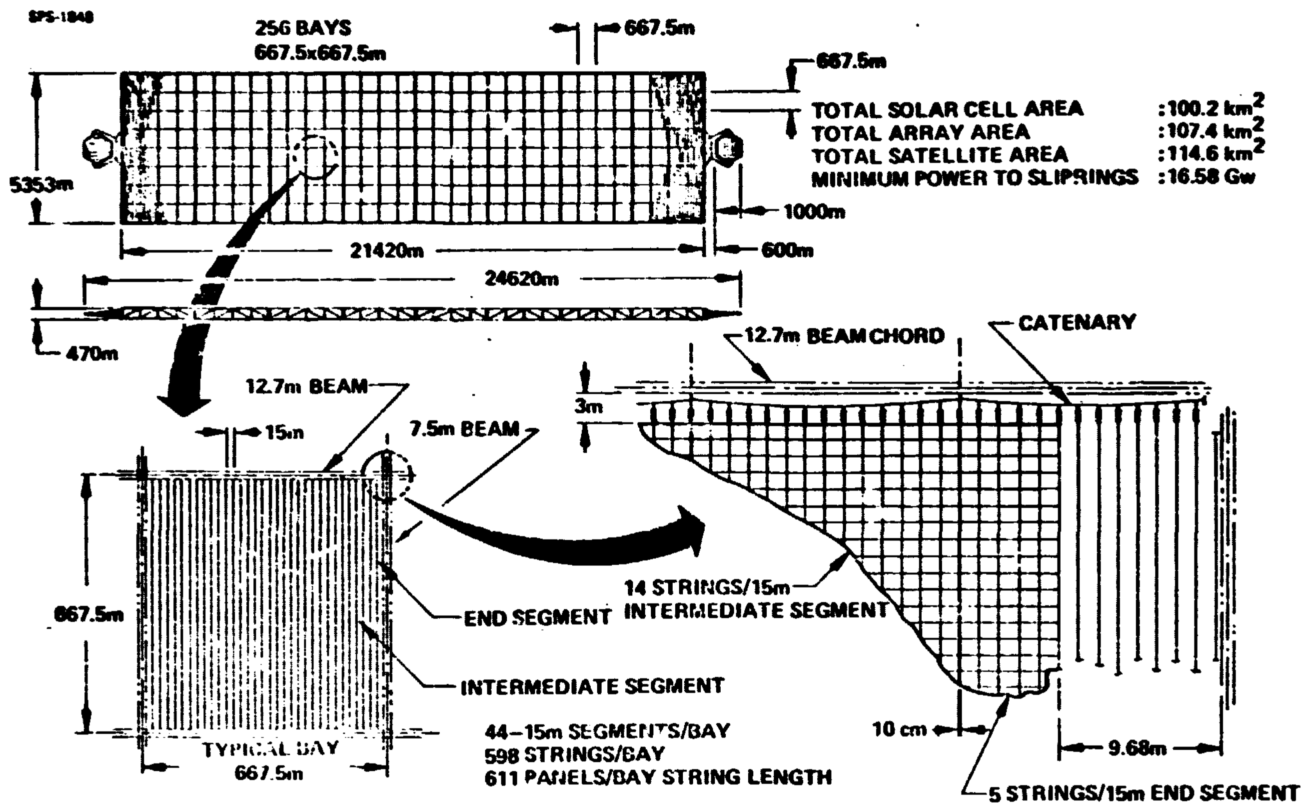


Figure 1.0-3 Point-of-Departure Reference Photovoltaic System Description

Figure 1.0-4 Ground Rectenna

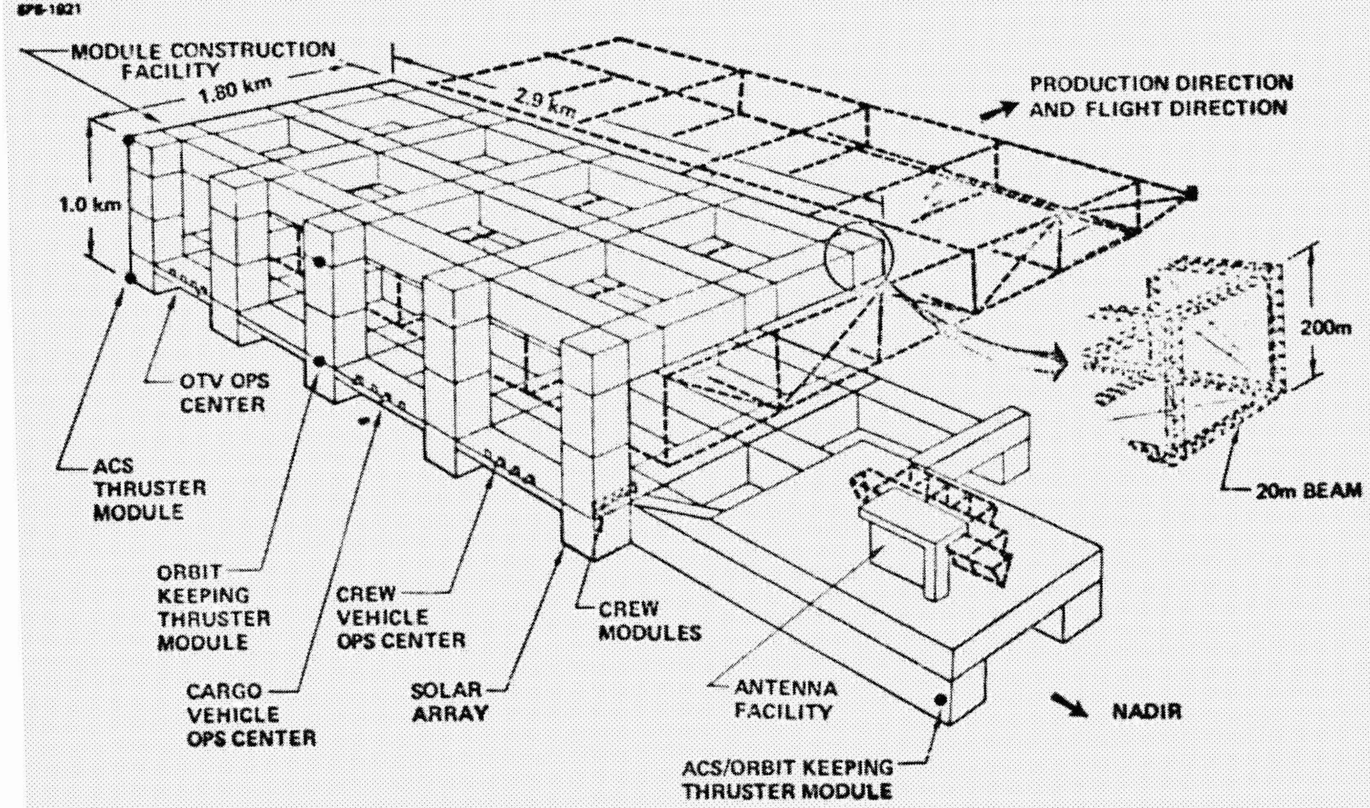
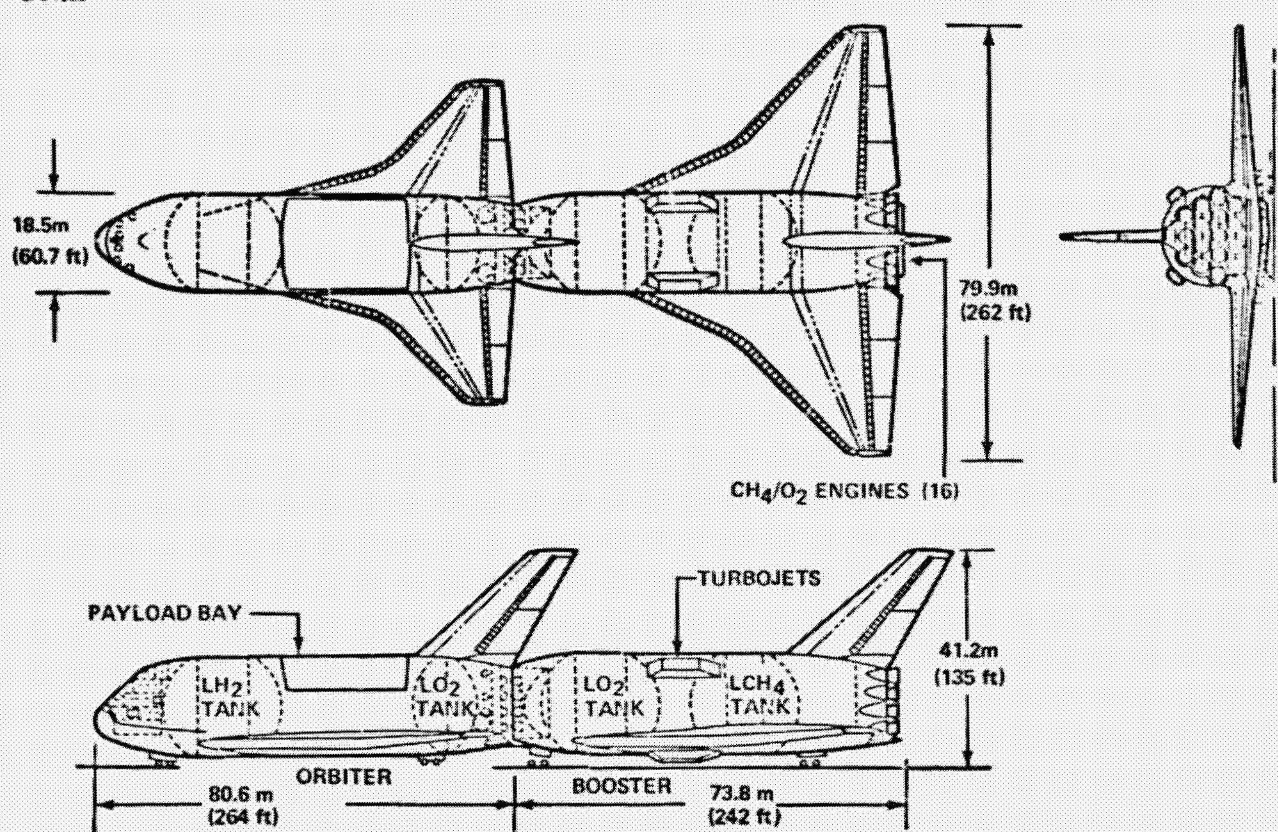


Figure 1.0-5 Point-of-Departure LEO Construction Base—Photovoltaic Satellite



HLLV (Fully Reusable Cargo Carrier)

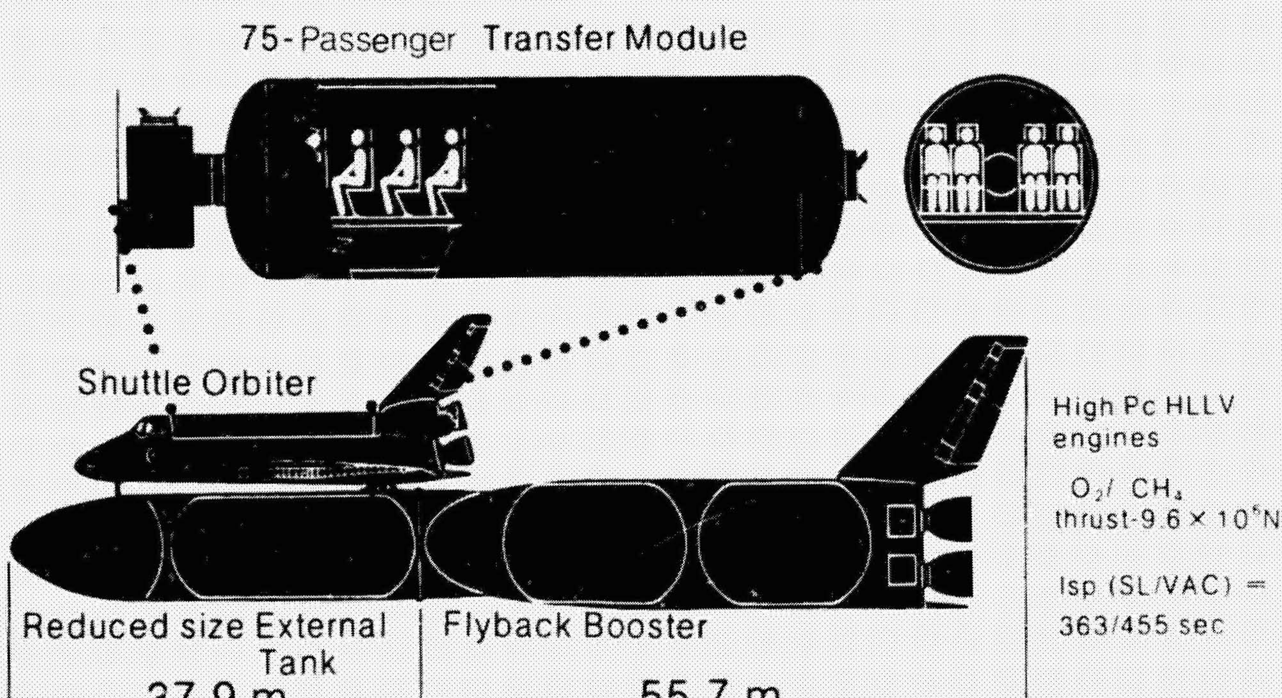


Figure 1.0-6 SPS Launch Vehicles

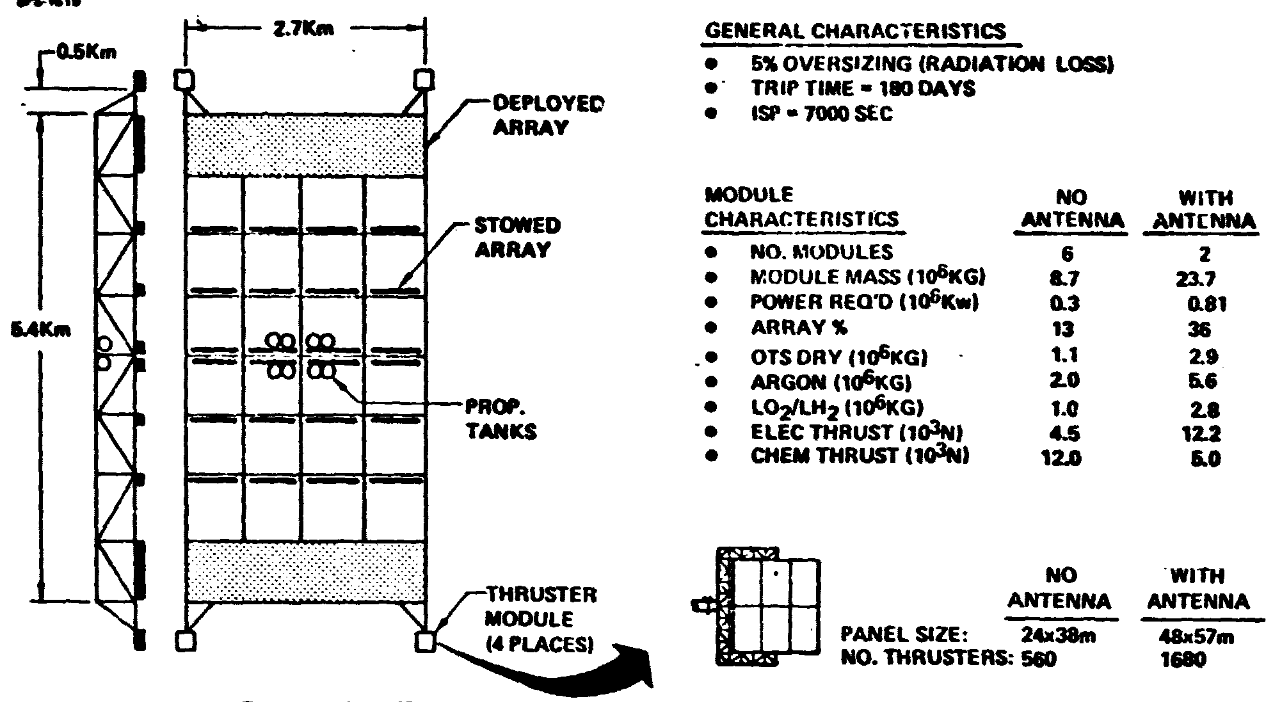


Figure 1.0-7 (Part 1) Self Power Configuration Photovoltaic Satellite

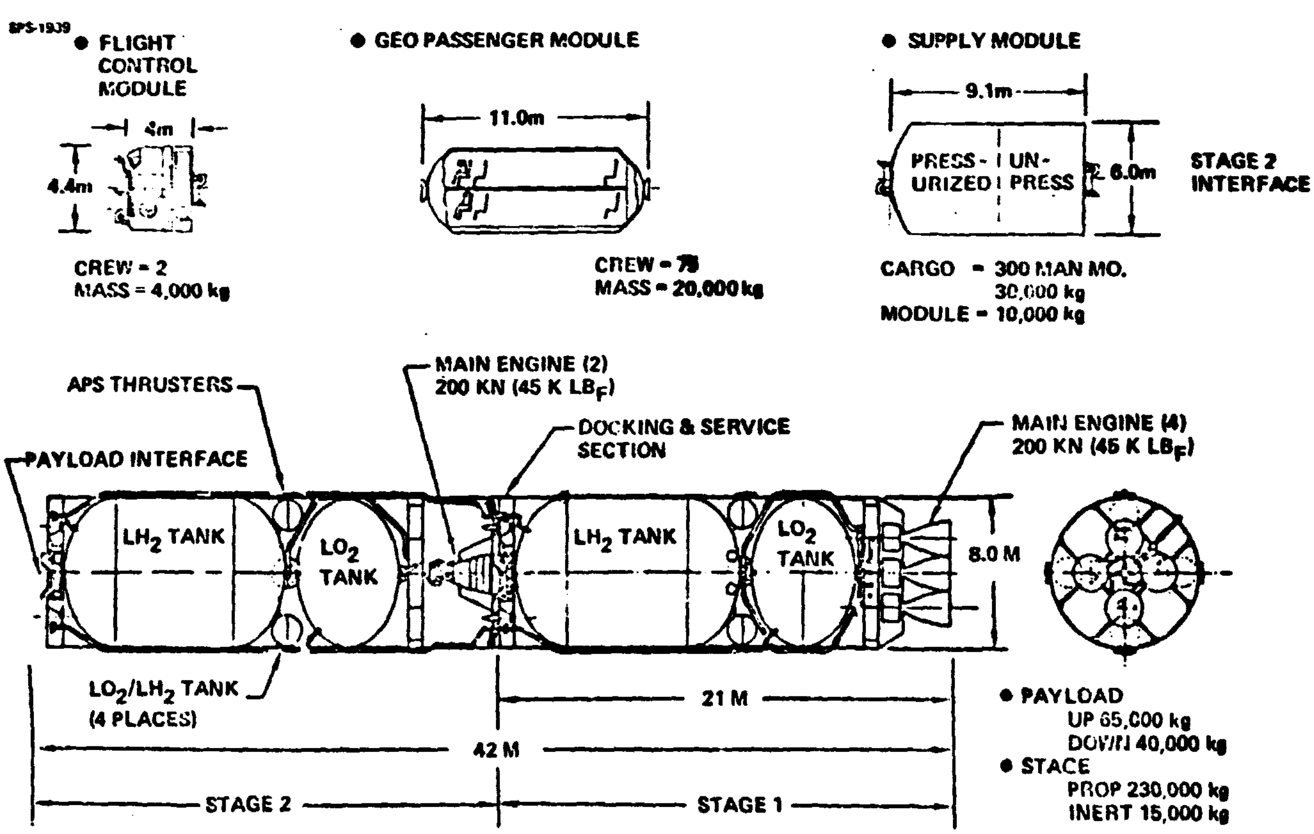


Figure 1.0-8. (Part 2) GEO Crew/Supply Delivery Orbit Transfer Vehicles

WBS 1.1 SATELLITE

WBS Dictionary

This element includes all hardware and resident software for operation of the solar power satellite. Maintenance equipment resident on the satellite is separately described under each element and is included in the summary SPS mass statement.

Element Description The reference configuration illustrated in Figure 1.1.0-1 is a photovoltaic SPS (without solar concentrators) employing glass-encapsulated single-crystal silicon blankets. The nominal ground output is 5000 megawatts through a single power transmission link.

A summary of the efficiency chain and sizing requirements are presentea in Table 1.1.0-1.

Element Mass

A comprehensive mass table is presented in Table 1.1.0-2. This table collects all available mass properties figures in an integrated presentation. Mass estimating factors and/or rationales are given under the lower element entries. The mass growth allowance was derived from the uncertainty analysis conducted under contract NAS9-15196.

Element Cost

The updated SPS cost summary is shown in Table 1.1.0-3. The cost estimating factors are described under lower level elements. Figure 1.1.0-2 shows the cost in bar chart form. Note that the space construction bar includes only support of the crew at GEO. Other costs attributable to space construction are PLV and POTV, accounted under space transportation according to the NASA WBS, and capital recovery for space construction. (This is amortization of the construction base and is carried as an indirect item).

WBS 1.1.1 Energy Conversion

WBS Dictionary

This element includes all production hardware required to convert incident sunlight into electrical power at the required voltage and deliver this power to the power transmission interface. The primary subelements are the solar blankets, the catenary support system, and interbay jumbers. Structure, power distribution, thermal control and maintenance equipment.

SPS-2470

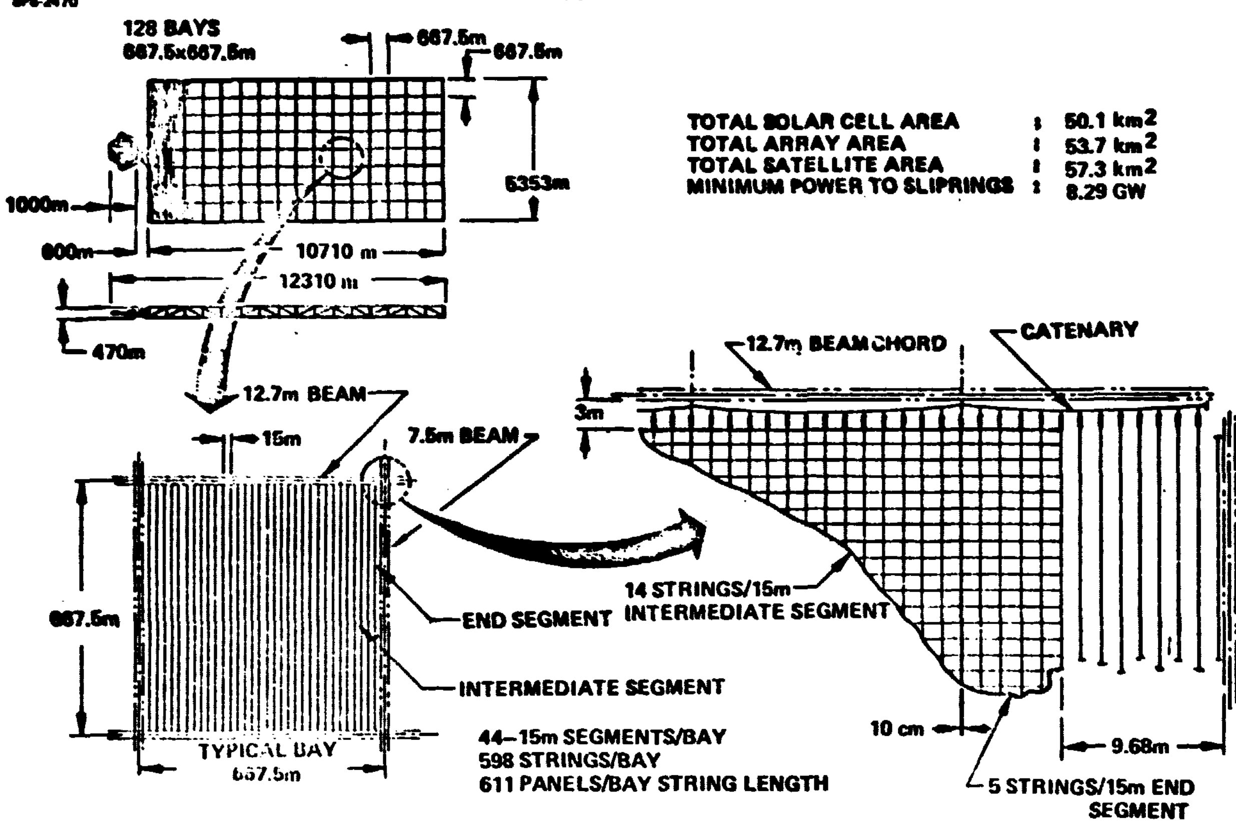


Figure 1.1.0-1 Reference Solar Power Satellite—5000 Megawatts

SPS-2435

Table 1.1.0-1 Updated Efficiency and Sizing

	EFFICIENCY	MEGAWATS PER LINK	
MAIN BUS I^2R	0.934	8,876	SOLAR ARRAY OUTPUT
ROTARY JOINT	1.0	8,290	
ANTENNA POWER DISTRIBUTION AND PROCESSING	0.97	8,290	TOTAL INPUT TO ANTENNA
DC-RF CONVERSION	0.85	8,041	
WAVEGUIDE I^2R	0.985	6,836	TOTAL RF POWER
IDEAL BEAM	0.965	6 733	TOTAL RADIATED POWER
INTER-SUBARRAY LOSSES	0.976	6,497	
INTRA-SUBARRAY LOSSES	0.981	6,341	
ATMOSPHERE LOSSES	0.98	6,221	
INTERCEPT EFFICIENCY	0.95	6,097	
RECTENNA RF-DC	0.89	5,792	INCIDENT ON RECTENNA
GRID INTERFACING	0.97	5,155	
	0.563	5,000	NET TO GRID

SOLAR INPUT:	1,353 W/m^2
SOLAR-CELL CONVERSION EFFICIENCY (0.173)	234.1
BLANKET FACTORS (0.9453)	221.3
THERMAL DEGRADATION (0.954)	211.1
ORIENTATION LOSS (0.919)	194.0
APHELION INTENSITY (0.9675)	187.7
NONANNEALABLE RADIATION DEGRATION (0.97)	182.1
REGULATION, AUXILIARY POWER, AND ANNEALING (0.983)	179
EOL BLANKET OUTPUT:	179 W/m^2
TOTAL SOLAR-CELL AREA:	49.6 km^2
SOLAR ARRAY OUTPUT:	8,876 MW

Table 1.1.0-2 Comprehensive Mass Properties

WBS ELEMENT	EQUIPMENT NOMENCLATURE	MASS	REMARKS
1.0	SOLAR POWER SATELLITE TOTAL	48473	
1.1	SATELLITE IDENTIFIED MASS	***40060***	
1.1.1	ENERGY CONVERSION	**27235**	
1.1.1.1	STRUCTURE	*3383*	
1.1.1.1.1	PRIMARY STRUCTURE	3198	
1.1.1.1.2	SUPPORT STRUCTURE	–	
1.1.1.1.3	BLANKET SUPPORT CABLES	128	
1.1.1.1.4	BLANKET TENSIONING DEVICES	–	INCLUDED IN 1.1.1.1.3
1.1.1.1.5	POWER DISTRIBUTION SUPPORT	57	
1.1.1.2	CONCENTRATORS	–	CONCENTRATORS NOT REQD
1.1.1.3	SOLAR BLANKET	*22553*	
1.1.1.3.1	BLANKET PANELS	21093	
1.1.1.3.2	BLANKET MECHANICAL ATTACHMENTS	952	
1.1.1.3.3	INTERBAY JUMPER WIRES	508	
1.1.1.4	POWER DISTRIBUTION AND SWITCHGEAR	*1213*	
1.1.1.4.1	MAIN POWER BUSES	1090	
1.1.1.4.2	ACQUISITION POWER BUSES	19	
1.1.1.4.3	SWITCHGEAR	42	
1.1.1.4.4	DISCONNECT SWITCHES	42	
1.1.1.4.5	BLOCKING DIODES	–	
1.1.1.4.6	INTERCONNECT CABLING	–	
1.1.1.4.7	DC/DC CONVERTERS	<1	
1.1.1.4.8	ENERGY STORAGE	20	
1.1.1.5	THERMAL CONTROL		THERMAL CONTROL WAS ALLOCATED TO THE SUBSYSTEMS
1.1.1.5.1	SWITCHGEAR THERMAL CONTROL		
1.1.1.5.2	CONDUCTOR THERMAL CONTROL		
1.1.1.5.3	DC/DC CONVERTER THERMAL CONTROL		
1.1.1.5.4	THERMAL CONTROL SURFACES		
1.1.1.5.5	ATTITUDE CONTROL SYSTEM THERMAL CONTROL		
1.1.1.5.6	AVIONICS THERMAL CONTROL		
1.1.1.6	MAINTENANCE	*86*	
1.1.1.6.1	SOLAR ARRAY ANNEALERS	8	
1.1.1.6.2	MAINTENANCE GANTRIES	66	
1.1.1.6.3	GANTRY TRACKS	2	
1.1.1.6.4	CREW PROVISIONS	–	
1.1.1.6.5	CARGO HANDLING	5	
1.1.1.6.6	DOCKING SYSTEMS	5	
1.1.2	POWER TRANSMISSION	**12234**	
1.1.2.1	STRUCTURE	*370*	
1.1.2.1.1	PRIMARY STRUCTURE	53	
1.1.2.1.2	SECONDARY STRUCTURE	198	
1.1.2.1.3	SUPPORT STRUCTURE	–	
1.1.2.1.4	SUBARRAY POSITIONING	–	
1.1.2.1.5	POWER DISTRIBUTION SUPPORT	119	
1.1.2.2	TRANSMITTER SUBARRAYS	*9382*	
1.1.2.2.1	DC/RF CONVERTER MODULE	4875	
1.1.2.2.2	DISTRIBUTION WAVEGUIDE	311	
1.1.2.2.3	RADIATING WAVEGUIDE	1485	
1.1.2.2.4	THERMAL CONTROL	1500	
1.1.2.2.5	WIRING HARNESS	} 544	
1.1.2.2.6	CONTROL CIRCUITS		
1.1.2.2.7	STRUCTURE	667	
1.1.2.3	POWER DISTRIBUTION AND CONDITIONING	*2210*	

NOTE: THIS TABLE REFLECTS REDISTRIBUTION OF WBS ITEMS TO CONFORM WITH THE DETAILS OF THE CURRENT NASA SPS WBS.

Table 1.1.0-2 Comprehensive Mass Properties (continued)

WBS ELEMENT	EQUIPMENT NOMENCLATURE	MASS	REMARKS
1.1.2.3.1	POWER CONDUCTORS	398	
1.1.2.3.2	SWITCHGEAR	1277	
1.1.2.3.3	DC/DC CONVERTERS		
1.1.2.3.4	CONVERTER THERMAL CONTROL	222	
1.1.2.3.5	DISCONNECT SWITCHES	–	
1.1.2.3.6	ENERGY STORAGE	313	
1.1.2.4	THERMAL CONTROL		THERMAL CONTROL WAS ALLOCATED TO THE RESPECTIVE SUBSYSTEMS
1.1.2.4.1	THERMAL CONTROL SURFACES		
1.1.2.4.2	POWER PROCESSING THERMAL CONTROL		
1.1.2.4.3	INSULATION		
1.1.2.4.4	CONTROL CIRCUITS THERMAL CONTROL		
1.1.2.4.5	MECHANICAL POINTING THERMAL CONTROL		
1.1.2.5	CONTROL		THE PHASE CONTROL SYSTEM IS NOW ACCOUNTED UNDER SUBARRAYS
1.1.2.5.1	RECEIVERS		
1.1.2.5.2	DIPLEXERS		
1.1.2.5.3	PHASE TRANSMITTERS		
1.1.2.5.4	PHASE RECEIVERS		
1.1.2.5.5	CONJUGATORS		
1.1.2.5.6	CABLING		
1.1.2.5.7	POWER DIVIDER		
1.1.2.5.8	SWITCHES		
1.1.2.6	MAINTENANCE	*144*	
1.1.2.6.1	MAINTENANCE GANTRIES	144	
1.1.2.6.2	GANTRY TRACKS		
1.1.2.6.3	DOCKING PORTS		
1.1.2.6.4	CARGO HANDLERS		
1.1.2.6.5	CREW BUSES		
1.1.2.6.6	CREW WORK STATIONS		
1.1.2.7	ANTENNA MECHANICAL POINTING	*127.9*	
1.1.2.7.1	CMG'S		
1.1.2.7.2	CMG DRIVES		
1.1.2.7.3	CMG CONTROL CIRCUITS		
1.1.3	INFORMATION MANAGEMENT AND CONTROL	**250**	THIS IS A ROUGH ESTIMATE BASED ON THE TRW CONCEPTUAL DEFINITION OF THIS SUBSYSTEM
1.1.3.1	TRANSDUCERS		
1.1.3.2	SIGNAL CONDITIONERS		
1.1.3.3	DATA ACQUISITION/MANAGEMENT		
1.1.3.4	CENTRAL COMPUTERS		
1.1.3.5	CONTROL CIRCUITS		
1.1.3.6	SIGNAL ROUTING		
1.1.3.7	SOFTWARE		
1.1.3.8	INTRA-SATELLITE VOICE		
1.1.4	ATTITUDE CONTROL AND STATIONKEEPING	**184**	
1.1.4.1	SENSORS	* 1*	
1.1.4.2	ELECTRIC PROPULSION	*155*	
1.1.4.2.1	THRUSTERS	14	
1.1.4.2.2	PROPELLANT	50	
1.1.4.2.3	TANKAGE	6	
1.1.4.2.4	PROPELLANT DELIVERY	1	
1.1.4.2.5	CONTROLS	–	
1.1.4.2.6	DEDICATED POWER PROCESSING	94	
1.1.4.3	CHEMICAL PROPULSION	* 4*	

NOTE: THIS TABLE REFLECTS REDISTRIBUTION OF WBS ITEMS TO CONFORM WITH THE DETAILS OF THE CURRENT NASA SPS WBS.

Table 1.1.0-2 Comprehensive Mass Properties (continued)

WBS ELEMENT	EQUIPMENT NOMENCLATURE	MASS	REMARKS
1.1.4.3.1	THRUSTERS/ENGINES	1	
1.1.4.3.2	PROPELLANTS	3	
1.1.4.3.3	TANKAGE	1	
1.1.4.3.4	PROPELLANT DELIVERY	–	
1.1.4.3.5	CONTROLS	–	
1.1.4.4	GIMBALS	*25*	
1.1.5	COMMUNICATIONS	**10**	
1.1.5.1	SATELLITE TO EARTH		
1.1.5.1.1	RECEIVERS		
1.1.5.1.2	TRANSMITTERS		
1.1.5.1.3	ANTENNAS		
1.1.5.1.4	SIGNAL INTERFACE		
1.1.5.1.5	CABLING		
1.1.5.2	GEO OPERATIONS COMMUNICATIONS		
1.1.5.2.1	RECEIVERS		
1.1.5.2.2	TRANSMITTERS		
1.1.5.2.3	ANTENNAS		
1.1.5.2.4	SIGNAL INTERFACE		
1.1.5.2.5	CABLING		
1.1.6	INTERFACE (ENERGY CONVERSION/POWER TRANSMISSION)	**147**	
1.1.6.1	STRUCTURE	*53*	
1.1.6.1.1	PRIMARY STRUCTURE	53	
1.1.6.1.2	SUPPORT STRUCTURE	–	
1.1.6.1.3	CABLES	–	
1.1.6.2	MECHANISMS	*94*	
1.1.6.2.1	MECHANICAL ROTARY JOINT	33	
1.1.6.2.1.1	DRIVE RINGS	(28)	
1.1.6.2.1.2	DRIVE MECHANISMS	(3)	
1.1.6.2.1.3	DRIVE MOTORS	(1)	
1.1.6.2.1.4	DRIVE CONTROL CIRCUITRY	(1)	
1.1.6.2.2	ELEVATION JOINT (YOKE)	41.2	
1.1.6.2.2.1	ELEVATION DRIVE		
1.1.6.2.2.2	DRIVE MECHANISMS		
1.1.6.2.2.3	DRIVE MOTORS		
1.1.6.2.2.4	DRIVE SUSPENSION		
1.1.6.2.2.5	DRIVE CONTROL CIRCUITRY		
1.1.6.2.3	POWER DISTRIBUTION	20	
1.1.6.2.3.1	SLIP RINGS	(12)	
1.1.6.2.3.2	BRUSH ASSEMBLIES	(2)	
1.1.6.2.3.3	FEEDERS	(4)	
1.1.6.2.3.4	INSULATORS	(1)	
1.1.6.2.3.5	POWER BUSES	(1)	
1.1.6.2.4	THERMAL CONTROL		THERMAL CONTROL IS ACCOUNTED IN THE VARIOUS SUBSYSTEMS
1.1.6.2.4.1	MECHANICAL ROTARY JOINT THERMAL CONTROL		
1.1.6.2.4.2	ELEVATION JOINT THERMAL CONTROL		
1.1.6.2.4.3	SLIP RING THERMAL CONTROL		
1.1.6.2.4.4	THERMAL CONTROL SURFACES		
1.1.6.2.4.5	INSULATION		
1.2	GROWTH AND CONTINGENCY ALLOWANCE (21%)	***8413***	

NOTE: THIS TABLE REFLECTS REDISTRIBUTION OF WBS ITEMS TO CONFORM WITH THE DETAILS OF THE CURRENT NASA SPS WBS.

Table 1.1.0-3 Projected Unit Cost of One 5-GW SPS (Millions of 1977 Dollars)

WBS	ITEM	COST: POINT OF DEPARTURE (AS 5-GW)	COST: CURRENT	REASON FOR CHANGE
1.1	SATELLITE	3798	3917	
1.1.1	SATELLITE ENERGY CONVERSION	2274	2139	REVISED EFFICIENCY CHAIN; GEO CONSTRUCTION
1.1.2	SATELLITE POWER TRANSMISSION SYSTEM	1227	1283	REDUNDANCY ADDED TO PHASE CONTROL
1.1.3	INFORMATION MGMT & CONTROL	42	42	
1.1.4	ATTITUDE CONTROL & STATION KEEPING	144	144	
1.1.5	COMMUNICATIONS	111	111	
1.1.6	INTERFACE	(INCLUDED IN ENERGY CONV)		
1.2	SPACE CONSTRUCTION AND SUPPORT • DIRECT	554**	218	GEO CONSTRUCTION
	• CAPITAL RECOVERY		420*	
1.3	SPACE TRANSPORTATION • DIRECT	3193**	1802	GEO CONSTRUCTION WITH EOTV; REDUCED SATELLITE MASS
	• CAPITAL RECOVERY		1446*	
1.4	GROUND RECEIVING STATION	2934	2242	NEW ANALYSIS OF RECTENNA DESIGN AND CONSTRUCTION
1.5	MGMT AND INTEGRATION	421	421	
	*INCLUDED IN TOTAL UNDER CAPITAL RECOVERY BELOW			
	TOTAL DIRECT OUTLAYS	**	8600	
	CAPITAL RECOVERY FOR SPACE CONSTRUCTION BASE AND TRANSPORTATION FLEET	–	1866	
	INTEREST DURING CONSTRUCTION	1041	826	2 YEARS CONSTRUCTION TIME @ 7-1/2%
	GROWTH AND CONTINGENCY	1558	1130	EARLIER FIGURE HAD GROWTH APPLIED TWICE TO TRANSPORTATION COST
	PROJECTED TOTAL CAPITAL COST	13,499	12,421	

*INCLUDED IN TOTAL UNDER CAPITAL RECOVERY BELOW

**CAPITAL RECOVERY AND DIRECT WERE NOT SEPARATED IN EARLIER WORK

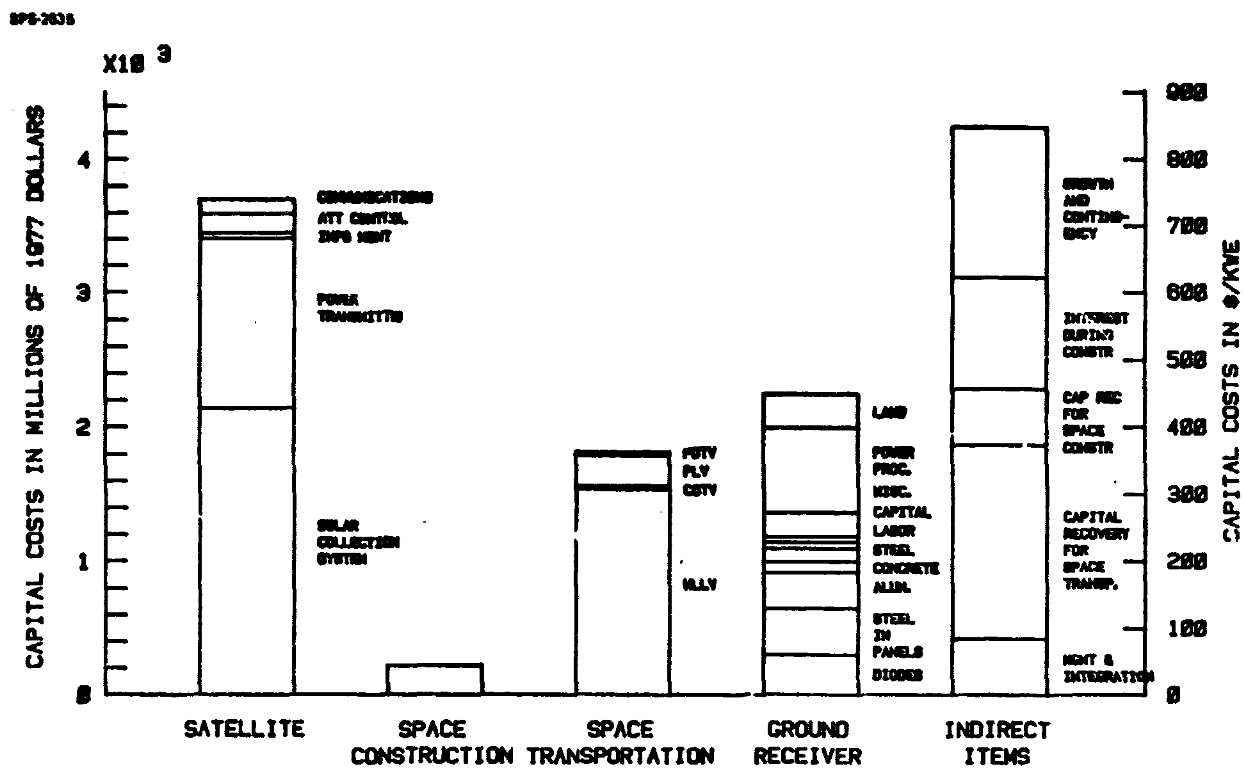


Figure 1.1.0-2 SPS Cost Distribution

Element Description

The reference energy conversion system configuration was illustrated in Figure 1.1.0-1. A summary of the efficiency chain and sizing requirements were presented in Table 1.1.0-1. A more detailed description is given under each of the subelements.

Element Mass

The energy conversion mass summary was included in Table 1.1.0-2. The mass estimating factors are discussed in the subelement entries.

Element Cost

The updated SPS cost summary was shown in Table 1.1.0-3. The cost estimating factors are described in the subelement entries.

WBS 1.1.1.1 Structure

WBS Dictionary

This element includes all structure in the energy conversion system that is not an integral part of one of the other subsystems.

Element Description

The structure supports the solar arrays in trampoline fashion as described earlier in Figure 1.1.0-1. The catenary (trampoline) support system is included as a part of the structure as is the power bus support system.

WBS 1.1.1.1.1 Main Structure

The mainframe structure is a repeating hexahedral (box) truss arrangement made up of two sizes of graphite composite tri-beams as shown in Figure 1.1.1-1. The heavier 12.5-meter beams support the uni-axial solar array stretching levels. The lighter 7.5-meter beams are used in all other locations. Characteristics of the beams are shown in Figure 1.1.1-2.

WBS 1.1.1.1.2 Catenary System

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

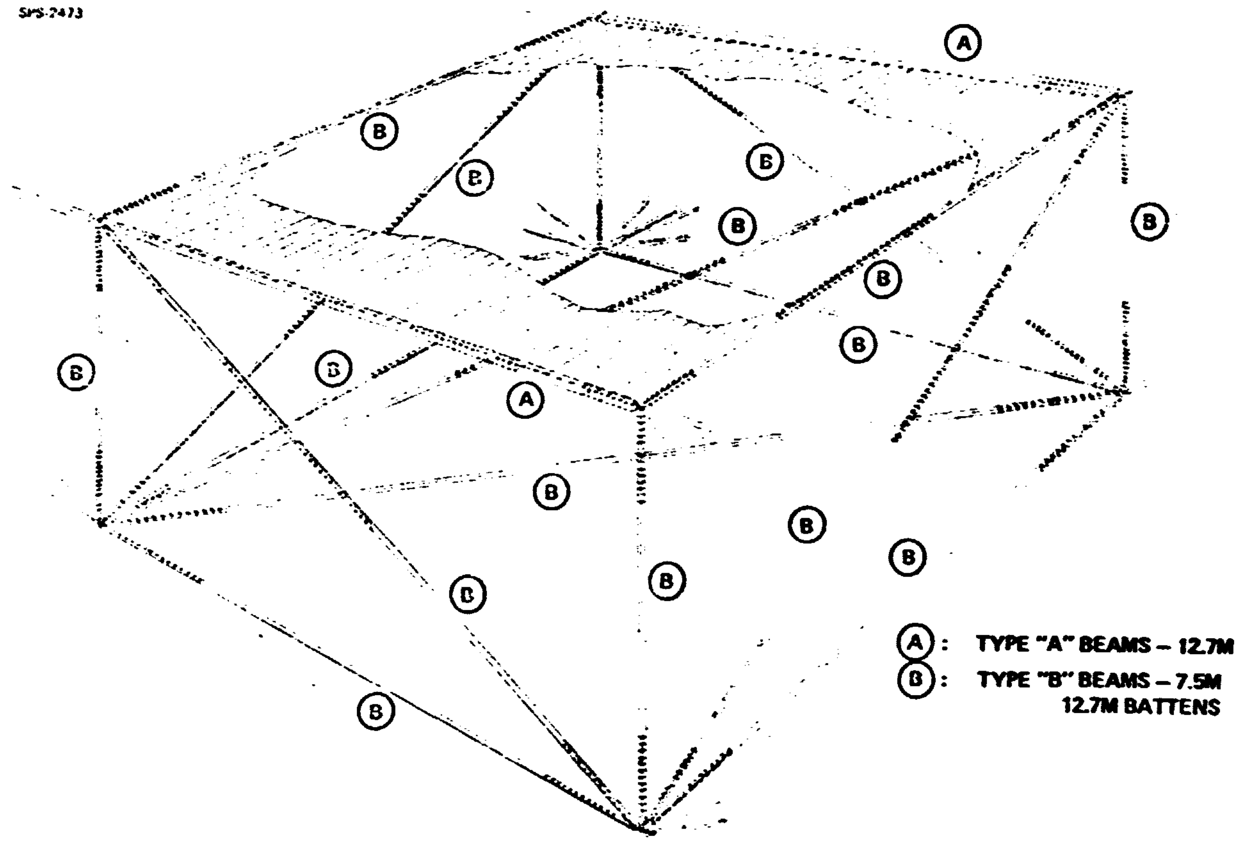
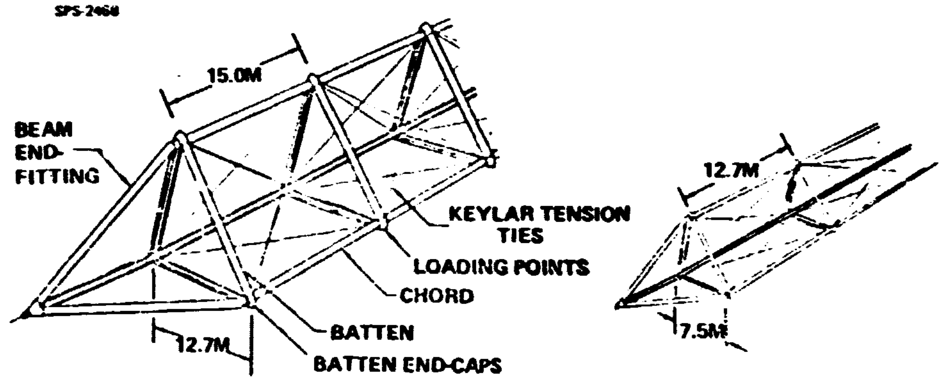


Figure 1.1.1-1 Solar Power Satellite Structural Bay Configuration



ITEM	TYPE A UPPER SURFACE LONGITUDINAL BEAM	TYPE B BEAM USED IN ALL OTHER LOCATIONS
SECTION	CLOSED	OPEN
REF. SIDE LENGTH	38 CM	38CM
MAT'L THICKNESS	0.86 MM	0.71 MM
EI_X	3.39 E8 N/CM^2	1.80 E8 N/CM^2
BEAM WIDTH	12.7M	7.5M
BATTEN SPACING	15.0M	12.7M
CRITICAL LOAD	17480N (CRIP. CHORD)	7090 N(BUCK BEAM)
MASS/LENGTH	7.48 KG/M	4.11 KG/M

Figure 1.1.1-2 Solar Power Satellite Structural Update Beam Configurations

blanket tensioning springs at each blanket support tape as shown in figure 1.1.1-3. These springs are also attached to a catenary cable that is then attached to the primary structure, upper surface, beams at 15 meter intervals. The springs are in compression, for better reliability, and exert a uniaxial force of approximately 4.1N to each blanket support tape.

WBS 1.1.1.1.2 Power Distribution Support

The basic requirements for the bus support subsystem are as follows:

- o Provide a natural frequency, substantially higher than the sateliite.
- o Accommodate thermal expansion without applying large loads to the main satellite structure.
- o Be light weight.
- o Have low ground fabrication cost.
- o Be easy to assemble in orbit, using mostly automated methods.

The support design presented here satisfies these basic requirements, but it is recognized that further study might lead to a better design.

The principal loads on the bus conductors are illustrated in Figure 1.1.1-4. The "compression" and "curling" loads are generated within the conductors and must be resisted by the conductors, with whatever form of reinforcement is provided. Fortunately, these forces are relatively small so the resulting stress level is very low. The elastic stability of the thin sheet conductors is a concern, however.

The major load on the main bus conductors is the magnetic force repelling two conductors carrying current in opposite directions. This load is so large that, for the current density being used, the bending stress in the sheet conductors over the span of a segment would almost certainly cause elastic instability in the compression side of the bus bar, especially when combined with the compression and curling forces. Fortunately, the force is repulsion, so it can be reduced by adding tension ties between the conductors at points intermediate to the supports at the main structure at segment joints. This reaction means that busses carrying currents in the opposite directions must be alternated.

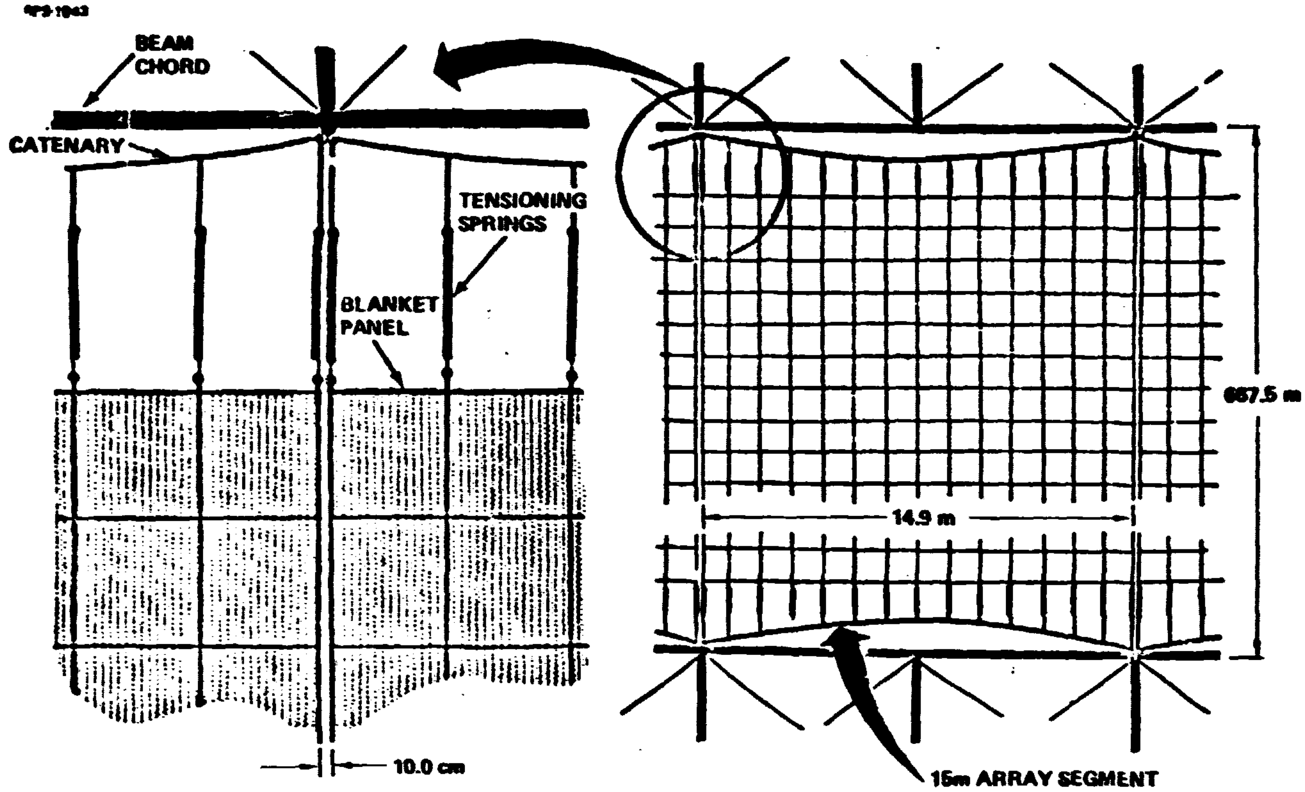


Figure 1.1.1-3 Reference Array Blanket Support

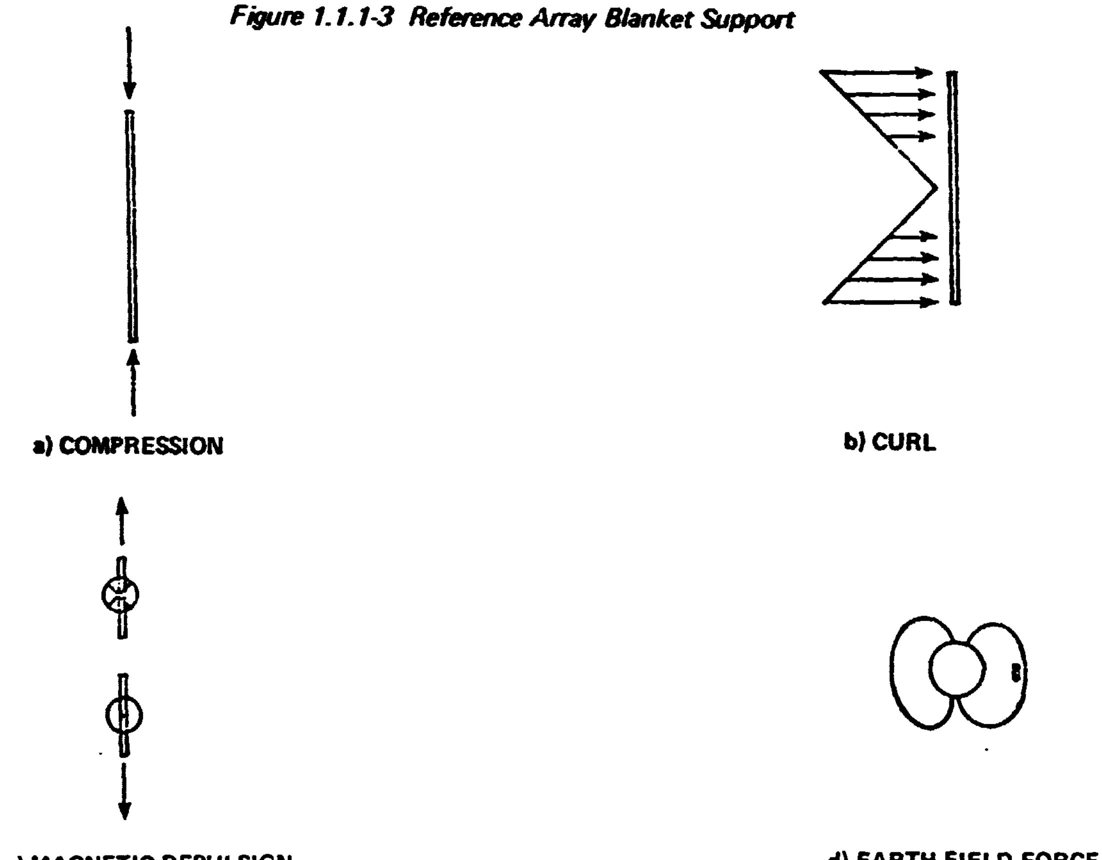


Figure 1.1.1-4 Sheet Conductor Loads

The other major factor which determines the design is the differential thermal expansion between the graphite-epoxy structure and the aluminum bus. The temperature variations between eclipse and full sunlight is from about 123K to 373K. Over the span of a full segment this results in a differential thermal expansion of a little over four meters. For the one millimeter thick sheet conductor a load of 443 kN for each meter of conductor with stress of 443 MPa would be required to overcome this change in length.

A total load in excess of 14 million Newtons would be developed. This is an unreasonably large load to impose upon the structure, so provisions for thermal expansion are made. After considering several alternatives, the design selected is to allow a thermal expansion curve at each bay joint, as shown in Figure 1.1.1-5.

The selected method of keeping the natural frequency of the sheet conductors above that of the satellite is to keep the bus conductors in tension. A preliminary analysis indicates that modest forces (of the close order of one Newton per centimeter of conductor width) will keep the natural frequency of the bus an order of magnitude higher than that of the satellite. To maintain this load in the conductors while allowing for thermal expansion requires springs. The easiest way to provide this spring action is to use high stresses in low modulus materials, such as Kevlar® or E-glass. (A stress going from 250 to 500 MPa in a 200 m Kevlar tension support will provide the four meter extension needed to accommodate thermal expansion, while varying the load on the bus by only a factor of two).

These factors led to the final selection of the main bus configuration shown in Figure 1.1.1-6. This view shows several bays near the slip-ring 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 tries to react the bus magnetic repulsion forces can be seen.

The acquisition buses which are triangular in shape are suspended within the center 12.7 meter beam by guy wires. These acquisition buses are also aluminum. Making the connection between the copper pigtails that interconnect the individual strings of solar cells and the aluminum acquisition bus is a problem that requires further study. Even though the joint is made and kept in vacuum so that galvanic corrosion and oxidation are eliminated as problems, differential expansion remains a problem that will make good joint design difficult. From that initial connection subsequent connections will be aluminum to aluminum and will be welded.

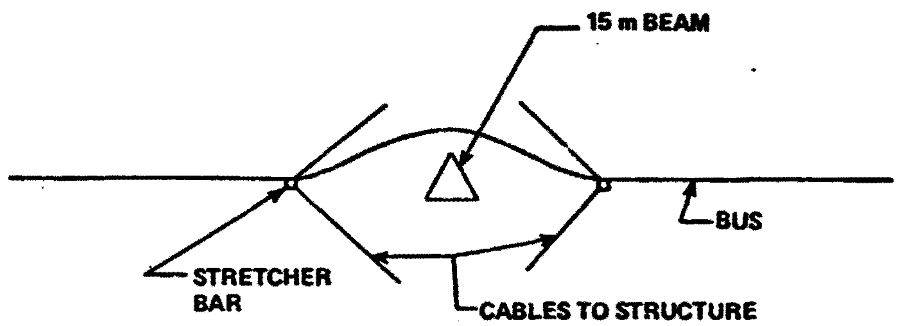


Figure 1.1.1-5 Bus Expansion Slack

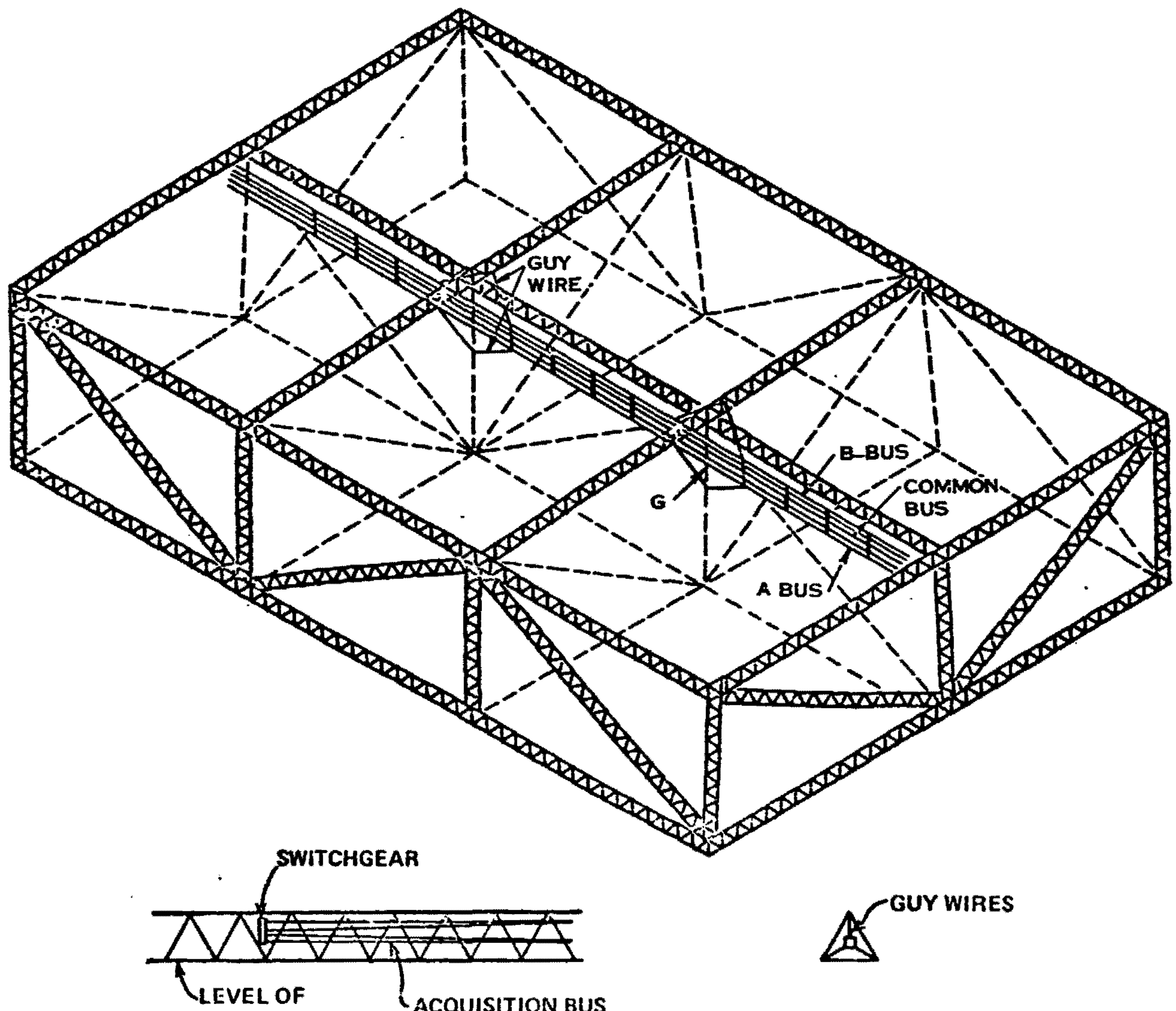


Figure 1.1.1-6 Main Bus Support

Element Mass

The structure mass estimate is summarized in Table 1.1.1-1.

Element Cost

The cost estimating factor used for primary structural members is 55$/kg. This factor was based on mature industry projections and was verified by detailed manufacturing and fabrication analysis.

WBS 1.1.1.2 Concentrators - concentrators are not required

WBS 1.1.1.3 Solar Blankets

WBS Dictionary

This element includes all production hardware required to convert incident sunlight into the required electrical power. Subelements include solar cell panels, and panel interconnect interbay jumpers.

Element Description

An illustration of the solar cell blanket is provided in figure 1.1.1-7. A silicon solar cell must be provided with a cover to increase front-surface emittance from around 0.25 to around 0.85, and to protect the cell from low-energy proton irradiation.

WBS 1.1.1.3.1 Solar Cell Panels

Cerium-doped borosilicate glass is a good cover material because it costs only a fraction of the best alternate, 7940 fused silica, matches the coefficient of thermal expansion of silicon, and yet resists darkening by ultraviolet light. Borosilicate glass can be electrostatically bonded to silicon to form a strong and permanent adhesiveless joint. In ATS-6 flight tests the cells having integral 7070 borosilicate glass covers lost only 0.8+ 1.1 percent of their output because of ultraviolet degradation. These cells had no cover adhesive. Other cells having cell-to-cover adhesives degraded twice as much. Jena Glaswerk Schoot & Gen. Inc., in West Germany, expects to be able to manufacture 75 μm borosilicate glass sheets one meter wide by several meters long.

The cell cover is embossed during bonding with grooves which refract sunlight away from the grid lines and buses on the cell surface. COMSAT Labs expects an 8 to 12 percent increase in cell output from this feature in cell covers.

Table 1.1.1-1 Structural Mass Estimating Summary

SPS-2708

MEMBER LENGTHS:

12.7M (UPPER SURFACE LONGITUDINALS) = 16 X 9 X 667.5M = 96120M

ALL OTHERS:

LONGITUDINALS	-	[16 X 9 X 667.5]	=	96120M
LATERALS	-	2[8 X 17 X 667.5]	=	181560M
LOWER FACE DIAG	-	[8 X 16 X 944.0]	=	120832
CROSS BAY DIAG	-	[8 X 16 X 1054.5]	=	134976
CORNER POSTS	-	[9 X 17 X 460.2]	=	70410.6

SUMMARY:

12.7M (TYPE "A" BEAM) = 96,120M

7.5M (TYPE"C" BEAM) = 603,898.6M

GEO STRUCTURE MASS

12.7M TYPE "A" BEAM - 96,120M @ 7.476 Kg/M = 718593.1 Kg

7.5M TYPE "C" BEAM - 603,898.6M @ 4.106 Kg/M = 2479607.7 Kg

TOTAL STRUCTURAL MASS = 3198.2 MT

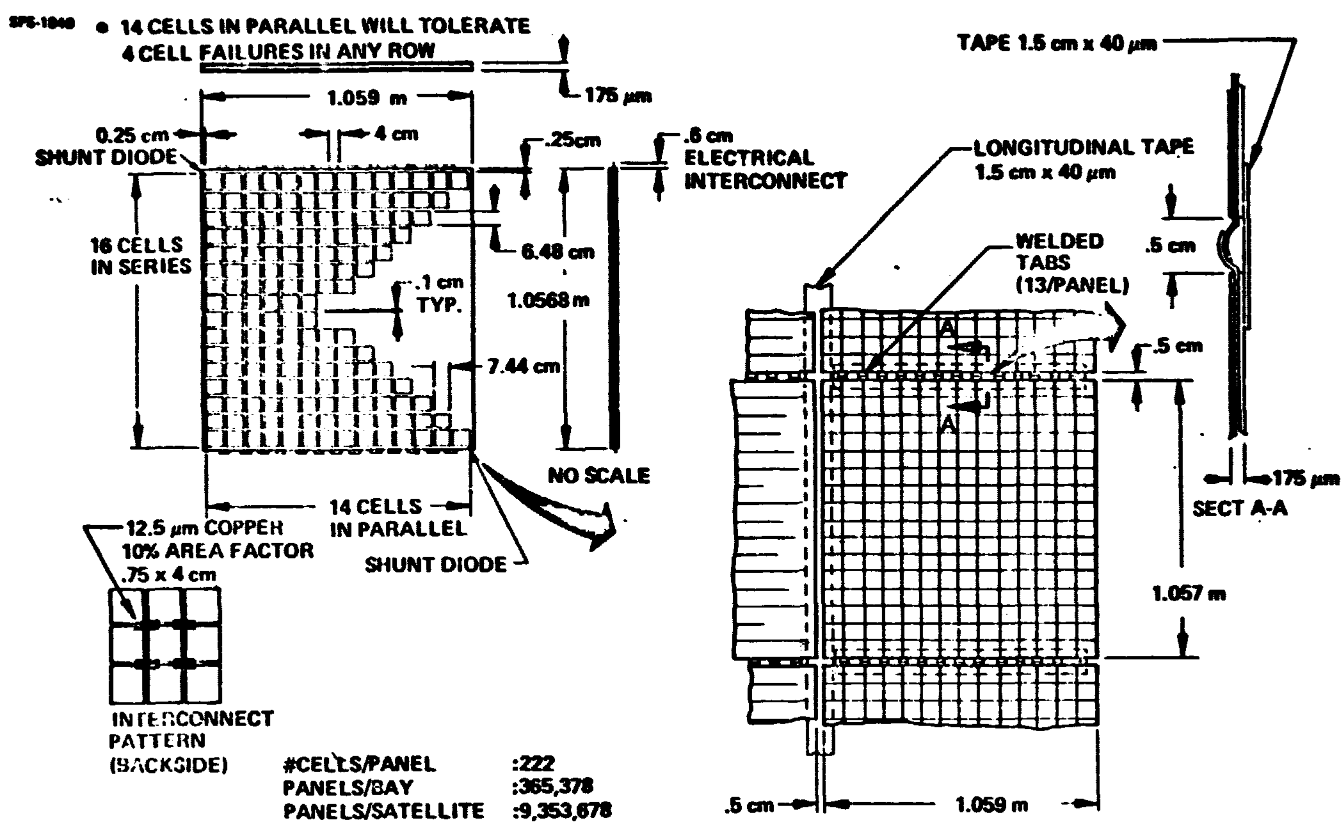


Figure 1.1.1-7 Reference Photovoltaic System Description

The cells are designed with both P and N terminals brought to the backs of the cells. This feature makes it possible to use simple 12.5 μm silver-plated copper interconnections which are formed on the substrate glass. Complete panels are assembled electrically by welding together the module-to-module interconnections.

Glass was chosen for the substrate to enable annealing of radiation damage by heating. With all glass-to-silicon bonds made by the electro-static process there are no elements in the blanket which cannot withstand the 773°K (931°F) annealing temperature, which at present seems to be required.

The basic panel adopted for design studies has a matrix of 222 solar cells, each 6.48 by 7.44 cm in size, connected in groups of 14 cells in parallel by 16 cells in a series. Spacing between cell and edge spacings are as shown. 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 is provided by shunting diodes at the panel level as illustrated in Figure 1.1.1-8.

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 50 μm sheets of substrate glass.

The panels are joined 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 low-Earth-orbit 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, with provisions for welding strips to join blanket segments, to form power sections. The conducting strips also 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.

SPS-2434

RATIONALE:

PREVENTS ARRAY DAMAGE CAUSED BY UNEVEN ILLUMINATION AND SHADOWING EFFECTS

PROVIDES MORE GRACEFUL POWER DEGRADATION FROM BLANKET PANEL FAILURES AND SHADOWING EFFECTS

DESIGN CRITERIA:

REVERSE-BIAS PROTECTION FOR BLANKET PANELS

LOW REVERSE LEAKAGE CURRENT

LOW FORWARD-VOLTAGE DROP

HIGH RELIABILITY

COMPATIBLE WITH BLANKET PANEL CONFIGURATION

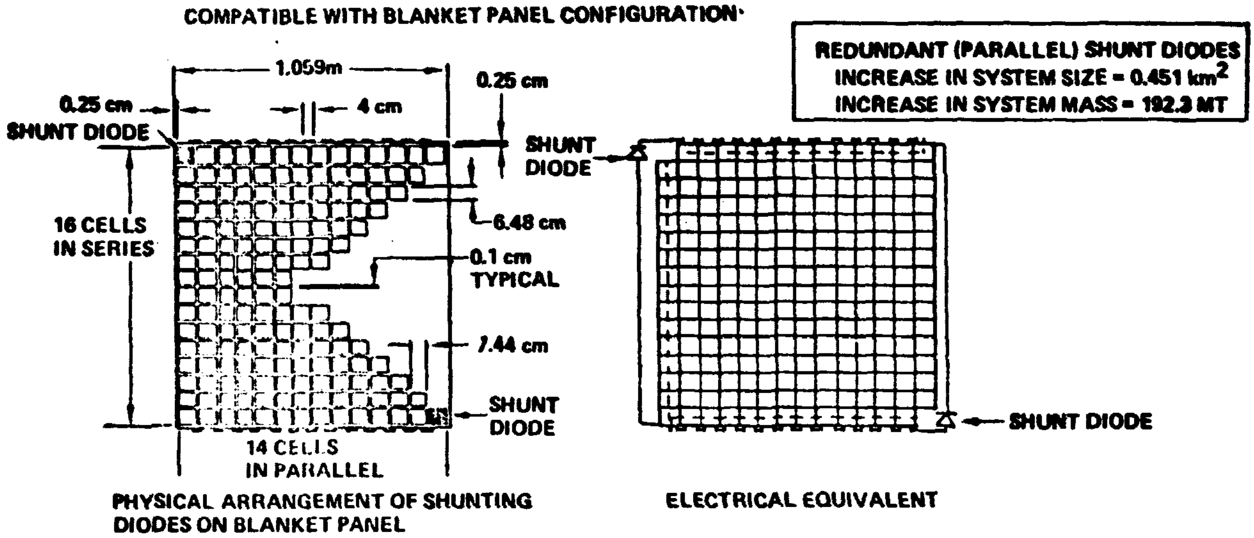


Figure 1.1.1-8 Implementation of Array Shadowing Diodes

Element Mass

A mass breakdown of the solar blanket is provided in Table 1.1.1-2. Also included in this table are the mass estimates for the array support system.

Element Cost

The cost etimating factors for the solar blanket elements have not changed from the documentation of Part 2. The mature industry project cost estimating factor for the reference solar blanket is $35/m^2$.

WBS 1.1.1.3.3 Interbay Jumpers

WBS Dictionary

This element includes all production hardware required to provide for interbay power distribution within a power sector of the solar blanket.

Element Description

The formulation of high voltage in the solar array is accomplished by connecting approximately 78,000 sets of solar cells in series. Since the strings of solar cells start at the centerline of the satellite, go to the outer edge and then back to the centerline, they must cross the primary structural beams, between bays, eight times. The purpose of the interbay jumpers is to provide a means of electrically connecting strings in one bay to the appropriate strings in the next bay of the string length.

The interbay jumpers (figure 1.1.1-9) are No. 12 aluminum cable. One-blanket segments jumpers are collected and run along the catenary cable to an end-connector. This end connector is joined with the next bays jumper end connector in the beam framework near the catenary support point. This method was chosen as a less complicated construction/maintenance scheme while still providing the necessary function.

WBS 1.1.1.4 Power Distribution

WBS Dictionary

This element includes power conductors and switches necessary to transmit electrical power from the power source to the rotary joint. Also included are cables and harnesses required to distribute power to equipment mounted on the solar array. Excluded are instrumentation and data buses which are a part of the data management assembly.

Table 1.1.1-2 Silicon Solar Cell Blanket Mass

AVAILABLE BLANKET @ PART II MIDTERM	DENSITY			AREA FACTOR	
COVERS–FUSED SILICA	2.20	55.88	3.0	1.0	167.64
CELLS–SILICON	2.36	59.94	2.0	0.9607	115.17
INTERCONNECTS–COPPER	8.94	227.08	.5	0.100	11.35
SUBSTRATE–FUSED SILICA	2.20	55.8C	2.0	1.0	111.76

7 MILS:
- 3 MILS COVER
- 2 MILS CELL
- 2 MILS SUBSTRATE & INTERCONNECTS

THEORETICAL PANEL WEIGHT	405.92
TOLERANCES ALLOWANCE (5%)	20.30
ESTIMATED PANEL WEIGHT	426.22
PANEL AREA FACTOR (.9913)	422.51
SEGMENTS AREA FACTOR (.9972)	421.33
JOINT/SUPPORT TAPES	2.93
CATENARY SYSTEM	2.52
ESTIMATED ARRAY WEIGHT	426.78

SPS-1752

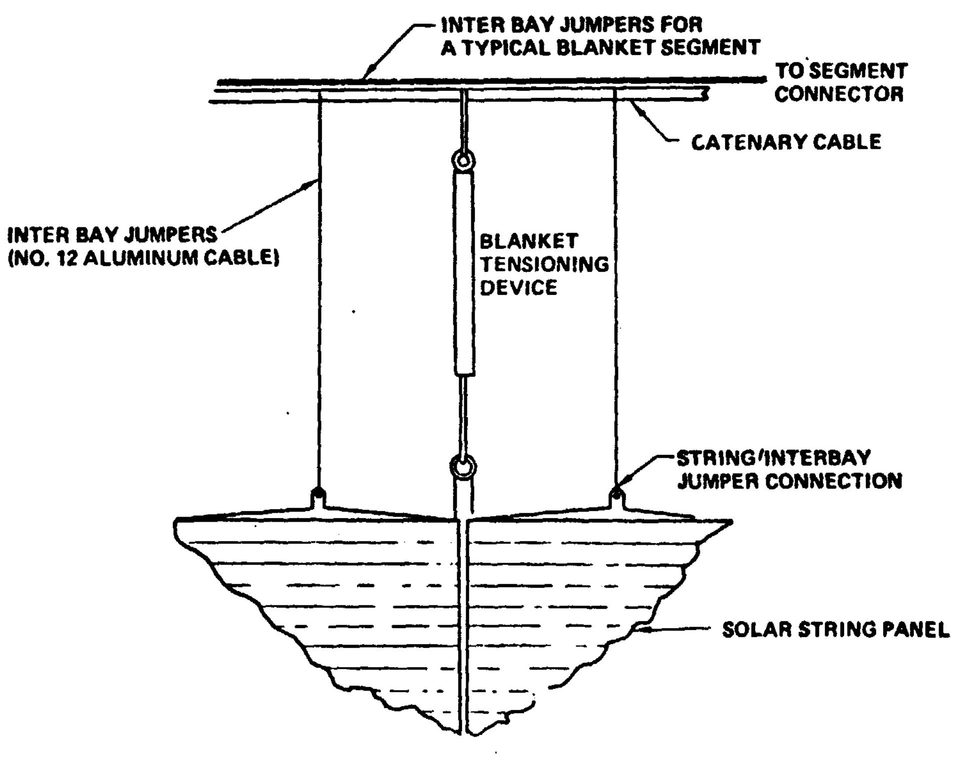


Figure 1.1.1-9 Inter Bay Jumpers

For power management and power distribution, the photovoltaic SPS is divided into typically 228 power sectors. Each power sector is switchable and can be isolated from the main power bus, facilitating annealing or other servicing.

Solar cell strings approximately 5.1 km long were selected for the reference photovoltaic system configuration. This permits generating the required voltage directly from the solar array without intervening power electronics. All solar cell strings are identical. Current generated by the solar cells are carried by conductors or by the solar cells themselves. The configuration in figure 1.1.1-10 uses the solar cells to the maximum possible extent for carrying the current. It is noted that no conductors are needed for bringing in the current from the edges of the array, the solar cell strings being arranged in loops which start from one center bus, loop around the edge of the array, and return to the other bus at the center of the array. (The solar array is part of WBS item 1.1.1.3; this description shows how the solar array interfaces with the power distribution system).

During the critique of the baseline system concept the system redundancy of the major power system busses were of some concern to both Boeing and TRW personnel who accomplished the critique. In addition, the potential fault currents that could occur with the single-line bus system was also of concern.

A redesign of the main power distribution bus system was accomplished to decrease the possibility of loss of all power to the antenna and to limit potential fault currents. The overall multiple bus system concept is shown in figure 1.1.1-10. A summary of the important parameters is shown in table 1.1.1-3.

One of the problems to be addressed in a multiple bus system is the delivery of power to all sections of the antenna at essentially the same voltage. Figure 1.1.1-11 shows a concept that was developed which will enable the delivery of power to the rotary joint with the voltage levels for all busses within 0.25% of each other which should satisfy distribution requirements. By staggering the bus connections as shown by figure 1.1.1-11, the voltage delivered only varies by the voltage drop across 1/3 of a satellite bay. The adoption of this multiple bus scheme will result in the loss of one quadrant of the antenna for faults on any of the main B source power busses and one-sixth of the antenna for faults on the main A source power busses.

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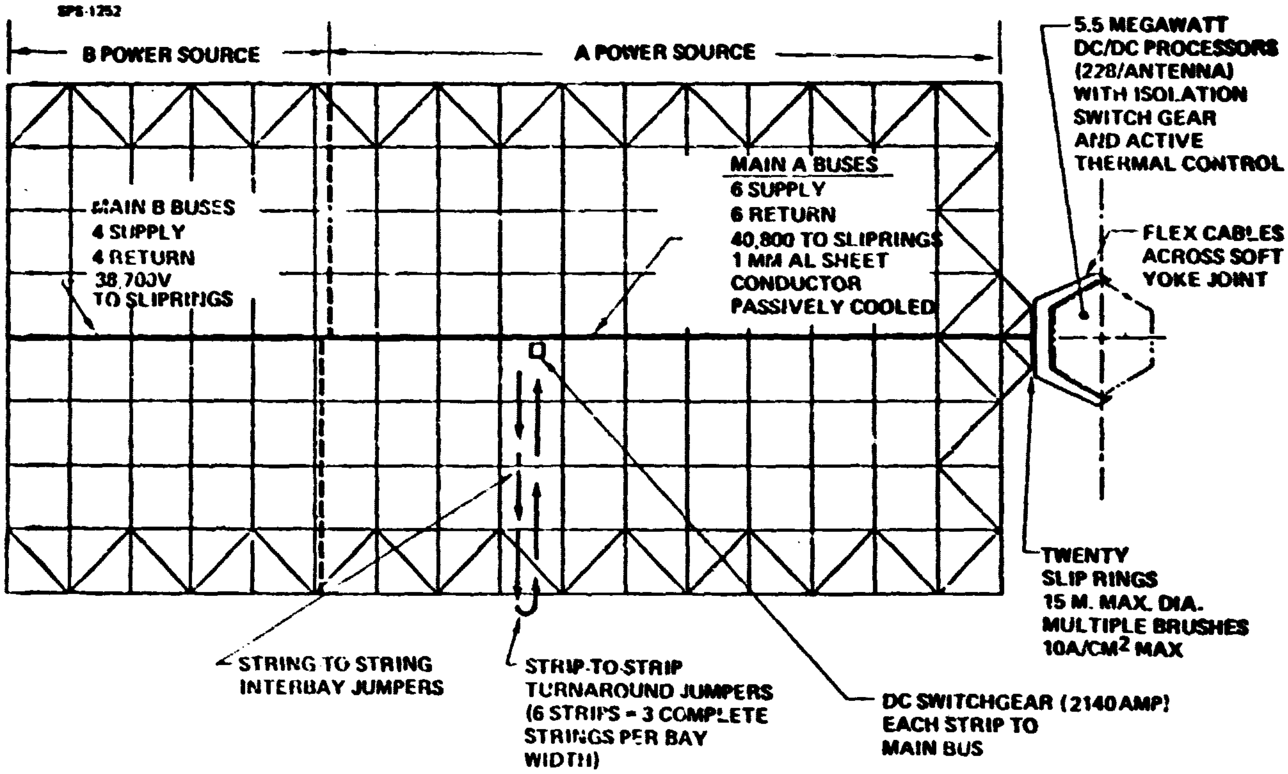

Figure 1.1.1-10 Multiple Bus SPS Power Distribution

SPS-2477

Table 1.1.1-3 Multiple Bus Conductor Summary

SATELLITE				ANTENNA	
POWER SOURCE	NO. OF BUSES	ARRAY POWER SECTORS	NORMAL BUS CURRENT (PER BUS)	NO. OF CONVERTERS PER BUS	NO. OF KLYSTRONS PER BUS
A	4 (+) 4 (-)	31	15,966	57	25,388
B	6 (+) 6 ( )	65	22,783		16,925

SPS-3621

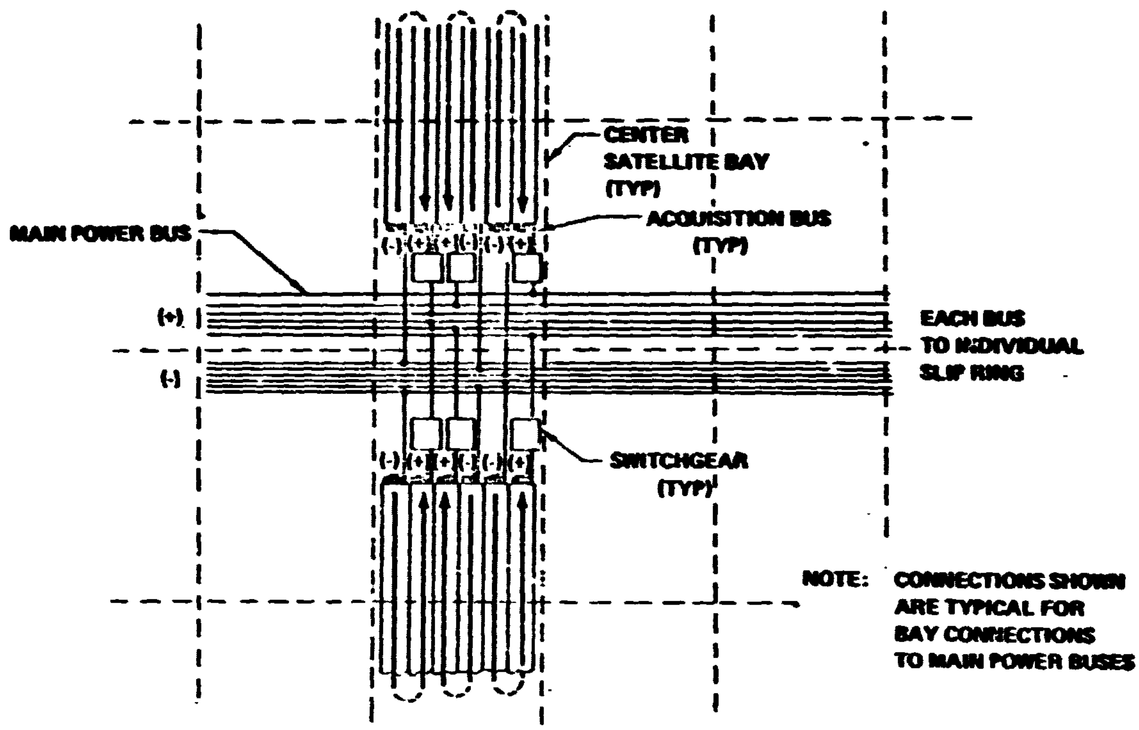

Figure 1.1.1-11 Multiple Bus/Array Connection

WBS 1.1.1.4.1 Main Buses

The main bus subsystem outlined here covers the portion of the power distribution subsystem from the solar cell interconnections to the antenna sliprings. The buildup of solar cells into st. .igs, within each bay was described above. The strings on each side of the satellite longitudinal centerline are connected in series to form a half string 39,104 (9776 x 4) cells in length. To obtain the 40,000 volts needed to operate the klystrons of the MPTS, the half strings are connected together at the outer edge of the satellite by triangular jumpers. This gives 298 series strings (for e. ch four bays-center to edge) each 78,208 cells long. Note that, to provide cell failure protection, each string is really 14 cells wide.

WBS 1.1.1.4.2 Acquisition Buses

Acquisition buses collect the raw dc power from the solar array strings and connect to the switchgear sets. To minimize satellite mass, conductor grade aluminum sheet was selected for the main and acquisition buses. Analysis of conductor operating temperature vs. mass led to the choice of a conductor operating temperature of 100°C. A one millimeter conductor thickness was selected as the minimum gauge on the bsis of handling and assembly. This leads to the result that the buses are 0.01581 centimeters wide for each ampere carried.

WBS 1.1.1.4.3 Switchgear

The silicon cell panels and bays form the power generation modules shown in the photovoltaic electrical schematic in figure 1.1.1-12. These modules are fed to vacuum circuit breaker switchgear controlled by load and system demands. The satellite switchgear is rated at 2,200 amps and 40 kv and is similar to the antenna switchgear.

WBS 1.1.1.5 Thermal Control - No Requirement Has Been Identified

WBS 1.1.1.6 Maintenance (Solar Array Annealing Equipment and Operations

WBS Dictionary

This element includes all hardware required to provide the capability of annealing radiation degradation from the solar cells. Subelements include the annealing device, support structure, and auxiliary equipment.

Element Description

Laser annealing was chosen as the reference approach to recover radiation induced performance degradation of the energy conversion system.

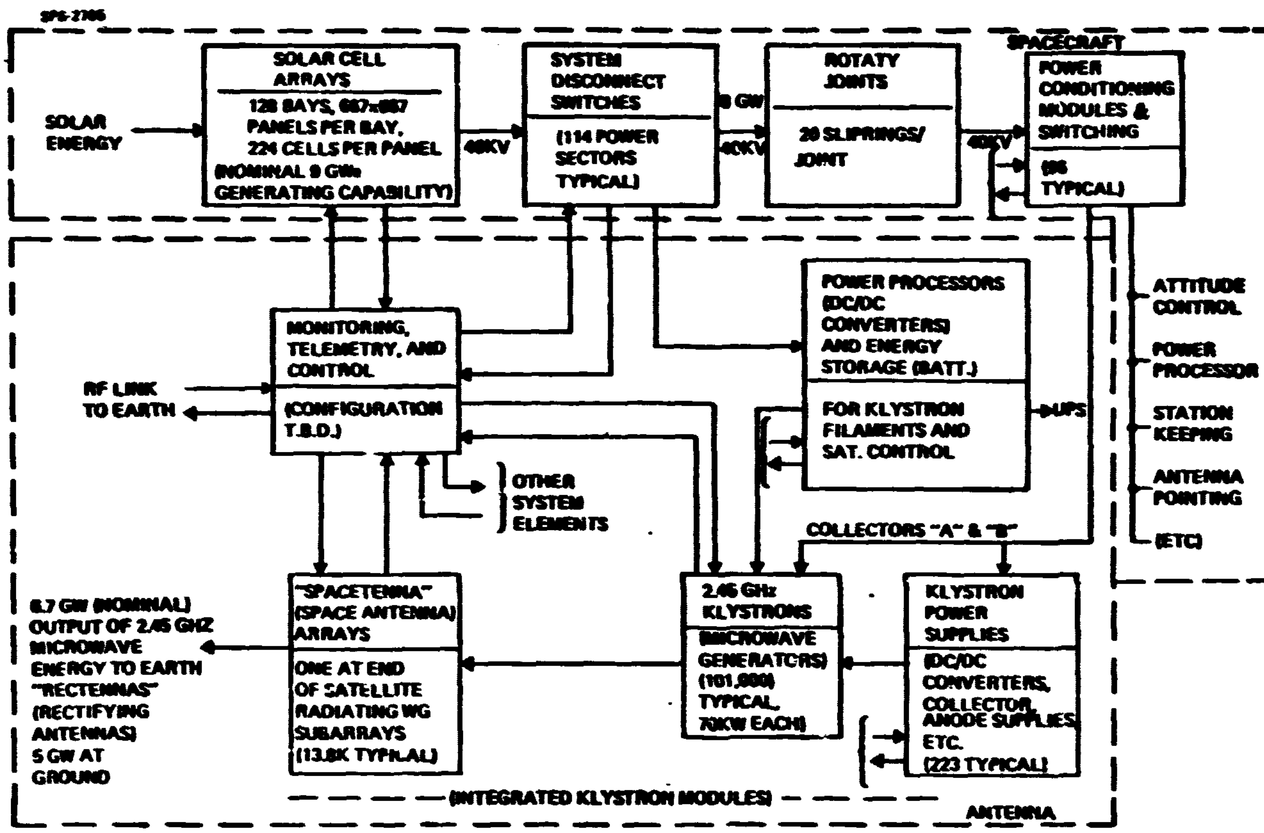

Figure 1.1.1-12. Simplified SPS Functional System Block Diagram

The design assumptions for the laser devices that was used in our analysis is given in Table 1.1.1-4. These are based on test results described in Volume 4 of the present report.

The option chosen for this study was to use one annealing device gantry per satellite module (4x8 by subsection) as shown in Figure 1.1.1-13. A typical annealing device gantry is also shown. The gantry would index to its first position, at the edge of the satellite, anneal that section (15 meter width x 600m length) and then move on to the next section. In this manner, it would traverse the length of the satellite annealing one bay wide sections. When one bay has been annealed, the gantry will index to the next bay and perform the annealing operating. These same operations are repeated until the complete array has been annealed. A total of four gantries will be used.

The gantry system travels on tracks provided on the satellite primary structural members, in the upper surface beams, running along the satellite length.

Within the gantry, there are 44 laser systems. Each laser system is gimballed to allow the laser set (8 lasers) to scan a 15 meter square section. The 15 meter section was chosen to be consistent with the array blanket segment widths. With all of the laser systems on a single gantry operating, it will take approximately 2.5 hours to anneal a 15 meter section one bay wide. This results in a time of 110 hours to anneal one bay of solar array.

WBS 1.1.2 Microwave Power Transmission System

WBS Dictionary

This element includes the entire spaceborne phased array power transmitter. This includes the dc distribution system from the rotary joint to the rf transmitters, the rf transmitters themselves (klystrons), their dc and rf control and monitor circuitry, and the rf antenna elements composed of slotted waveguides, support structure, rf feed circuits, mechanical pointing control, and all the components required for distribution and control of the phase of the retrodirective antenna subarrays.

Element Description

The MPTS system serves the basic function of converting dc power to microwave power in space, transmitting it through the medium with a minimum of environmental impact

SPS-2157

Table 1.1.1-4 Gimbaled Scanning Laser Characteristics Update

• ANNEALING ENERGY DENSITY:	16 W-sec/cm^2
• POWER DENSITY:	8 W/cm^2
• T_{MAX} (ACTIVE REGION):	550°C
• LASERS/GIMBAL:	8
• SCANNING SPOT SIZE:	500 cm^2 (44.0 x 11.4 cm)
• SPOT SWEEP RATE:	5.7 cm/s
• POWER REQUIRED/LASER GIMBAL:	28.7kW
• POWER REQUIRED/GANTRY:	1.17 MW
• NUMBER OF GANTRIES/SATELLITE:	8 (1/SATELLITE MODULE)
• TOTAL ANNEALING POWER REQUIREMENT:	9.4MW
• TIME REQUIRED TO ANNEAL ARRAY:	147 DAYS

SPS-2000

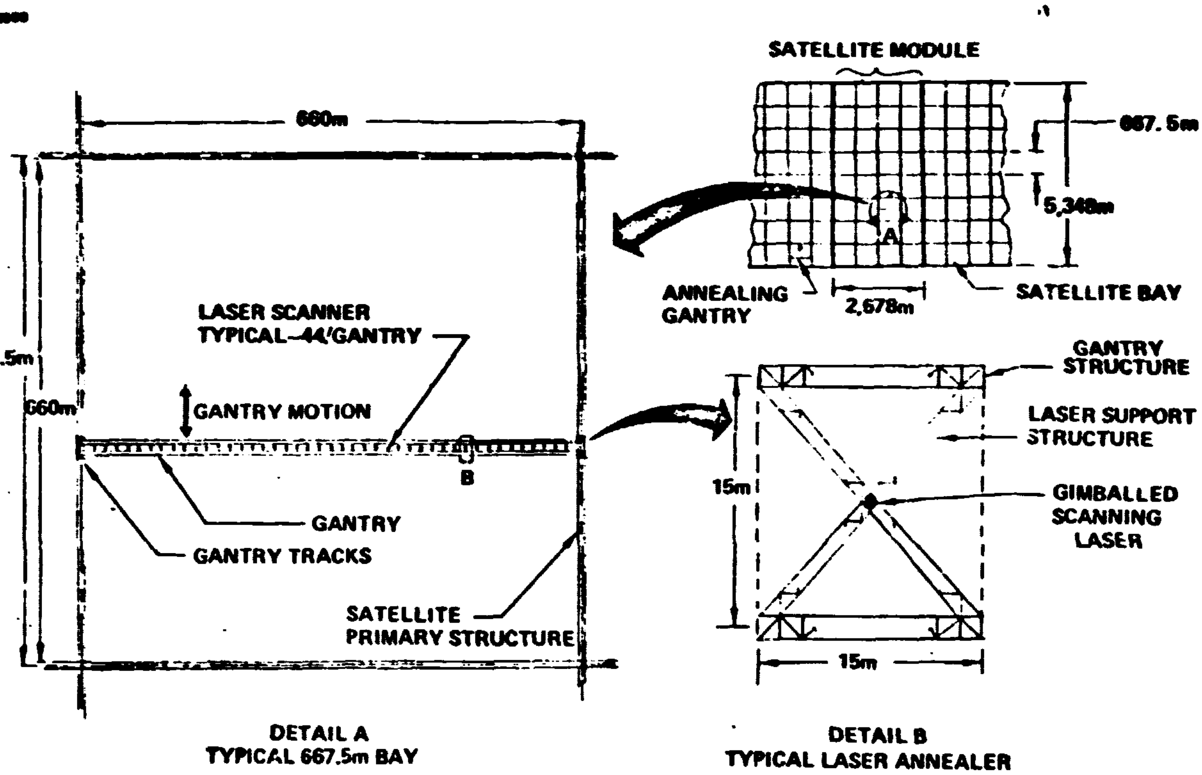

Figure 1.1.1-13 Laser Annealing Concept

and converting it back to dc on the ground. The baseline approach utilizes a retrodictive phased array described in Section 1.1.2.3, powered by dc-rf klystron converters described in Section 1.1.2.3.2. DC power from the rotary joint is distributed in a manner to minimize I^2R losses to the klystrons, utilizing 85% unprocessed power with a maximum voltage of 42 kv. The transmitter design constraints are outlined in Figure 1.1.2-1. The high efficiency klystrons are described in Section 1.1.2.3.1 and are combined to provide a tapered (10 db quantized Gaussian) illumination of the array resulting in low sidelobe levels and high antenna efficiency (over 95%). The thermal loading to the center of the array (22 kw/m^2 rf) permits a design for a 1 km diameter array which provides roughly 5 GW of dc power on the ground per antenna. The phased distribution system is designed to minimize line lengths and cumulative phase errors in the distributing transmission lines by using a 3-node reference distribution system with line length compensation. The pilot reference signal from the ground utilizes spread-spectrum modulation with a suppressed carrier at the power beam frequency, to effect conjugation (i.e., electronic fine beam steering) in an efficient manner.

WBS 1.1.2.1 Structure

This element includes those subsystems not directly associated with conversion of electric power into rf beam power.

WBS **1.1.2.1.1 Primary Structure**

WBS Dictionary

The Power Transmitter Primary Structure is the main structure that provides overall shape and form to the transmitter.

Description

The Primary Structure is an A-frame open truss structure, 130 meters deep, with a quasi-octagonal shape in excess of 1,000 meters width and length. The Primary Structure and its relationship to the Secondary Structure and the rest of the power transmitter are shown in Figures 1.1.2.-2 and 1.1.2-3. The A-frame elements of the Primary Structure are made up of 7-1/2 meter continuous chord beams composed of graphite polysulfone composite structure.

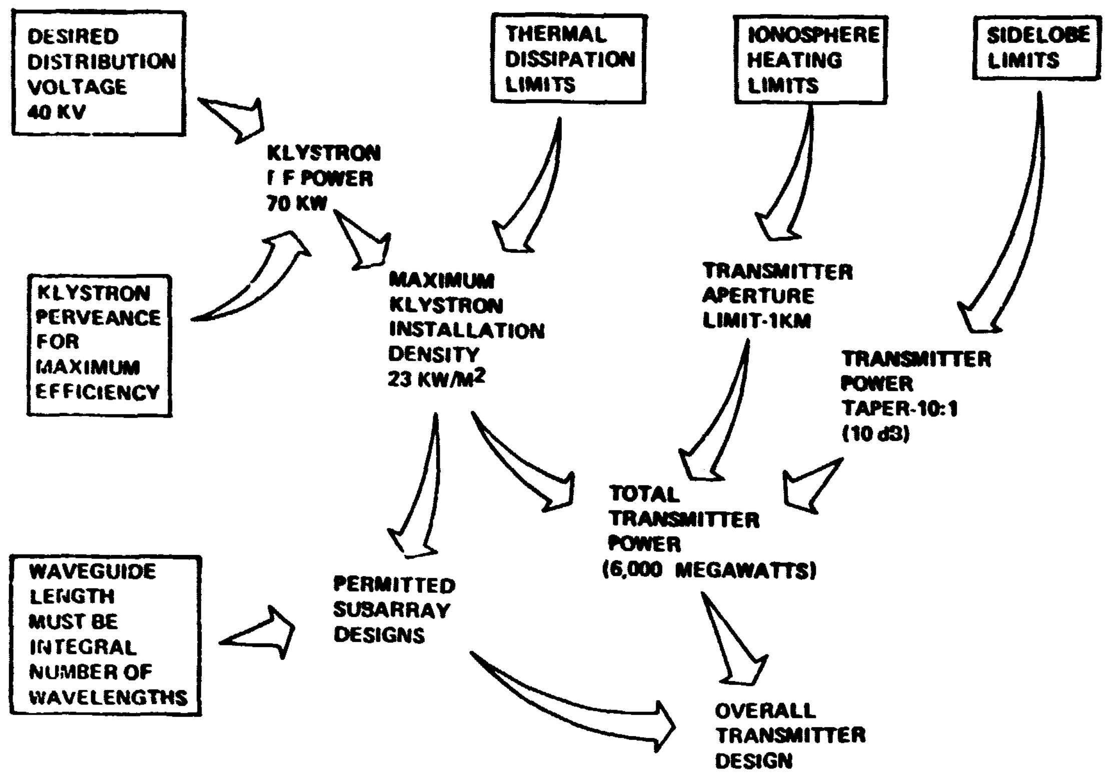

Figure 1.1.2-1 Constraints Dictate Power Transmitter Design

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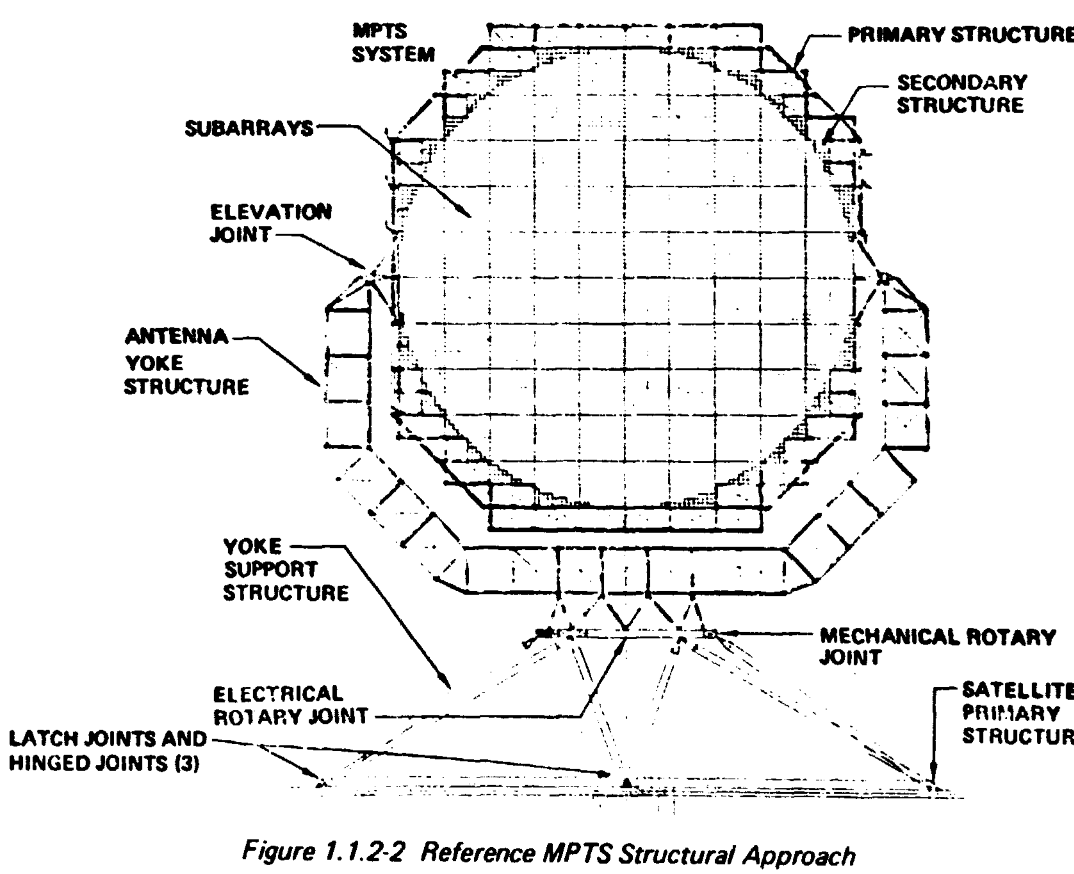

Figure 1.1.2-2 Reference MPTS Structural Approach

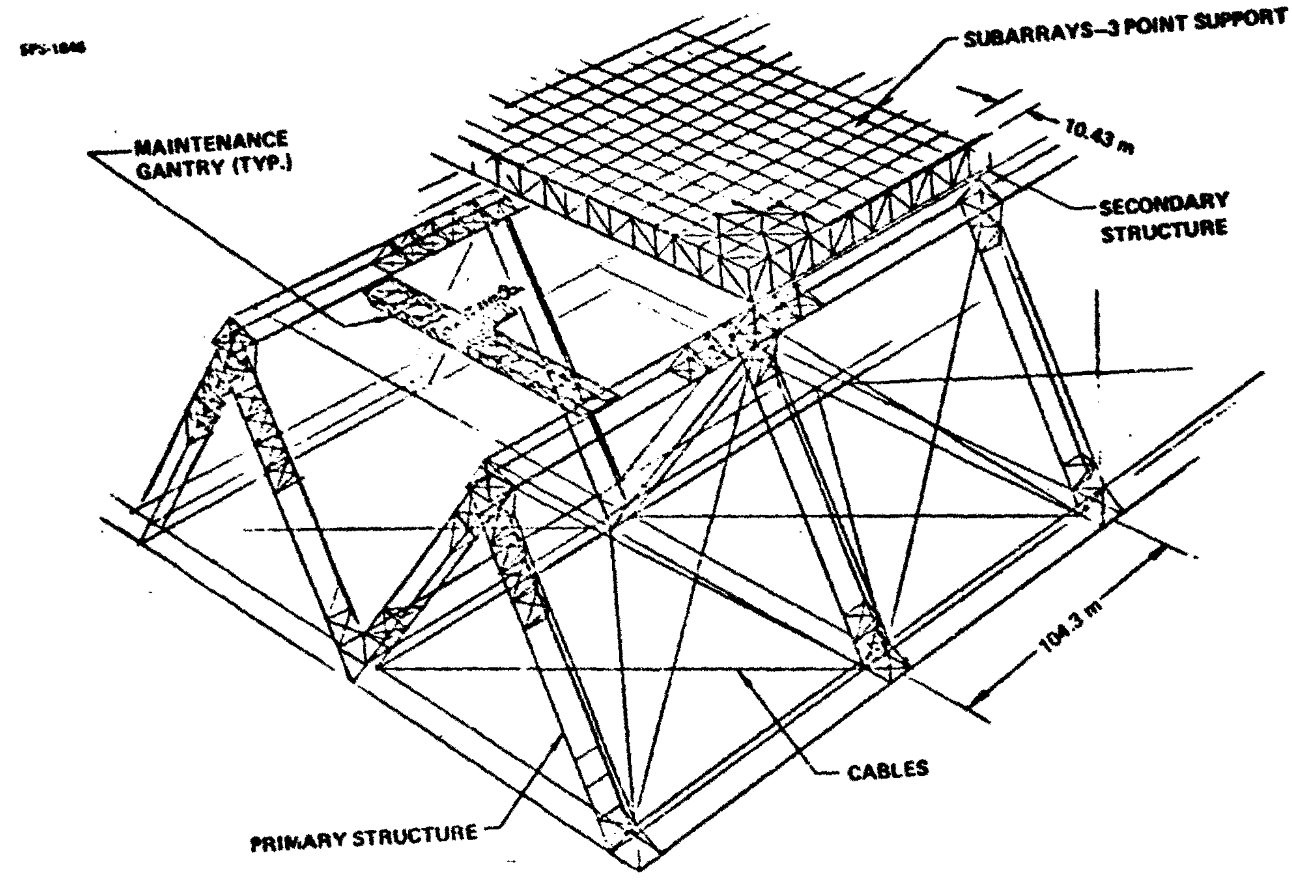

Figure 1.1.2-3 Reference MPTS Struture Interfaces

Mass

The mass of the Primary Structure is 52,500 kilograms.

Cost

The cost of the Primary Structure was estimated at $125 per kilogram.

WBS 1.1.2.1.2 Secondary Structure

WBS Dictionary

The Secondary Structure provides structural bridging over the Primary Structure with a sufficiently small repeating structure element interval to allow installation of the transmitter subarrays. The Secondary Structure does not include subarray structure.

Description

The Secondary Structure is a deployable cubic truss, with telescoping vertical members to minimize packaging volume. The members are made from graphite composite materials and the joints all include a rigidizing mechanism of device to provide complete rigidity of the structure after deployment. Diagonal cross--members are removable as necessary to allow for maintenance of the subarrays by the maintenance system.

Mass

The Secondary Structure mass estimate was 197,500 kilograms.

Cost

The cost estimate for the Secondary Structure was estimated as $129/kilogram.

WBS 1.1.2.2 Transmitter Subarrays

WBS Dictionary

This element includes all hardware required for the generation, distribution, phase control, and radiation of the microwave energy including thermal control.

Element Description

The retrodirective phase array configuration utilizes 7220-10.4 x 10.4 meter subarrays arranged in a quantized 10 db taper configuration conforming to dimensional requirements which will result in a maximum RSS error associated loss of 2%. The concepts of configuration for fine beam steering have been adequately defined to the block diagram stage but require further design refinement and laboratory verification. The array features a standing wave slotted waveguide approach with a maximum effective stick length of 5.2 meters and maximum power level of 3.5 kw per stick. A test program for a plated composite waveguide has been suggested to verify the potential advantages of this light-weight approach currently in modest use on some communication satellites.

A modular concept integrates klyston power tubes with subarray radiators. One quarter of the transmitting array is shown in Figure 1.1.2-4. The square subarrays, complete with associated klystrons tile the face of the antenna which is in turn supported by the secondary structure. A taper of the microwave power density across the antenna aperture is achieved by varying the number of klystrons used per subarray. A section of a subarray called the integrated klystron module is shown in Figure 1.1.2-5. It shows the 70 kw klystron mounted on the back of the slotted waveguide antenna array. The passive cooling system can be seen. Also illustrated here is the phase control system installation on the subarray, required to insure that the radiation from the modules will be in phase at the rectenna. This system will tie the modules within a subarray together with waveguide and all the subarrays together with coaxial cable or an equivalent transmission link.

Element Mass

Detailed mass estimates for this element are given in Table 6-9 of Vol. IV of the Final Report for Contract NAS9-15196. A mass summary was included in the mass table on page 13.

Element Cost

Cost estimates for this element are given in the summary table (1.1.5-1) as $1.43 billion per antenna for structure, waveguide, klystrons, thermal control, and control circuits (mature industry estimate at 1 SPS per year).

WBS 1.1.2.2.1 DC/RF Converter Module

WBS Dictionary

This element includes all the hardware and control circuits for the klystron rf transmitters, namely the cathode subassembly, the rf circuit (body), the collector, the output waveguide and window (if required) and the solenoid for beam focusing. External monitor circuits, both dc and rf are also included.

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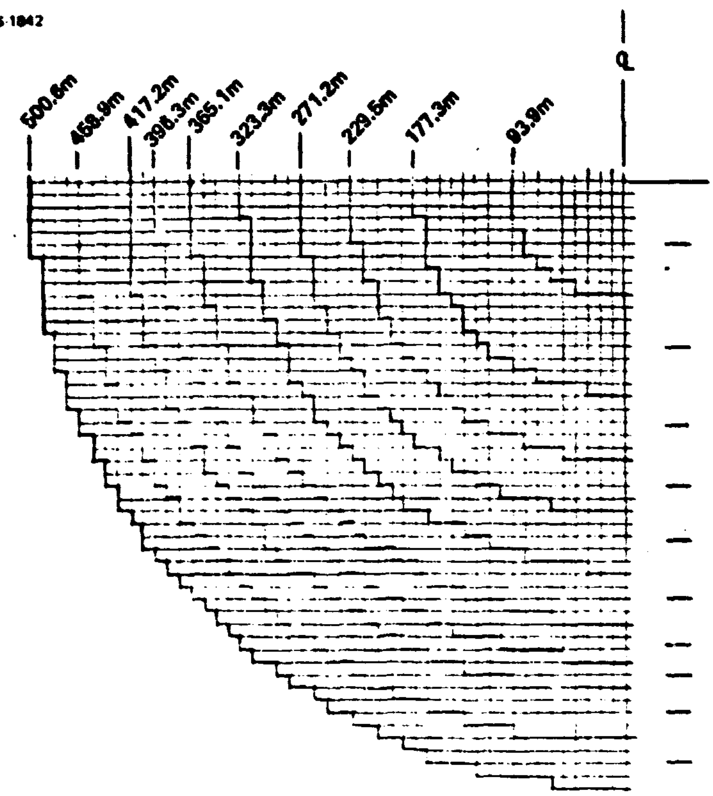

STEP	NUMBER SUBARRAYS	NUMBER KLYSTRONS/ SUBARRAYS	NUMBER KLYSTRONS
1	276	36	9,936
2	632	30	18,960
3	644	24	15,456
4	628	20	12,560
5	784	16	12,544
6	900	12	10,800
7	664	9	5,976
8	612	8	4,896
9	1,052	6	6,312
10	1,028	4	4,112
Totals	7,220		101,552

Figure 1.1.2-4 Transmitting Array

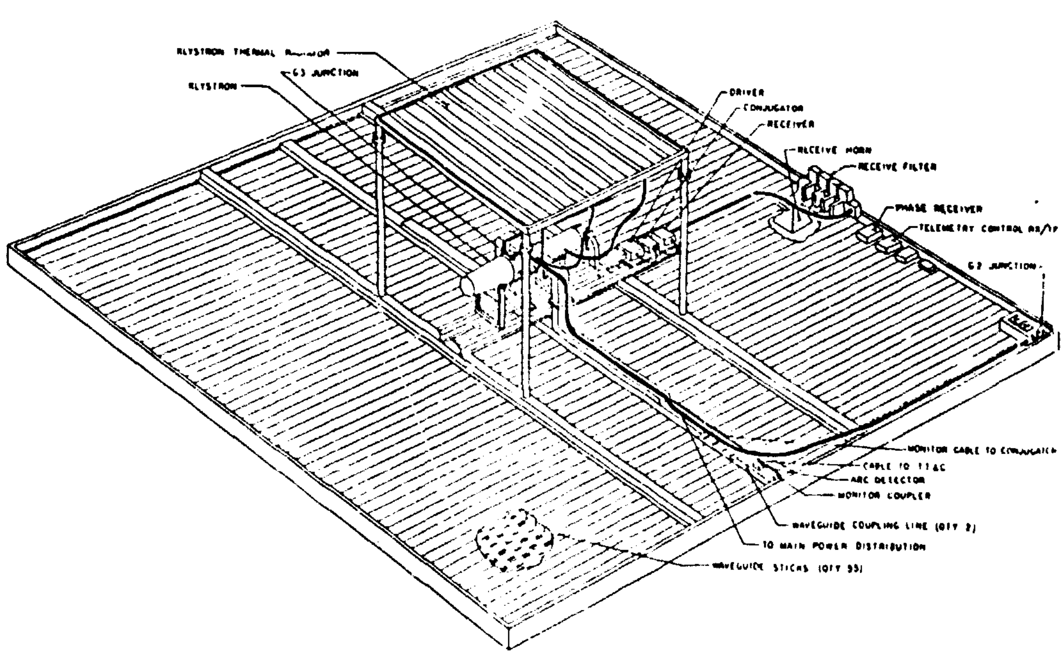

Figure 1.1.2-5 Integrated Klystron Module

Element Description

An rf transmitter and configuration of 101,552- 70 kw CW klystron amplifiers operating 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 amps/cm^2 cathode loading) to achieve long life has been chosen. This 5 stage depressed collector design provides a complementary design to the amplitron alternative. Proposed multiple tube development programs and assessment of high voltage operation in space will provide the final answer to the transmitter selection. The layout of the basic klystron building block module is shown in Figure 1.1.2-6 with the various elements shown. The 6 cavity design, with a second harmonic bunching cavity for short length and high efficiency, features a dual output waveguide with 35 kw in each arm. The thermal control system used to cool the output gap, the depressed collector and the solenoid (with a design temperature of 300^{o}C maximum on the body and 500^{o}C on the collector is described below. An MTBF improvement of 3 to 10 from the present value for several hundred spaceborne tubes of 2 years, and best tubes of small groundbased radar systems of 10 years will have to be realized through conservative design and proper burn-in procedures. The driver for the final klystron power amplifier will require an output of about 3 watts cw for a 45 db output amplifier saturated gain. This power level is available in several off-the-shelf reliable low power low noise TWT amplifiers which can be driven directly from phase regeneration circuitry at power levels well below a milliwatt. The driver tube could be either an off-the-shelf low-noise high-gain TWT or a multi-stage transistor amplifer with up to 10 db gain per stage at this frequency. All phase configuration functions will be performed at low drive levels.

Element Mass

The klystron mass per tube is estimated to be 48 kg, with an additional 13 kg for thermal control.

Element Cost

The mature industry mass production cost per klystron has been estimated between $1900 and $2500 per klystron depending on production rate (1977 dollars).

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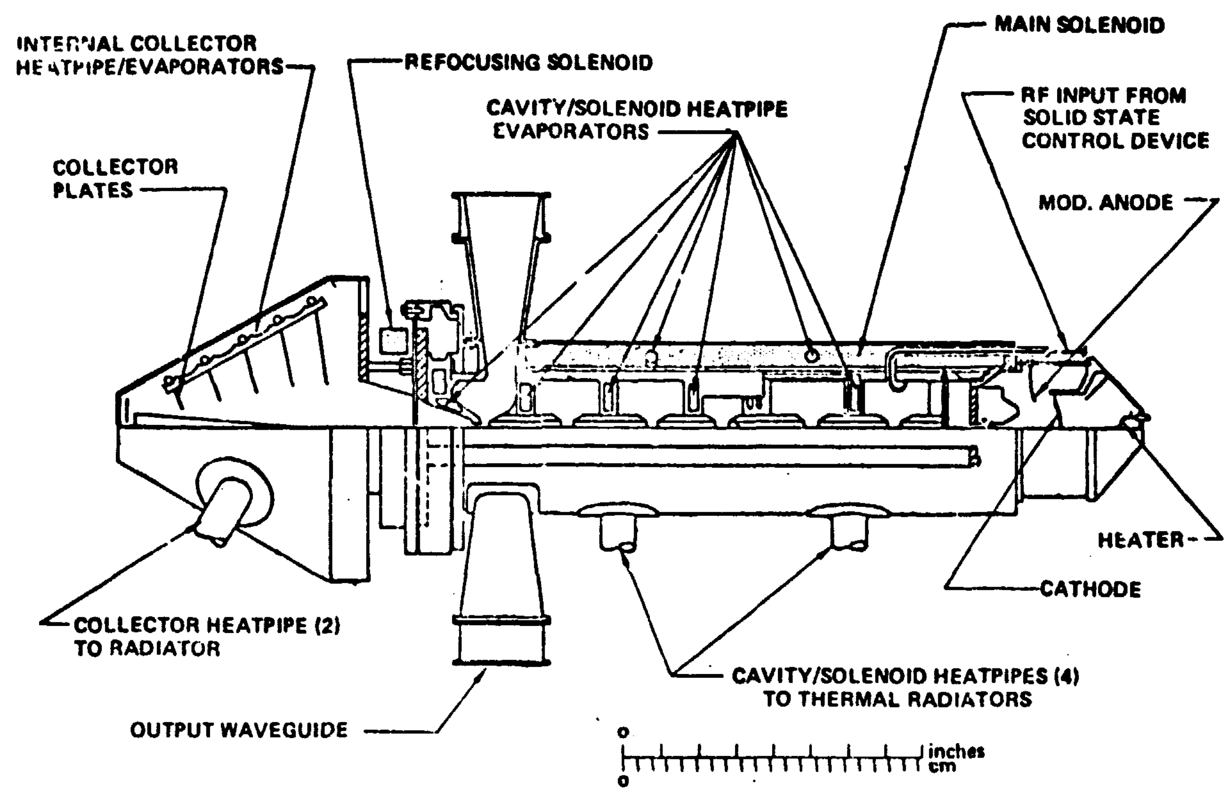


Figure 1.1.2-6 70 Kw Klystron

WBS 1.1.2.2.2,3 & 7 Structure and Waveguide

WBS Dictionary

This element includes all production hardware required for the radiating waveguide, distribution waveguide, subarray support structure and attachment provisions for subarray components. These WBS items are grouped together because this is an integrated assembly.

Element Description

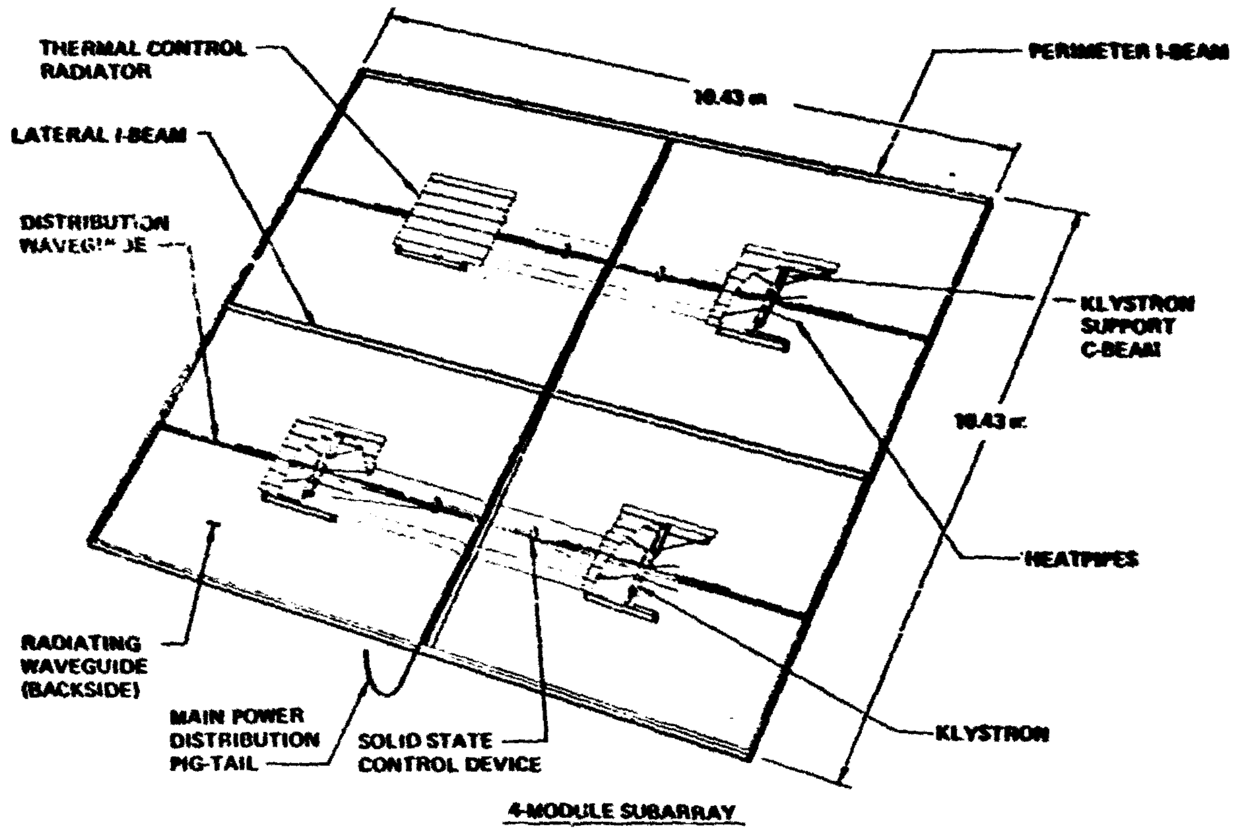
A typical, four module, subarray is shown (Figure 1.1.2-7) with all pertinent systems installed. The elements to be discussed in this section are the radiating waveguide, distribution waveguide, subarray support structure, and the klystron support structure.

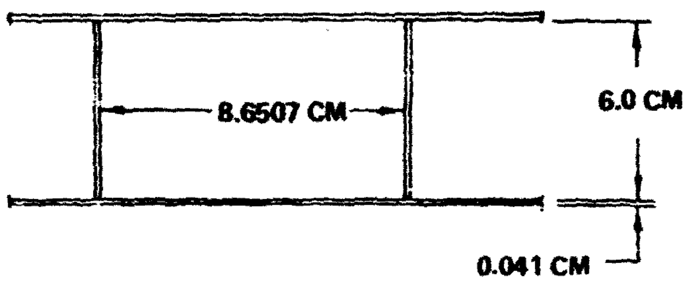
The radiating waveguide, at the subarray level, is composed of 120 waveguide sticks (Figure 1.1.2-7) that are 10.43 meters long. The method of attaining various numbers of module units per subarray is to install internal shorts, conducting elements, within the stick lengths and to distribute rf power with the distribution waveguide sticks to the desired number of waveguide sticks, for a single klystron. In this manner, it was possible to obtain ten types of subarrays, ranging from 36 to 4 klystrons per subarray (Table 1.1.2-1), to achieve the desired power taper. The integral radiating waveguide forms a subarray unit 10.43 meters square, which remains unchanged throughout the array, and is based on realizable mechanical tolerances and acceptable error plateau levels.

The distribution waveguides feed power from the klystron output waveguide to the radiating waveguide. The distribution waveguide sticks are arranged in pairs, each one supplying half of the rf power to a given klystron module. There is also an attachment point, at half of the distribution stick length, to connect/disconnect the klystron output waveguide.

The subarray support structure is composed of perimeter beams, lateral and longitudinal I-beams. These beams have a web of 12.0 cm and flanges of up to 6.0 cm and are bonded directly to the back of the radiating waveguide. The lateral and longitudinal I-beams form a matrix with a klystron module being framed within each box.

Attachment provisions are made on the subarray structure for the klystron support structure, power distribution harnesses, module power connectors, solid state control devices, and subarray support to the secondary structure. The klystron is supported, within the





STRUCTURAL MAT'L: $G_R E_P$ -8PLY

CONDUCTING MAT'L: ALUMINUM ($T = 6.67\ \mu M$)

Figure 1.1.2-7 Reference MPTS—Integrated Subarray

Table 1.1.2-1. Subarray Module Dimensions

SUBARRAY TYPE	NO. MODULES SUBARRAY	ARRANGEMENT OF MODULES (W x L)	MODULE DIMENSION W (m) x L (m)
1	36	6 x 6	1.738 x 1.738
2	30	6 x 5	1.738 x 2.086
3	24	6 x 4	1.738 x 2.608
4	20	5 x 4	2.086 x 2.608
5	16	4 x 4	2.608 x 2.608
6	12	5 x 4	2.608 x 3.477
7	9	3 x 3	3.477 x 3.477
8	8	4 x 2	2.608 x 5.215
9	6	3 x 2	3.477 x 5.215
10	4	2 x 2	5.215 x 5.215

module, by a C-beam/saddle fixture that has a support block on each end for load transmittal into the radiating waveguide. Further support of the klystron is provided through the klystron output waveguide/distribution waveguide connection.
The power distribution harnesses are supported by the subarray support structure beams with tiedown bands at half module lengths. At the point of departure of the cables from the harness to the module a connector support attachment is provided for the module power connector.

Provisions must also be made on the perimeter beams, at three points, to attach the subarray to the secondary structure. This attachment will allow the adjusting mechanism, located on the secondary structure attachment points, to attach to the subarray structure to facilitate relative movement between the subarray and the MPTS structure.

Element Mass
The element masses for the element in this section were shown in the comprehensive mass Table. The structural mass includes attachment and support provisions for the subarray.

Element Cost
The cost estimating factor used for the elements in this section, was 66$/kg. This factor covers both waveguides and structure at the subarray level using a mature industry approach.

WBS 1.1.2.2.4 Thermal Control

WBS Dictionary
This element includes all production hardware required to remove and dissipate waste heat from the klystron modules at the subarray level. Subelements include the klystron thermal control, solid state control device thermal control, and thermal insulation within the subarray.

Element Description
The two major waste heat sources, at the subarray level, are the collector and cavity/-solenoid sections of the klystron. A small amount of waste heat must be dissipated from the solid state control devices. Tables 1.1.2-2 and 1.1.2-3 list the waste heat sources and thermal limitation assumption for subarray components.

Two options have been identified for the klystron thermal control system. The first option is the heat pipe approach developed under Contract NAS9-15196. The second

Table 1.1.2-2 Waste Heat Sources

SPS-1553

SOURCE	LEVEL	QUALITY
A. KLYSTRON:		
1) COLLECTOR	8.0 KW/UNIT	500°C
2) CAVITY LOSSES	3.8 KW/UNIT	300°C
3) SOLENOID	1.4 KW/UNIT	300°C
B. SOLID STATE CONTROL DEVICES	10 W/UNIT	0-70°C
C. RADIATING AND FEED WAVEGUIDE	1.0 TO 9.1 KW/SUBARRAY	0-125°C

Table 1.1.2-3 Thermal Limitation Assumptions

KLYSTRON:	COLLECTOR	500°C
	SOLENOID AND CAVITIES	300°C
	SOLID STATE CONTROL CKTS	70°C
STRUCTURES:	COMPOSITE MATERIALS	
	1. GRAPHITE–EPOXY	175°C
	2. GRAPHITE–POLYMIDE	260°C

is an active (circulating) system largely defined by the Vought Corporation on their IR&D, in cooperation with the current contracted effort. The principal motivation for the active system is the elimination of liquid metals (mercury) necessary for heat pipe operations at 500°C. Both systems are described below.

Option A: Heat Pipe

Heat pipes and radiators were designed to dissipate klystron waste heat losses. The heat pipe evaporators, an integral part of the klystron, pick up the waste heat for transfer to the thermal radiators (Figure 1.1.2-8). The thermal radiator has six sections, two sections for the collector and four for the cavities and solenoid. A cross-brace is used to retain the radiators along two edges. The collector section operates at 500°C and the cavity/solenoid section at 300°C. A better description of the heat pipe/radiators is given in Table 1.1.2-4.

Even though the thermal control system removes the heat released by the klystron, a high temperature still existed at module components such as solid state control, power distribution buses, and composite materials in the structure and waveguides. A lower temperature environment for these components was provided simply by isolating the high temperature sections of the klystron and the back side of its thermal radiator with thermal insulation (Table 1.1.2-5). The small amount of waste heat from the solid state control device is dissipated by its own radiator/heat sink.

Failure analyses conducted during the current contract indicated a problem with the heat-piped-cooled klystron. The difficulty is that the 500°C segment would utilize a mercury vapor heat pipe. In the event of a meteoroid puncture or other leak, the liquid metal would be released into the high voltage environment of the transmitter system and lead to arcing and damage. Plating of liquid metals on insulators might lead to a permanent damage situation that would require repair and replacement. Vought Corporation examined a circulating fluid cooling option and found that a mass reduction was possible and that fluids could be selected that would minimize risk of arcing. Their analysis indicates that a circulating fluid system can be made as reliable as the heat pipe system and cetainly more reliable than the expected lifetime of the klystron themselves. Figure 1.1.2-9 and Table 1.1.2-6 show principal features of the circulating fluid system option for the klystron cooling circuit.

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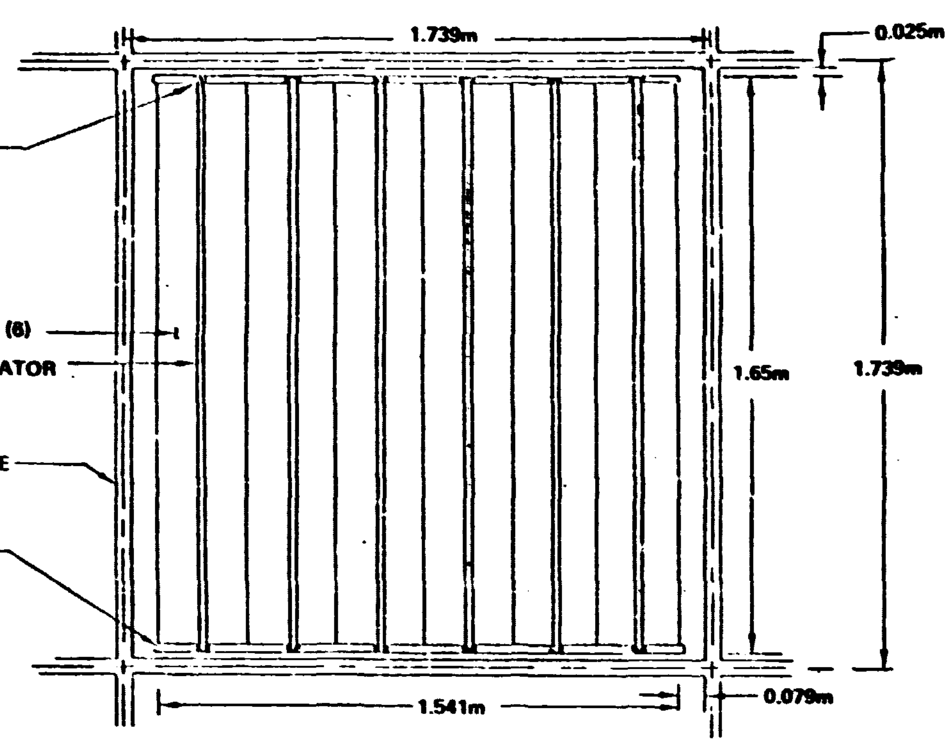

Figure 1.1.2-8 Top View of Klystron Module Thermal Radiator

Table 1.1.2-4 Klystron Thermal Control

CAVITY AND SOLENOID SECTION:	300°C HEAT PIPE TYPE–1.339 KG/M WORKING FLUID–HG 4 HEAT PIPES @ 1.30 KW EACH RADIATOR – ALUMINUM – THICKNESS = .081 CM – AREA = 0.432 M² EACH MASS (EACH) = 3.18 KG
COLLECTOR SECTION:	500°C HEAT PIPE TYPE – 1.339 KG/M WORKING FLUID – HG 2 HEAT PIPES @ 4.0 KW EACH RADIATOR – COPPER THICKNESS = 0.086 CM AREA = 0.406 M² EACH MASS (EACH) = 2.08 KG

MASS/KLYSTRON = 13.9 KG

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Table 1.1.2-5 Thermal Insulation

COMPONENTS:		TYPE:
500°C		
COLLECTOR SECTION (RADIATOR & KLYSTRON)	–	9 LAYER MULTIFOIL (ZrO SPACER) 6 LAYER KAPTON (SILK NET SPACER)
300°C		
CAVITY & SOLENOID (RADIATOR & KLYSTRON)	–	15 LAYER KAPTON (SILK NET SPACER)
WAVEGUIDES	–	10 LAYER KAPTON (SILK NET SPACER)

MASS/MODULE = 2.80 KG

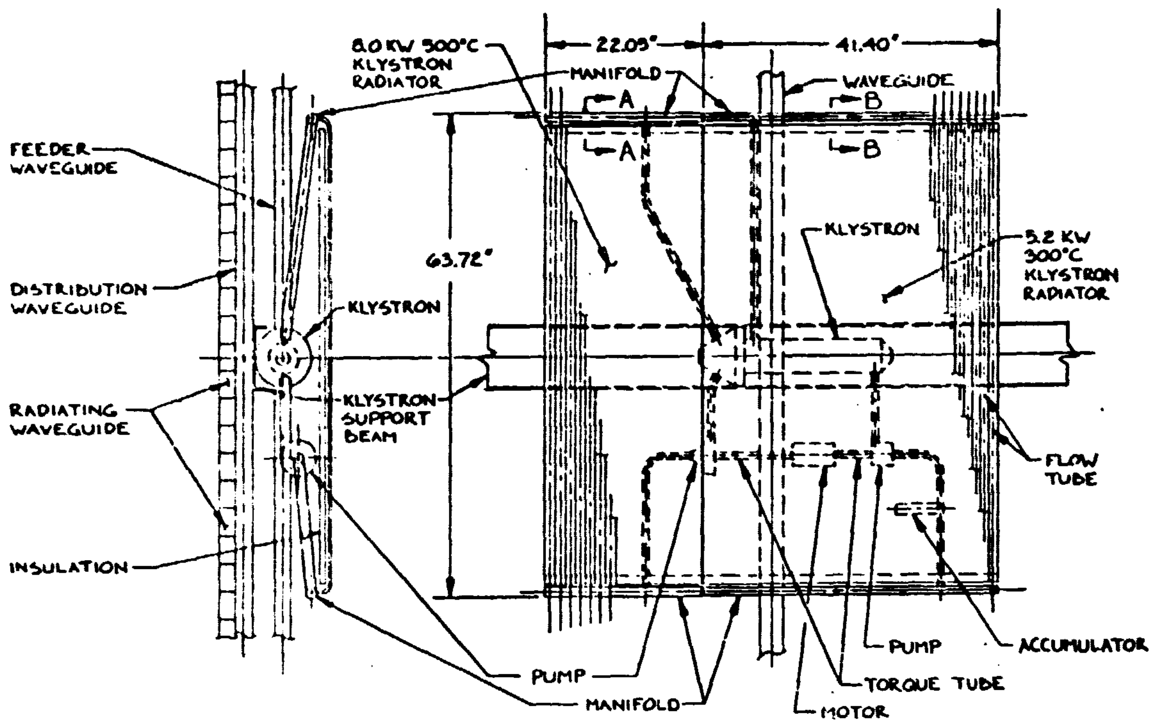

Figure 1.1.2-9 Klystron Pumped Fluid Thermal Control System

Table 1.1.2-6 Klystron Module Thermal Control System Characteristics

	500°C	300°C
MATERIAL	COPPER	COPPER
FLUID	AIR @ 60 ATM	DOWTHERM–A
INLET TEMP	477°C	277°C
OUTLET TEMP	413°C	260°C
LENGTH X WIDTH	0.57m x 1.61m	1.04m x 1.61m
TUBE SPACING	3.7 cm	2.84 cm
TUBE DIAMETER	5.6 mm	1.27 mm
TUBE THICKNESS	0.886 mm	0.71 mm
FIN THICKNESS	0.163 mm	0.066 mm
EMISSIVITY	0.8	0.8
ABSORTIVITY	0.3	0.3
TSINK	36.3°C	36.6°C
PUMP EFFY.	0.3	0.3
FIN EFFECTIVENESS	0.894	0.920
AREA	0.91 m²	1.67 m²
MASS/MODULE	7.95 kg	5.13 kg
CURRENT MASS/MODULE – 13.18 kg PART III MASS/MODULE – 18.88 kg		

Element Mass

The major thermal control system element masses are included in the comprehensive mass table. The total thermal control mass per subarray varies between 575 kg and 64 kg, depending on the subarray power density. The total mass of subarray thermal control systems is 1612.6 MT.

Element Cost

The cost of thermal control elements was estimated as $1410 each.

WBS 1.1.2.2.5 Wiring Harnesses

WBS Dictionary

This element includes all production hardware to provide power distribution at the subarray level. The subelements in this category include the pigtail connector for the subarray, busing between this connector and the klystron module connector, and the klystron module connector.

Element Description

The conductors on the individual MPTS antenna subarrays are insulated circular aluminum conductors. The thermal environment for the conductors is relatively benign since the klystron radiator system is designed to radiate away from the waveguide surface. Each subarray conductor is routed from the interface connection at the subarray drop to the klystron. For reliability reasons no conductor taps are made on the subarray to provide for multiple klystron feeds from a single conductor. Connectors are provided at the interface connection, of the secondary structure and subarray and also at the interface of the harness and the klystron module. This provides the capability to physically connect/disconnect either the module or subarray for maintenance options.

Figure 1.1.2-10 presents the conductor summary for the four klystron subarray. Also shown in this figure are per unit length tabulations of conductor mass and I^2R losses. All subarray conductor calculations for subarray distribution mass and losses were computed using these per unit length values. Figures 1.1.2-11 through 1.1.2-15 present the results for the other antenna subarray types. Total antenna subarray conductor mass and losses were computed by multiplying these quantities by the number of each subarray types.

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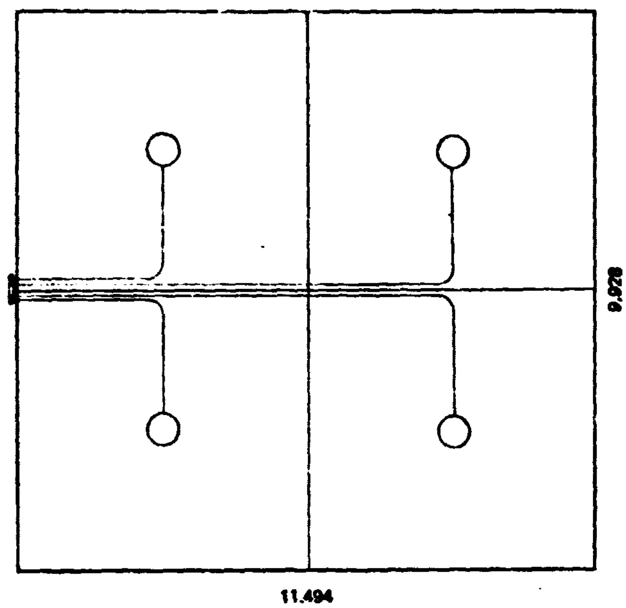


4 KLYSTRONS 2X2

VOLTAGE	CURRENT/TUBE	TOTAL CURRENT
21,050		
42,100	0.088	0.352
21,050	0.044	0.176
25,160	0.088	0.352
29,470	0.154	0.616
37,890	0.330	1.320
40,000	1.452	5.808
10 V	5.000	20.000
130V (2 EA)	10.000	40.000
COMMON	7.156	28.624

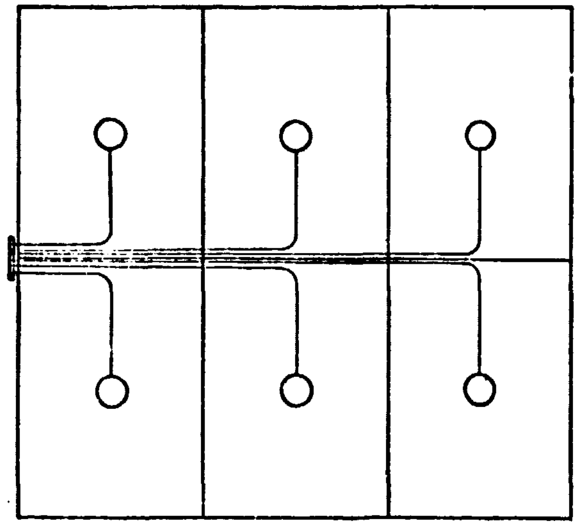
$L_T = 32.916$

$W_W = 1.38$ KG. $I^2R = 241.08$

WIRE		NO. REQ'D	WIRE SIZE AWG.	INSUL THICK (MIL)	WT/M KG.	I^2R/M WATTS
VOLTAGE (REF TO BODY ANODE)	CURRENT					
21,050		1	30	8.6	.0009	
	0.088	1	30	8.6	.0009	0.004
21,050	0.044	1	30	8.6	.0009	0.001
16,940	0.088	1	30	6.8	.0007	0.004
12,630	0.154	1	28	5.2	.0007	0.008
4,210	0.330	1	27	2	.0004	0.030
2,100	1.452	1	22	1	.0010	0.184
42,100	5.000	1	18	16.8	.0068	0.861
42,100	7.156	1	16	16.8	.0090	1.107
42,100	10.000	2	15	16.8	.0103	1.709

Σ = 0.0419 5.617

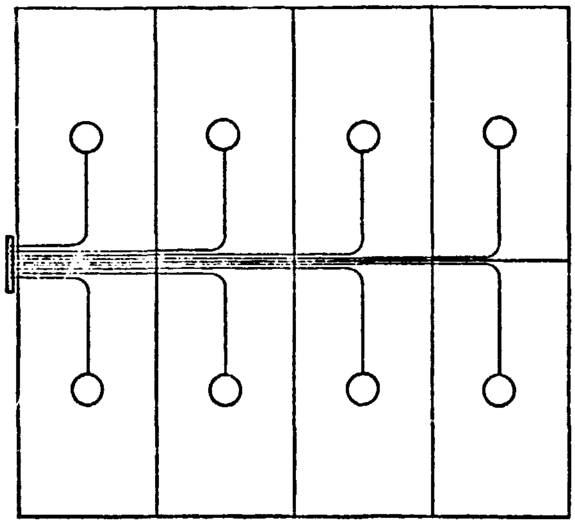
Figure 1.1.2-10 Four Klystron Subarray Conductor Summary



VOLTAGE	TOTAL CURRENT
21,050	—
42,100	0.528
21,050	0.264
25,160	0.528
29,470	0.924
37,890	1.980
40,000	8.712
10	30.000
100	60.000
COMMON	42.936

L_T = 49.374 M
W_W = 2.49 Kg
I^2R = 333.50

6 KLYSTRONS 2X3

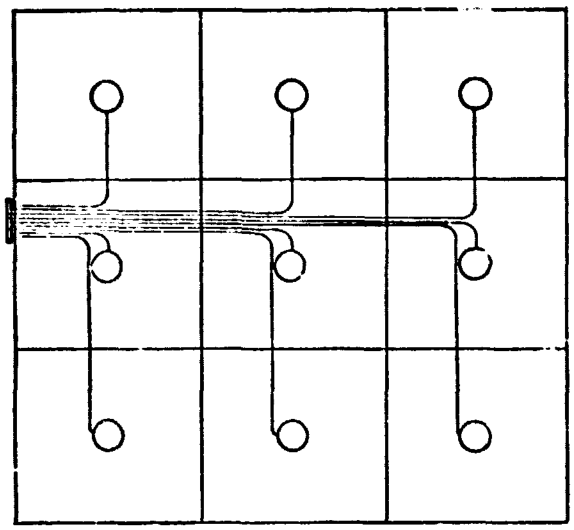


VOLTAGE	TOTAL CURRENT
21,050	—
42,100	0.724
21,050	0.352
25,160	0.724
29,470	1.232
37,890	2.640
40,000	11,616
10	40.000
100	80,000
COMMON	57.248

L_T = 65.832
W_W = 3.18 Kg
I^2R = 369.78

8 KLYSTRONS 2X4

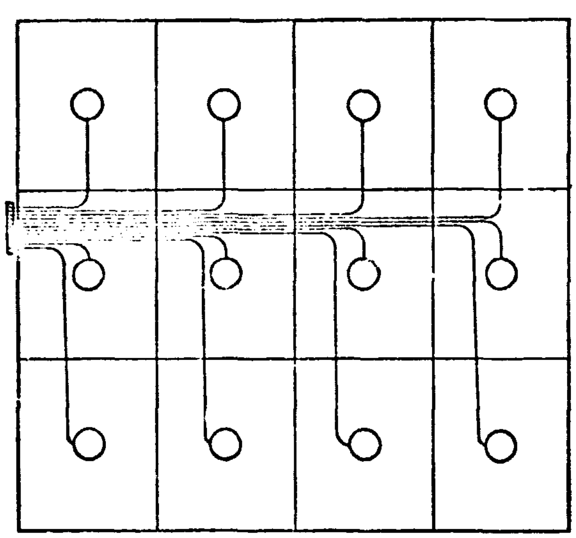
Figure 1.1.2-11 Six and Eight Klystron Subarray Conductor Summary



VOLTAGE	TOTAL CURRENT
21,050	—
42,100	0.792
21,050	0.396
25,160	0.792
29,470	1.386
37,890	2.970
40,000	13.068
10	45.000
100	90.000
COMMON	64.404

$L_T = 71.579$
$W_W = 3.42$ Kg
$I^2R = 458.23$

9 KLYSTRONS 3X3

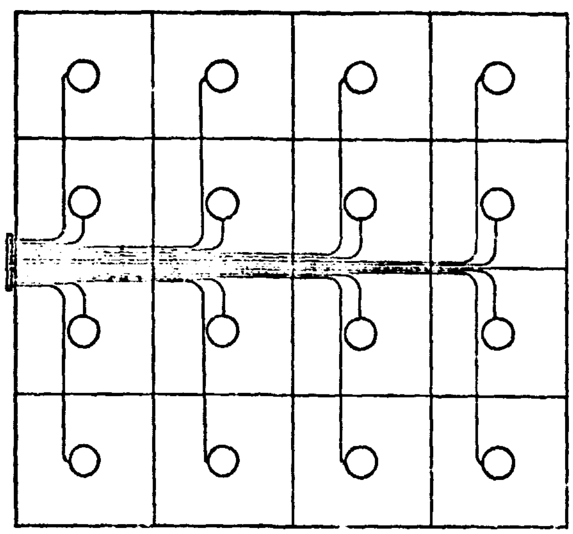


VOLTAGE	TOTAL CURRENT
21,050	—
42,100	1.056
21,050	0.528
25,160	1.056
29,470	1.848
37,890	3.960
40,000	17.424
10	60.000
100	120.000
COMMON	85.872

$L_T = 95.439$ M
$W_W = 4.42$ Kg
$I^2R = 592.25$

12 KLYSTRONS 3X4

Figure 1.1.2-12 Nine and Twelve Klystron Subarray Conductor Summary



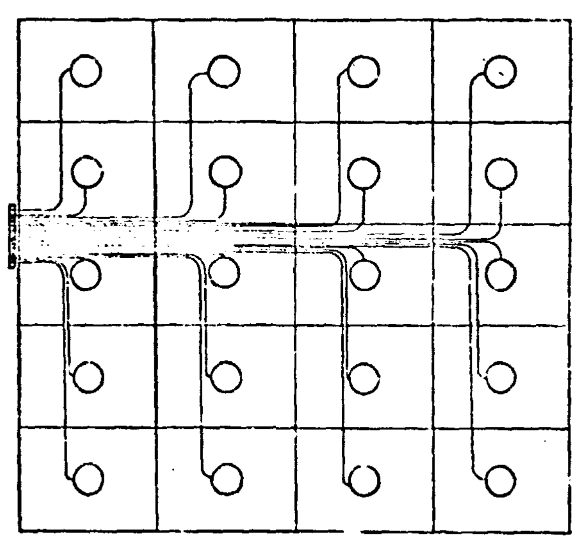
VOLTAGE	TOTAL CURRENT
21,050	—
42,100	1.408
21,050	0.704
25,160	1.408
29,470	2.464
37,890	5.280
40,000	23.232
10	80.000
100	160.000
COMMON	114.496

L_T = 131.664

W_W = 5.94 Kg

I^2R = 795.73

16 KLYSTRONS 4X4



VOLTAGE	TO[illegible] [illegible]URRE[illegible]
21,050	-
42,100	1.7[illegible]
21,050	0.880
25,160	1.760
29,470	3.090
37,890	6.600
40,000	29.040
10	100.000
100	200.000
COMMON	143.120

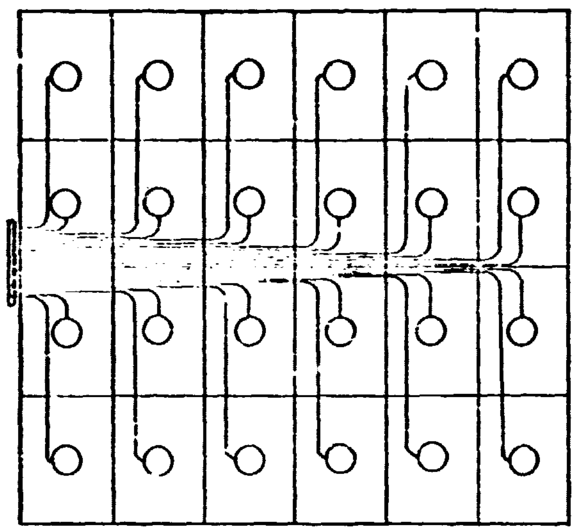
L_T = 166.566 M

W_W = 7.40 Kg

I^2R = 991.77

20 KLYSTRONS 5X4

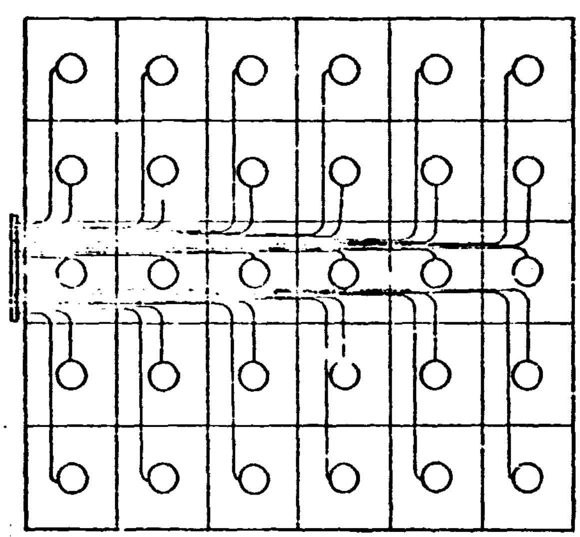
Figure 1.1.2-13 Sixteen and Twenty Klystron Subarray Conductor Summary



VOLTAGE	TOTAL CURRENT
21,050	—
42,100	2.112
21,050	1.056
25,160	2.112
29,470	3.696
37,890	7.920
40,000	34.848
10	120.000
100	240.000
COMMON	171.744

L_T = 197.496
W_W = 8.69 Kg
I^2R = 1,165.51

24 KLYSTRONS 4X6

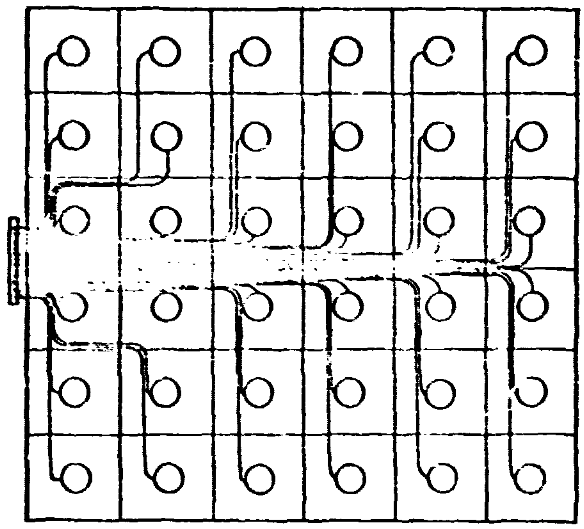


VOLTAGE	TOTAL CURRENT
21,050	—
42,100	2.640
41,050	1.320
25,160	2.640
29,470	4.620
37,890	9.900
40,000	43.560
10	150.000
100	300.000
COMMON	214.680

L_T = 231.677 M
W_W = 10.13 Kg
I^2R = 1,357.50

30 KLYSTRONS 5X6

Figure 1.1.2-14 Twenty-four and Thirty Klystron Subarray Conductor Summary



VOLTAGE	TOTAL CURRENT
21,050	—
42,100	3.168
21,060	1.584
25,160	3.168
29,470	6.544
37,890	11.880
40,000	52.272
10	180.000
100	360.000
COMMON	257.616

L_T = 296.244 M

W_W = 12.83 Kg

I^2R = 1,720.17

36 KLYSTRONS 6X6

Figure 1.1.2-15 Thirty-six Klystron Subarray Conductor Summary

Element Mass

The harness mass for each type of subarray was listed in the tables on Figures 1.1.2-11 through 1.1.2-15. The total mass of harnesses for an MPTS antenna is 35.9 MT.

Element Cost

The cost estimating factor for the harnesses is 45 $/kg.

WBS 1.1.2.2.6 Control Circuits

Much of the phase control equipment is installed on the subarrays. An integrated phase control discussion is provided under WBS 1.1.2.5.

WBS 1.1.2.3 Power Distribution and Conditioning

1.1.2.3.1 DC Power Distribution System

The DC power distribution of the antenna is defined between flexible elevation yoke cable output interface and the local power output associated with a transmitter (klystron) module.

The antenna receives its DC power via a total of 228 main DC power lines, called sector lines. Approximately 35.7 MW of DC power is carried on each of these lines.

Since the antenna RF power distribution is axially symmetrical and tapered along the radius from the center it is logical to divide the antenna into sectors and rings in a somewhat similar fashion then for the reference phase distribution. Figure 1.1.2-16 shows the division of the antenna into 20 sectors. Half of the sector lines reach the antenna via the left and right yoke joint respectively. Eleven sector lines are going toward each of the 20 sectors. The remaining eight sector lines are feeding the outer ring of the antenna, which is divided eight ways, thus on the average 11.4 sector lines are available for each sector.

There are 361 subarrays in each sector. These subarrays are divided into 19 groups for the purpose of the phase distribution network and 19 subarrays are in each group. The group designation is A_1, A_2,...A_{19} as shown on Figure 1.1.2-17 which exhibits a typical sector. The same figure shows the distribution of the incoming sector lines and the out-going subarray lines The division from sector lines to subarray lines is achieved at the J_1 level junction stations. The figure also shows the location of the J_1 stations.

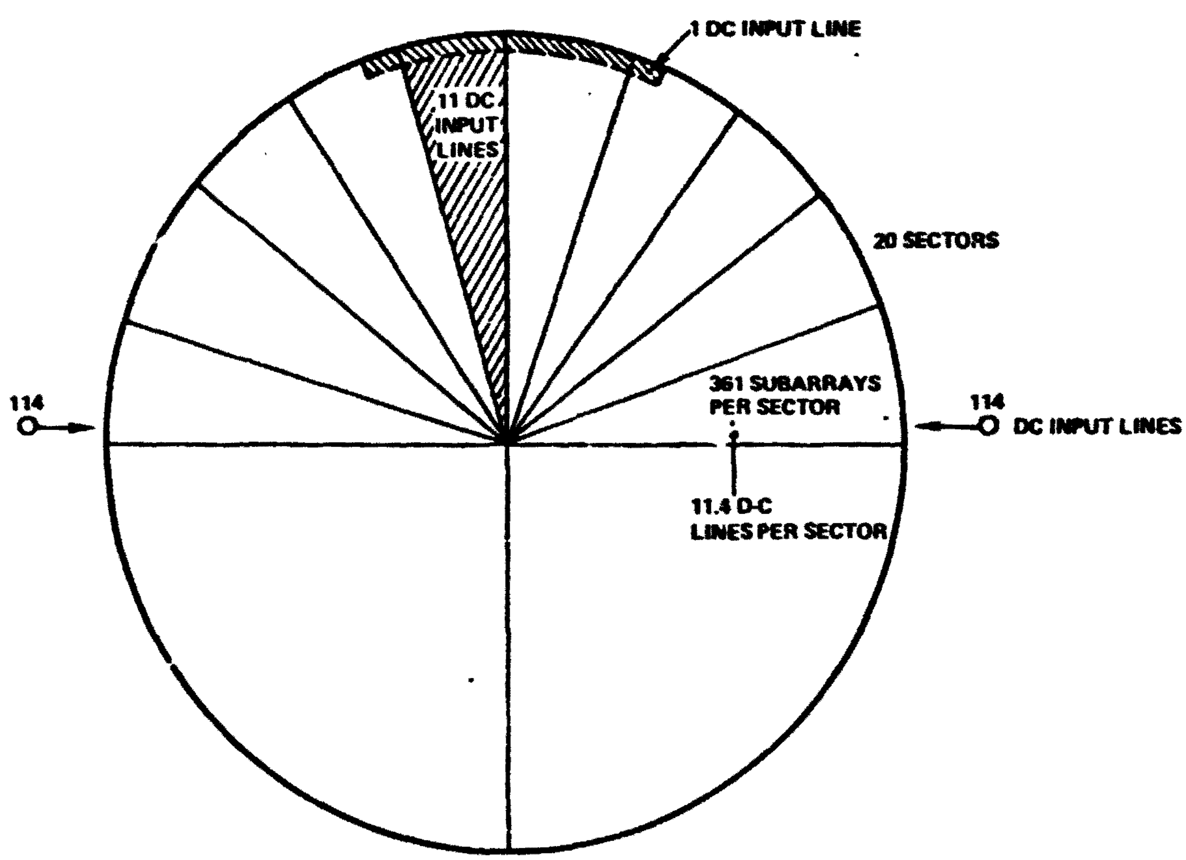


Figure 1.1.2-16 Distribution of DC Sector Lines for the Space Antenna

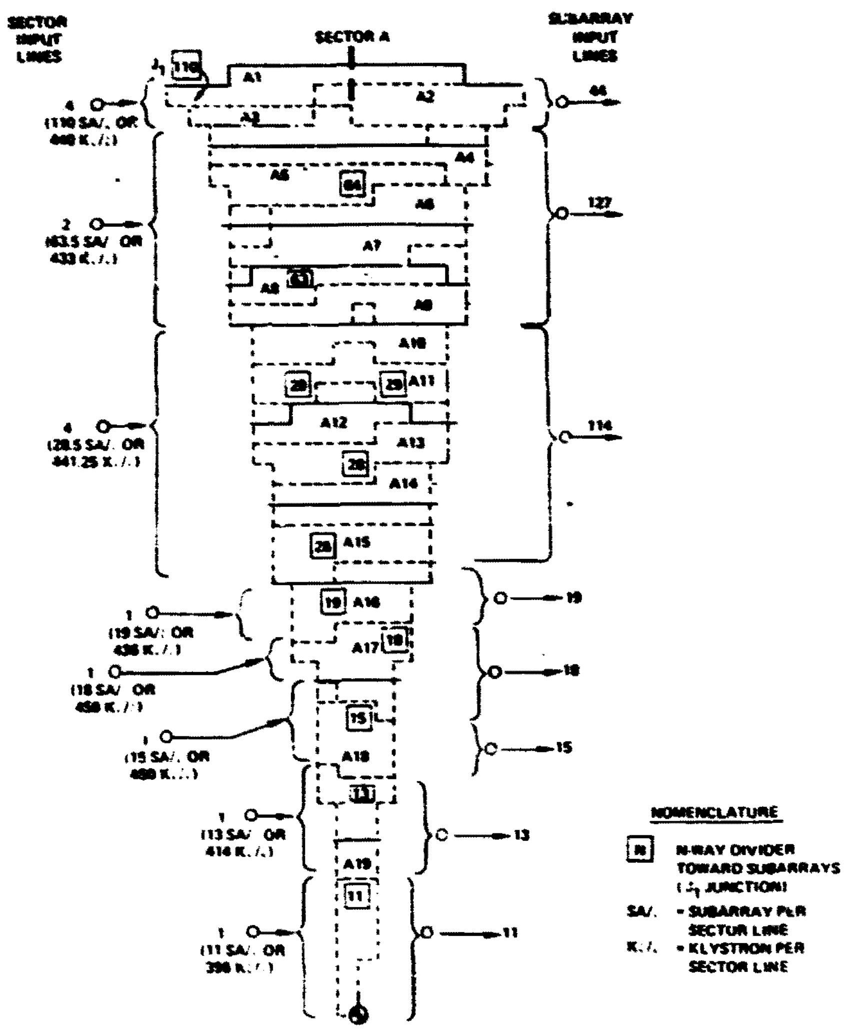


Figure 1.1.2-17 Distribution of DC Sector Lines Within One of the 20 Sectors

The distribution of the J_1 stations is selected in such a way that each sector line is loaded by approximately the same number of Klystrons. Ideally 446 klystron gives the equal loading condition. Actually the number of klystrons vary between 396 to 456 klystrons, representing maximum -11.2% and +2.2% variations from the nominal.

At each J_1 station a switch gear and DC to DC converter is located designed for a nominal 35.7 MW capacity. Part of the power goes through a DC to DC Converter with 5.4 MW input power capacity and 96% efficiency, thus approximately 218 kw thermal power has to be radiated at the converter.

Figure 1.1.2-18 shows the distribution of DC subarray lines from the J_1 junction station for a typical part of the antenna, close to the edge of the aperture. There are two main alternatives available for this part of the network.

One extreme alternative is to use a separate line from the output of J_1 to the terminal points T of each individual klystrons. In this case a failure in any of these lines do not affect the rest of the distribution system. Except for line length differentials, which vary between approximately 4 m and 187.2 m all lines can be made equal if drop off differentials are negligible.

The other extreme alterantive is to use as much as possible common cables. This requires the introduction of additional junction stations J_2 and J_3 as Figure 1.1.2-18 indicates. An open circuit or short circuit in a main line could influence as many as 110 Klystrons for the shown example causing an approximate .108% loss of output power of the antenna. The total amount of required conductor is the same as for the previous case, the insulating material associated with the DC cables is much less while the number of connectors is a larger, which further increases the failure rates.

The first alternative was assumed for the failure mode analysis.

WBS 1.1.2.3.2 and 1.1.2.3.3 Switchgear and DC/DC Converters

The MPTS antenna power distribution system provides power transmission, conditioning, control, and storage for all MPTS elements. The antenna is divided in to 228 power control sectors, each providing power to approximatey 420 klystrons. Two of the klystrons' depressed collectors "A" and "B" which require the majority of supplied power are provided with power directly from the power generation system to avoid the dc/dc

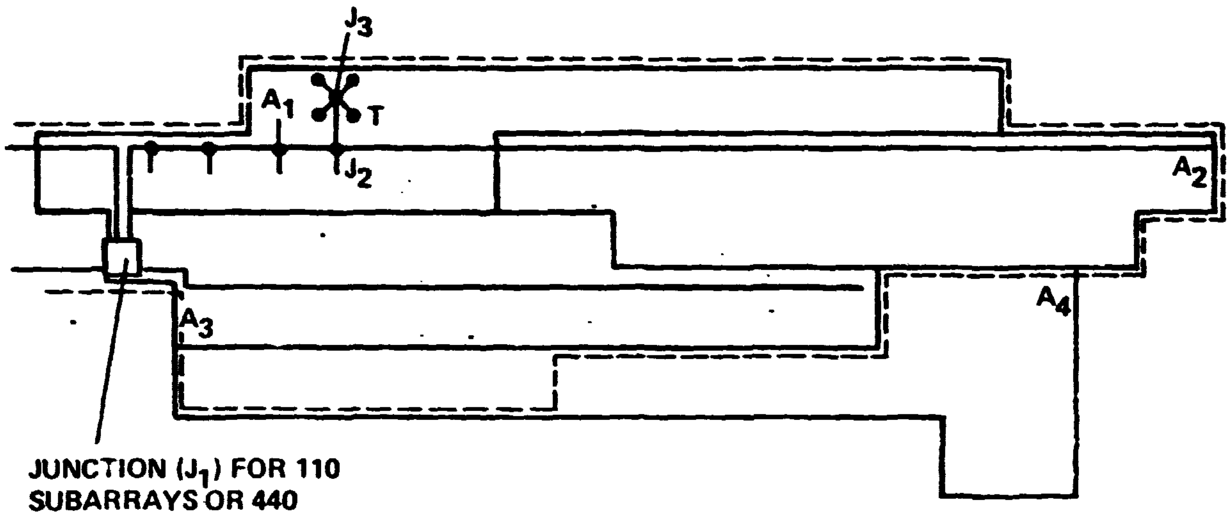


Figure 1.1.2-18 Distribution of DC Subarray (Klystron) Lines Within a Typical (Outer) Part of a Sector

conversion losses. All other klystron element power requirements are provided by conditioned power from the dc/dc converter. System disconnects are provided for isolation of equipment for repair and maintenance. Each dc/dc converter provides power to approximately 0.5% of the total number of antenna klystrons. The dc/dc converter outputs are shown in Figure 1.1.2-19.

The MPTS antenna was divided into approximate equal power areas to define power control sectors. Figure 1.1.2-20 shows the location of the power sector control substation and the associated dc/dc converters. No substations are located on the center structural node, since this node is in the center of the highest waste heat flux region.

The reference antenna structural design concept consists of a relatively sparse primary structure, fairly dense secondary structure and ten different types of antenna subarray elements to achieve a ten step approximation of the desired illumination taper. Within the subarray element, one set of connections provides the interface between the external power distribution system and the subarray distribution system. Power is routed from the power sector substations to the antenna subarray elements. Disconnects are installed at the power sector substations to provide isolation for maintenance and repair. The power sector substation location was selected to be at the back of the primary structure. Aluminum sheet conductors are routed from the rotary joint to the power sector control substation located at the primary structure truss intersection nodes at the back of the structure.

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 which utilize power directly from the SPS Collector A supplies and Collector B solar panel supplies. The power conditioning subsystem block diagram is shown in Figure 1.1.2-21. The estimated input power to each dc/dc converter is about 5400KW.

Figure 1.1.2-22 shows a simplified diagram of the individual dc/dc converter modules employed. The selection of the particular switching circuit device has not yet been made but an analysis has shown that a switching speed of 20 KHz with SCR's or power transistors can yield a dc/dc conversion efficiency of about 95%.

Overall power distribution system mass and losses are summarized in Table 1.1.2-7.

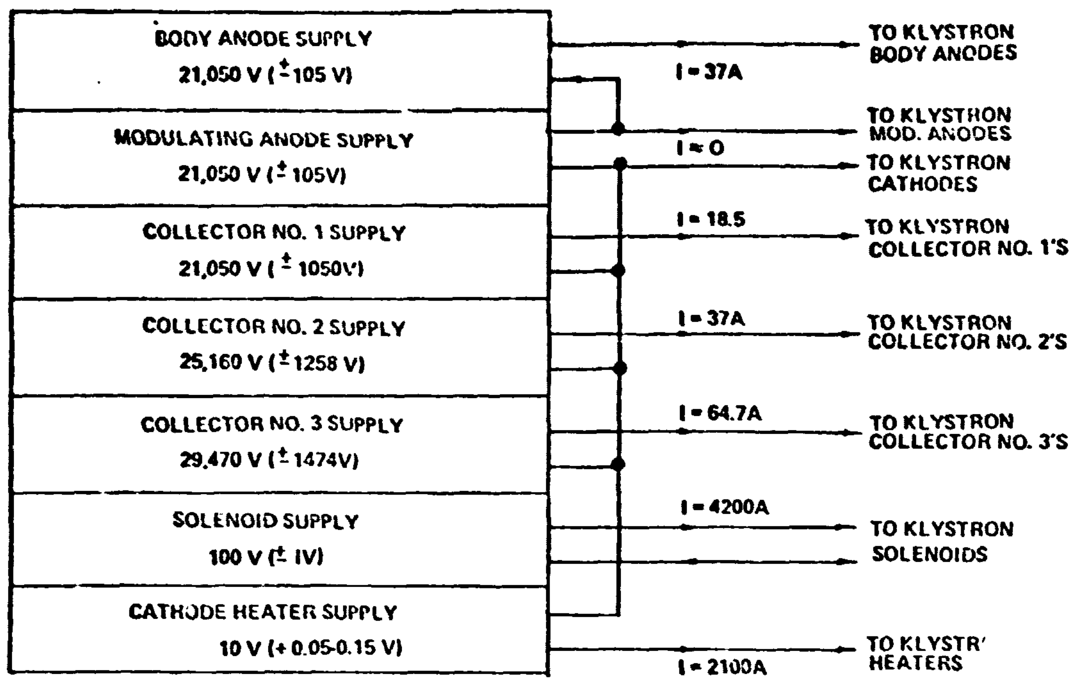


Figure 1.1.2-19. DC/DC Converter for Five Segment Depressed Collector Klystrons for MPTS

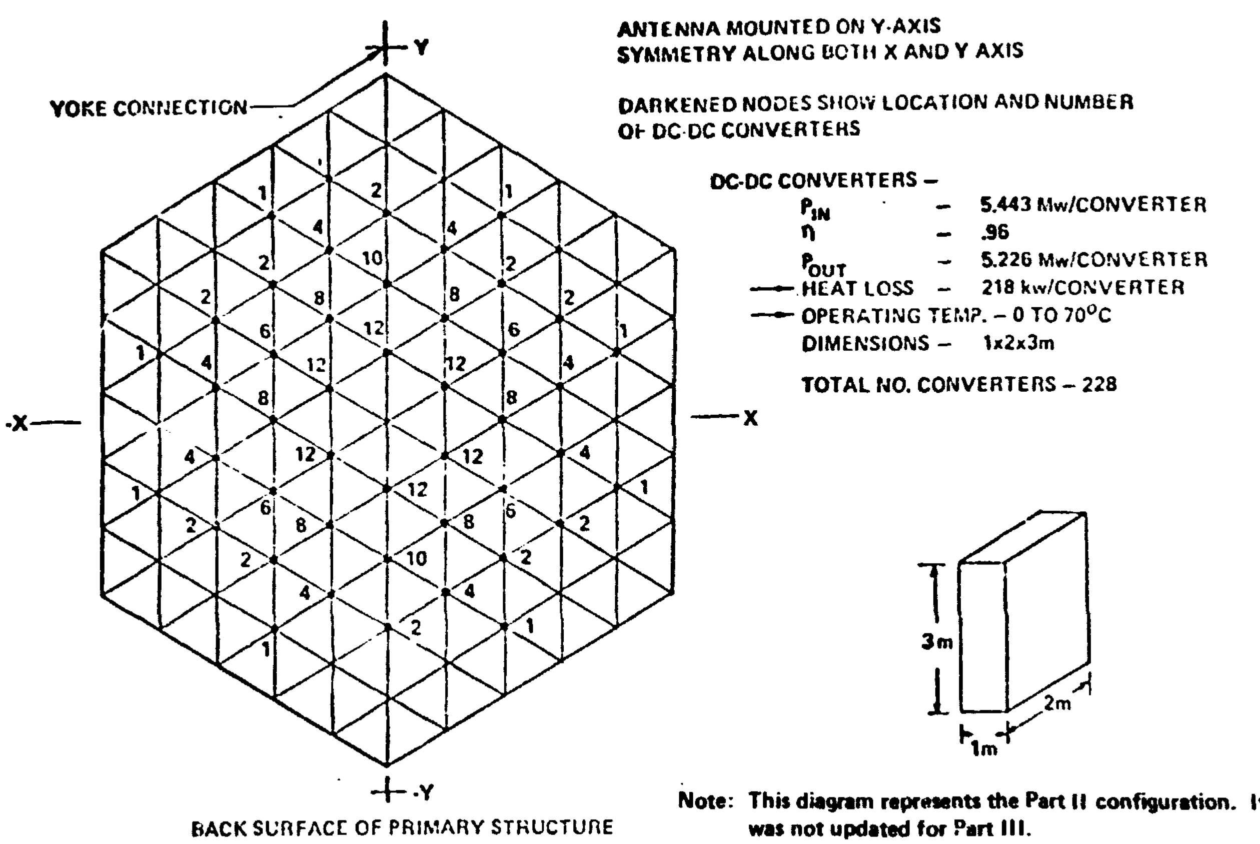


Figure 1.1.2-20. MPTS Reference Antenna Power Conditioning Placement

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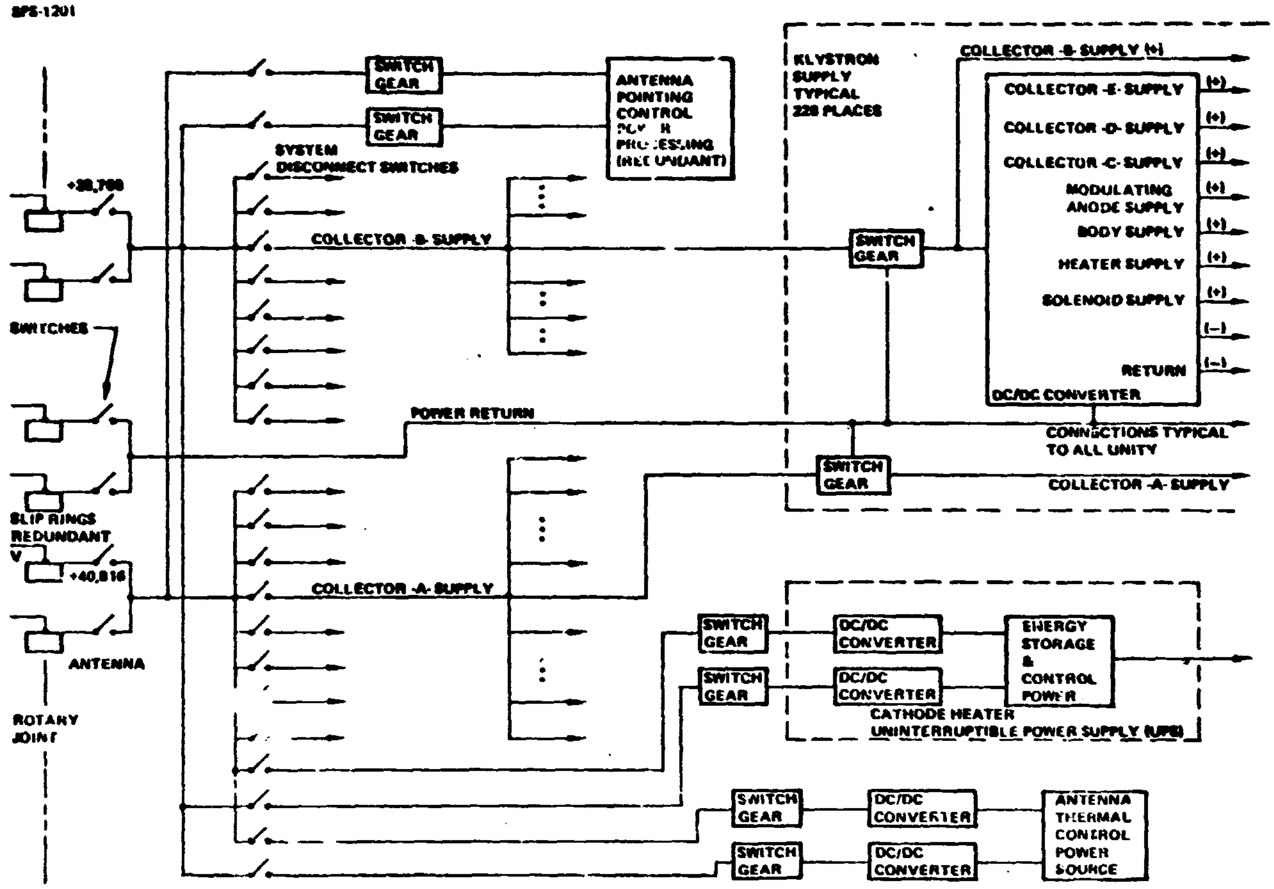

Figure 1.1.2-21 MPTS Power Conditioning Subsystem

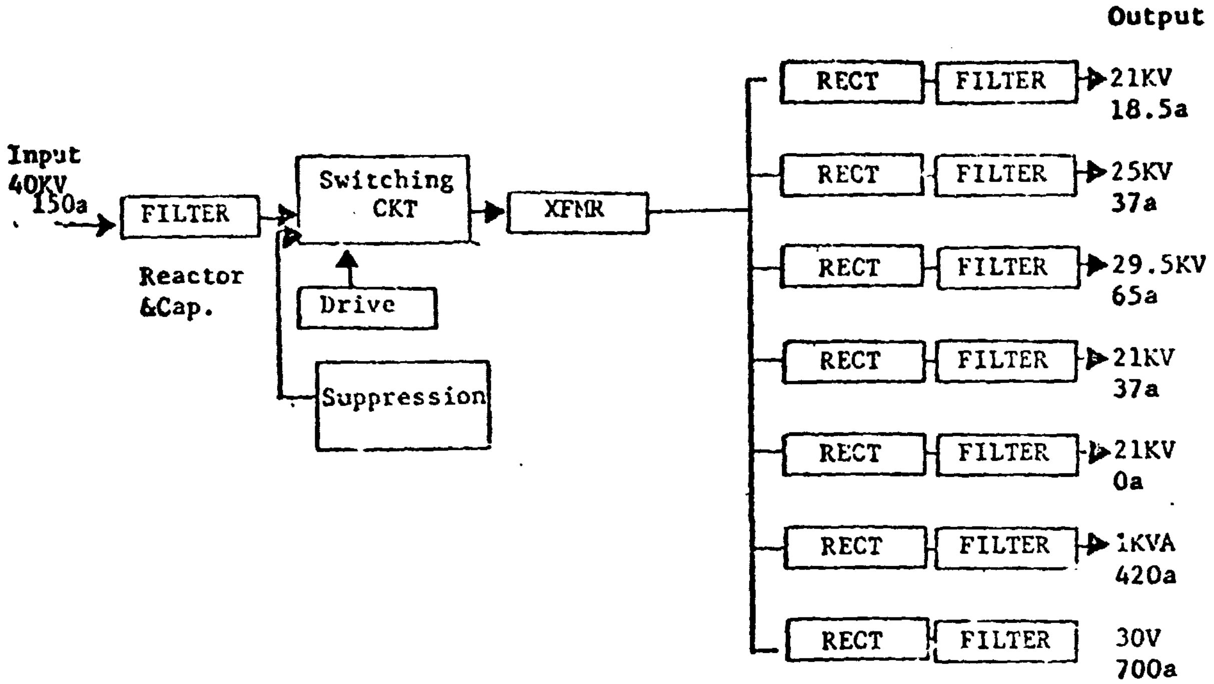

Figure 1.1.2-22. Simplified DC/DC Converter Block Diagram

Table 1.1.2-7 Calculated Power Distribution System Mass and Loss Summary

LOCATION	CONNECTION & COMPONENT	MASS (KG)	I^2R LOSS (WATTS)
"ANTENNA"	SECTOR CONTROL DC/DC CONVERTERS AND SWITCHGEAR	1,441,596	49,644,720
"ANTENNA"	SUBARRAY WIRING (INSULATION INCLUDED)	35,871	4,774,760
	TOTAL	1,877,034	249,776,890

Each MPTS antenna in the baseline design contains over 101,000 dc/rf converters and 228 power sector control substations. During the conceptual design of the klystron, an effort to minimize the mass of the individual tube elements resulted in an overall lightweight tube. However, removing mass from the tube imposes the requirement that the probability of internal arcing must be minimized and, in the event that arcing should occur, rapid removal of the power sources is required. Preliminary requirements placed on the MPTS switchgear were extremely stringent—10 microseconds current interruption time. The development of switchgear to perform this task will require an improvement of two orders of magnitude in current interruption time over present switchgear capabilities (milliseconds to hundredths of milliseconds). Analyses are required of possible klystron design changes and possible uses of current limiting reactors to increase this time. The antenna circuit breakers could be either solid state (present configuration) or vacuum switches (proposed configuration). The rating of the switchgear is 600A at 49KV. Table 1.1.2-8 summarizes the two circuit breakers.

An additional circuit breaker is required which clamps the anode to the cathode at the klystron. Microsecond switching is required at 40KV and no current. A solid state circuit breaker is proposed.

The antenna power distribution system fault protection scheme is shown in Table 1.1.2-9.

In addition to the fault protection required in the MPTS Power Distribution System, isolation of the switchgear for maintenance purposes is required. The use of isolation disconnects would enable isolation of a single power sector substation without powering down the main power busses. The disconnects are not designed for current interruption and are only operated when no current flow exists (i.e., the downstream breaker is open when the disconnect is operated).

WBS 1.1.2.3.4 Processor Thermal Control

WBS Dictionary

This element includes all production hardware required to collect and dissipate the waste heat flux from the power processing equipment on the MPTS system.

Table 1.1.2-8 Summary of DC Circuit Breakers

GE VACUUM SWITCH (PRESENT TECHNOLOGY)

- o RATING: 40 KV, 300 to 2000A continuous, 20,000 A interrupt
- o MASS: 10 gm/KW
- o COST: $100/KG
- o SWITCHING TIME: 5 milliseconds range

SOLID STATE SWITCHES (FUTURE TECHNOLOGY)

- o Rating: 40 KV, 300 to 2000A continuous, 10,000 A interrupt
- o Mass: 18 gm/KW
- o Cost: $260/KG
- o Switching Time: 5 microseconds range

Table 1.1.2-9 Antenna Power Distribution Fault Protection

FAULT AREA	PROTECTION SCHEME
MAIN BUS	REMOVE ALL SATELLITE POWER SOURCES
ANTENNA SUB DISTRIBUTION BUS	OPEN APPROPRIATE MAIN ANTENNA CIRCUIT BREAKER
ANTENNA DC/DC CONVERTER	OPEN CONVERTER CIRCUIT BREAKER
KLYSTRON INTERNAL ARCING	TAKE KLYSTRON MODULATING ANODE TO CATHODE POTENTIAL
OUTPUT WAVEGUIDE ARCING	REMOVE KLYSTRON INPUT RF DRIVE

Element Description

The power processors (dc-dc converters) have a waste heat of approximately 218 Kw per unit. The thermal limitation of the power processors is 70°C (for high reliability) so it was necessary to baseline an active thermal control system for this equipment.

The active thermal control system (Figure 1.1.2-23) was sized, for the MPTS system, using a heat flow of 1000 watts per square centimeter. Redundancy was built into the system (pumps, valves, and control equipment) for higher reliability.

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 processors thermal control systems was estimated at 928 Kw.

Element Mass

The estimated mass of a typical power processor thermal control system is 972 kg. Approximately 83 percent of this mass is for the thermal radiator with the remaining mass distributed between working fluid, piping, pumps motors, control valves, and includes redundant components. The total processor thermal control systems mass is 222.1 MT.

Element Cost

The cost estimating factor for this element was 414 $/kg.

WBS 1.1.2.3.5 Energy Storage

In Figure 1.1.2-21, the need for an Uninterruptable Power Supply (UPS) was indicated. This is provided by suitable dc/dc converters that continuously charge an energy source (battery bank). Klystron life is impacted by cathode heater power on-off cycles. In order to increase the MTBF of the klystron, heater power is maintained during the period of time when occultation (caused either by the earth or other solar power satellites) is encountered.

It is anticipated that significant increase in the MTBF of klystrons can be achieved if thermal cycling of the klystron cathode heater can be minimized. There are 101,552

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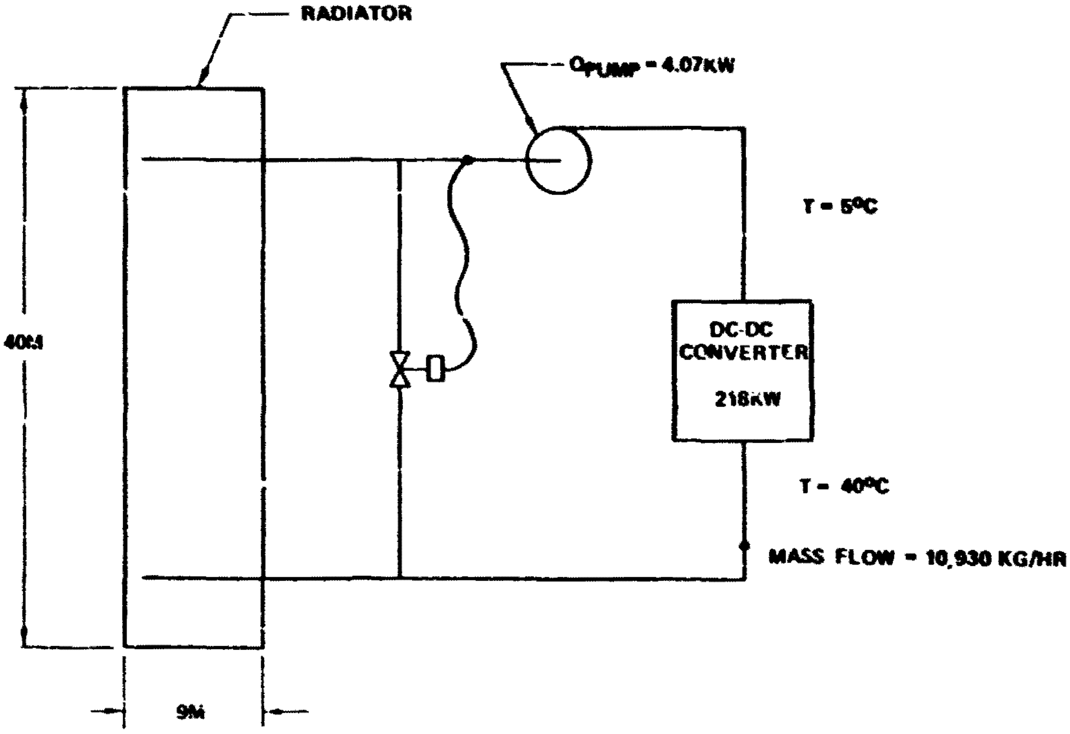


Figure 1.1.2-23 Power Processor Thermal Control

klystrons per antenna each requiring heater power of 50 watts at 30 VDC. Thus, a total of 5.08 megawatts of power is used for klystron heaters. If a distribution loss of 20% (because of the low voltage) and a period of 2 hours required for operation from stored energy are assumed, then 12.186 megawatt hours of stored energy are required for klystron heaters.

Gas electrode (i.e., nickel hydrogen) battery systems offer the advantage of numerous recharge cycles and high energy densities. A nickel hydrogen battery system is selected for the reference configuration and should provide at least four times the service life of conventional nickel cadmium battery systems. With an energy storage system of this size, an energy density of 57.3 watt-hours/kg (26 WHr/lb) including tankage was derived. With a depth of discharge of 0.7 during a normal 2 hour operation, a density of 40.1 WHR/kg is used to determine the mass of the required energy storage system. The estimated mass for the energy storage system is 313.2×10^3 kilograms (313.2 metric tons).

WBS 1.1.2.5 Phase Control

Reference Phase Distribution System. The purpose of the reference phase distribution system is to provide each klystron with a phase reference as required for a focused radiation into the ground receive antenna.

The layout of the reference phase distribution system was developed on the basis of the following assumptions:

- 7220 subarray, 10.4 m x 10.4 m each
- Ten level power distribution approximating Gaussian function with -9.54 dB taper
- Separate phase distribution and conjugaxion circuits
- Electronic circuits as per Lincom report
- Phase distribution tree employs three layers to subarray or four layers to klystron level

- Fourth layer is add on and can be omitted if so desired without influencing the rest of the tree design

- First layer is triple redundant, second layer is double redundant in phase distribution tree

Figure 1.1.2-24 shows one quadrant of the antenna with the boundaries between constant power level rings. In the center region, L_1, K = 36 klystrons are used per subarray representing 0 dB power density. In the outer ring, L_{10}, only K = 4 klystrons are employed per subarray resulting in -9.54 dB power density.

Figure 1.1.2-25 displays how the antenna is divided into sectors and groups. There are a total of 20 sectors within the antenna, each representing approximately an 18^{o} wide pie shaped area. Actually there are three different types of sectors, Qty 4, sector A, Qty 8, sector B and Qty 8, sector C.

Each sector is divided into 19 groups and each subarray contains 19 subarrays. This results in 361 subarrays per sector. The fine subdivision to subarray groups have to be developed only for the three separate cases of A, B and C.

The selected subdivisions allow a three layer tree layout containing 20 x 19 x 19 = 7220 output terminals, corresponding to the input terminals of the subarrays.

Figure 1.1.2-26 shows the beginning of the tree, which has triple redundancy.

The antenna has Qty 3 B_{20} junction boxes (20 way dividers) which are located 50 m from the center of the antenna, 120^{o} apart on a circle. Any of the receivers associated with these junctions can be commanded that they become the phase reference receivers for the antenna. A total of 20 cables go from a B_{20} junction to the B_{19} junctions located in the middle of a sector, thus the overall system has a total of 60 of these first layer cables.

Into a sector center the reference signal arrives from three separate starting points. At a command one of these signals are selected, synchronously for all 20 sector centers. At a sector center the selected reference signal is divided into 19 way and the signal is transmitted down to group centers. The electronic equipment associated with this transmission is redundant at the sector centers and the group centers, accept for the

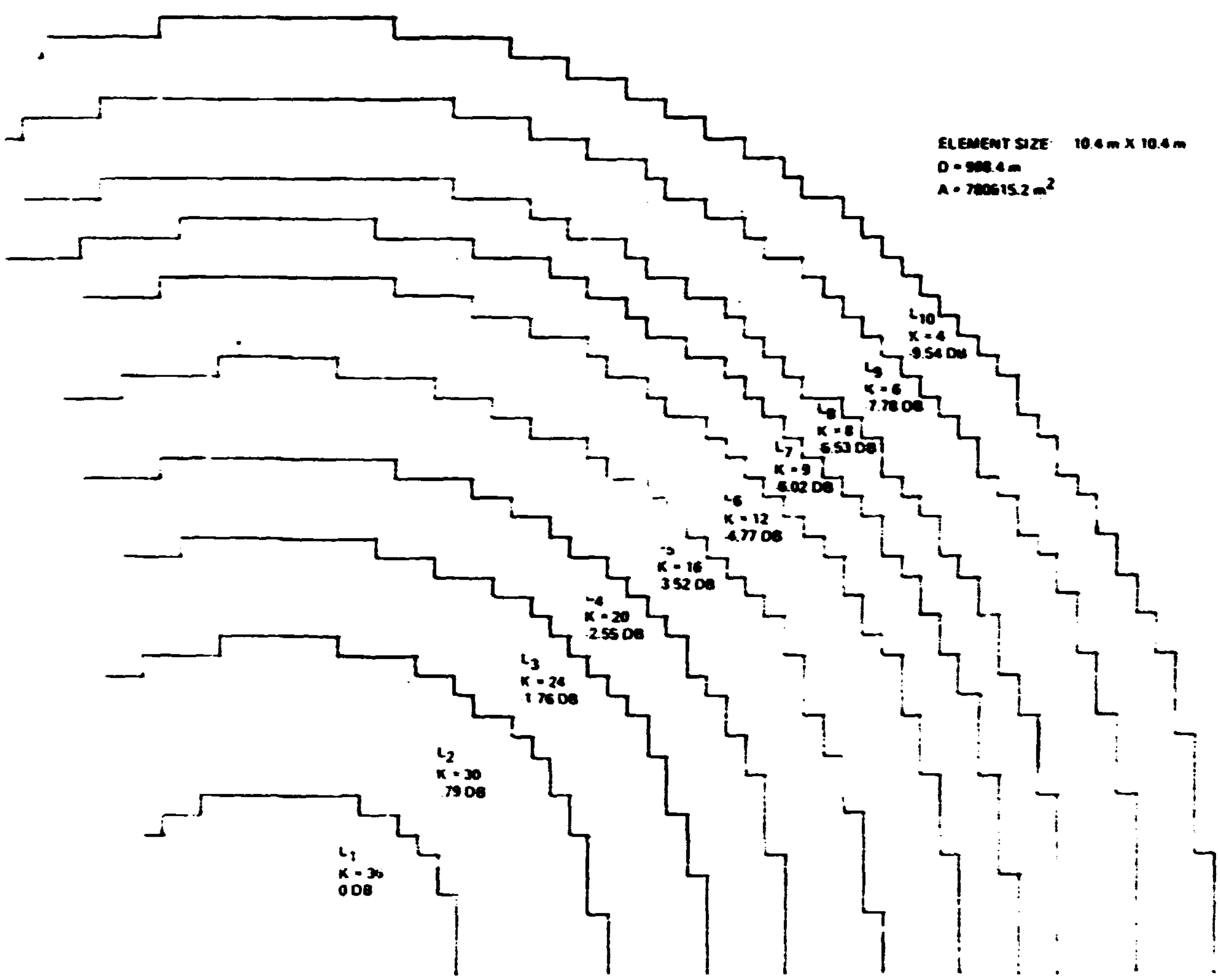


Figure 1.1.2-24 Division of 7220 Element Space Antenna into Ten Power Level Rings

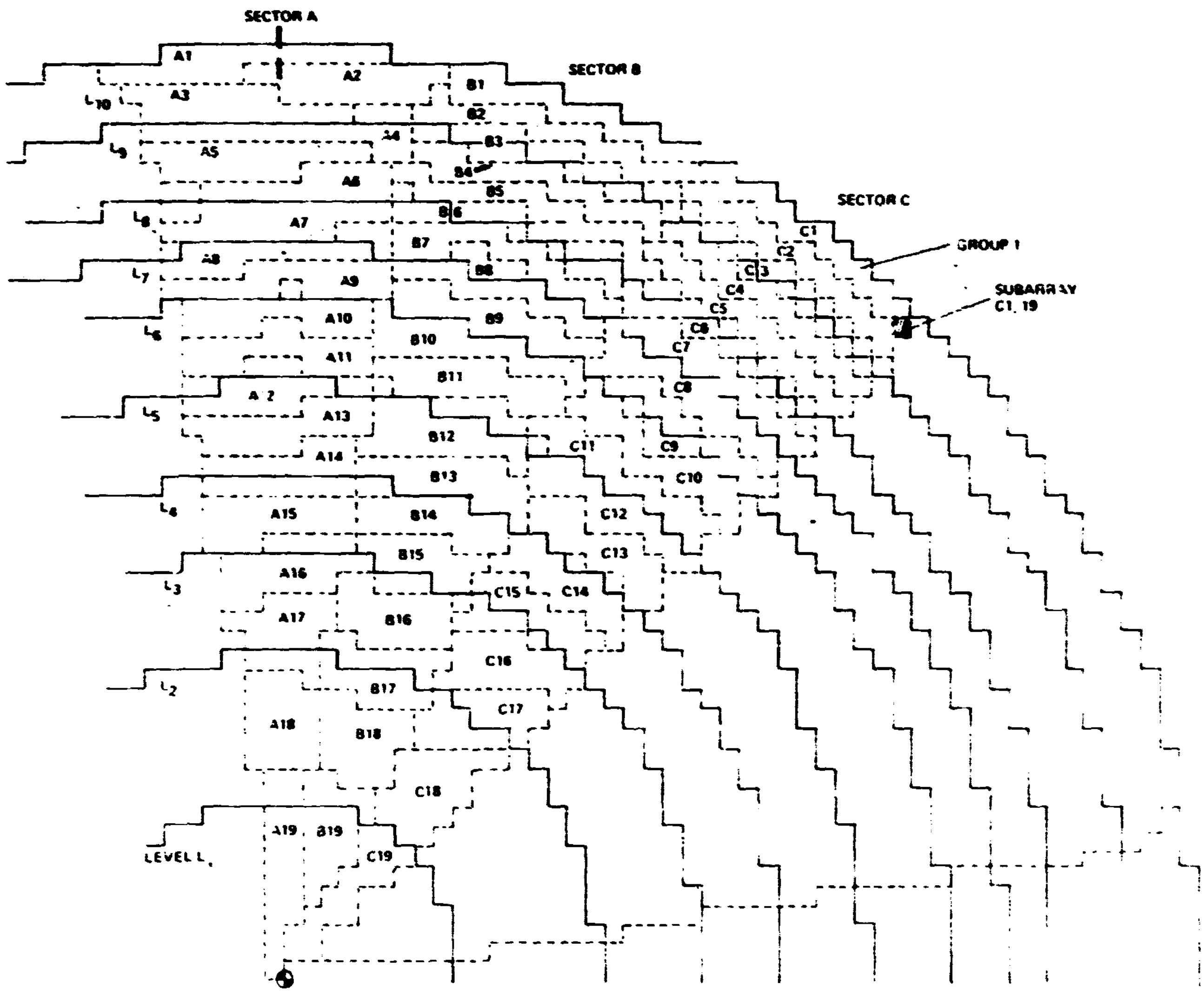


Figure 1.2-25. Layout of Phasing Sectors and Groups

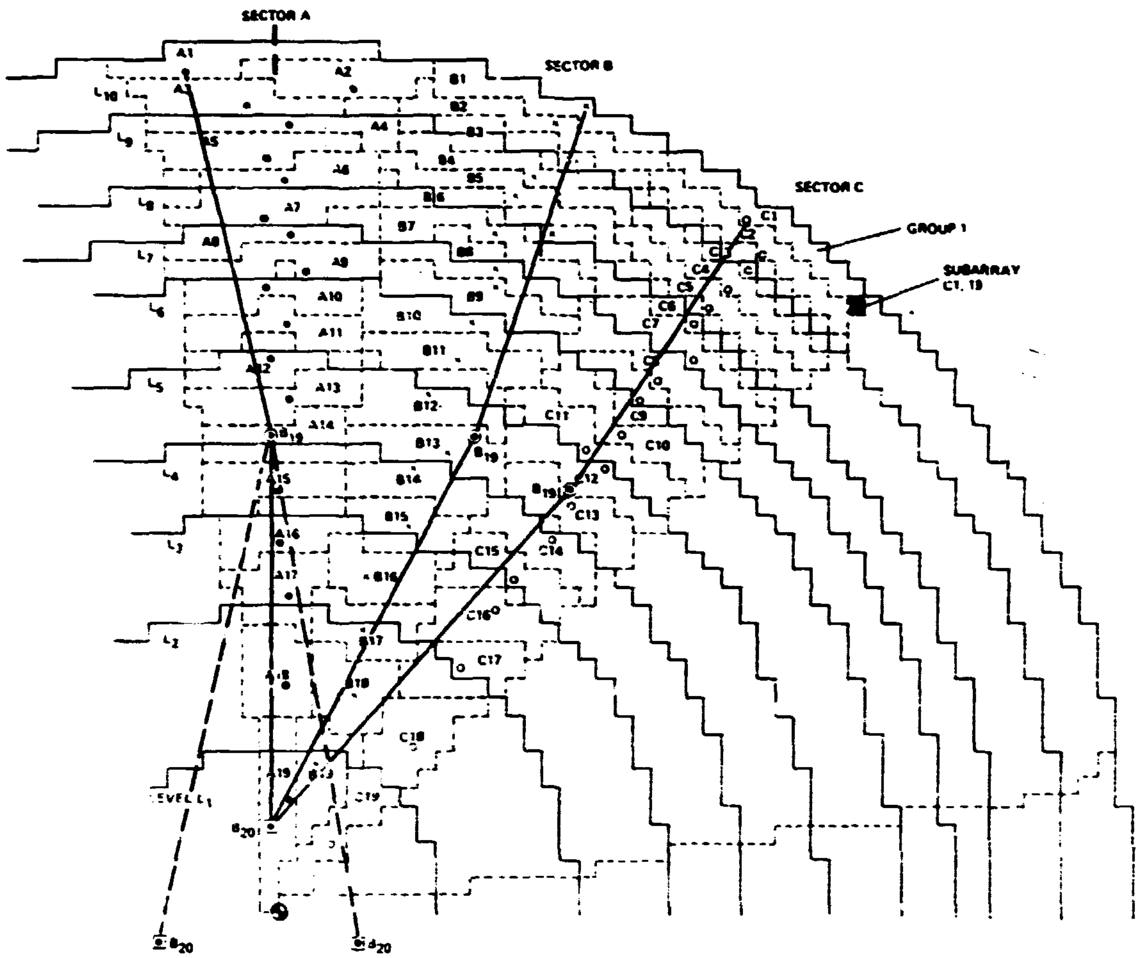


Figure 1.1.2-26 Location of Reference Phase Repeater Stations of Sectors and Groups

Table 1.1.2-12 Summary of w.g. Stick Quantities

		Qty/Subarray		Qty of Sticks	
Stick Type		1	2	1	2
Length (m)		2.6	1.733	2.6	1.733
Level	Qty of Subarrays				
1	308		648		199584
2	624	660		411840	
3	656	432		283392	
4	632	440		159280	
5	744	432		321408	
6	872		648		565056
7	664		648		430272
8	536	432		231552	
9	1112	432		480384	
10	1072	440		471680	
Total	7220			2359536	1194912
Grand Total				3554448	
Length^{Km}				6134.79	2070.78
Grand Total Length^{km}				8205.57	
Av. Length, m				2.308	

cable which is between the sector center and group center. (The availability analysis indicates that the omission of the second cable has very little effect.)

Once the signal arrived to a group center is again divided by a B_{19} divider and is sent to the subarrays. No redundancy is provided at this level, instead a bi-yearly maintenance is implemented.

From subarray centers the number of phase distribution lines are dependent on the number of klystrons mounted on the particular subarray. These B_{mn} dividers provide 36 output lines in the middle of the antenna and four output lines at the edge.

Tables 1.1.2-10 and 1.1.2-11 shows the quantities of subarrays in various power levels, sectors and groups.

Figure 1.1.2-27 shows the layout of the subarrays, including the dimensions of klystron modules, w.g. stick sizes and number of w.g.'s (n_r = number of w.g. forming a row per klystron, n_s = total number of w.g. sticks per subarray). The figure also shows the location and number of terminals of the B_{mn} type power dividers serving a subarray.

Table 1.1.2-12 summarizes the Qty of subarrays and associated w.g. stick types associated with the various power levels. It can be seen, that ten different types of subarrays are required but only two different types of w.g. sticks. The total length of w.g. in the radiating elements is approximately 8205 km. Additional w.g. is needed for the coupling lines between klystrons to w.g. sticks.

Figure 1.1.2-28 shows the basic redundancy concept of the phase distribution network and Figure 1.1.2-29 displays a more detailed block diagram from which applicable quantities of the various components can be determined. The same figure indicates the failure rates which are assumed for availability calculations.

Table 1.1.2-13 lists the Qty of phase dividers to subarray and klystron level respectively. Down to subarray level only two types of dividers (B_{20} and B_{19}) are needed. An additional type of 11 is required to klystron level.

Table 1.1.2-14 lists the required phase distribution cables and their total length. Characteristics for two types of systems are listed using equal or unequal length of cables

Table 1.1.2-10 Quantities of Subarrays in Various Levels, Sectors and Groups

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

Table 1.1.2-11 Summary of Subarray Quantities in Various Phasing Sectors and Groups

LEVEL	QTY	
1	$A_{19} = 60$ $B_{19} = 96$ $C_{19} = 152$	$T_{19} = 308$ $T = 308$
2	$A_{19} = 16$, $A_{18} = 76$, $A_{17} = 20$ $B_{19} = 56$, $B_{18} = 152$, $B_{17} = 80$ $C_{18} = 152$, $C_{17} = 72$	$T_{19} = 72$, $T_{18} = 380$, $T_{17} = 172$ $T = 624$
3	$A_{17} = 56$, $A_{16} = 56$ $B_{17} = 72$, $B_{16} = 153$, $B_{15} = 40$ $C_{17} = 80$, $C_{19} = 152$, $C_{15} = 48$	$T_{17} = 208$, $T_{16} = 360$, $T_{15} = 88$ $T = 656$
4	$A_{16} = 20$, $A_{15} = 76$, $A_{14} = 32$ $B_{15} = 112$, $B_{14} = 152$ $C_{15} = 104$, $C_{17} = 136$	$T_{16} = 20$, $T_{15} = 292$, $T_{14} = 320$ $T = 632$
5	$A_{14} = 44$, $A_{13} = 76$, $A_{12} = 64$ $B_{13} = 152$, $B_{12} = 96$ $C_{14} = 16$, $C_{13} = 152$, $C_{12} = 144$	$T_{14} = 60$, $T_{13} = 380$, $T_{12} = 304$ $T = 744$
6	$A_{12} = 12$, $A_{11} = 76$, $A_{10} = 72$ $B_{12} = 56$, $B_{11} = 152$, $B_{10} = 152$ $C_{12} = 8$, $C_{11} = 152$, $C_{10} = 152$, $C_9 = 40$	$T_{12} = 75$, $T_{11} = 380$, $T_{10} = 376$, $T_9 = 40$ $T = 872$
7	$A_{10} = 4$, $A_9 = 76$, $A_8 = 56$ $B_9 = 152$, $B_8 = 112$ $C_9 = 112$, $C_8 = 152$	$T_{10} = 4$, $T_9 = 340$, $T_8 = 320$ $T = 664$
8	$A_8 = 20$, $A_7 = 76$, $A_6 = 8$ $B_8 = 40$, $B_7 = 152$, $B_6 = 32$ $C_7 = 152$, $C_6 = 56$	$T_8 = 60$, $T_7 = 380$, $T_6 = 96$ $T = 536$
9	$A_6 = 68$, $A_5 = 76$, $A_4 = 64$ $B_6 = 120$, $B_5 = 152$, $B_4 = 152$, $B_3 = 16$ $C_6 = 96$, $C_5 = 152$, $C_4 = 152$, $C_3 = 64$	$T_6 = 284$, $T_5 = 380$, $T_4 = 368$, $T_3 = 80$ $T = 1112$
10	$A_4 = 12$, $A_3 = 76$, $A_2 = 76$, $A_1 = 76$ $B_3 = 136$, $B_2 = 152$, $B_1 = 152$ $C_3 = 88$, $C_2 = 152$, $C_1 = 152$	$T_4 = 12$, $T_3 = 300$, $T_2 = 380$, $T_1 = 380$ $T = 1072$

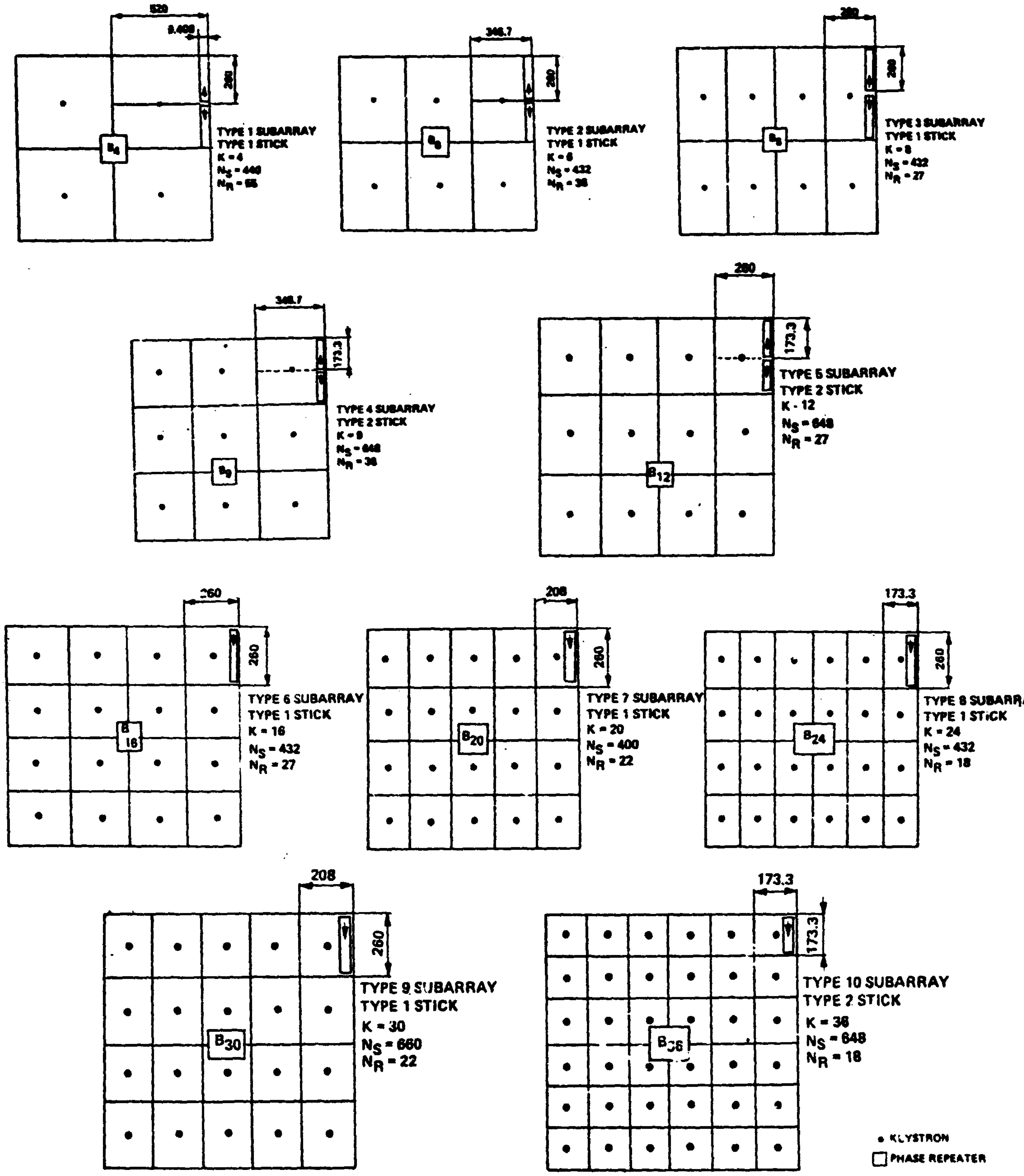


Figure 1.1.2-27 Layout of the Ten Different Type of Subarrays, Showing Klystron and Phase Repeater Locations and Waveguide Stick Sizes

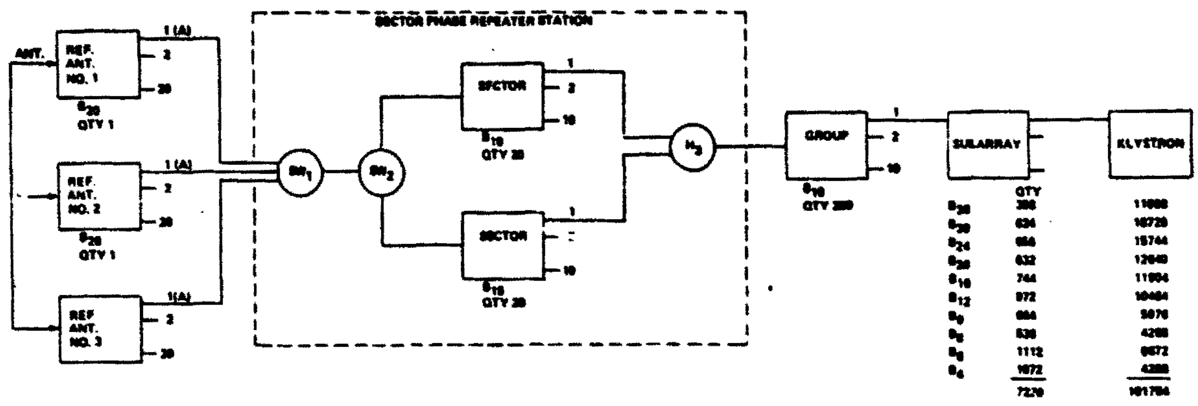


Figure 1.1.2-28 Redundancy Concept of Phase Distribution Network

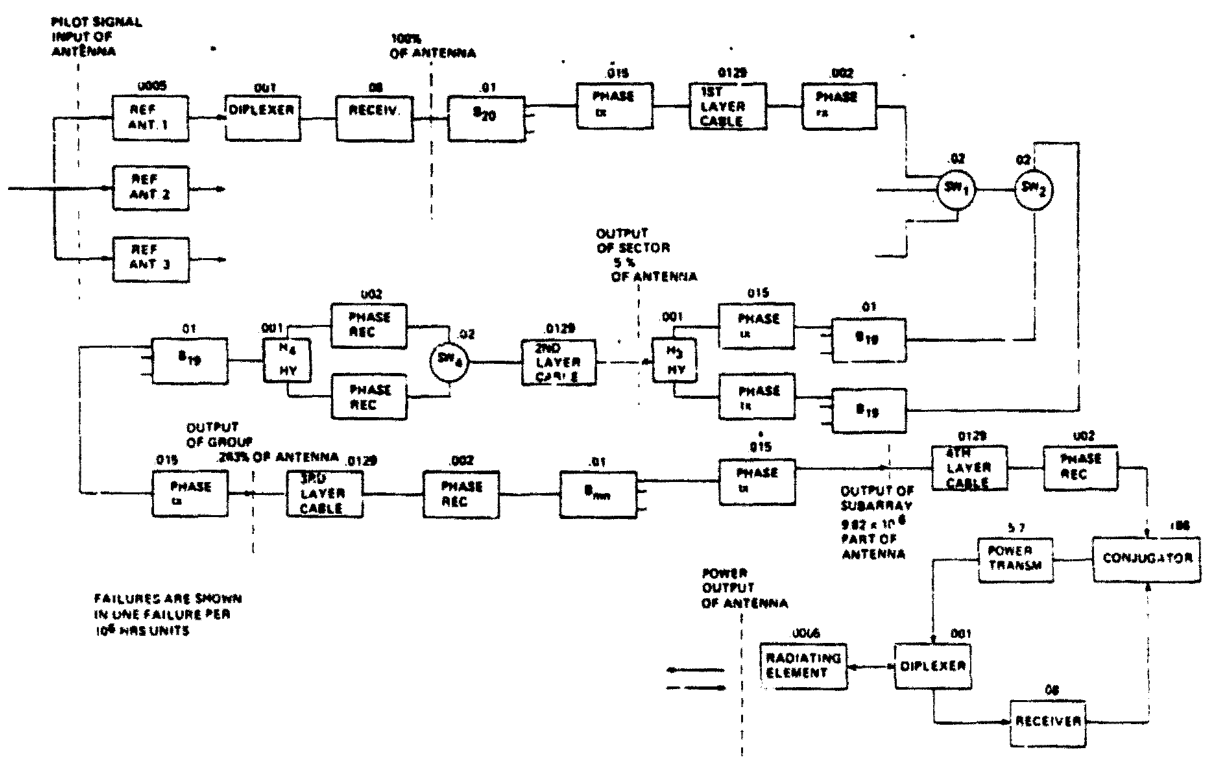


Figure 1.1.2-29 Block Diagram of Phase Distribution Network, Showing Applicable Failure Rates for Various Components

Table 1.1.2-13 List of Phase Dividers to Subarray Level

BASIC SYSTEM

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

REDUNDANT SYSTEM

	QTY		
B_{20}	2		
B_{19}	20		

TOTAL SYSTEM

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

ADD ON TO KLYSTRON LEVEL
(NO REDUNDANCY)

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

Table 1.1.2-14 List of Phase Distribution Cables

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

within the same layer of the phase distribution tree. Either system is usable, but the equal length system may provide a slight reduction in the achievable net phase error. For this system the able length is about an order of magnitude smaller than the length of the w.g. which yield about two order of magnitude smaller weight. The equal cable length system is about twice as long as the unequal length system.

Table 1.1.2-15 lists all the components in the phase control system. It also displays the differential quantities between a phase control system down to subarray level and a phase control system down to klystron level.

Mechanical Layout of the Distribution System. The mechanical layout of the DC and RF (phase) distribution system of the antenna can be represented by two figures.

The first is an overall diagram, which shows the layout of the DC cables and junction stations, (switch gear, DC to DC converters) and the RF cables with the associated phase transmitter, phase receiver and divider boxes. The components in this system are not related to any particular subarray but they must be supported on or behind the subarrays or on the secondary structure.

The second figure is showing the components which are directly associated with a subarray. This layout is obviously different for each subarray type. Only one of the necessary ten layouts was developed (for a Type 1 subarray, at the edge of the antenna). This is exhibited on Figure 1.1.2-30.

WBS 1.1.2.6 MPTS Maintenance Equipment and Operations

A number of major components of the satellite have been analyzed for their nature of failures, mean time between failure, power loss per failure, and finally the power loss per year. The component having the greatest impact in terms of power loss and in the time required to fix the failures is the klystron tube modules. A total of 3800 tubes are estimated to fail per year resulting in an annual power output loss of 500,000 Kw. The antenna maintenance system has therefore been designed around replacement of the klystron tube module.

WBS Dictionary

This element includes the description of the antenna items requiring maintenance, the level of replacement, the replacement concept, logistics provisions, and the maintenance equipment. The description provided here is the result of a preliminary analysis

C-2

Table 1.1.2-15 List of Components in Phase Control Circuit

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

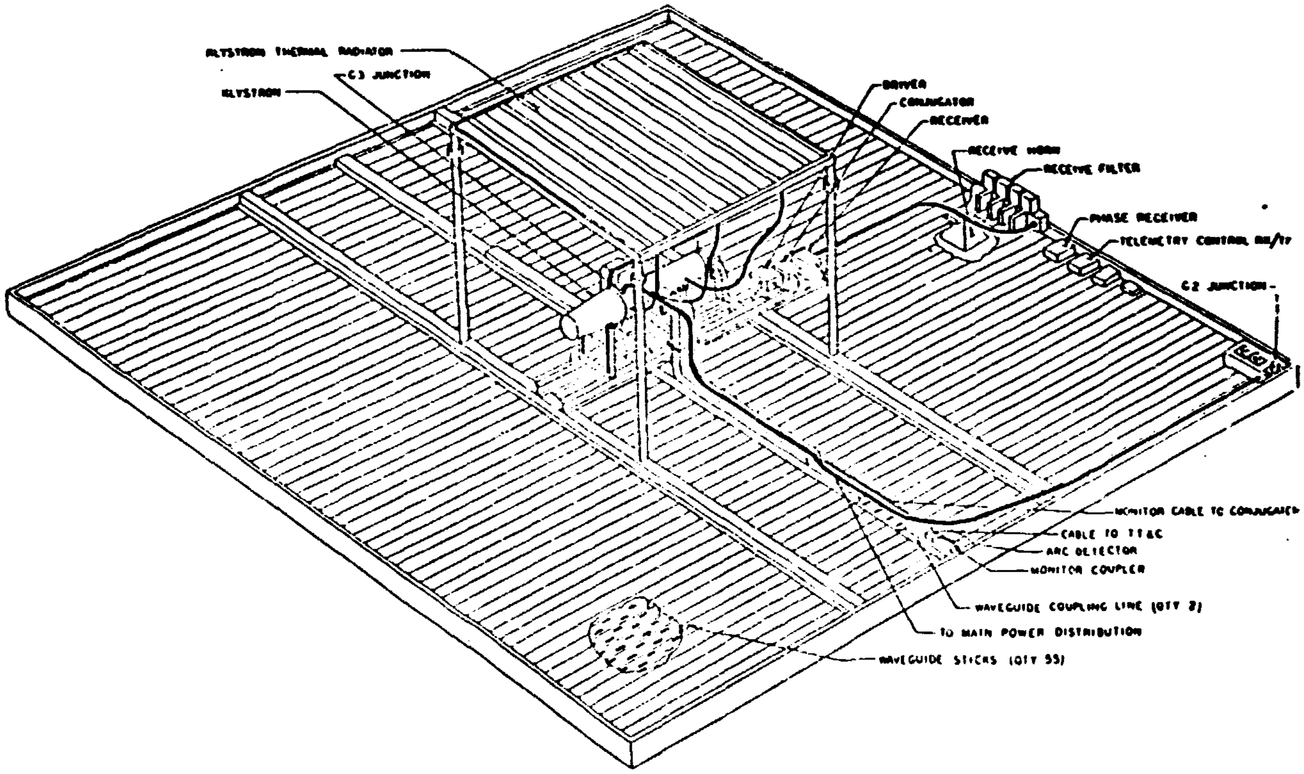


Figure 1.1.2-30 Mechanical Layout of a Typical Klystron Module in the Outer Ring of the Space Antenna

conducted under contract NAS9-15196. It describes only the klystron power amplifier maintenance.

Level of Replacement. The level of replacement selected is that of the klystron tube module plus its thermal control system as shown in Figure 1.1.2-31. Actual removal of the tube module involves access through holes in the radiator to reach the distribution wave guide attachment bracket which secures the module to the distribution wave guide. Once this attachment is released the module is free to be removed.

Concept

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

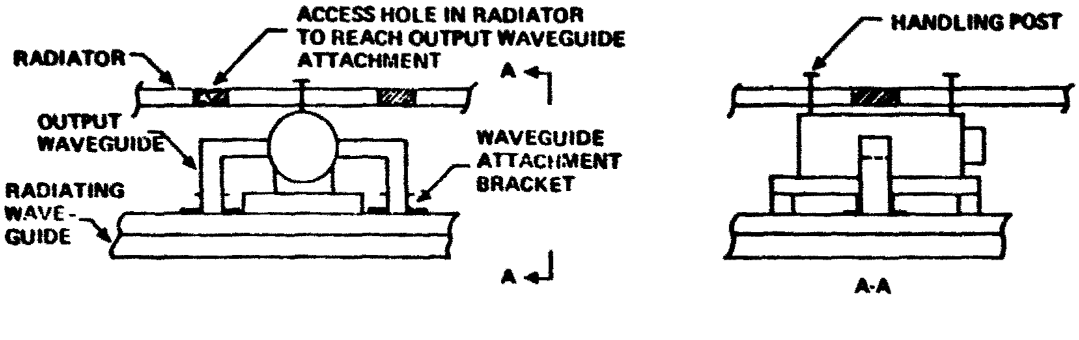
The overall cocept is illustrated in Figure 1.1.2-32. The primary structure is an A-frame design forming ridges that allow free unobstructed movement of the maintenance gantry moving horizontally across the antenna.

The antenna will have a total of 10 channels in which maintenance gantries can be mounted. 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 1.1.2-33.

Additional detail of the cubic secondary structure and the maintenance vehicle is presented in Figure 1.1.3-34 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-man 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 repaired. In the case of a 36 tube subarray as many as three tubes may require replacement.

Using this concept a tube replacement time of 45 minutes is expected, which includes removal and replacement of two diagonals (in lower and upper surface of secondary structure), removal and replacement of one klystron tube module, and movement to the next failed klystron tube estimated at a distance of 2 subarrays away or 20 meters.

SPS-1912



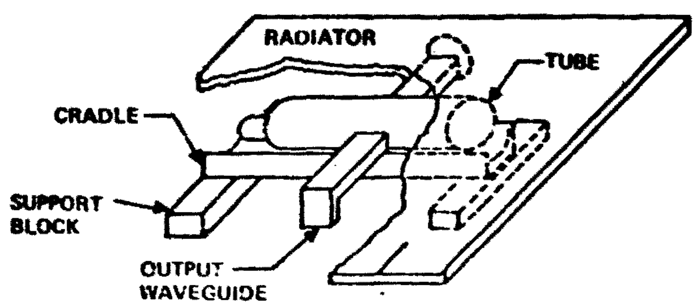


Figure 1.1.2-31 Level of Replacement Selection

SPS-1190

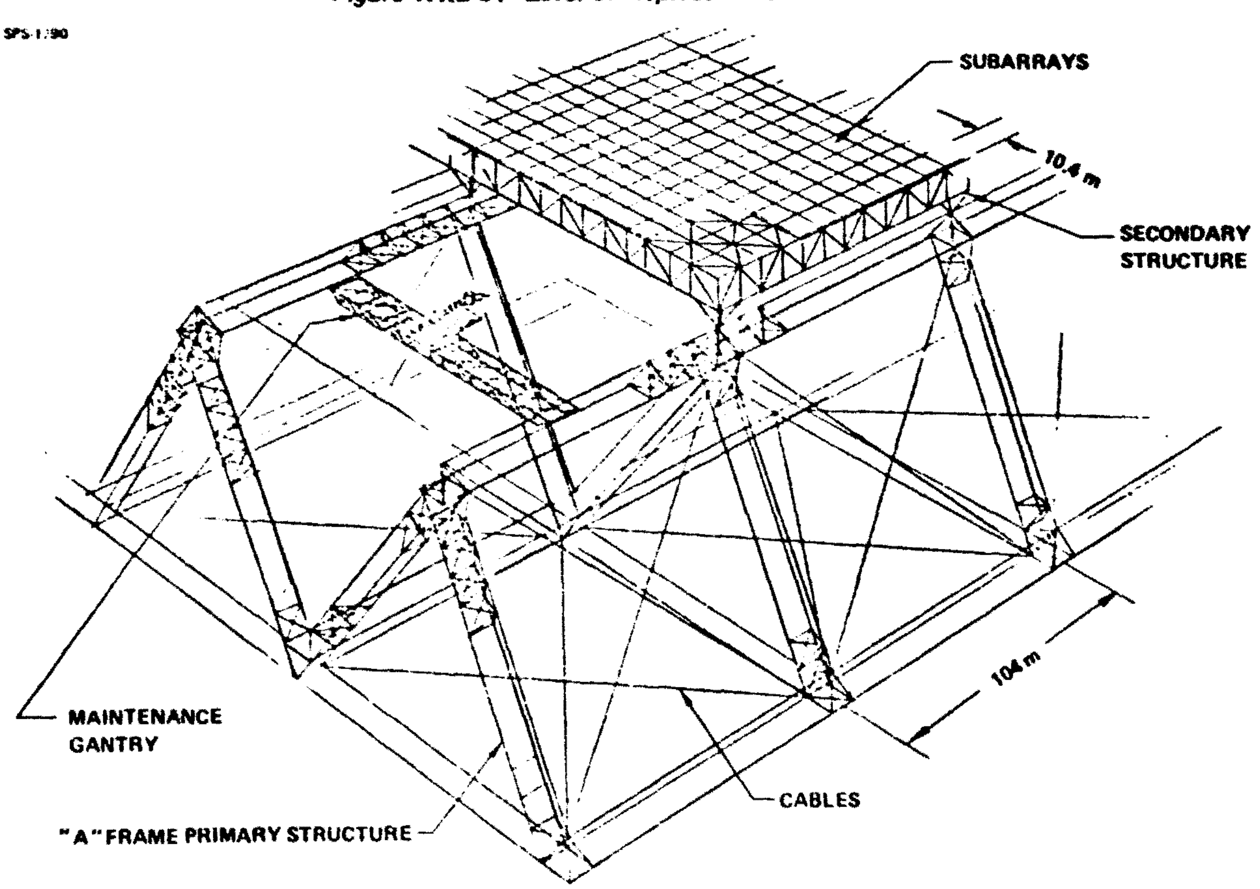


Figure 1.1.2-32 Vertical Access for Tube Maintenance

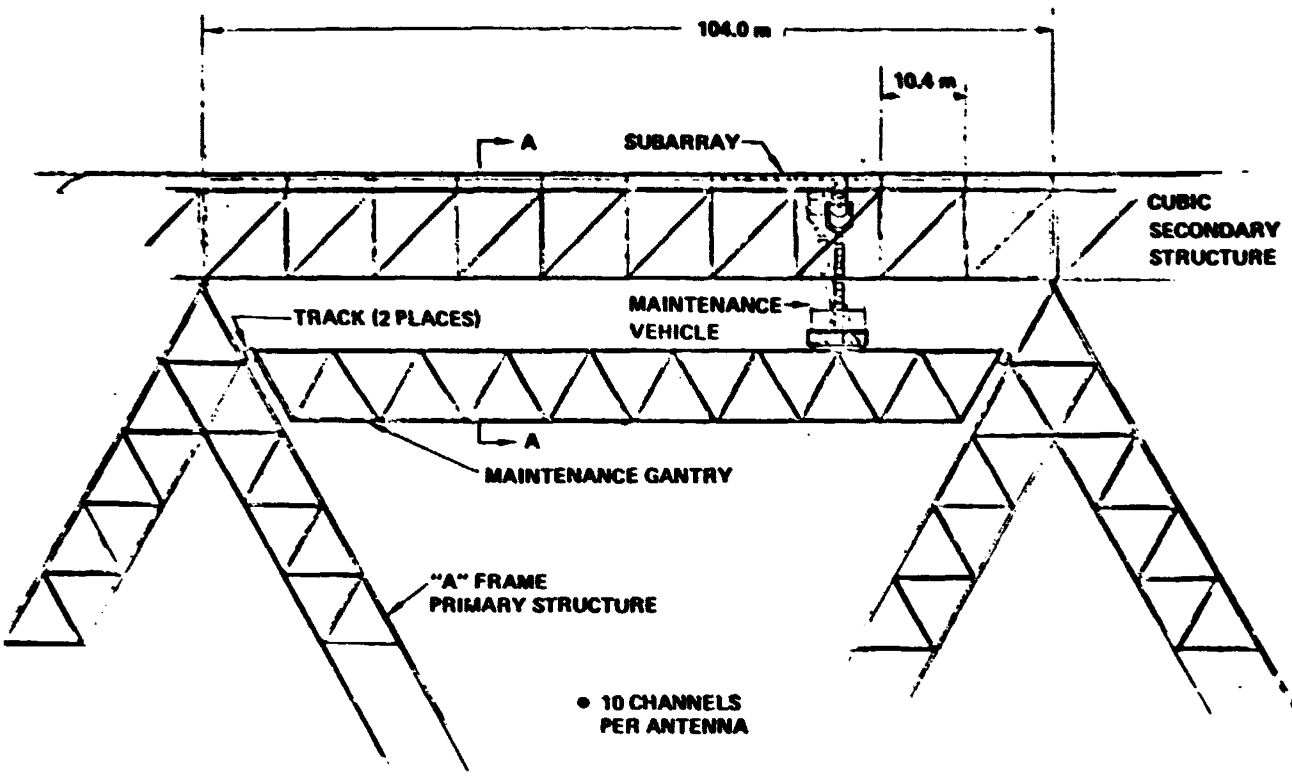


Figure 1.1.3-33 Vertical Access for Tube Maintenance

SPS-1702

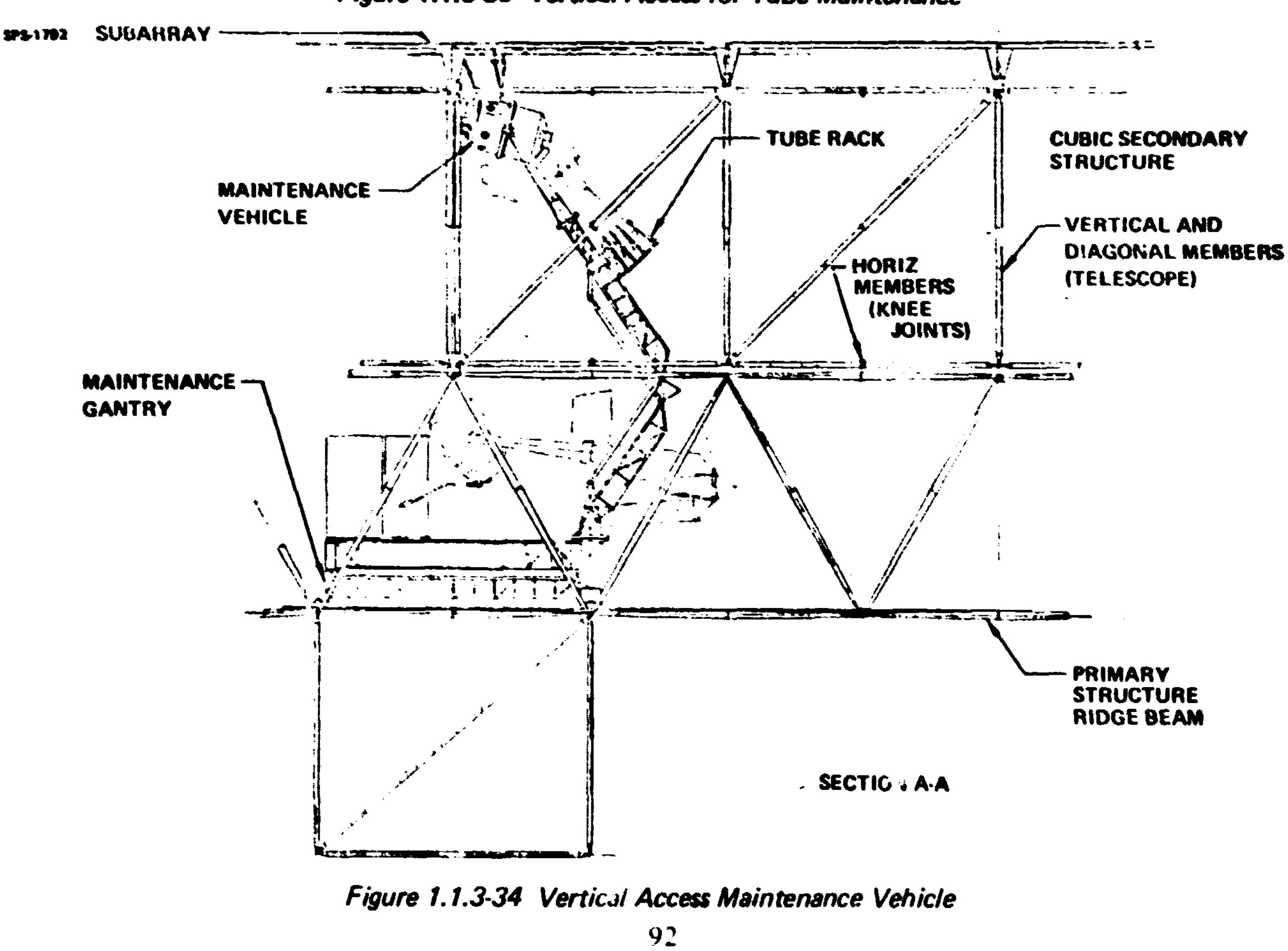


Figure 1.1.3-34 Vertical Access Maintenance Vehicle

The Satellite based maintenance systems will be installed during satellite construction. The systems are shown as they relate to one side of one antenna in Figure 1.1.2-35 and 1.1.2-36. Since two crews work on each satellite, these same systems are present on both sides of the antenna.

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 maintained and supplied with new klystron tube modules.

The 60 person crew is delivered to the satellite in the crew habitat using the second stage of the POTV that initially brought the crew from the LEO construction base to the GEO final assembly base. Once at the satellite (antenna), a crew bus is used to transfer persons between the habitat and the maintenance repair vehicles.

Cargo, primarily in the form of klystron tube modules is also delivered to the satellite using a dedicated POTV (stage 2) that had initially brought klystron components to the GEO final assembly base for refurbishment of "failed" kystron tubes. The operations associated with a POTV include docking and release of one klystron tube pallet on one side of the antenna. The POTV then flies to the other side of the antenna leaving another pallet. At the completion of the repair operation, the pallets are loaded with failed klystron tubes. The POTV then moves to the two docking locations collecting the pallets with failed tube modules and returns them to the GEO final assembly base where they are refurbished. Following the release of the pallets, the POTV returns to the LEO construction base where it is made ready to deliver another load of klystron components.

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 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 have been removed. The train system 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.

SPS-1940

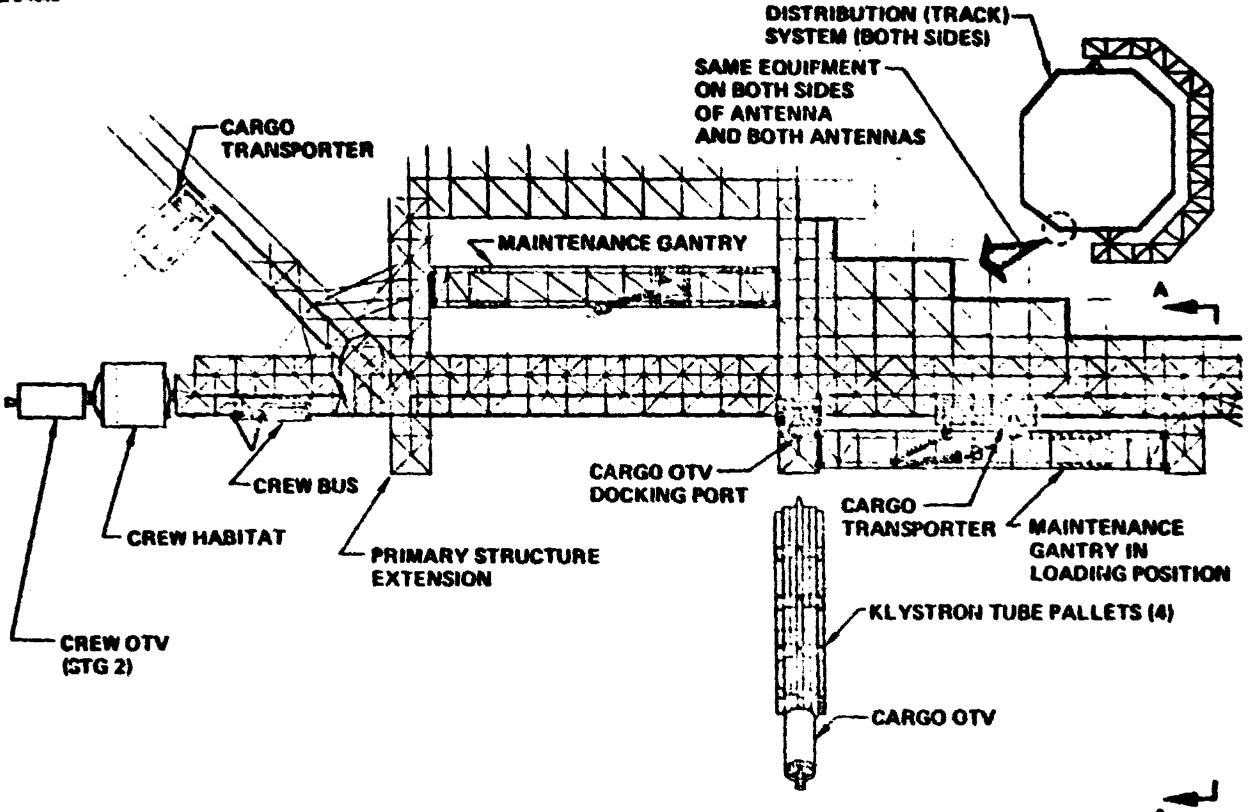


Figure 1.1.2-35 Satellite Maintenance Systems

SPS-1941

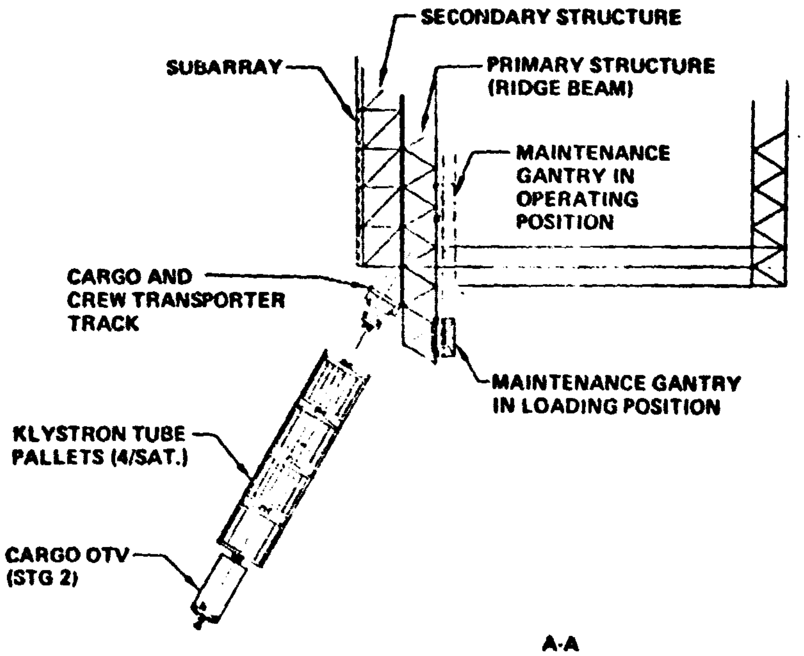


Figure 1.1.2-36 Satellite Maintenance Systems

The installation location of the maintenance equipment on an antenna being repaired by two crews is shown in Figure 1.1.2-37.

The number of maintenance vehicles (machines) installed in each channel of the antenna is a function of the estimated number of tube failures. This value is larger in the middle channels of the antenna since the center of the antenna has subarrays containing 36 and 30 klystron tube modules while near the edge of the antenna, the subarrays have 4 or 6 tubes per subarray. Consequently it will be noted that the middle channel has three maintenance systems each consisting of a gantry and repair vehicle.

With this equipment distribution and working 20 hours per day, the middle channels require slightly more time than previously identified for repair—3 1/2 days per satellite. The addition of 1/2 day to the schedule, however, will not appreciably alter the prior analysis.

It should also be noted, the outside channels require far less time to repair and less equipment due to fewer failed tubes. Cnsequently when the crews assigned to this particular equipment are finished, they can then be used to repair other components on the satellite such as the dc-dc converters mentioned earlier in the discussion.

WBS 1.1.2.7 Mechanical Pointing

WBS Dictionary

The Power Transmission System 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.

Description

The CMG's 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 antenna attitude. The control system concept is described under WBS 1.1.6

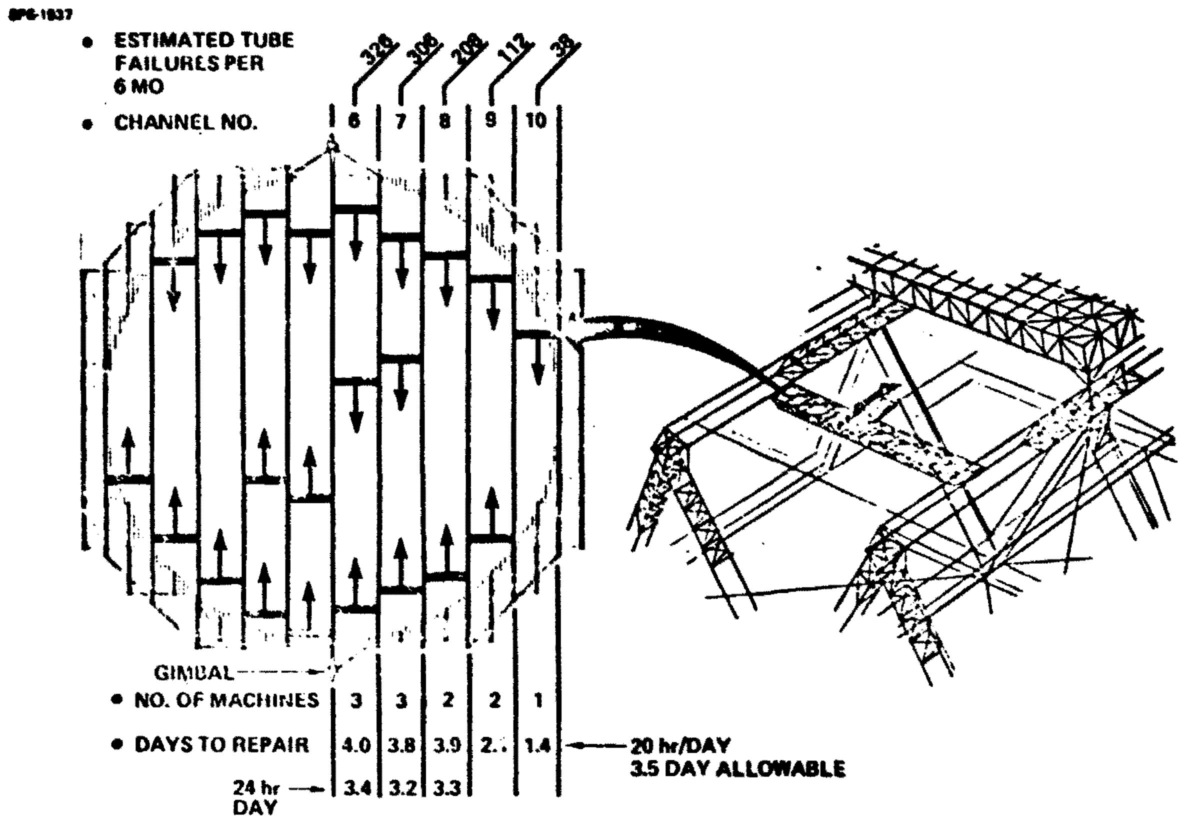


Figure 1.1.2-37 Antenna Maintenance System Installation

Mass

Each CMG was estimated to have a total mass of 10,660 kilograms for a total per antenna of 127,920 kg.

Cost

The total cost for the attitude control systems including the 24 CMG's for two antennas was estimated as $202 million based on a CER. This averages to $790/kilogram for the CMG hardware.

WBS 1.1.3 Information Management and Control

WBS Dictionary

The Information Management and Control System 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.

A. Requirements

The telemetry and command requirements for the IMCS were determined by examining the satellite design in detail and estimating the instrumentation required to determine the satellite state of health and to make decisions concerning the commands in the event of anomalies. It was also necessary to define the commands. The results presented are for a 5 GW satellite, that is one MPTS antenna and its related power generation system.

The process of requirements determination necessitated many decisions concerning the component level to which each satellite subsystem will be instrumented and the level to which a command capability will be provided. For the subsystems which are relatively well defined, this process was accomplished on the existing design. For those subsystems on which very little design information exists, the estimates were made by extrapolating requirements of typical current satellites to a system of the magnitude of SPS.

Two of the major satellite areas generating telemetry and command requirements are the solar arrays and the klystrons. As an example of the decisions involved, for the solar arrays it was decided to measure the voltage of each solar cell string once in each bay, and to measure the array current at each load sector. A disconnect command is provided for each load sector string. In the case of the klystrons selected currents and temperatures as well as output and on/off status are monitored for each klystron, however, on/off commands are provided down to the subarray level only.

Tabel 1.1.3-1 summarizes the estimated telemetry requirements and Table 1.1.3-2 summarizes the estimated command requirements. The estimates are presented separately for the spacecraft (i.e., the solar array portion of the satellite up to and including the slip rings) and for the MPTS antenna (from the slip rings throughout the antenna). This segregation became necessary as the magnitue of the requirements developed and it became apparent that two CDHS systems with a limited interconnect might be required, one for spacecraft and one for the MPTS antenna.

B. System considerations and Features

The large numbers of telemetry points and commands required by each satellite made it apparent that if all telemetry data were transmitted to the ground, either very large numbers of ground personnel would be required to monitor the data and generate commands, or the equivalent work would have to be accomplished by automatic processing. It also became apparent that if automatic processing had to be used, it could be done by a distributed processing system in the satellite with processors located near the equipment being monitored and commanded. This system provides two other advantages, the amount of data transmitted throughout the satellite and to the ground would be reduced, and the delay time between detection of an anomaly and receipt of a correcting command would be reduced. In view of these considerations the on-board processing system was selected.

In order to process telemetry data and generate commands locally within the satellite, numerous microprocessors and memories are required, distributed throughout the satellite. These processors are organized into groups, each of which is monitored by a processor that is one of another tier of processors. This tiering process continues up to a Central Processor Unit which manages the data traffic to and from the ground.

Table 1.1.3-1 SPS Telemetry Requirements

SATELLITE SUBSYSTEM	TELEMETRY TYPE ANALOG	BILEVEL	DIGITAL
SPACECRAFT			
SOLAR ARRAY	89,152	19,200	
ATTITUDE CONTROL & DETERMINATION	26	28	4
ELECTRIC PROPULSION	656	128	
CHEMICAL PROPULSION	112	112	
COMMAND & DATA HANDLING	4,805	9,610	24,025
COMMUNICATIONS	30	48	6
POWER CONTROL	426	204	12
THERMAL CONTROL	200	400	
TOTAL	95,407	29,730	24,047
MPTS ANTENNA			
CENTRAL POWER DISTRIBUTION	1,648	4,120	
POWER SECTORS	4,560	131,708	1,140
KLYSTRONS	970,560	485,280	
PHASE CONTROL/RF DRIVE	679,372	388,224	
ATTITUDE CONTROL & DETERMINATION	26	28	4
CONTROL MOMENT GYROS	48	24	24
COMMAND AND DATA HANDLING	9,194	18,388	45,970
COMMUNICATIONS	30	48	6
THERMAL CONTROL	200	400	
TOTAL	1,665,638	1,028,220	47,144

Table 1.1.3-2 SPS Command Requirements

SATELLITE SUBSYSTEM	COMMAND TYPE	
	PULSE	STATE
SPACECRAFT		
SOLAR ARRAY		19,200
ATTITUDE CONTROL & DETERMINATION	84	32
ELECTRIC PROPULSION	1,000	
CHEMICAL PROPULSION	224	
COMMAND & DATA HANDLING	220	2,400
COMMUNICATIONS	54	200
POWER CONTROL	90	96
THERMAL CONTROL		400
TOTAL	1,672	22,328
MPTS ANTENNA		
CENTRAL POWER DISTRIBUTION		1,848
POWER SECTORS	1,140	485,280
ATTITUDE CONTROL & DETERMINATION	84	32
CONTROL MOMENT GYROS	24	
COMMAND AND DATA HANDLING	18,388	9,194
COMMUNICATIONS	54	200
THERMAL CONTROL		400
TOTAL	19,690	496,954

The recommended approach is essentially two systems connected by a limited data link thorough the slip rings. The reasons for this approach are:

a) The large amount of information which must be handled
b) Transmission of large amount of data at high rates across the slip rings will be very difficult
c) A redundant link with the ground is provided

The use of fiber optics is recommended for data transmission because such a system is of lighter weight, is more fault tolerrant (because it is a non-conductor it does not propogate faults), has a wide-band multiplexing capability, is inherently immune to EMI and arc discharges, and the raw materials required 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 which contains the 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 results in an appreciable increase in complexity and cost.

C. Recommended Configurationn

The recommended IMC system is two systems, one for the spacecraft and one for the MPTS antenna with a limited data interconnect through the slip rings.

Figure 1.1.3-1 shows the configuration for the spacecraft which utilizes four tiers of control including the Central Processor Unit as tier (1). The tiers for monitor and control of the solar array are organized in the same order as the solar array. At the lowest tier (4), each RTU monitors and controls two of the 100 strings which constitute a load sector. At the next tier (3), each processor (load sector controller) monitors and controls 50 of the lower tier RTU's plus the other load sector functions. The next tier (2), of processors (module controllers) monitor and control 48 load sector controllers and interface with the CPU. The other spacecraft subsystems require a relatively small number of RTU's, hence there are only three levels of control, with module controller #3 inter facing directly between the RTU's and the CPU.

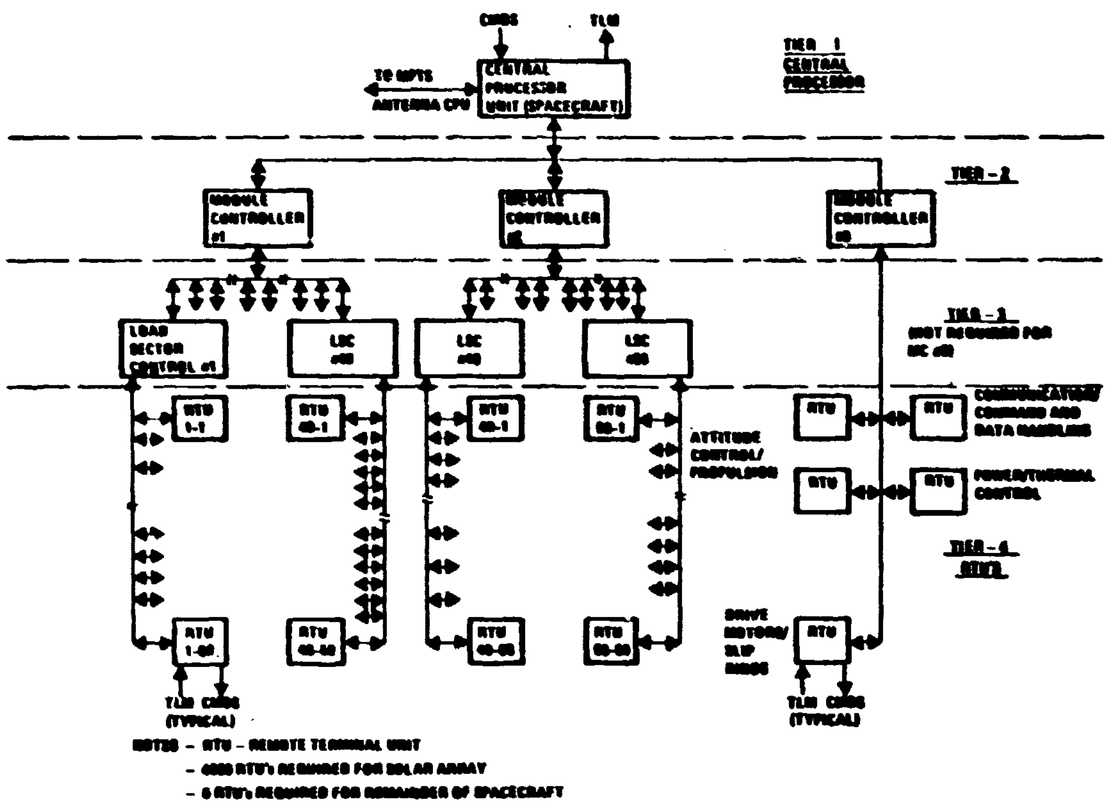


Figure 1.1.3-1 Spacecraft CDHS Using Four Tiers of Processors

The 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 maintaining stored commands for opperating and testing the data subsystem in the absence of ground control and control of telemetry data storage for later tranmission.

Each tier monitors operation of the tier below, instigates check on subordinate units and establishes priority for upward communication. The lowest tier interfaces the CDHS to other subsystems 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 RTU involved, or information from another RTU, warrants such action.

Figure 1.1.3-2 shows the configuration for the MPTS antenna which utilizes five tiers of control not only because of the much greater telemetry and command requirements, but because much quicker response is required by the power sectors and klystrons of the MPTS in order to prevent extensive damage in the event of an anomaly. The RTU's (5), monitoring these components monitor fewer sensors but sample them at nearly twice the rate of the spacecraft RTU's. Similarly, at the next level above the RTU's, the RTU controllers (4), monitor fewer RTU's but sample their outputs at a higher rate.

Tiers (3) and (2) provide communications management and test programs for the subordinate tiers except in the case of module controllers #4 and #5 which monitor and control the antenna subsystems other than the MPTS. For these subsystems the number of RTU's is much smaller because of the lower requirements. As in the case of the spacecraft the number of intermediated tiers is reduced for the portion of the CDHS associated with these subsystems.

WBS 1.1.4 Attitude Control and Station Keeping

WBS Dictionary

The attitude control subsystem includes all operational elements and software required to maintain orbit station keeping and attitude control of the SPS in the operational orbit or to establish attitude control from an initially uncontrolled condition.

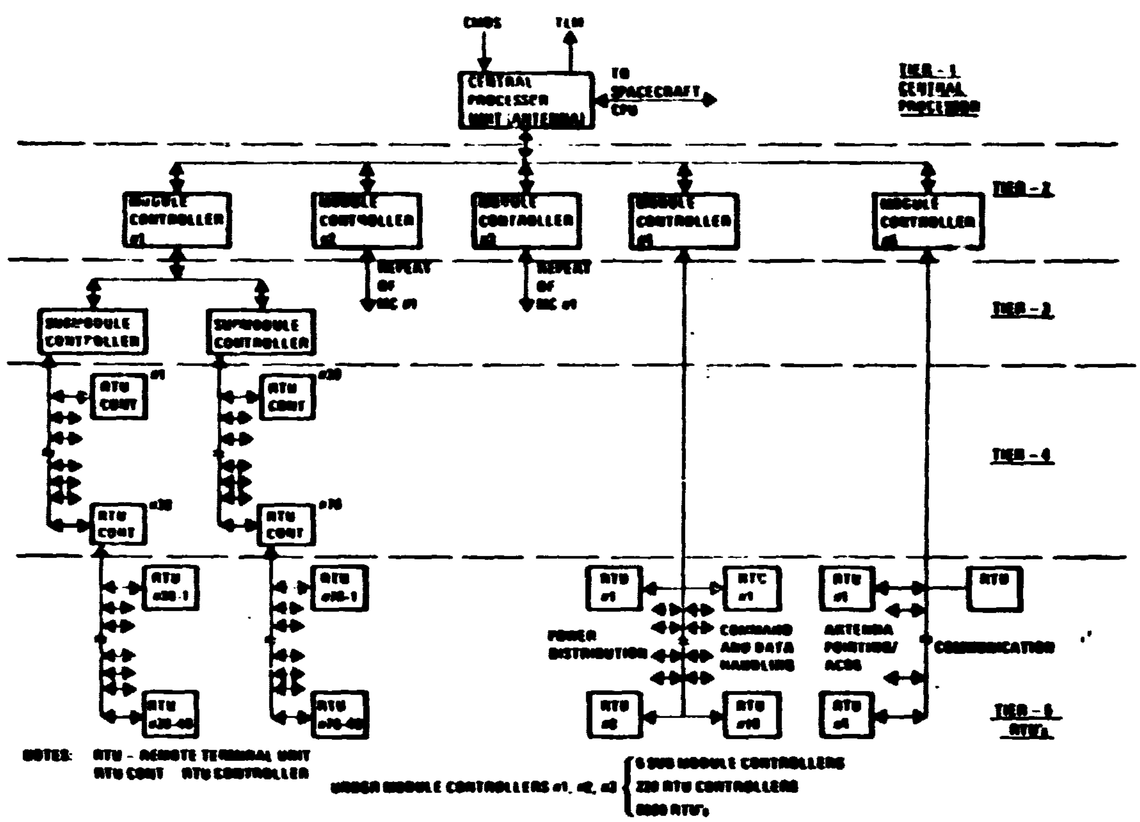


Figure 1.1.3-2 MPTS Antenna CDHS Using Five Tiers of Processors

Description

The attitude control system includes attitude sensing and an electric propulsion system withfour installations, one at each corner of the SPS energy conversion system. A typical corner constallation is illustrated in Figure 1.1.4-1. 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 equinoctal occultations or unexpected loss of electric power. Additional discussion of attitude control operations may be found in Sections 1.1.0.3 and 1.1.0.4 of Volume II of this report.

Mass

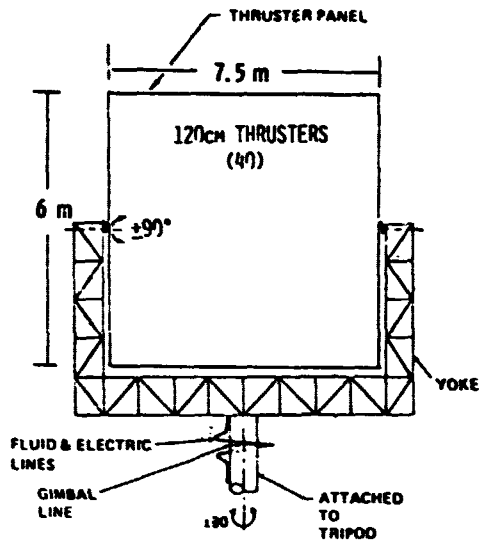
A mass summary of the attitude control system was given in the comprehensive mass table. This mass estimate is based on Part II results described in Volumes 5 and 6 of the Part II Final Report, adjusted to reflect the current 5-GW configuration.

Cost

A cost sumary for the attitude control system is given in Table 1.1.4-1. The cost data represents an update from the Contract NAS9-15196 Part II Final Report results.

WBS 1.1.4.1 Sensor Systems

Velocity control is required to maintain orbit station by offsetting solar pressure and orbital drift toward the neutral point. Attitude control is required to provide Sun orientation of the collector and high accuracy Earth rectenna pointing of the two antennas. In addition to countering the gravity-gradient disturbance torgues, the control concept must avoid unstable interaction of the antenna and collector control loops and structural flexibility effects. The current baseline approach for 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. The basic features of this concept are illustrated in Figure 1.1.4-2. 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.



ELECTRIC THRUSTERS

- 4 PANELS (ONE AT EACH CORNER)
- THRUST/PANEL - 150N
- 15 OPERATING THRUSTERS/PANEL (25 TOTAL)
- I_{SP} = 20,000 SEC
- ARGON PROPELLANT (50,000-60,000 Kg/YEAR)
- OPERATING LIFE - 2 YEARS (0.5 DUTY CYCLE AND 80A BEAM CURRENT)

CHEMICAL THRUSTERS (LO_2/LH_2)

- CONTROL DURING EQUINOCTAL OCCULTATIONS
- I_{SP} = 400
- 1500 - 3000 KG/YEAR

Figure 1.1.4-1 Attitude Control System Thrusters

Table 1.1.4-1 Flight Controls System Cost

THRUSTERS 160 X $10,000*	= $ 1.6 MILLION
PROCESSORS $3.57M EACH X 12	= $42.84 MILLION
INSTALLATION	= $25.0 MILLION
TANKS	= $ 5.8 MILLION
CONTROL	= $12.6 MILLION
	$85.0 MILLION

*LOW COST RESULTS FROM COMMONALITY WITH ORBIT TRANSFER THRUSTERS. THEY ARE THE SAME EXCEPT FOR ACCELERATION VOLTAGE AND OPTICS.

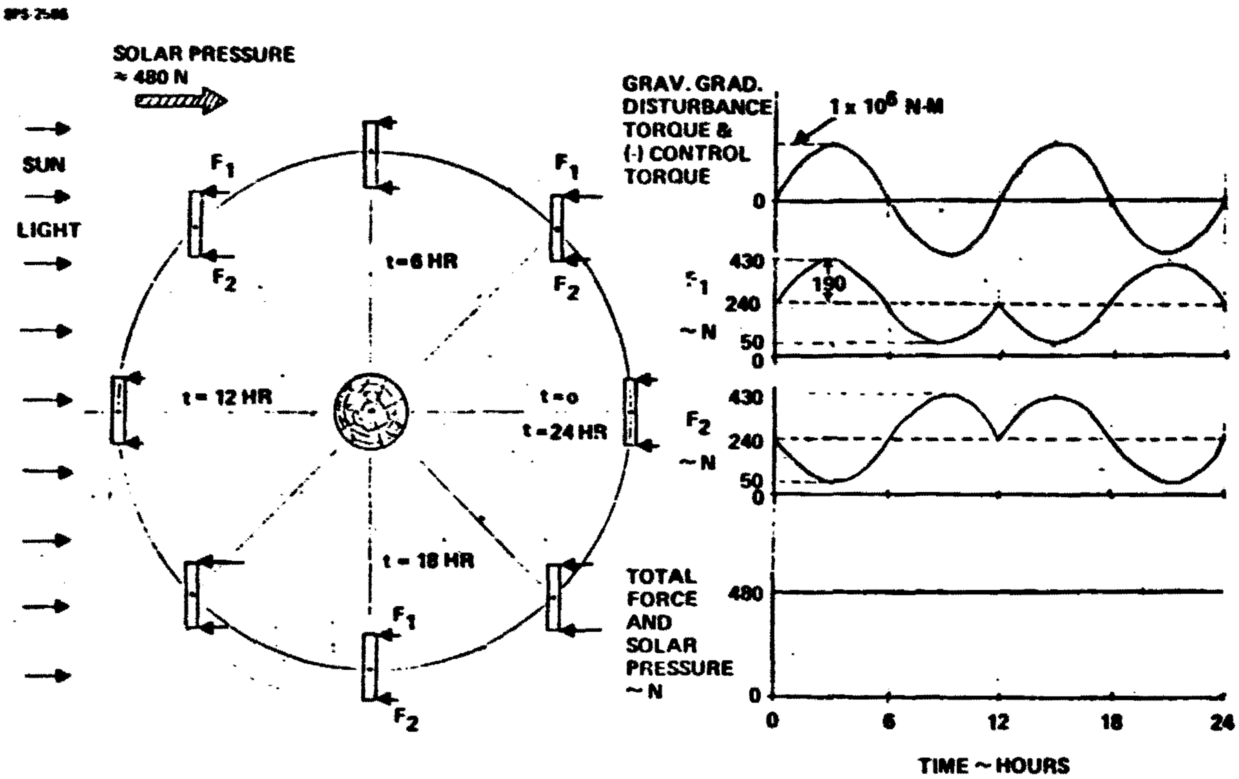


Figure 1.1.4-2 Operational (GEOSYNC) Orbit—Combined Attitude and Station Control

WBS 1.1.4.2 Electric Propulsion

WBS 1.1.4.2.1 Thrusters

WBS Dictionary
Thrusters include the primary electric thrusters for maintenance of attitude control, and auxiliary chemical thrusters required for establishment of attitude control when electric power is not generated by the SPS.

Description
The electric thrusters are 120 centimeter diameter ion thrusters operated on argon as primary propeelant. A typical thruster is illustrated in Figure 1.1.4-3. Performance characteristics for such a thruster are illustrated in Figure 1 1.4-4.

Mass
Electric thruster mass was estimated at 50 kilograms each based on extrapolations from the 30 centimeter thrusters presently in experimental production.

Cost
The thruster cost estimate was derived from an electro-mechanical cost estimating relationship and a production rate extrapolation. A cost check was made between this result and a cost estimate provided to NASA by the thruster manufacturer (Hughes) with good agreement.

WBS 1.1.4.2.2 Propellant
The propellant for the electric propulsion system is liquid (cryogenic) argon. 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 counter-thrust. The chemical propulsion system employs liquid hydrogen and liquid oxygen.

WBS 1.1.4.2.3 Propellant Tanks

WBS Dictionary
This element includes the argon, oxygen, and hydrogen propellant tanks for the SPS attitude control thrusters. It also includes tank-mounted equipment such as propellant gauging and vent valves and the multilayer insulation on the tank.

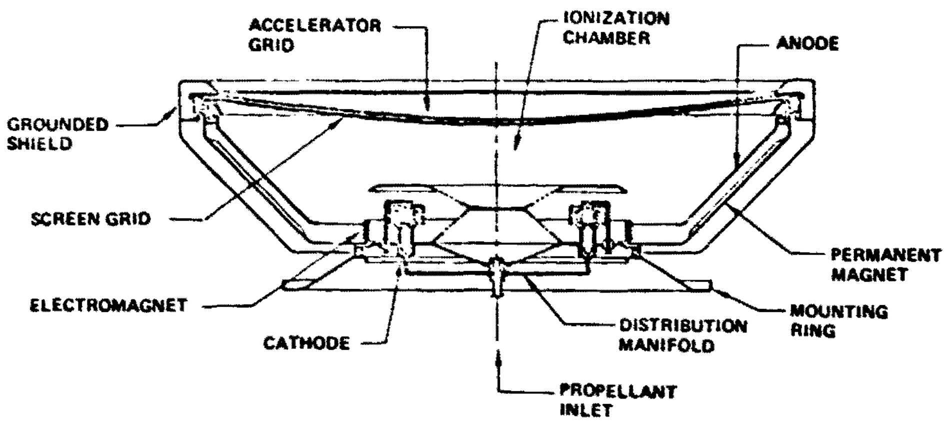


Figure 1.1.4-3 120 CM Argon Ion Thruster

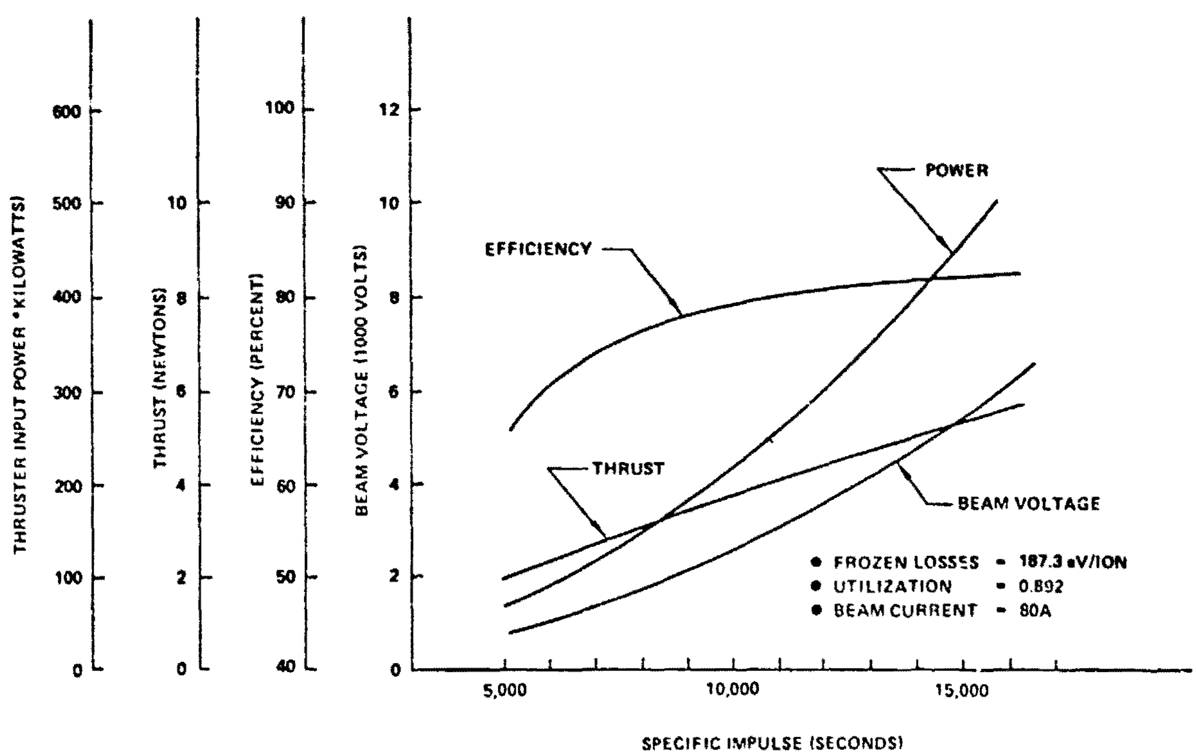


Figure 1.1.4-4 120 CM Argon Ion Thruster Performance

Description

The propellant containers are spherical aluminum tanks located near each thruster installation. Tanks are sized to hold one year's supply of propellant plus a 20% margin. The oxygen and hydrogen tasks include a 20,000 kilogram maneuvering reserve in addition to the normal control propellant. This is sufficient to re-establish the SPS normal attitude from any initial attitude.

Because of the long propellant storage time the tanks are designed with a light-weight hard-shelled vacuum jacket that includes approximately 50 layers of multilayer insulation. The tanks are designed to be refilled from a tanker or removed and exchanged with new tanks brought from Earth.

Mass

The mass of the propellant tanks was estimated as 7½% of the fluid contained. The total mass is 1500 kilograms per corner not including contained propellant. The contained propellant is 80,000 kg including the maneuvering reserve.

Cost

The cost of the tanks was estimated using a cost estimating relationship for tank structures. The total cost for all tankage was estimated at $5.8 million, about $970/kg.

WBS 1.1.4.2.4 and 1.1.4.2.5 Propellant Feed Thrust Control System

WBS Dictionary

These elements include all propellant feedlines and thrust control electronics and intrumentation.

Description

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

WBS 1.1.4.2.6 Power Processors

WBS Dictionary

The power processor element includes all power processing required to convert the SPS-generated electrical power (at 40,000 volts) to the voltages and conditions required by the attitude control system, including thruster requirements, control requirements, as well as computing and other requirements.

Description

Power processors are solid state electronic processors that convert the 40,000 volts from the SPS to the lower voltages required by thrusters and other equipment. There are a total of 12 processors, three at each corner.

Mass

Mass of each power processor was estimated as 15,583 kilograms based on a mass scaling relationship of 1.7 kilograms per kilowatt. This estimate includes the thermal control that would be required for these processors.

Cost

Each processor was estimated to cost $3.57 million dollars based on production rate scaling from cost estimate projections derived for similar hardware in commercial production. This is about $230/kg.

WBS 1.1.4.3 Chemical Propulsion

A detailed definition was not developed

WBS 1.1.4.4 Structure and Installation Hardware

WBS Dictionary

This element includes all structure and attitude control installation hardware not accounted for under other WBS items. As such, it includes all structural equipment and standoffs added to the basic SPS structure to mount the attitude control systems. Also included are secondary structure or support of propellant tanks and other equipment, and the gimbal system and thruster panels required to control the thrust vector direction of the thrusters.

Description

The structure was illustrated earlier in Figure 1.1.4-1. The structure would be similar to the SPS primary structure including truss beams with suitable terminations to form the tripod-like standoff. The gimbal system is a 2-axis motor-driven slow rate gimbal system. Gimbal commands are derived from the instrumentation and control system. The thruster panels provide mounting for the thrusters and support routing for the electric power feeds from the power processors.

Mass

Each structural installation was estimated at 6000 kg, for a total of 2500 kg.

WBS 1.1.5

Communication Subsystem

The design of the communication subsystem must take into consideration not only normal but also contingency operations. In developing the recommended system two of the first alternatives considered were use of the uplink pilot signal from the rectenna for transmittal of commands and modulation of one of the MPTS antenna klystrons for transmission of telemetry. Both of these techniques have the disadvantage that the MPTS antenna beam is deliberately despoiled in the event of loss of attitude control, thus severely degrading the communication link at a critial period of operation.

The recommended communication subsystem configuration consists of a spacecraft system and an MPTS antenna system which have a limited data link by the data bus through the slip rings. The recommended IMC system is such that approximately one megabit/sec. rate is require for both the command uplink and the telemetry downlink. Figure 1.1.5-1 is a block diagram of the recommended communication subsystems. Both subsystems have a two foot parabolic antenna each providing an earth coverage gain of 18 dB at S-band. An omni-antenna is located on the spacecraft to provide for command reception in the event of a major error in spacecraft attitude control. The configuration shown, with a 20 watt transmitter will transmit up to 20 Mbps and receive up to 10 Mbps.

Figure 1.1.5-2 is 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. A concern with this frequency plan is the broadband

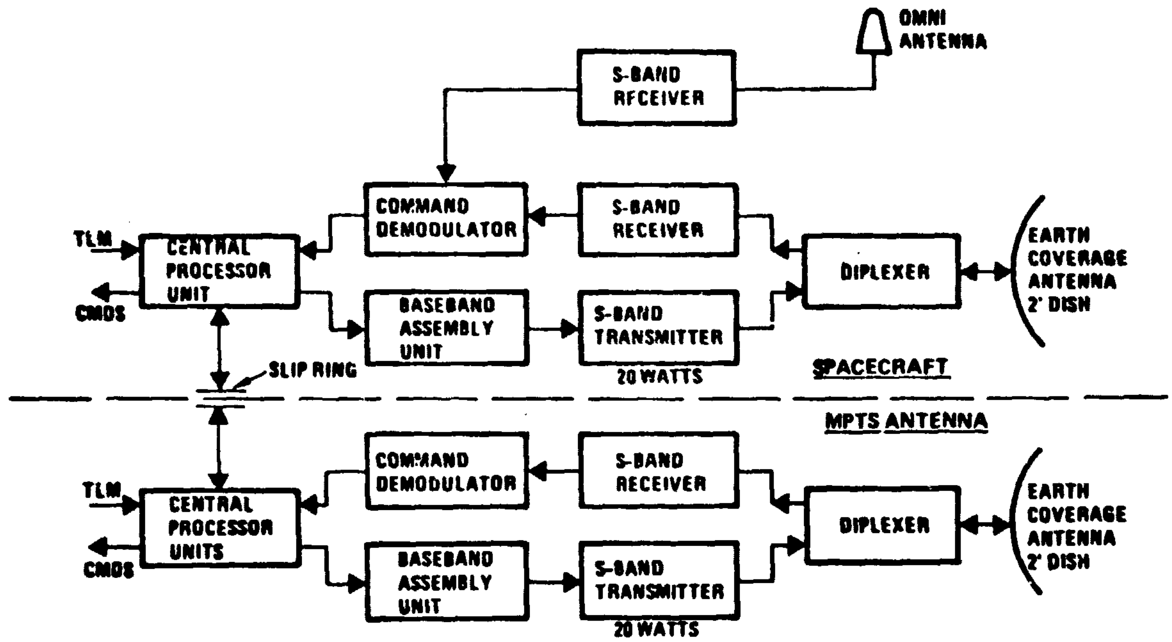


Figure 1.1.5-1 SPS Communication Subsystem

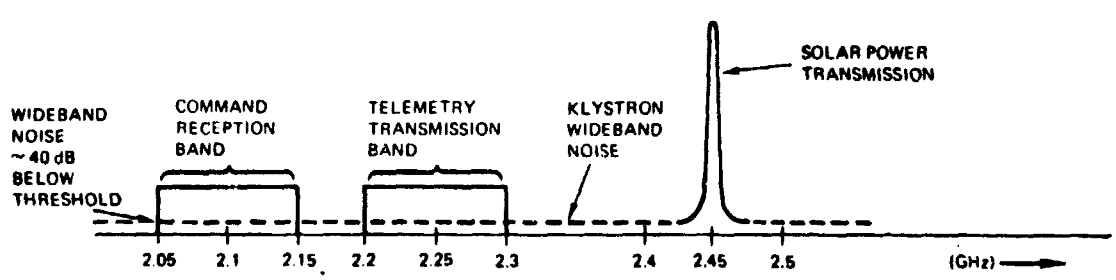


Figure 1.1.5-2 Communication Subsystem Frequency Plan

noise transmitted from the MPTS power transmission klystrons falling within the 2.050 to 2.150 GHz reception band. A typical klystron transmits AM and FM noise in the vicinity of the RF carrier. At about one megahertz from the carrier, the noise character. .c is relatively constant at a value of 130 dB/KHz below the carrier component. Beyond the klystron's passband (typically 10 MHz) the noise characteristic is further attenuated by the rolloff characteristic of the klystron cavities. For a six cavity klystron, approximately 400 MHz away from the carrier (at the uplink command reception band), the rolloff characteristic of the klystron is approximately 220 dB (six octaves). The output noise from the 100,000, 70 KW klystrons at the edge of the klystron passband is 10 dBW, while within the command reception band it is 220 dB below this value or -210 dB (-180 dBM). A typical phase-lock loop command receiver has a sensitivity or threshold of -140 dBM. Under the above assumptions, then, the wideband klystron noise is approximately 40 dB below the command receiver threshold. Had this not been the case, some other frequency band, such as the 11.0 to 14.0 GHz band could have been selected. Higher frequencies may be desirable to minimize band crowding and interference in the SPS time frame.

WBS 1.1.6 Interface Antenna Yokes and Turntables

WBS Dictionary

This element includes all production hardware required to mechanically interface the satellite primary structure with the MPTS structure. Subelements include the mechanical rotary joint and drive system, the elevation yoke joint, and interface structure between the satellite and MPTS systems.

WBS 1.1.6.1 Structure

The MPTS antenna is attached to the satellite primary structure by the use of an antena yoke, yoke support sturcture, a mechanical rotary joint and an elevation joint (figure 1.1.6-1). The entire MPTS support structure is hinged at the edge of the satellite structure for LEO/GEO transport configuration.

The yoke support structure is composed of the 7.5 meter beams baselind for the satellite primary structure. The support structure beams join to form a hexagonal interface that provides eight support points for the mechanical rotary joint circular beam (figure 1.1.6-2).

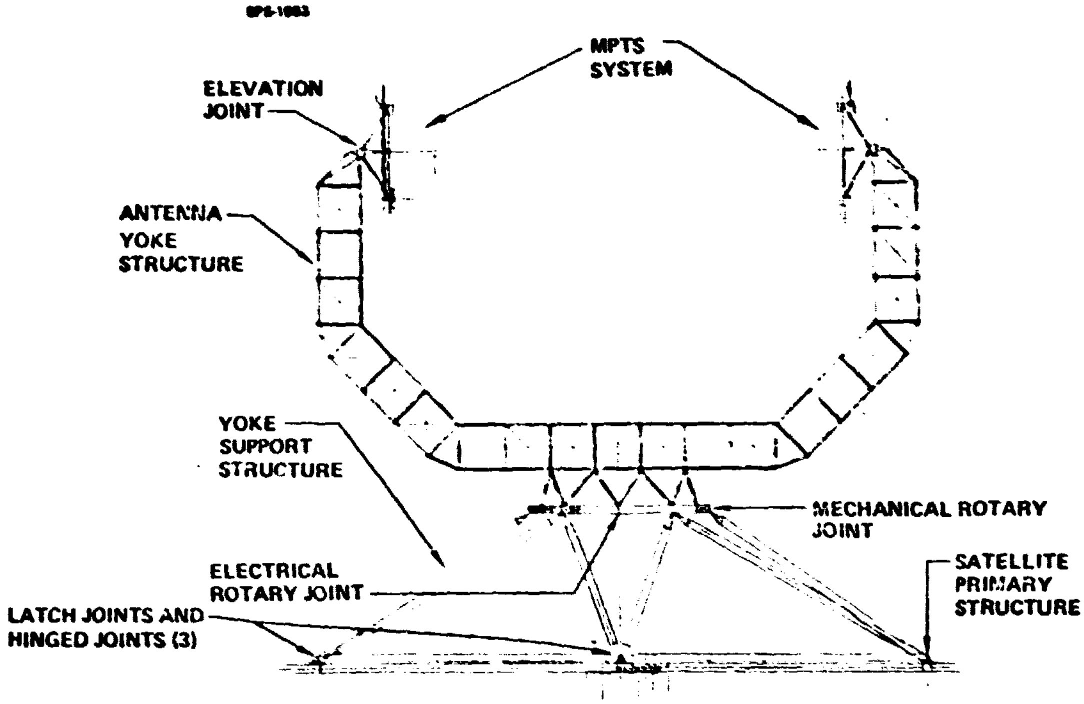


Figure 1.1.6-1 Antenna Yoke and Turntables

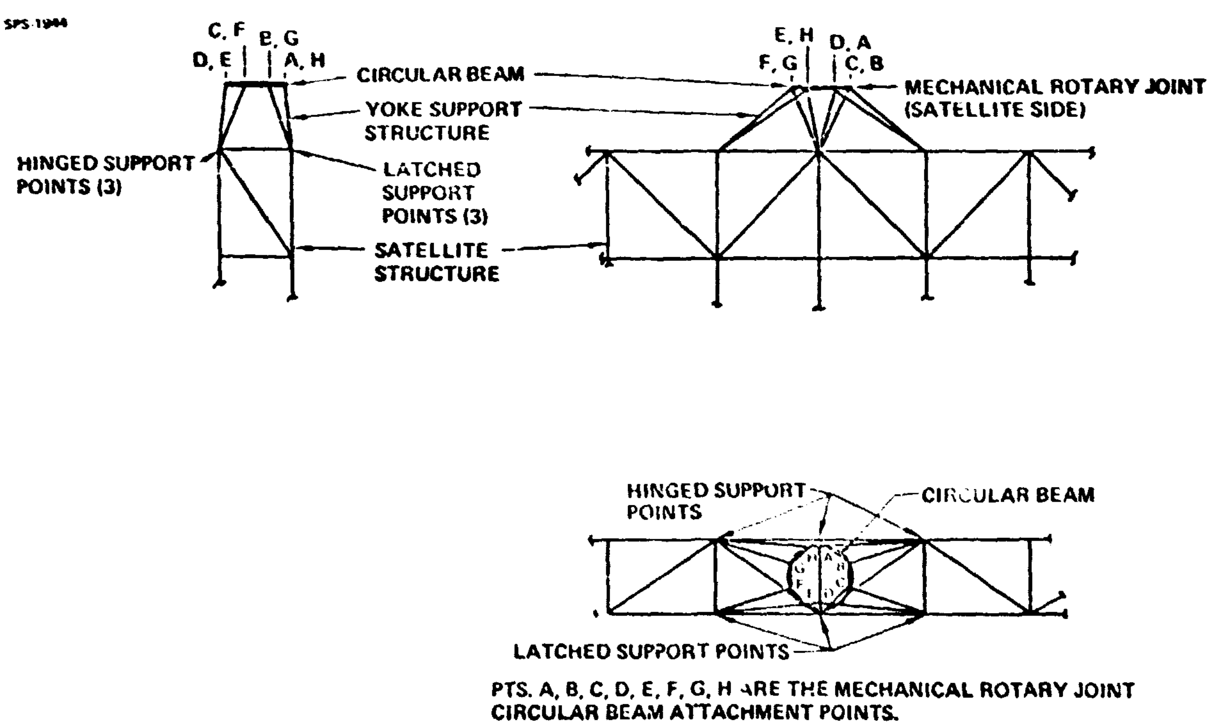


Figure 1.1.6-2 Yoke Support Structure

WBS 1.1.6.2 Mechanisms

The mechanical rotary joint is composed of two segmented circular beams (one on the satellite side and one on the yoke side), a section of which is shown in figure 1.1.6-3. Each circular beam is supported at eight points, ever 45 degrees, to its adjacent support structure. The inner and outer base chords of each circular beam are arranged adjacent to each other. Between each set of base chords, a drive ring and roller assembly is attached (figure 1.1.6-4) to provide relative movement between the satellite and MPTS system. The antenna yoke attaches to its circular beam in a similar method as described for the yoke support structure.

The yoke is composed of one hundred meter trusses made up of the same beams as that for the MPTS primary structure. At the antenna end of the yoke, a special end fitting is provided to interface with the antenna elevation joint. The elevation joint provides for a small pointing angle adjustment (approximately 7 degrees) of the MPTS system for alternate rectenna transmission capabilities.

There is an electrical rotary joint at the interface of the yoke and yoke support structure. The electrical connection across the elevation joint uses flex cables because of the small angle adjustment involved.

Element Mass

The mass of the antenna yoke and turntable, for one MPTS, is listed in Table 1.1.6-1. Included in these masses are the attachment provisions and mechanical elements necessary for the subelement supports.

Element Cost

The element costs estimating factors, for the items listed in Table 1.1.6-1, are listed in Table 1.1.6-2. Also listed is the total cost for one MPTS antenna yoke and turntable system.

Electrical Rotary Joint

The MPTS antenna-to-satellite interface requires 360^{o} rotation about the spacecraft central axis with limited motion for elevation steering while maintaining structural and electrical integrity between the satellite and the antenna. Figure 1.1.6-7 illustrated the rotary joint in relationship to the basic "satellite" structure.

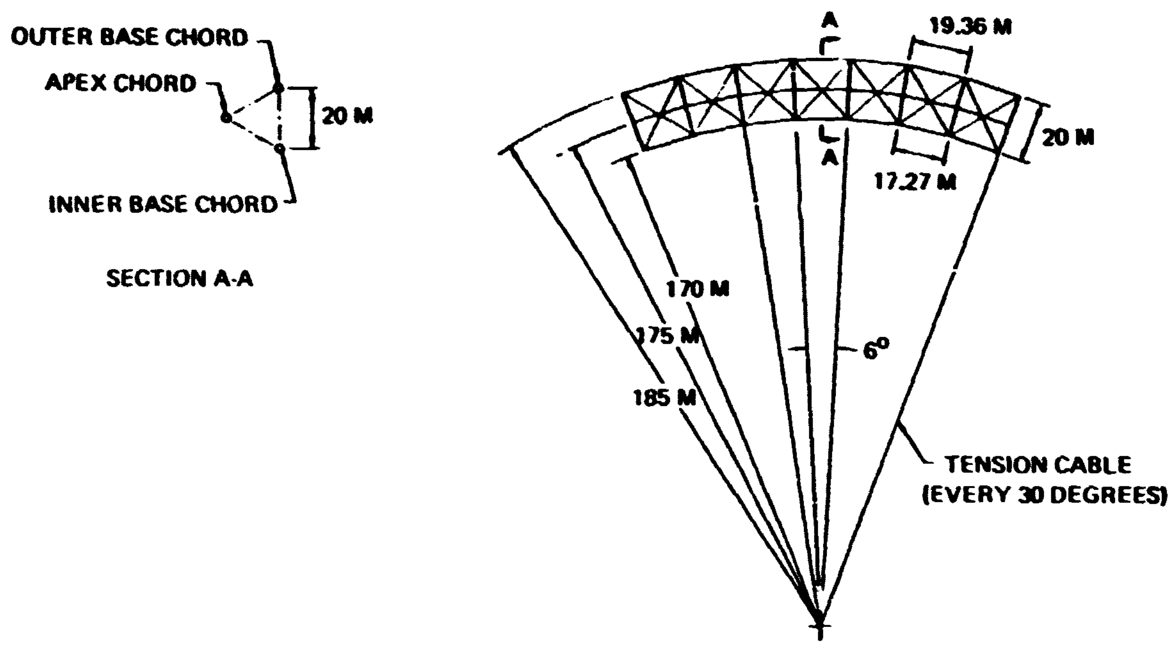
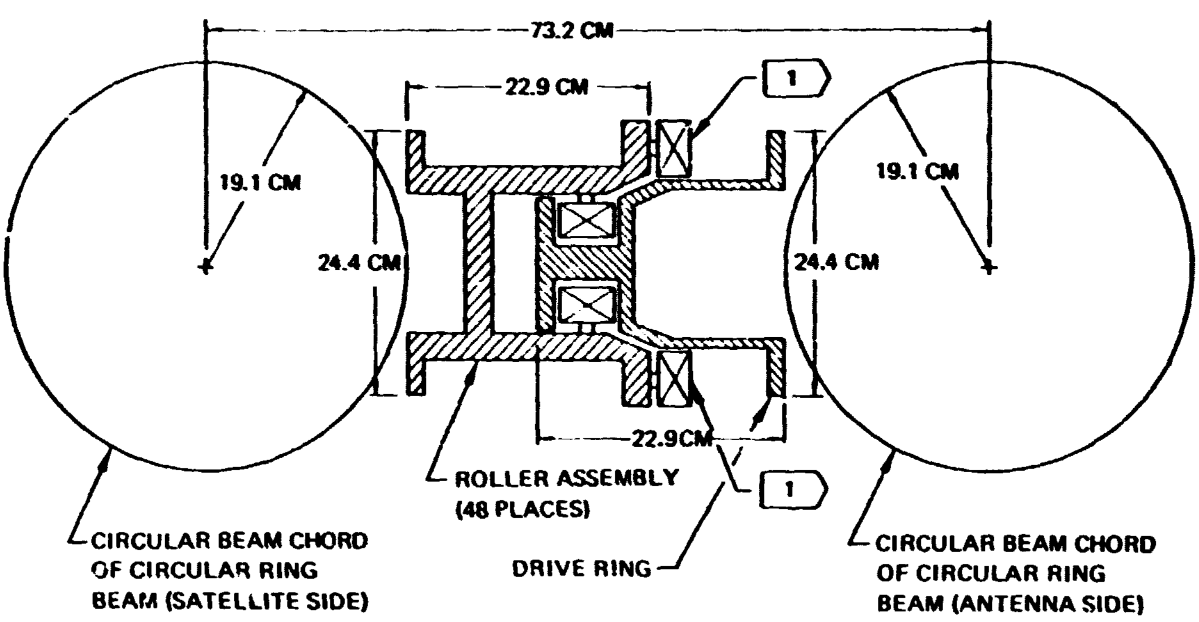


Figure 1.1.6-3 Circular Ring Beam Geometry



[1] A ROLLER/DRIVE ASSEMBLY IS LOCATED AT 12 PLACES (EVERY TENSION CABLE) AROUND THE PERIPHERY OF THE CIRCULAR BEAM (SATELLITE SIDE). THIS ASSEMBLY IS SIMILAR TO THAT SHOWN EXCEPT THAT THE WHEELS INDICATED BY FLAG [1] ARE MOTOR DRIVEN FRICTION WHEELS WHICH ARE SPRING LOADED ACROSS THE ASSEMBLY.

Figure 1.1.6-4 Drive Ring and Roller Assembly Location Relative Base Chords of Circular Ring Beams

Table 1.1.6-1 Antenna Yoke and Turntable Mass Estimate

ANTENNA SUPPORT STRUCTURE	53.0 MT
MECHANICAL ROTARY JOINT	33.4 MT
ANTENNA YOKE	41.2 MT
TOTAL	127.6 MT

Table 1.1.6-2 Antenna Yoke and Turntable Cost Estimate

ELEMENT	CER ($/KG)	COST ($10 ^{6})
ANTENNA SUPPORT STRUCTURE	111	5.87
MECHANICAL ROTARY JOINT	340	11.36
ANTENNA YOKE	128	5.27
TOTAL COST		22.5X10 ^{6}

Coin silver (90% silver and 10% copper) was selected for the slip-ring material and a silvermolybdenum disulfide brush with 3% graphite was selected. The characteristics of this combination are shown in Figure 1.1.6-5. With a design using a brush current density of 20 amps/cm^2 only about 40 kW of power is dissipated in the rotary joint.

The installation of a single brush assembly on a circular slip-ring causes unwanted deflections due to assymetrical loading. For this reason, the slip-ring/brush assembly was designed for symmetical loading as shown in Figures 1.1.6-7 and 1.1.6-8. Brush drag (with a coefficient of friction of 0.14) at a brush pressure of 4 PSI (25.6KPa) was computed to be 307N, and 463N (69, 87 and 104 pounds force) for each inner, middle and outer slip-ring brush assembly. The brush design in shown in Figure 1.1.6-9.

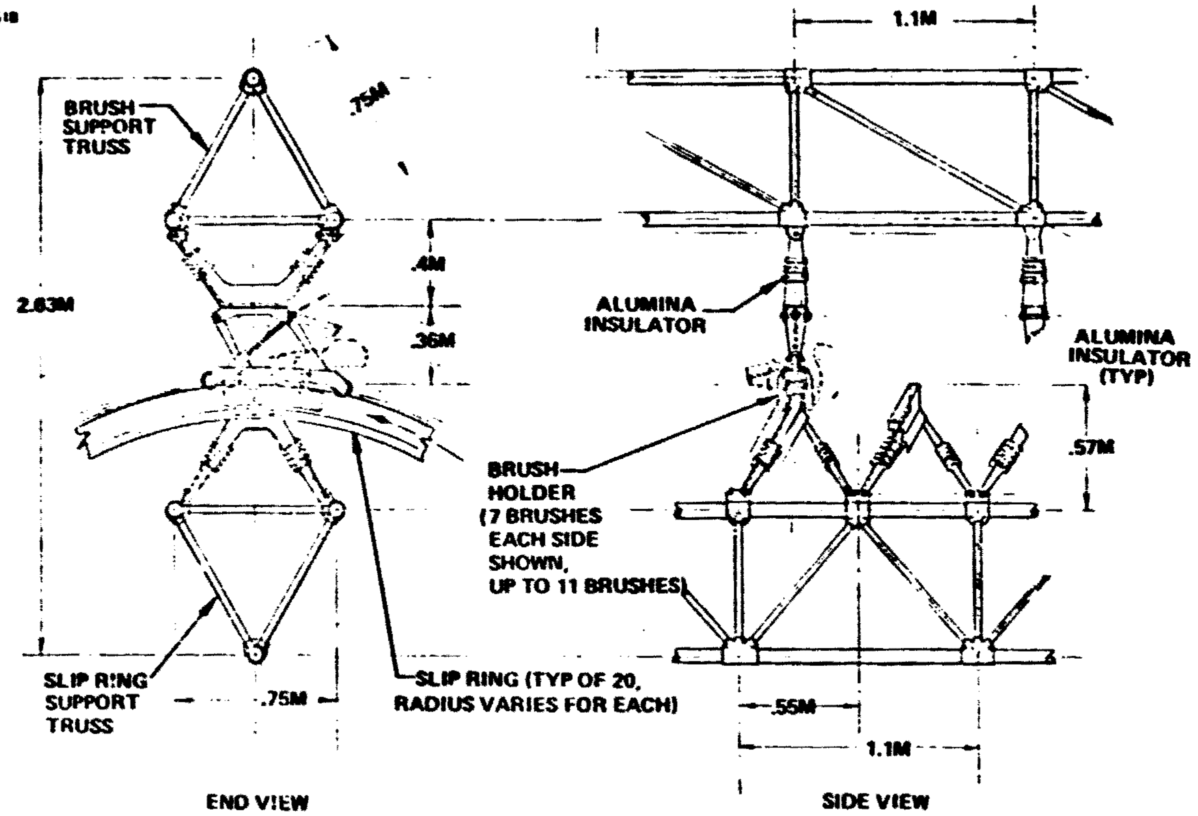
The coin-silver slip-ring is a bright surface and, hence, rejects heat very poorly. Coin silver is a very good conductor. The combinations of the two results in acceptable slip-ring temperatures based on IR&D test results. It was assumed that no heat is rejected through the slip-ring feeders. Actual operating temperatures will thus be somewhat lower than shown since the feeders are designed to operate at a much lower temperature and will help in removing slip-ring waste heat.

With the selection of the multiple bus system for SPS power distribution, the requirement for a multiple slip-ring rotary joint exists for accomplishing the transfer of power between the power generation (sun-facing) portion and the power tranmission (earth-facing) portion of the SPS. A design was developed which provides for twenty slip-rings to accomplish power transfer for the ten pairs of power buses.

The concept shown in figure 1.1.6-10 was developed bsed on the following requirements:

1. twenty separate slip-ring assemblies
2. normal slip-ring current capabilities
3. maximum brush current density of 20 amperes per square centimeter
4. brush feeder current density of 400 amperes per square centimeter
5. brush pressure of 25.9 Kpa (4 psi)
6. coin silver slip-ring (90% silver and 10% copper)
7. silver-molybdenum disulfide-graphite (85% Ag, 12% MOS_2, and 3% Graphite) brushes

SPS-2518



SPS 2540

Figure 1.1.6-7 Multiple Slip Ring Brush Assembly

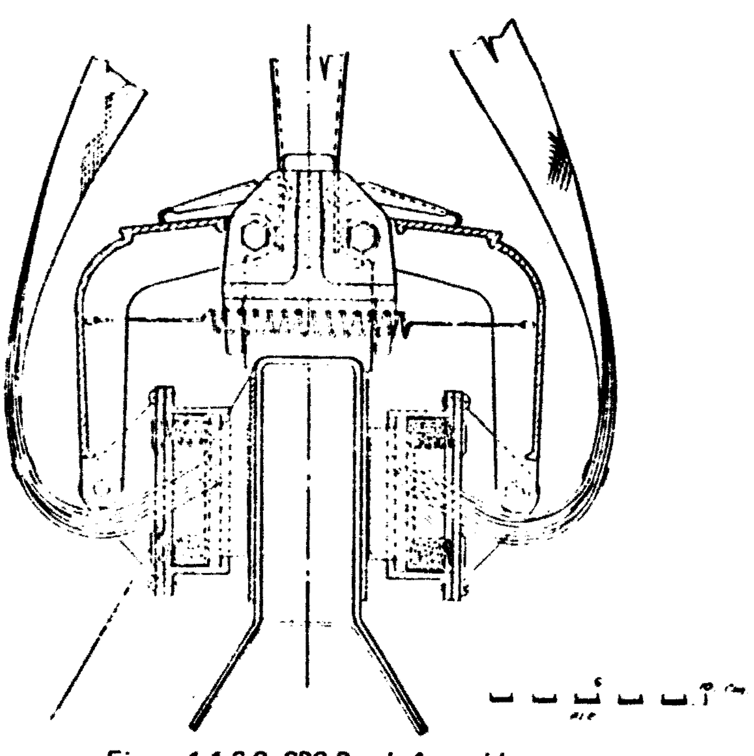


Figure 1.1.6-8 SPS Brush Assembly

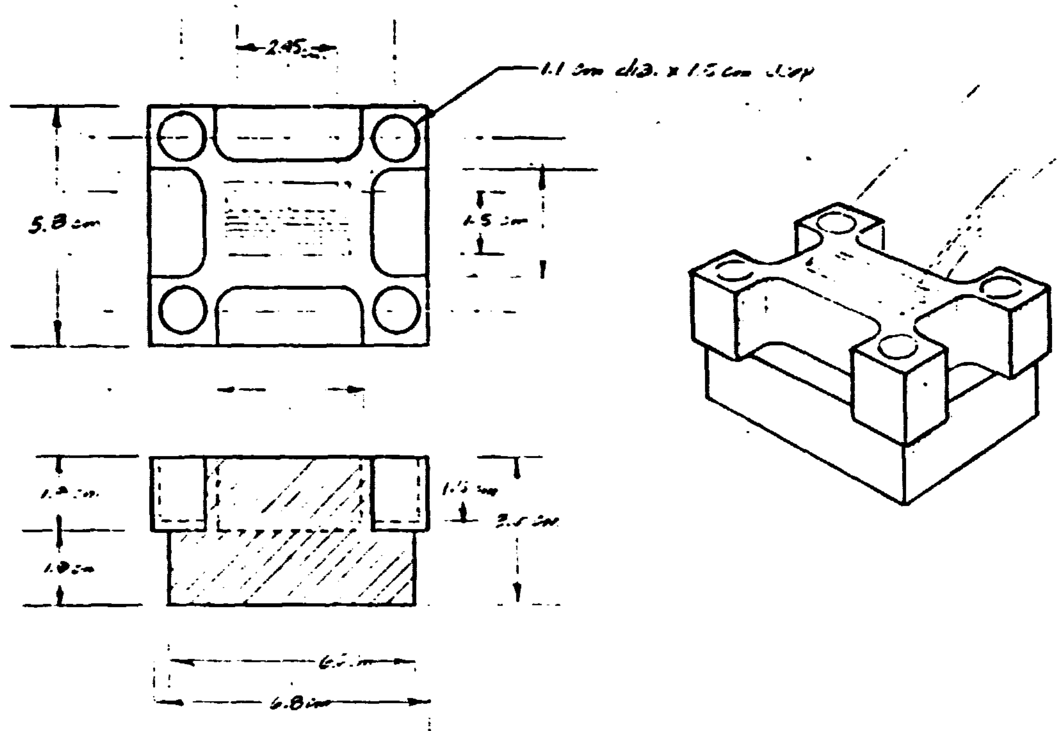


Figure 1.1.6-9 Brush for SPS Application

SPS-2552

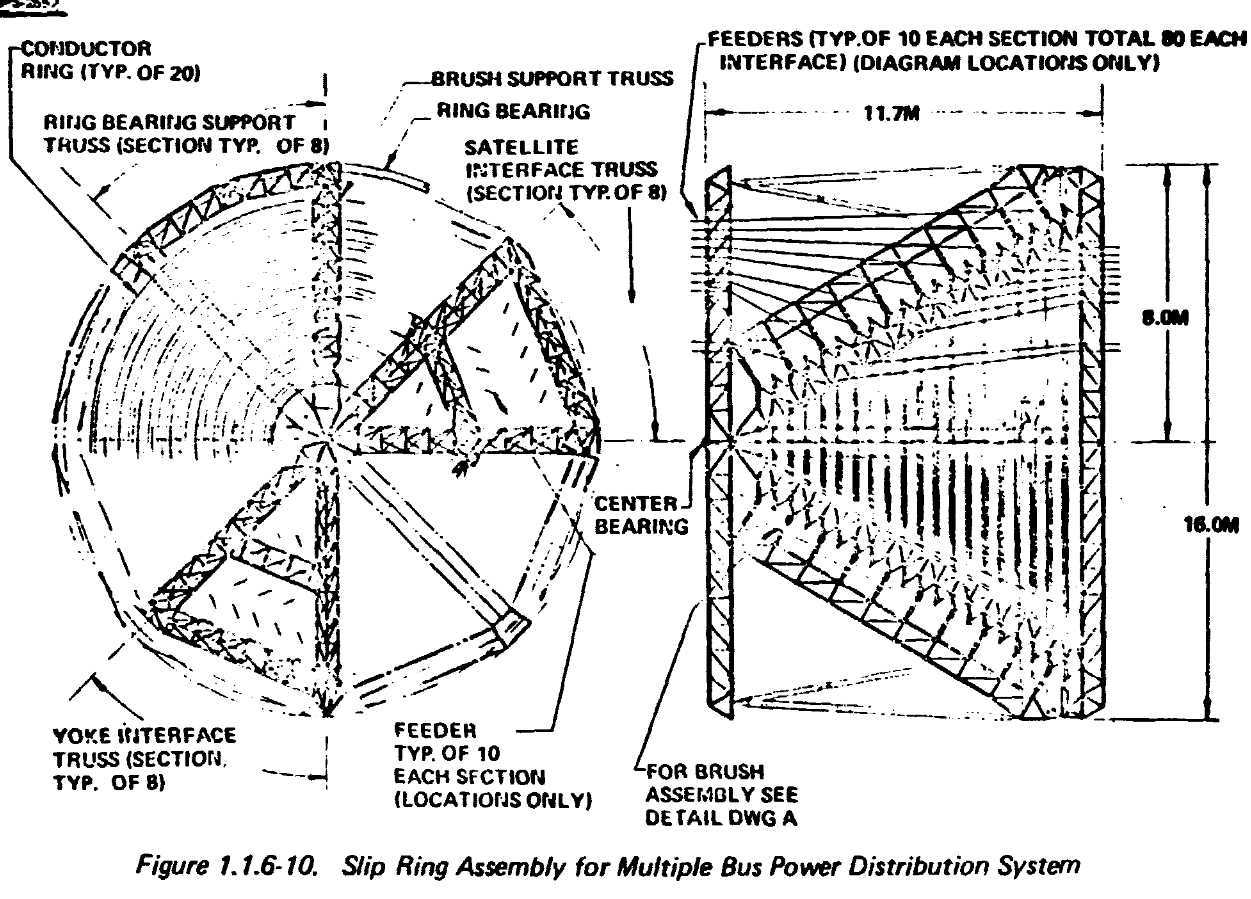


Figure 1.1.6-10. Slip Ring Assembly for Multiple Bus Power Distribution System

8. maximum outside diameter of 16 meters (fits inside HLLV payload bay)
9. Earth assembled
10. minimum spacing between different conductor systems of 0.7 meters
11. positive retraction of the brush assembly from the slip-ring contact surface
12. All feeder conductors to have maximum surface exposure to free space for thermal dissipation purposes.

The design shown meets the above requirements. A typical brush assembly/slip-ring interface, a cross-section of the brush assembly, and a typical brush were shown earlier.

WBS 1.2 SPACE CONSTRUCTION AND SUPPORT

WBS Dictionary

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

Although WBS 1.2.1.2-3 "Operations" is used to collect certain costs, descriptions of operation of equipment is integrated with descriptions of the equipment in order to enhance clarity. Crew count and operations costs are summarized under WBS 1.2.1.3.

Element Description

The baseline construction concept entails constructing a 5 GW photovoltaic SPS at geosynchronous orbit (GEO) using electric orbital transfer vehicles (EOTV's) to haul cargo between a low Earth orbit (LEO) base and a GEO base, see Figures 1.2.0-1 and 1.2.0-2.

Cargo is delivered to the LEO base by heavy lift launch vehicles (HLLV's). There would be three HLLV flights every two days. Crews are delivered to the LEO base either by the HLLV's or by shuttle orbiter crew bus once 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 the vehicles which will deliver them to GEO. During the EOTV construction operations there would be about 200 people at the LEO base. During the on-going 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) orbital transfer vehicles (OTV's).

The SPS's are constructed at GEO using a 4-bay- wide end builder construction base. The GEO construction base will construct one 5 GW SPS in approximately 6 months employing a crew of approximately 385 people.

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

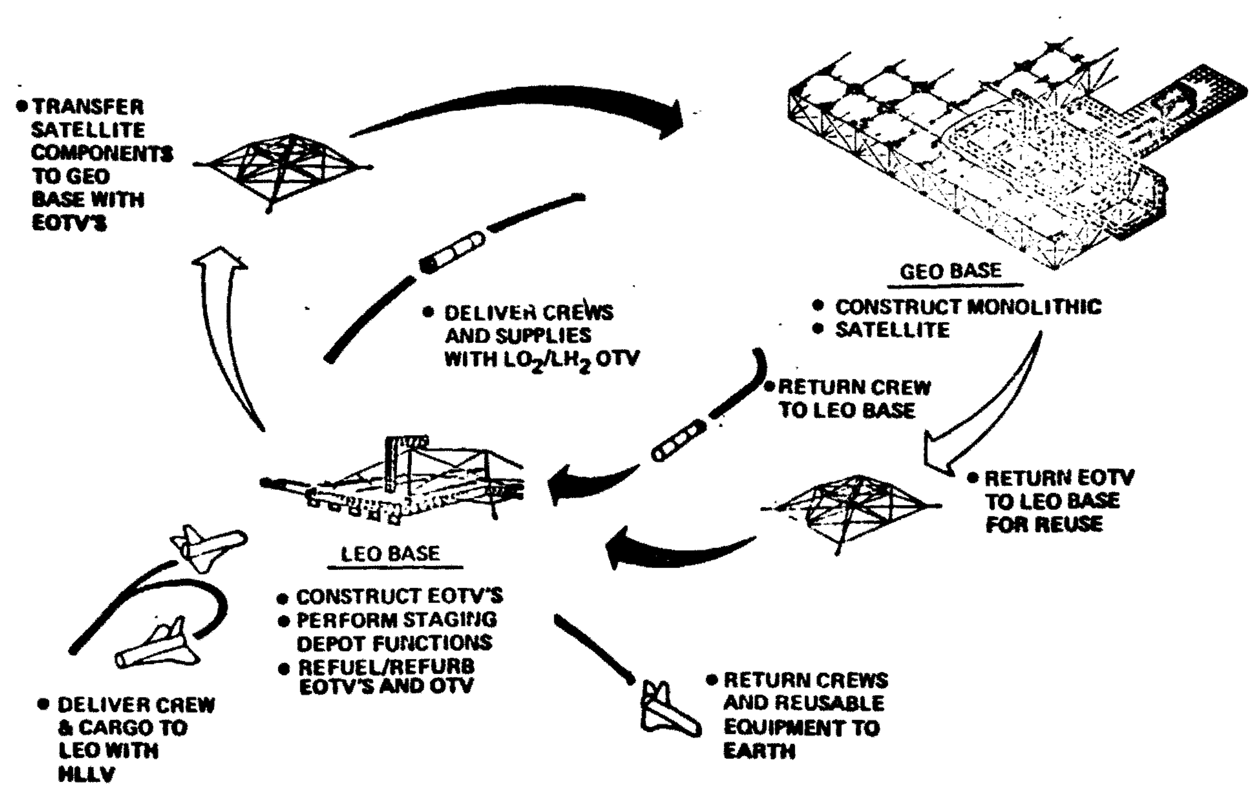


Figure 1.2.0-1 GEO Construction Concept

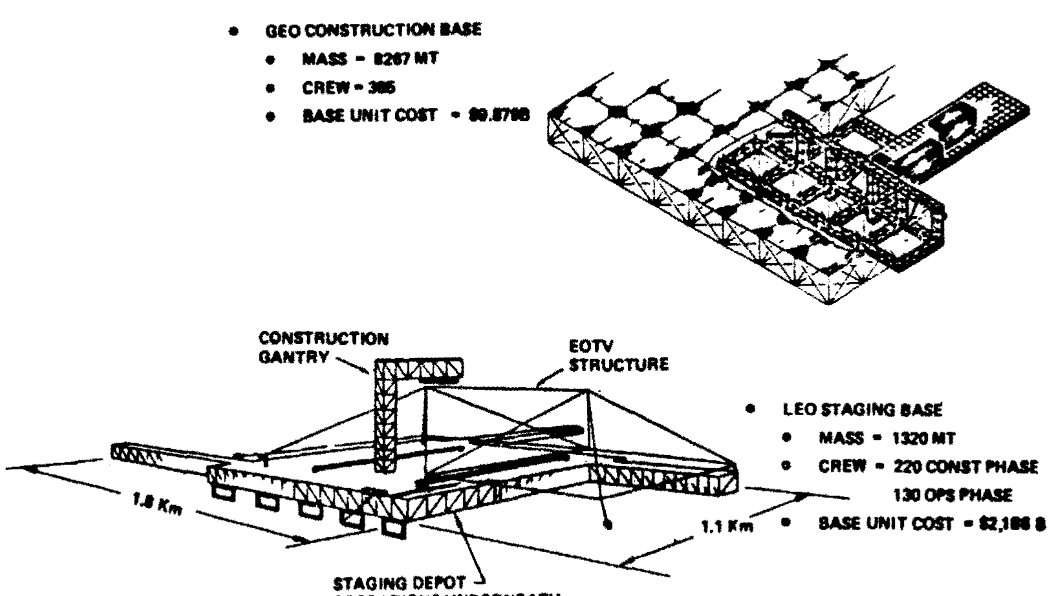


Figure 1.2.0-2 Orbital Bases—GEO Construction

to operational SPS's. The maintenance crew size at GEO depends upon how many operational SPS's are in orbit. If 20 SPS's were in place, it is estimated that there would be 240 maintenance people at the GEO base and 240 people visiting the satellites.

The GEO base, its configuration, equipment, and operations are described in WBS 1.2.1. The LEO base, its configuration equipment and operations are described in WBS 1.2.2. The mobile maintenance equipment and operations are described in WBS 1.2.3.

WBS 1.2.1 CONSTRUCTION FACILITIES: GEO base

WBS Dictionary

This element 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.

Element Description

The GEO base is shown in Figure 1.2.1-1. It's primary function is constructing the 5 GW photovoltaic satellites. The base is designed to meet the requirements listed in Table 1.2.1-1.

The GEO base has three contiguous areas used to construct the energy conversion system, the power transmission system, and the interface system. For simplicity, these areas will be referred to as the Solar Array, Antenna, and Yoke construction areas.

The GEO base is referred to as a 4-Bay End Builder construction base. It gets this name from the manner in which the solar array portion of the SPS is constructed. Construction of the solar array takes place in an L-shaped facility, 2.96 km long with 700 m and 860 m wide legs. Solar array construction equipment (beam machines and handling devices, solar blanket installation facilities, and bus installation mechanisms, as well as habitation, docking, storage, etc) are mounted on the 700 m deep leg. The other leg of the facility guides and supports the longitudinal beams of the SPS until the bay structure is completed and self supporting. The antenna and yoke construction platform is mounted at a distance from the solar array facility to provide an area in which the rotary joint and mating structure can be built.

Table 1.2.1-1 GEO Base Requirements

1. Construct the 5 GW monolithic SPS within 6 months ± 5%.
2. Power collection system construction operations to be performed:
   a. Frame assembly
   b. Solar array deployment
   c. Power bus system installation
   d. Thruster system installation (electric and chemical thruster systems)
   e. Avionics system installation
   f. Module test and checkout
   g. Annealing machine gantry assembly and installation.
3. Antenna construction operations:
   a. Primary frame assembly
   b. Secondary structure deployment
   c. Wiring harness installation on the secondary structure.
   d. Antenna subarray deployment
   e. Power distribution system installation
   f. Antenna test and checkout
   g. Maintenance system track and gantry installation
4. Yoke construction operations to be performed:
   a. Frame assembly
   b. Mechanical rotary joint assembly
   c. Electrical rotary joint installation
   d. Power bus system installation
   e. Elevation joint installation
   f. Gimbal mechanism installation

(Continued)

Table 1.2.1-1 GEO Base Requirements (Cont'd)

5. Other construction operations to be performed:
   a. Antenna-to-yoke mating
   b. Antenna/yoke-to-module mating
   c. Subassembly operations
      1. Thruster assembly
      2. Antenna switchgear assembly
      3. Module switchgear assembly
      4. Power bus support hardware assembly
      5. Structure subassembly
6. The antenna and module construction facilities must be contiguous.
7. Provide docking and offloading systems for the following vehicles:
   a. Personnel OTV's
   b. EOTV-to-Base cargo transfer vehicles
   c. Maintenance Sortie OTV's and crew habitats
8. Provide operational areas for the following activities.
   a. OTV operations
      1. Stage handling
      2. Cargo handling
      3. OTV maintenance
      4. Propellant transfer and storage
   b. Cargo sorting and storage
   c. Subassembly factories
   d. Crew quarters, work modules
   e. Base maintenance
9. Free-flying of assemblies or construction and logistics equipment is to be avoided.

(Continued)

Table 1.2.1-1 GEO Base Requirements (Cont'd)

10. Provide a common base logistics track network for moving cargos, crew, and construction equipment. The logistics track will have a gauge compatible with the size of the base framework beams. Provide alternate pathways to every facility location. Ensure that there will not be competition for a specific track location. All vehicles self-powered and operator driven.

11. Ensure that relative motion between the facility/construction equipment and the parts being assembled are compatible with the accuracy and time constraints involved in the construction operations.

12. Provide moving indexing/support machines that interface the module-to-facility and antenna-to-facility.

13. Provide for base attitude control and station keeping, transfer capability from one longitudinal position to another. Thruster installation and thrust level to accommodate mass and CG excursions during construction operations. Thrust level not to exceed 5×10^{-5}g. Thrust will be constant thus allowing burn time to vary.

Table 1.2.1-2 gives the mass and cost summary for this base. Values in the table reflect SPS maintenance operations support facilities added to the GEO base as a result of maintenance analyses conducted during Part III of the prior study (Contract NAS9-15196).

WBS 1.2.1.1 Work Support Facilities

WBS Dictionary

This element includes the facilities and equipment required for satellite assembly and check out. Included are beam fabricators, manipulators, assembly jigs, installation and deployment equipment, and cargo storage depots. Excluded are the facilities related to crew support.

Element Description

This element describes the configurations of the GEO base structure, construction equipment, cargo handling/distribution system, subassembly factories, test/checkout facilities, transportation vehicle staging/maintenance facilities, and base subsystems. The mass and cost summary for these items was included in Table 1.2.1-2.

WBS 1.2.1.1.1 Structure

WBS Dictionary

This element includes the primary and secondary structure of the GEO base.

Element Description

The GEO base structural configuration is shown in Figures 1.2.1-2 and -3. The facility primary structure is composed of 100 m square section open truss beams. Each member of the trusses are 12.5 meter triangular-section beams. The mass and costs for the base structure were computed as shown below:

$$(240{,}000\text{m}) + (247{,}824\text{m})\ (1.2)(5\text{KG/m}) = 2927 \times 10^3\text{KG}$$

Antenna Platform	Solar Array Facility	20% Allowance	Total Base Structure Mass

$$(2927 \times 10^3\text{KG})\ (\$100/\text{KG}) = \$293 \times 10^6 \text{ Total Base Structure Cost}$$

SPS-2881

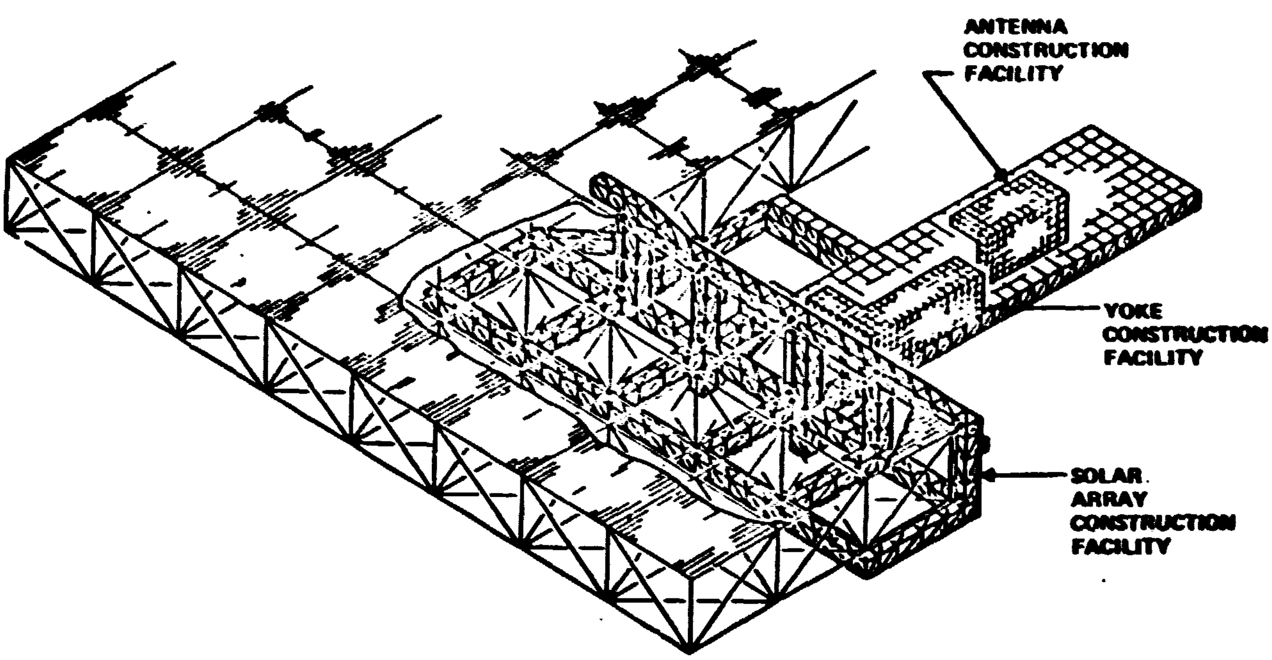


Figure 1.2.1-1 4 Bay End Builder

Table 1.2.1-2 Mass and Cost Summary for GEO Construction Base

SPS-2849

WBS NO. ITEM NAME	NUMBER OF UNITS	TOTAL MASS, 10^3 kg	TOTAL COST, $\$10^6$
1.2.1 GEO CONSTRUCTION AND OPERATIONS BASE	1	8359	9796
1.2.1.1 WORK SUPPORT FACILITIES		3985	2419 [1]
1.2.1.1.1 STRUCTURE		2927	293
1.2.1.1.2 CONSTRUCTION EQUIPMENT		401	1312
1.2.1.1.3 CARGO HANDLING/ DISTRIBUTION SYSTEM		255	313
1.2.1.1.4 SUBASSEMBLY FACTORIES		38	281
1.2.1.1.5 TEST/CHECKOUT FACILITIES		TBD	TBD
1.2.1.1.6 TRANSPORTATION VEHICLE MAINTENANCE FACILITIES		TBD	TBD
1.2.1.1.7 SPS MAINTENANCE SUPPORT FACILITIES		TBD	TBD
1.2.1.1.8 BASE SUBSYSTEMS		TBD	TBD
(ADD 10% FOR UNDEFINED ITEMS)		364	220
1.2.1.2 CREW SUPPORT FACILITIES		4374	4245 [1]
WRAPAROUND COSTS [2]			3132
SPARES (15%)			999.6
INSTALL, ASSEMBLY, CHECKOUT (16%)			1066.2
SE&I (7%)			466.2
PROJECT MANAGEMENT (2%)			133.3
SYSTEM TEST (3%)			200.0
GSE (4%)			266.6

[1] BASIC HARDWARE IS THE SUM OF 2419 + 4245 = $6664 x 10^6

[2] 47% OF BASIC HARDWARE

WBS 1.2.1.1.2 Construction Equipment

WBS Dictionary

This element includes all equipment items dedicated to construction of the SPS with the exception of equipment utilized in subassembly operations (the latter are included in WBS 1.2.1.1.4).

Element Description

Table 1.2.1-3 provides a summary listing of the equipment types, where used, quantities, mass and cost. Each of the major equipment items are described in the subelement descriptions beginning page 155.

Construction Operations Overview

SPS assembly operations commence with the construction of the energy conversion system as shown in Figure 1.2.1-4. Assembly of the energy conversion system is timed for simultaneous completion and mating with the interface system and power transmission system. The 5GW monolithic satellite is constructed and checked out in GEO in six months.

The 4 bay end builder uses two passes to construct the 8 x 16 bay energy conversion system; each pass provides a 4 x 16 bay module which contains the appropriate subsystems (i.e., structure, solar blanket; power distribution and control, attitude control, etc.). The main power bus is installed during the first pass in parallel with the fabrication of continuous logitudinal beams. The second construction pass is somewhat shorter since one side of the structure is already built, and therefore less vertical and diagonal support beams are required.

The interface system is constructed separately and then joined to the power transmission system. The satellite is fully assembled, when these systems are mated with the energy conversion system.

Energy Conversion System Construction Sequence

Figures 1.2.1-5 and -6 illustrate the generic sequence for assembling the energy conversion system on the end builder construction base. The construction process entails fabrication of continuous logitudinal structural members, fabrication and attachment of segmented structural members, and installation of power busses, solar arrays, and other required subsystems.

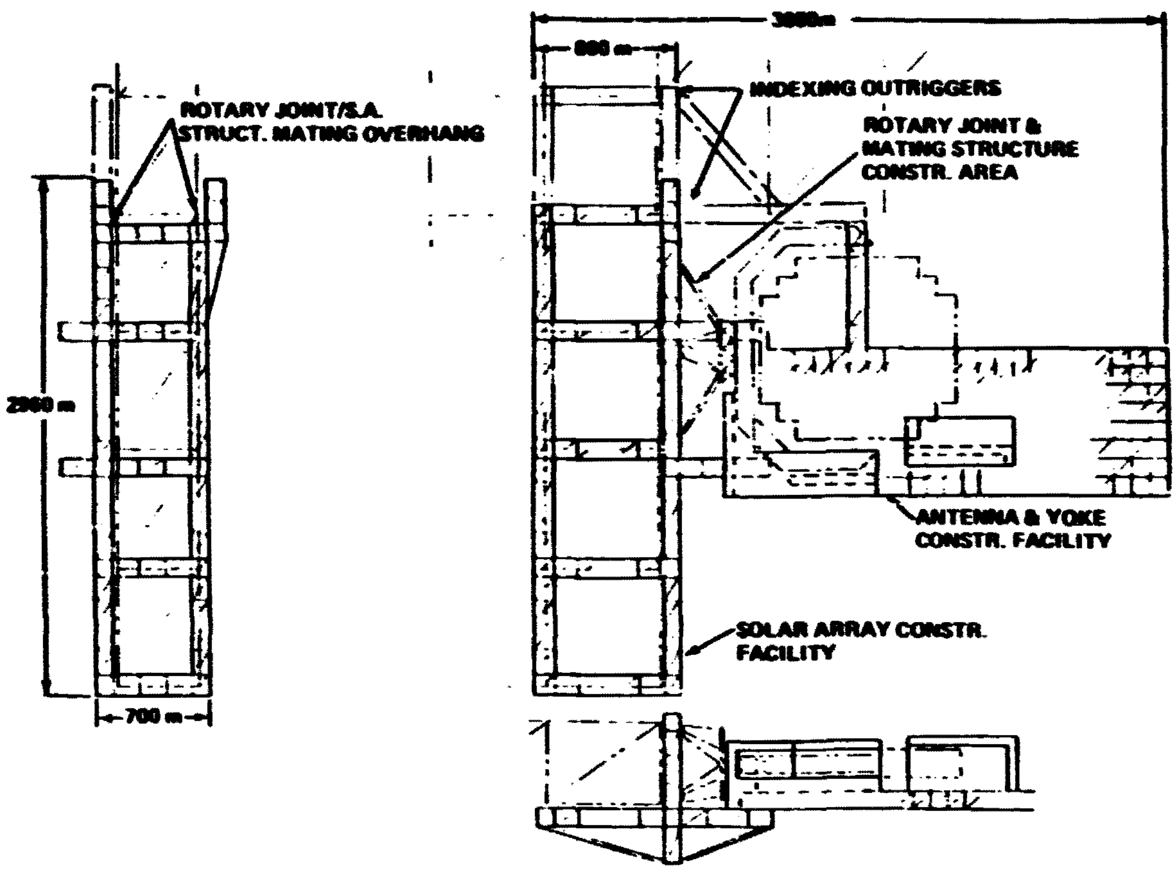


Figure 1.2.1-2 4 Bay End Builder Construction Base

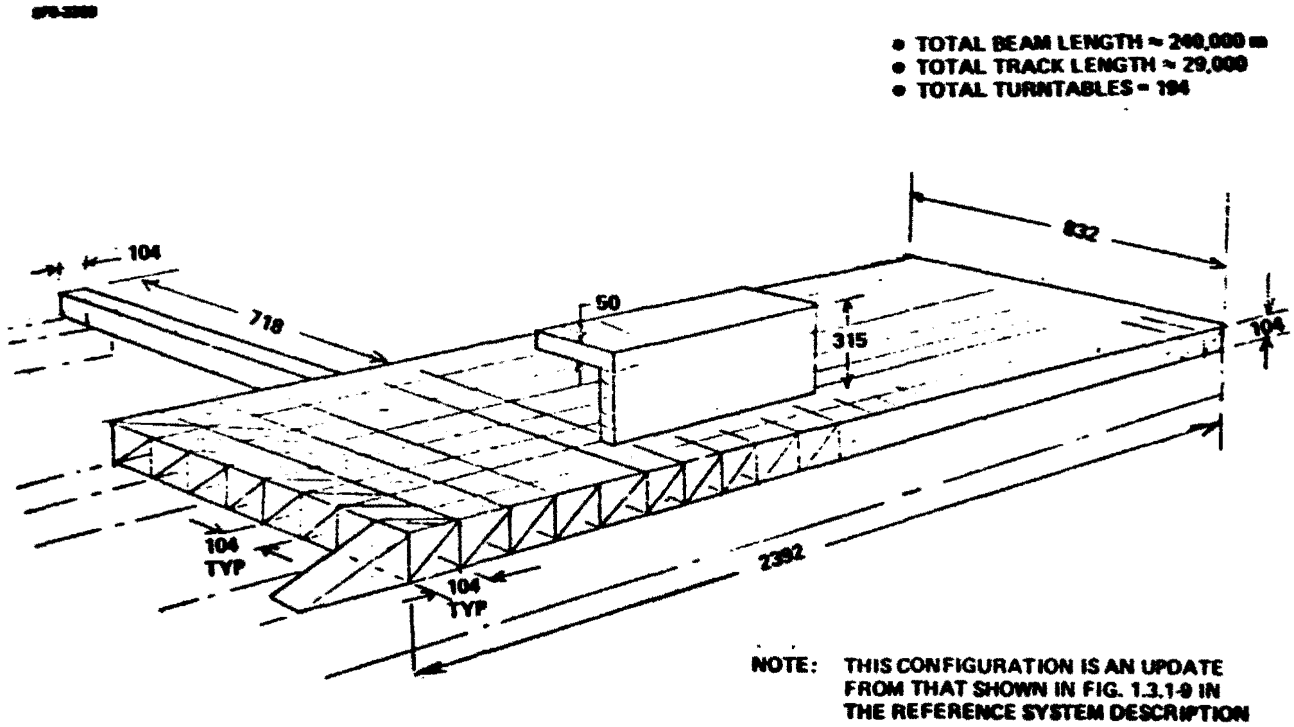


Figure 1.2.1-3 Antenna Construction Platform

Table 1.2.1-3 Construction Equipment Mass and Cost Summary

ITEM	QTY [1]				MASS, 10^3 kg		COST $\$10^6$		
	M	A	Y	T	EA.	SUB TOTAL	TFU	AVE EA.	SUB TOTAL
WBS 1.2.1.1.2.1									
BEAM MACHINES									
. 7.5 m SYNCH TRAVEL	10			10	11	110	35	26.9	269
. 7.5 m GIM. MOBILE, MANNED	2	2		4	15	60	65	49.8	199
. 12.5 m SYN.									
. 12.5 m GIM. MOBILE, MANNED	1			1	21	21	75	75	75
WBS 1.2.1.1.2.2								[2]	
CHERRYPICKERS									
. 30 m	7			7	2.5	17.5	26	18.72	131
. 90 m	4	2		6	5	30	36	27.84	167
. 120 m		2		2	7	14	38	29.38	59
. 250 m		1		1	9	9	41	31.7	32
WBS 1.2.1.1.2.3									
INDEXERS									
. 45 m	6		2	7	1.3	9		3.8	27
. 130 m		6		6	3.0	18		6	38
. 200 m			2	2	5.0	10		10	20
. 230 m		2		2	5.5	11		10.5	21
WBS 1.2.1.1.2.4									
BUS DEPLOYER									
. 90 m (ALSO 80 m)	1	1		2	8.0	16		25	50
. 110 m			1	1	8.0	8		25	25
WBS 1.2.1.1.2.5									
SOLAR ARRAY DEPLOYMENT EQUIPMENT						TBD			TBD
WBS 1.2.1.1.2.6									
ANTENNA DEPLOYMENT PLATFORM		1		1	28	28		80	80
ADD 10% ALLOWANCE FOR UNDEFINED EQUIPMENT						39			119
						401×10^3 kg (TOTAL CONST. EQUIPMENT MASS)			$\$1312 \times 10^6$ (TOTAL CONST. EQUIP. COST)

[1] USED ON
M – SOLAR ARRAY SYSTEM
A – ANTENNA
Y – YOKE
T – TOTAL

[2] AVE. UNIT COSTS OF CHERRYPICKERS BASED ON TOTAL QTY OF EA SIZE USED THROUGHOUT THE BASE

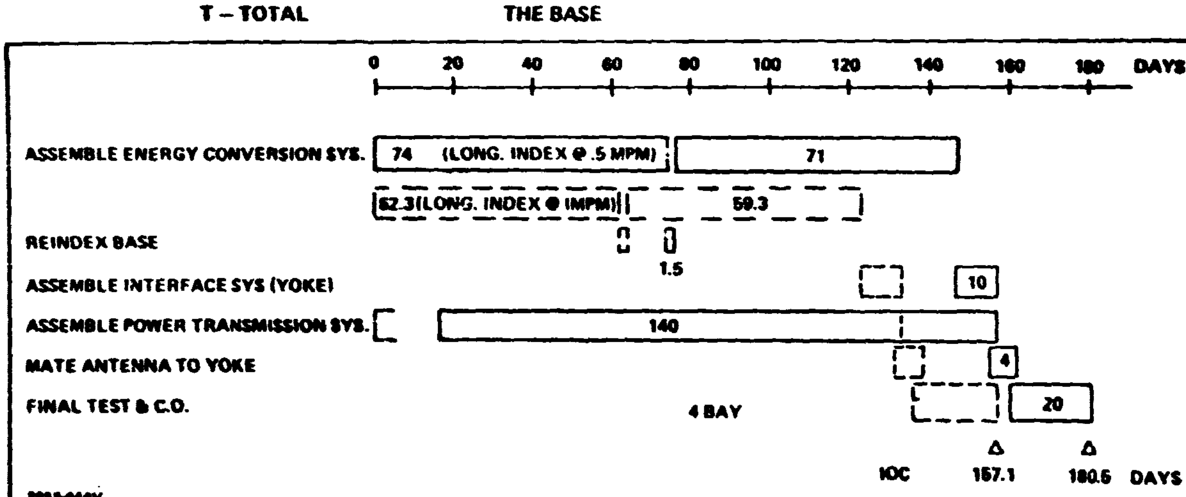


Figure 1.2.1-4 4 Bay End Builder Timeline

The construction operations begin with synchronized operation of the ten 7.5 meter longitudinal beam machines, which fabricate short lengths of beams to establish nodal joints for assembling the first structural frame. Mobile beam machines for 7.5 meter and 12.7 meter members are used to fabricate the lateral and diagonal beam segments of the end frame. The 12.7 meter upper lateral beams used to support solar blanket tensioning are fabricated and jointed to the longitudinal beams. Next, the other beam machines begin fabricating the 7.5 meter beam segments, which comprise the remainder of the end frame. Simultaneously solar array canisters are anchored on the construction base and the distal end of the solar arrays are attached to the upper laterals.

Upon completion of the end frame assembly and solar array attachment, the structure is indexed by continuing the fabrication of longitudinal members. As the fixed beam machines fabricate the 667 meter longitudinal beams, the main bus is deployed (on the first pass) and the sollar array panels, are also deployed.

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

During this process, other structural members of the frame are fabricated as needed to complete the assembly. Various sensors, avionic components and thrusters are installed in parallel as needed. These assembly operations are repeated until the entire 4 bay by 16 bay module is completed.

Frame Assembly. In the end builder concept, the frame is assembled by joining beam segments (fabricated by the mobile beam machines) to the continuous longitudinal beams (fabricated by the fixed beam machines). The production buildup of the energy conversion system starts with assembly of 7.5 m and 12.7 m structural tri-beams. Figure 1.2.1-7 depicts major beam installation activity at each frame-station with the longitudinal-diagonal

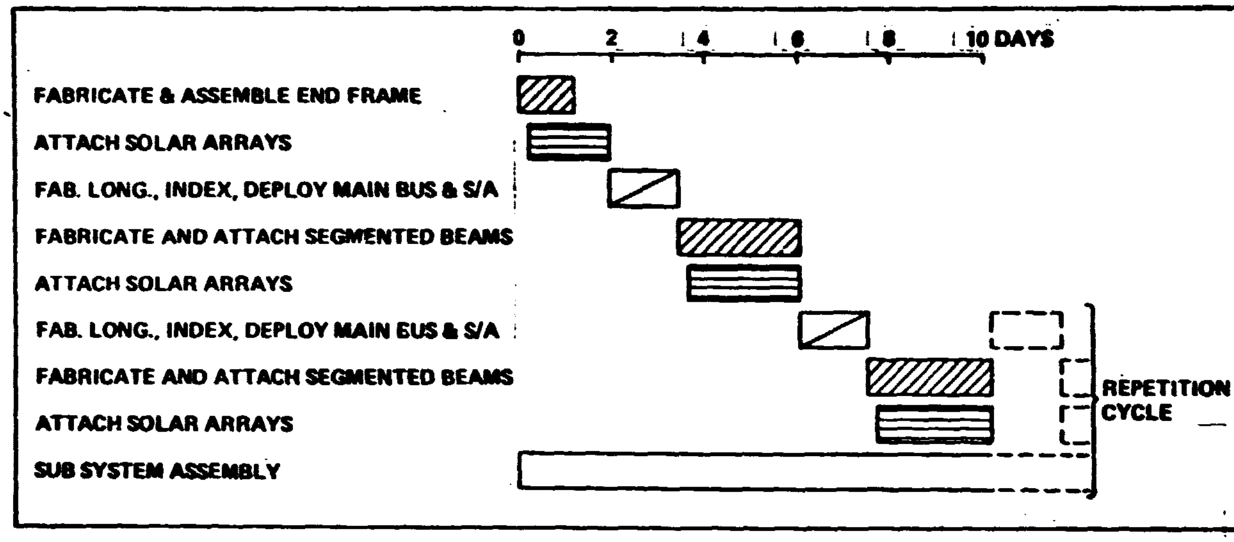


Figure 1.2.1-5 4 Bay End Builder Energy Conversion System Construction Operations

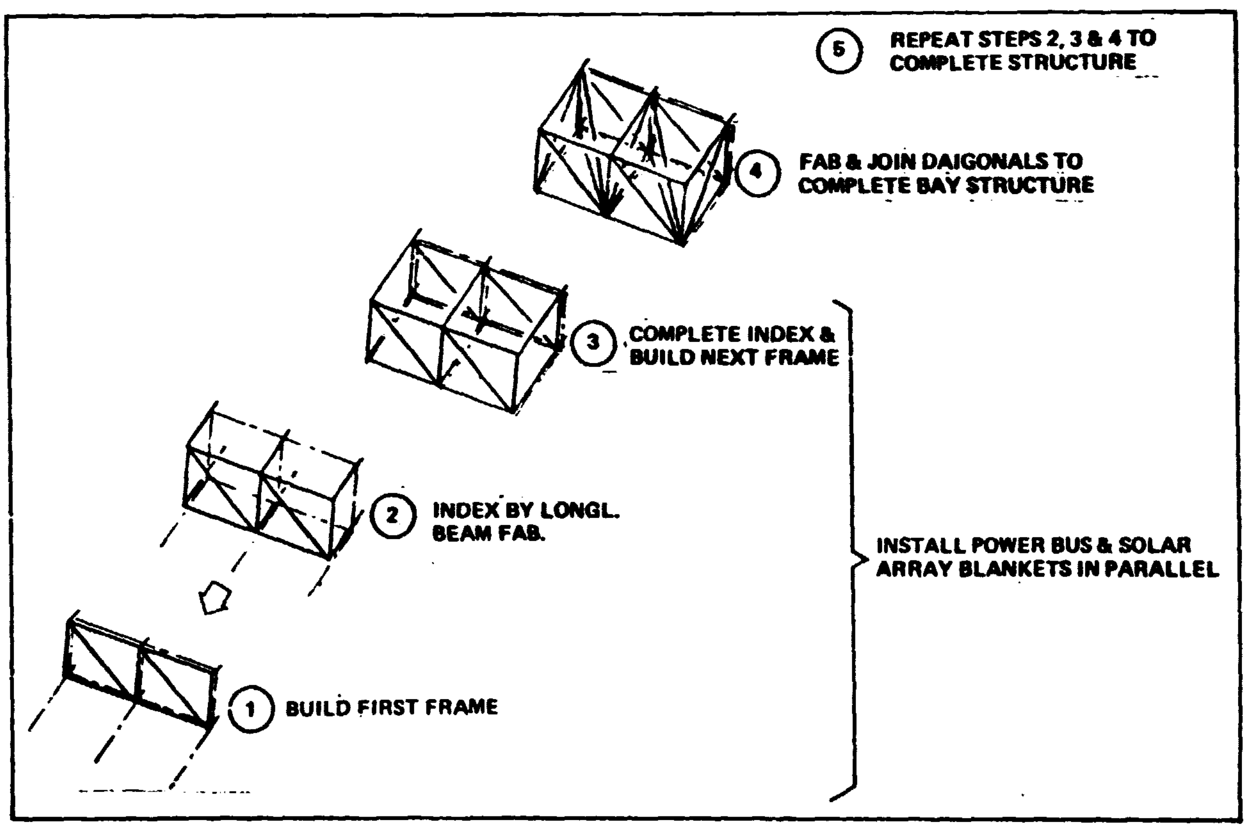


Figure 1.2.1-6 Typical End Builder Structural Assembly Sequence

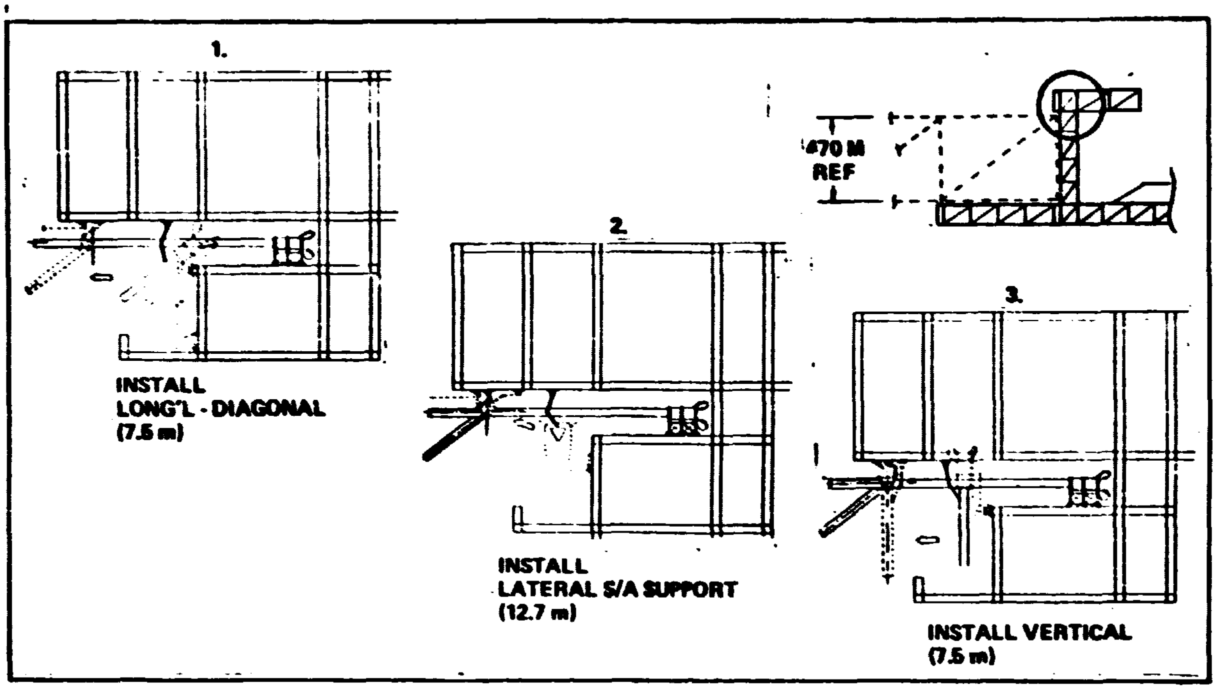


Figure 1.2.1-7 End-Builder Construction Approach (Primary Structure)

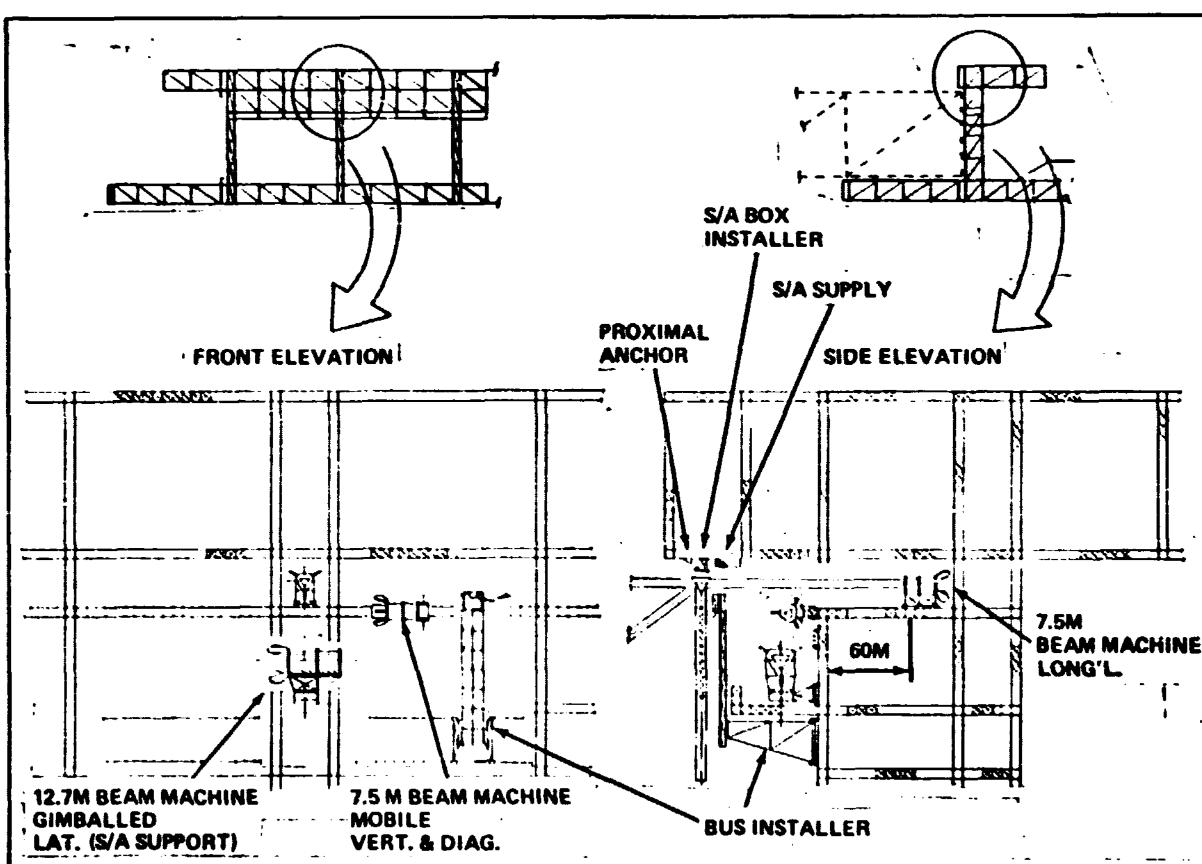


Figure 1.2.1-8 End-Builder—Construction System

(7.5 m) being installed before the lateral solar array (S/A) supportbeam (12.7m) to facilitate cherry-picker accessibility and mobility in the end-attachment process. The 12.7 m beam machine shuttles up and down on a short length of track to preclude interference with the beam machine producing the vertical beam elements. The beam elements in the plane of each frame (verticals, lateral diagonals, and lower-transverse elements) are installed last and complete the structural buildup of each bay.

Major equipment functions and their specific locations in the construction base are identified in Figure 1.2.1-8. A 60 m travel distance is provided for the longitudinal beam builders to permit on-line maintenance and repair in a 60 min period (assuming a fabrication rate of 1m/min). The two views shown represent what is probably the most active location in the base. The 12.7m beam machine provides the required S/A support beams, while nearby a mobile (track mounted) 7.5 m beam machine is shown at its mid point of travel between one end of the base and the other. In addition, the 7.5 longitudinal beam machine; bus installer and solar array implacement equipments are shown.

Solar Array Deployment. The solar array blankets can be installed by either method shown in Figure 1.2.1-9. One method aligns the solar array blankets in the direction of construction. Hence all solar arrays are deployed automatically as the longitudinal beams are fabricated from one end frame to the next frame. The second method illustrated in the lower half of the figure, installs the solar blankets normal to the direction of construction, during progressive stop and go beam fabrication operations (i.e., build 15 m length deploy array - build 15 m, etc.).

The first method is preferred because it allows shorter construction times to be achieved while also permitting significantly slower rates for thin film solar array blanket deployment. This method requires the least equipment to implement. The alternate approach, which deploys fewer blankets at a higher rate, can also be implemented with little impact on construction base design.

As shown in Figure 1.2.1-10, the installation of energy conversion solar arrays (S/A) occurs at the same work station in the base as the assembly of structural frame elements in order to mamimize time-line benefits from parallel activites.

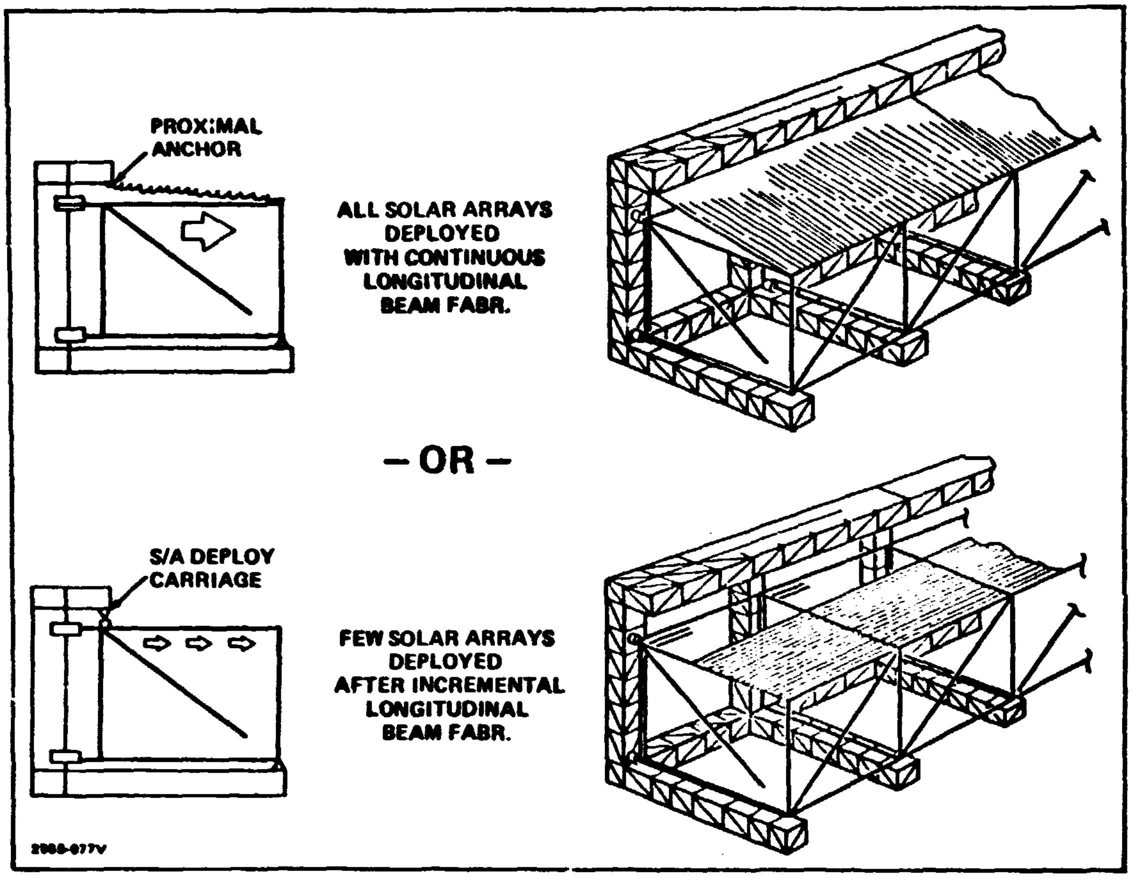


Figure 1.2.1-9 End Builder Frame Assembly/Solar Array Deployment (Coupled Operations)

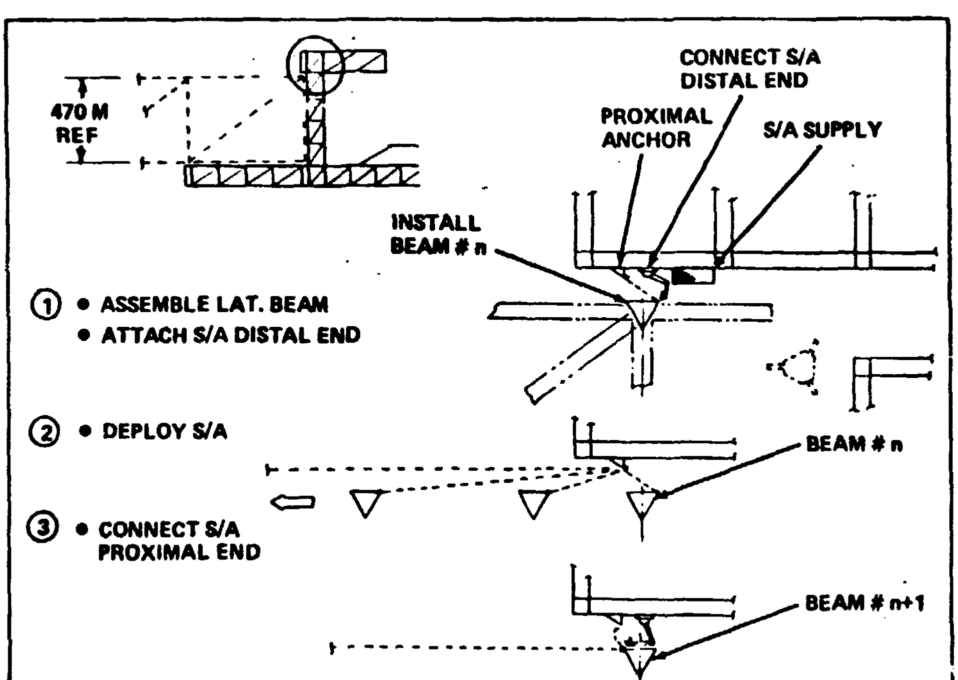


Figure 1.2.1-10 End-Builder Construction Approach (Solar Array)

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

Power Bus Installation. In the end-builder construction concept, it is necessary to install power bus systems in two directions. A longitudinal centerline power bus system has to be installed "on-the-fly" as the longitudinal beams are being fabricated. After 4 rows bays are fabricated in the longitudinal direction, it is necessary to install a lateral power bus system.

Installation of a power bus system requires three major suboperations: power bus support structure installation, switch gear subassembly installation, and power bus deployment.

The power bus support structure is a cable suspension system. The cables are installed by a pair of 90m cherrypickers, one operating on the upper facility surface and one operating on the lower facility surface.

The switch gear subassemblies are preassembled in the Level A subassembly factory. These subassemblies are delivered to the upper facility surface where they will be installed by 30m cherrypickers. The installed configuration is shown in Figure 1.2.1-11. Approximately two of these subassemblies are installed per bay on the lateral power bus system installation locations.

The power busses are deployed by the power bus deployer, (WBS 1.2.1.1.2.3.) The power bus material is delivered to the GEO base in rolls that can be loaded into the bus dispensers on the bus deployer by the cherrypicker that is part of the deployer equipment. The power bus strips are welded to the bus connection bar stock pieces that are part of the previously installed switch gear subassembly.

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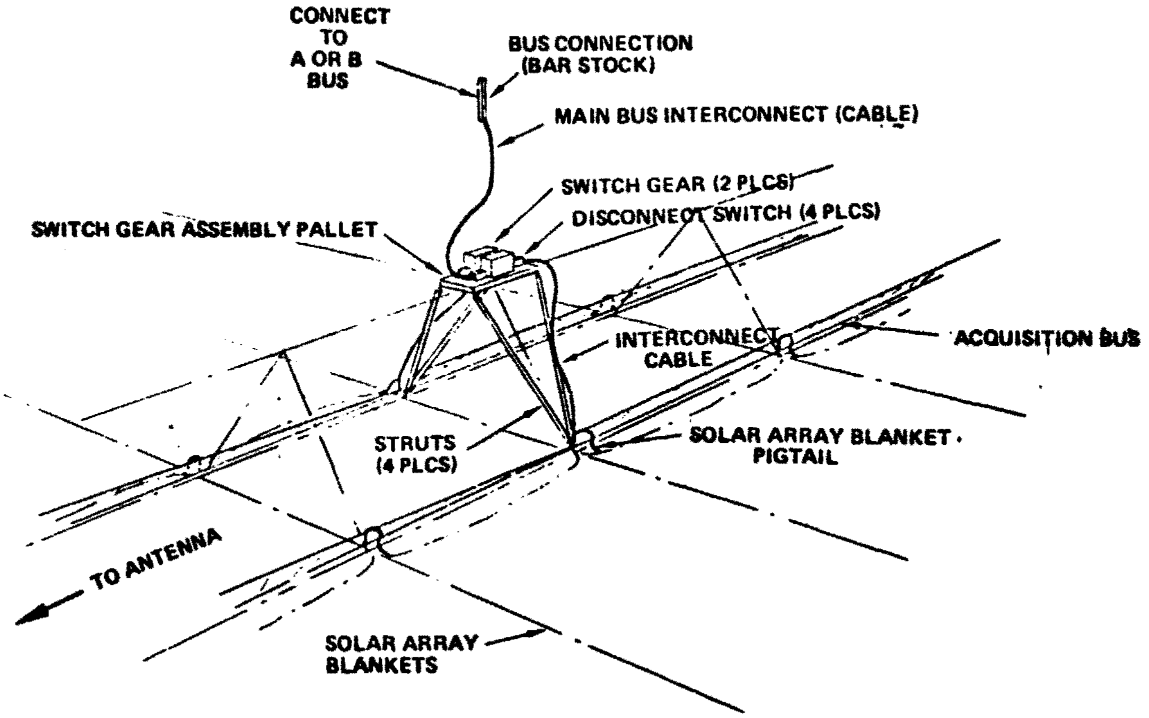

Figure 1.2.1-11 Switch Gear Assembly Installed Configuration

Attitude Control Thrust Systems. The thruster systems are installed at the four corners of the SPS. After the other construction operations are completed on the end bays (solar array electrical connections, bus installation and, bay framing, etc.), the mobile 12.5m beam machines are reoriented to fabricate thruster support beams. The unoccupied cherrypickers help assemble the structure.

The SPS electric and chemical thrusters are installed within their yoke assembly at the Level A Subassembly Factory. These units are delivered to the solar array module final assembly area where they are installed on the thruster support beams. The 30m cherrypickers will perform these operations. These cherrypickers will also participate in the assembly of the support structures.

The propellant tanks arrive at GEO on pallets ready to be installed on the SPS. This pallet is installed by 30m cherrypickers.

The propellant plumbing and the radiator systems are installed piece-by-piece by 30m cherrypickers.

Other. The installation operations associated with the avionics, communications, data processing, and other miscellaneous SPS energy conversion subsystems have not been analyzed.

Microwave Power Transmitter Construction Operations. The antenna is constructed upon the antenna construction paltform shown in Figure 1.2.1-3 as a part of the construction base. It is constructed in parallel with the construction of the energy conversion system (solar array) module.

Construction of the antenna entails the following suboperations: primary frame assembly, secondary structure assembly, power distribution system installation, phase control system installation, subarray installation and final test and checkout. These operations are described in the following subsections.

Figure 1.2.1-12 shows a side view looking into the antenna construction facility. This picture illustrates the relative locations of the various construction equipment items. Figure 1.2.1-13 illustrates the general construction sequence. The antenna is indexed through the facility one bay at a time. When a full width of bays is completed, the antenna is indexed longitudinally out of the facility so that the next row of bays can be assembled. When the antenna is completed, it will be located at the proper position so that it can be mated to the yoke, see Figure 1.2.1-14.

The integrated antenna construction timeline is shown in Figure 1.2.1-15.

Structure Assembly. Figure 1.2.1-16 illustrates the configuration of the antenna primary structure. Figure 1.2.1-17 illustrates the frame construction sequence, the beam machine and cherrypicker locations, and time required. Figure 1.2.1-18 illustrates that both "tall" and "short" indexers are required during the frame assembly sequence. The beam end fittings and the battens are preassembled in Subassembly Factory B and are then delivered in sets or magazines to the antenna construction facility.

The antenna secondary structure is conceptually a preassembled deployable cubic structure. The structure is delivered as a collapsed and telescoped package. The construction task is to expand and lock the structure into a 104 x 104 meter square platform that can then be placed upon mounting points on the antenna primary structure.

The collapsed secondary structure package is delivered to the antenna deployment platform. This platform is the most prominent assembly of equipment on the antenna construction facility. Its location is shown in Figure 1.2.1-19. Many pieces of equipment operate on this platform as illustrated in Figure 1.2.1-20. The equipment platform is used to deploy the secondary structure, install phase control wiring, install power distribution wiring, and to install subarrays.

After each secondary structure package arrives at the platform, it is then placed onto the secondary structure de-telescoper machine mounted on one of the gantries. The phase control system installation cherrypicker is employed to anchor one face of the secondary structure while the de-telescoper retracts to expand the structural package to its full 10m depth. A lanyard is then pulled which allows the secondary structure to expand using spring-activated hinges on the structural struts. When

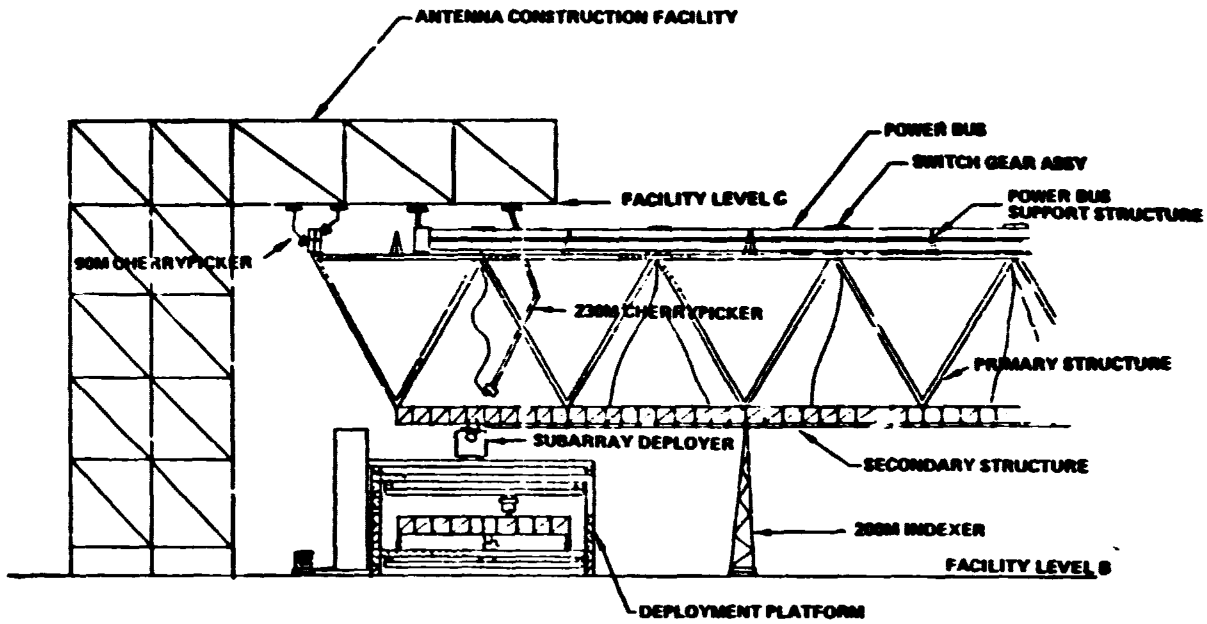

Figure 1.2.1-12   Antenna Construction

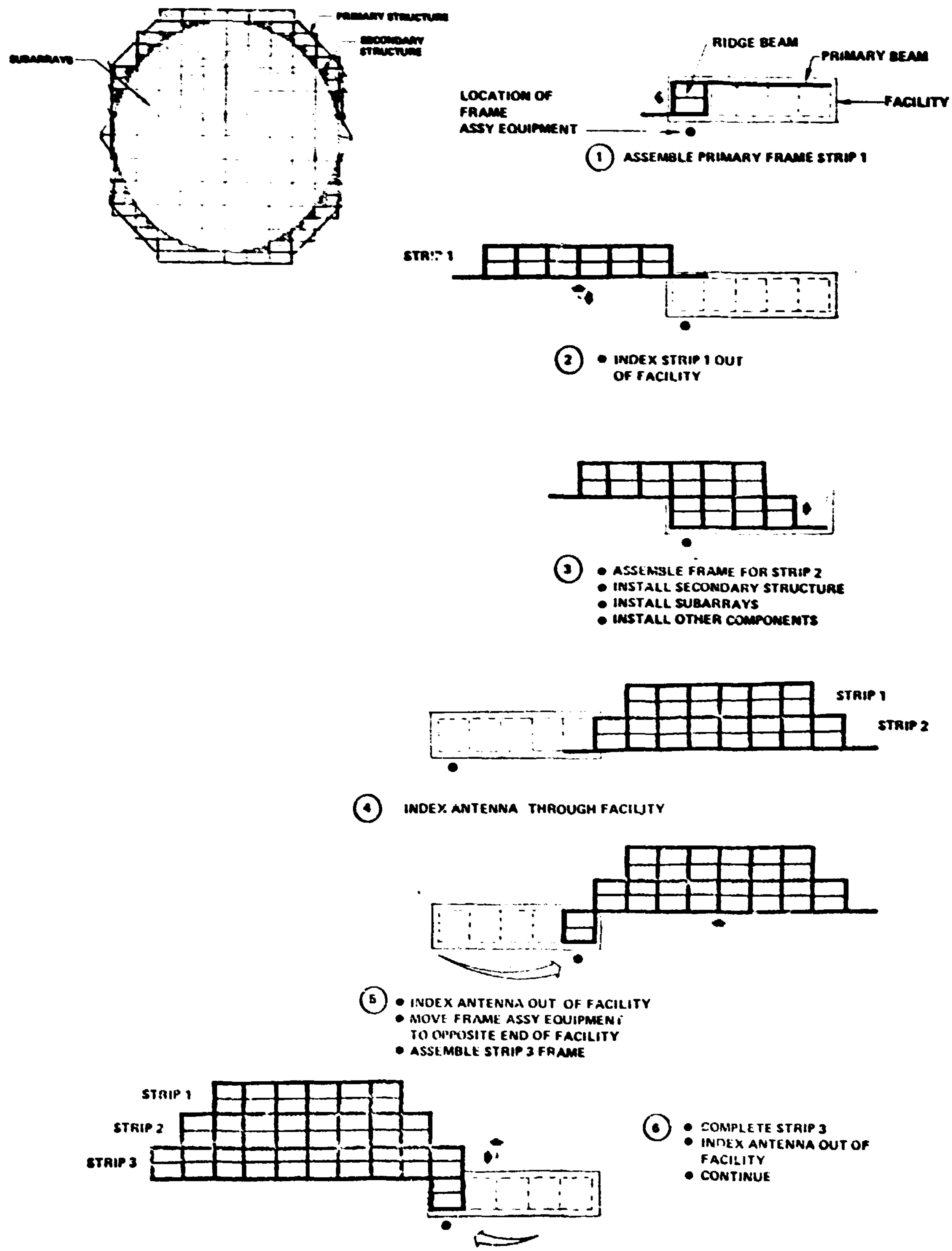

Figure 1.2.1-13 Antenna Assembly Sequence

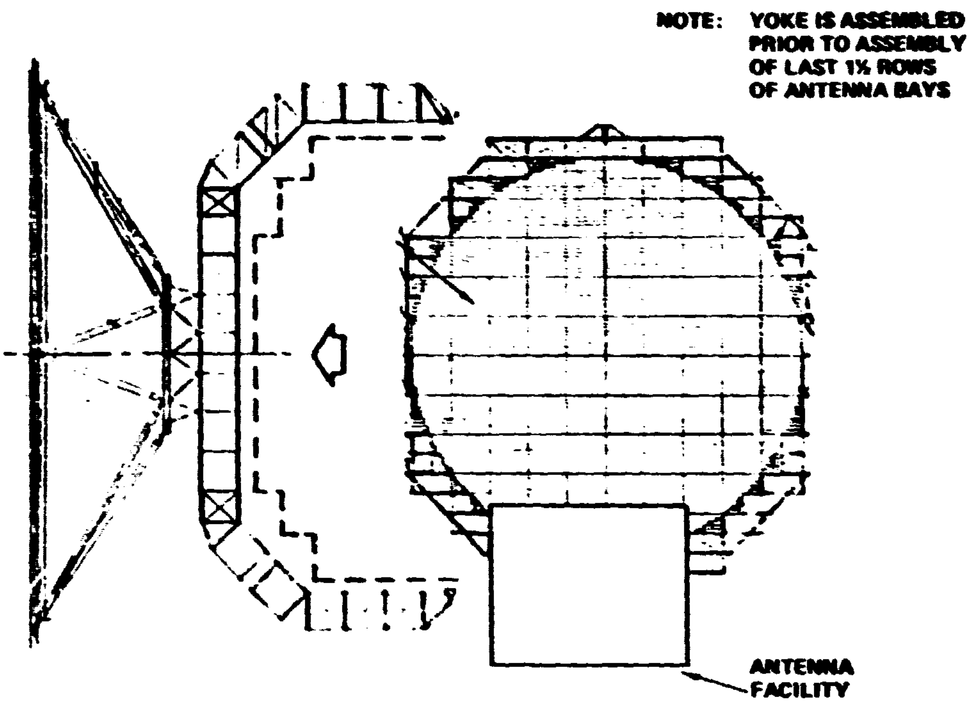

Figure 1.2.1-14 Provide Capability to index Antenna Within Confines of the Yoke

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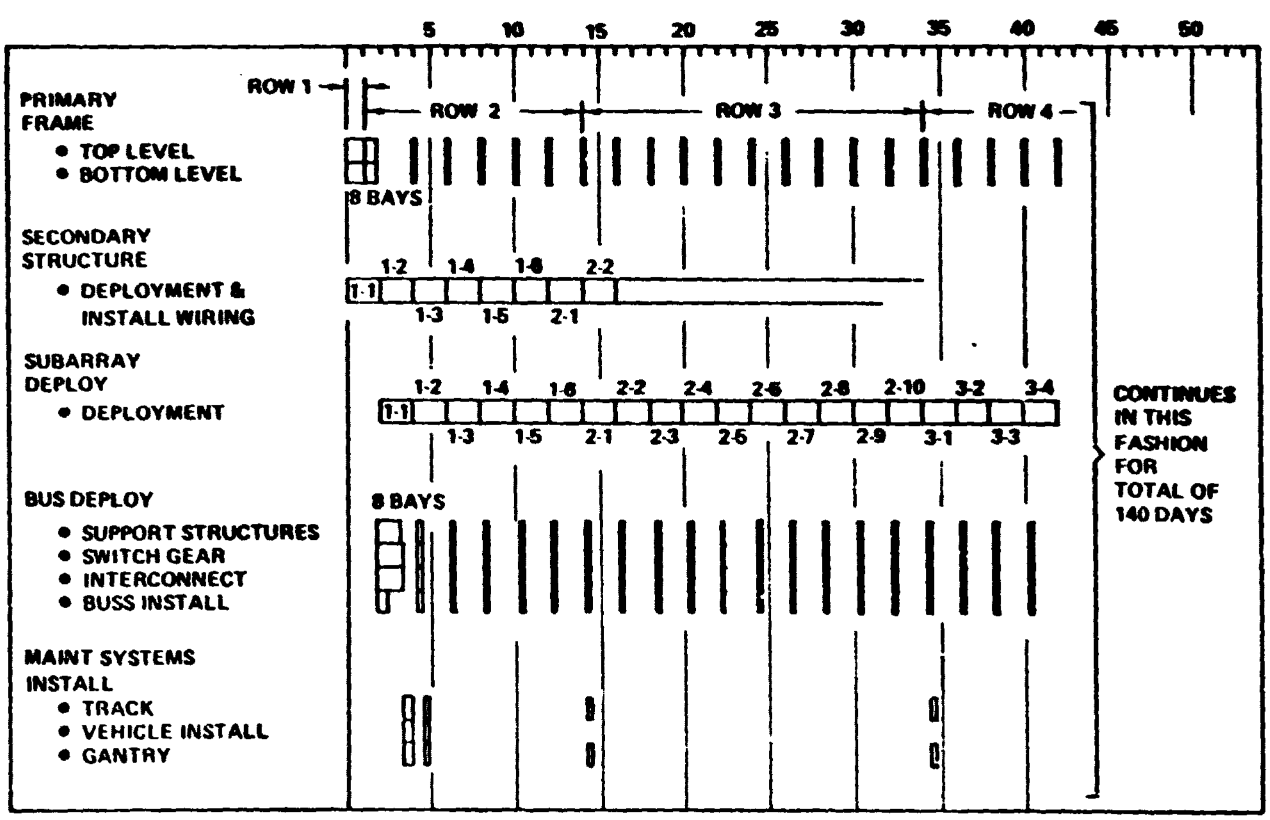


Figure 1.2.1-15 Antenna Construction Timeline

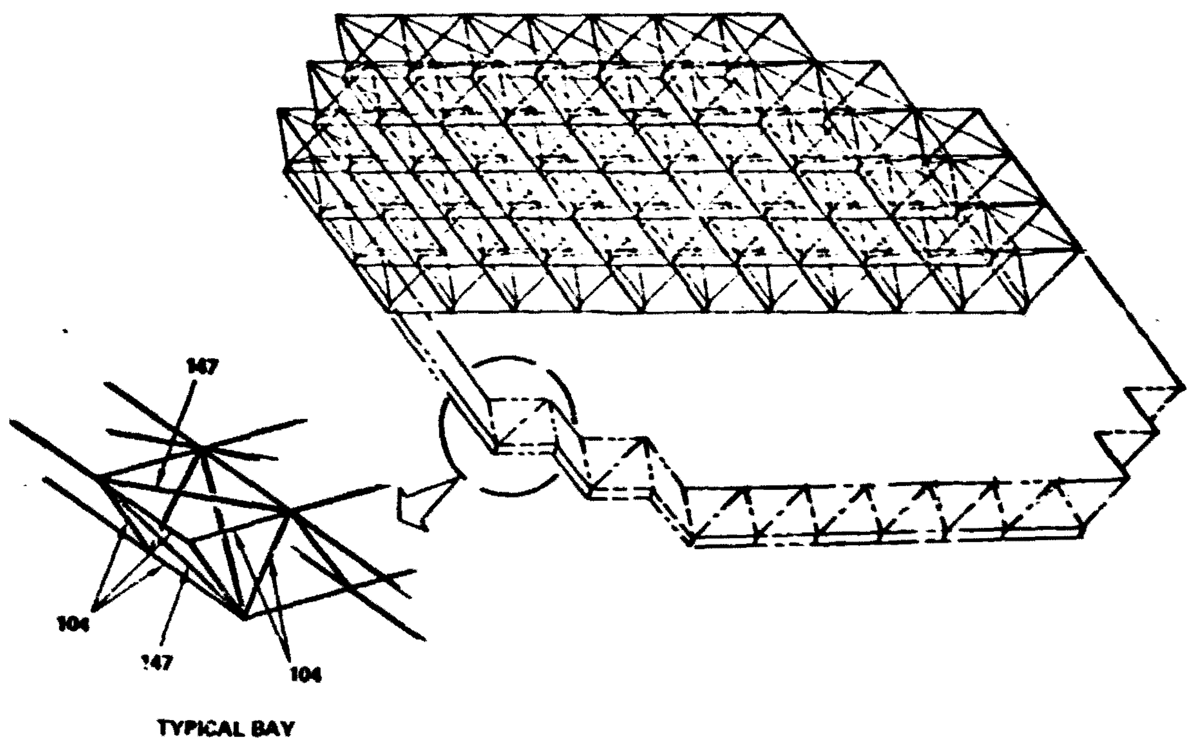


Figure 1.2.1-16 MPTS Primary Structure

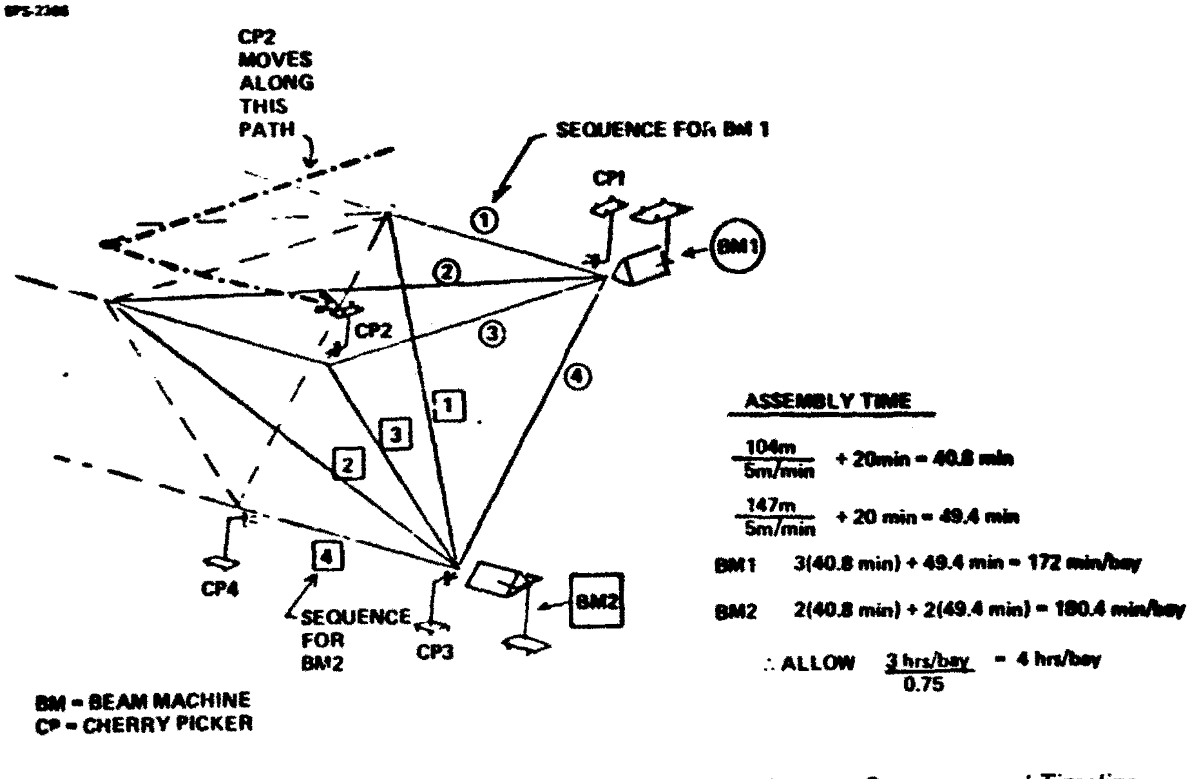


Figure 1.2.1-17 MPTS Primary Frame Assembly Equipment, Sequence, and Timeline

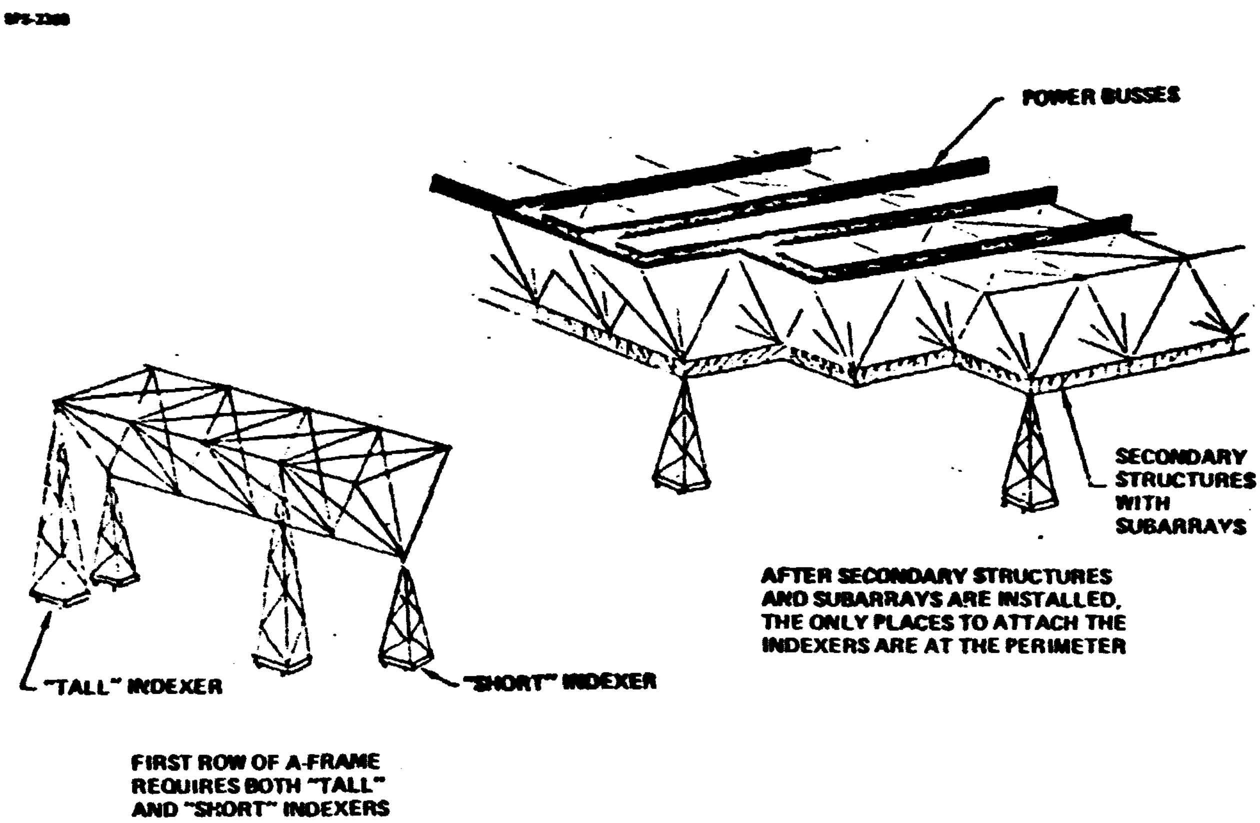
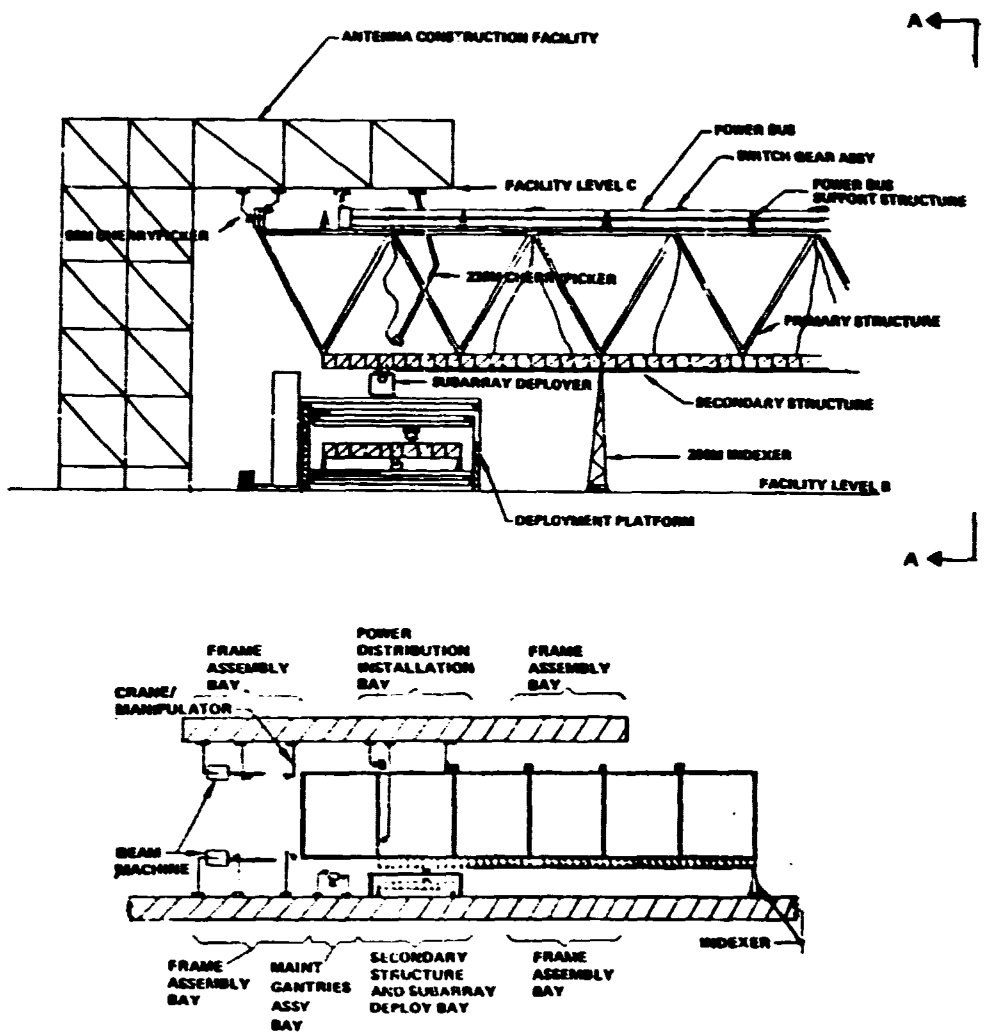


Figure 1.2.1-18 Antenna Indexers



VIEW A-A

Figure 1.2.1-19 Antenna Facility

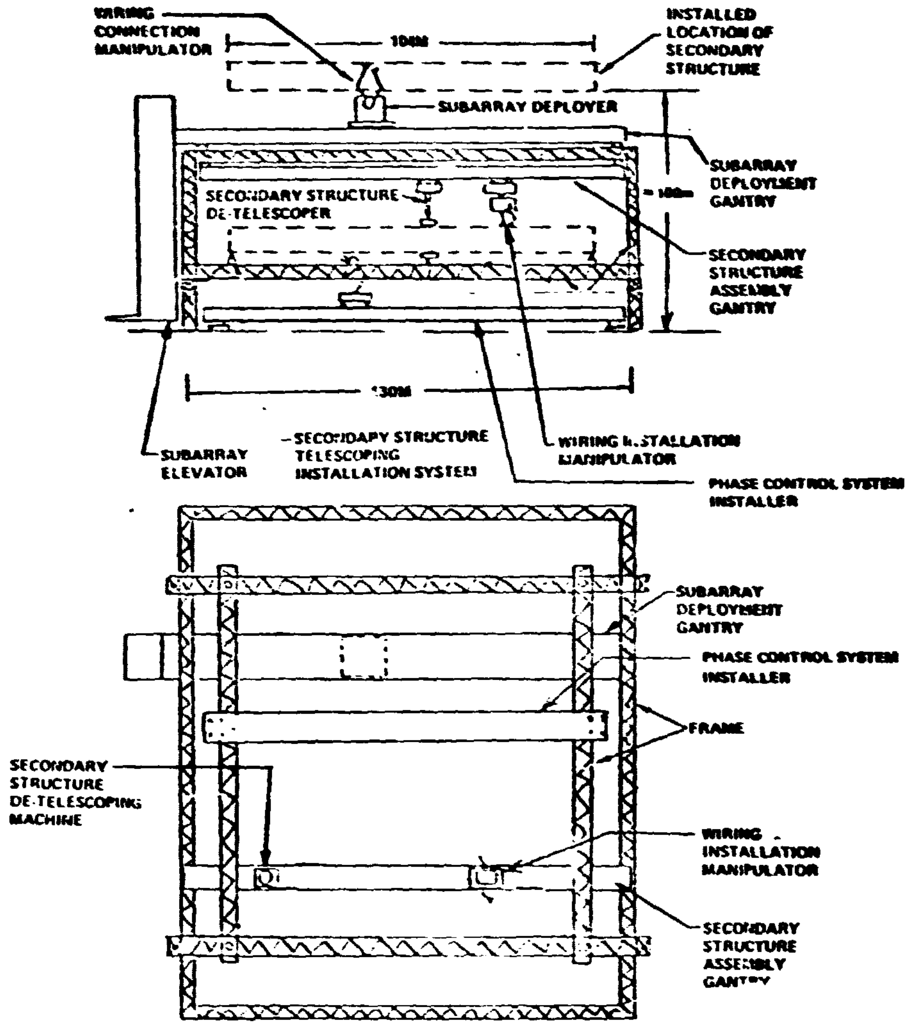


Figure 1.2.1-20 Antenna Deployment Platform

the secondary structure is fully expanded and self-locked into a rigid structure, the corners are attached to the secondary structure telescoping installation system. The structure is then ready to be wired. After the wiring is completed and the primary structure correctly positioned, the secondary structure is raised into contact with the primary structure by the telescoping actuators. Cherrypickers then make the necessary structural joints between the primary and secondary structures.

Power Bus Installation. After each bay of primary structure is completed, it is then time to install the power distribution system on the surface opposite the subarrays. The first step is to install bus support subassemblies which have been preassembled in Subassembly Factory B. A pair of cherrypickers are employed (the same ones used to install the upper surface of the primary frame). At the nodal joints of the primary structure, it is necessary to install a preassembled antenna switch gear subassembly. After the support structures and switchgear assemblies are installed, a bus deployment machine moves into place and deploys the necessary power bussing for the bay.

It is necessary to install a power distribution wiring harness on the secondary structures. This harness goes onto the face of the secondary structure opposite where the subarrays will be installed. A gantry and cherrypicker has been incorporated into the deployment platform for this purpose.

After a secondary structure element has been installed onto the primary structure, it is necessary to run power cables between the antenna switch gear subassemblies (on the primary structure) to the power distribution wiring harness on the secondary structure. A 230m cherrypicker is employed for this operation.

Phase Control. After the secondary structure is deployed and attached to the installation telescopes, it is necessary to install a phase control wiring hardness (perhaps a fiber optics harness) onto the face of the secondary structure adjacent to where the subarrays will be installed. A gantry and cherrypicker have been incorporated into the deployment platform for this purpose.

The phase control interconnect operation between the subarrays and the harness installed on the secondary structure is accomplished as a part of subarray deployment.

Subarrays. Before subarrays are delivered to the deployment area, the pallet of subarrays are delivered to a subarray test area where each subarray will be tested for mechanical and electrical integrity, see Figure 1.2.1-21. The subarrays that require refurbishment would be taken to a nearby facility for repair. The tested subarrays are loaded onto a transporter for delivery to the deployment platform.

Figure 1.2.1-22 shows how pallets of subarrays are transferred to and from the subarray deployer using an elevator. The deployment machine traverses along the gantry, stopping every 10.4 meters. Figure 1.2.1-23 shows a close-up view of the subarray deployment machine. The deployment machine mechanisms extract each subarray panel from the pallet and raise it into position where the jackscrews can be attached to hardpoints on the secondary structure. The subarray is then leveled. The cherry-picker on the side of the deployer then makes the phase control and power distribution pigtail connections to the respective harnesses previously installed onto the secondary structure.

Yoke Construction and Mating; Final Checkout

The construction and mating sequence for the satellite interface system is illustrated in Figure 1.2.1-24. Assembly of the interface yoke can lead the antenna build-up as shown or be delayed until antenna is almost fully assembled as shown in Figure 1.2.1-25. With either approach the interface system is fully assembled and ready for mating operations when the 8 x 16 bay energy conversion system has been completed.

In the early stages of construction, the rotary joint and supporting yoke structure are assembled on the back face of the energy conversion construction facility. The rotary joint is subsequently indexed outboard for attachment to the yoke (see Figure 1.2.1-52). At the same time, the rotary joint/solar array interface structure is partially assembled. Step 2 shows the completion of build and mating of the antenna, the yoke and the rotary joint. The energy collection system has also been completed. The interface structure between the rotary joint and solar array is attached in incremental steps to permit the base to gradually transfer the antenna mass while indexing

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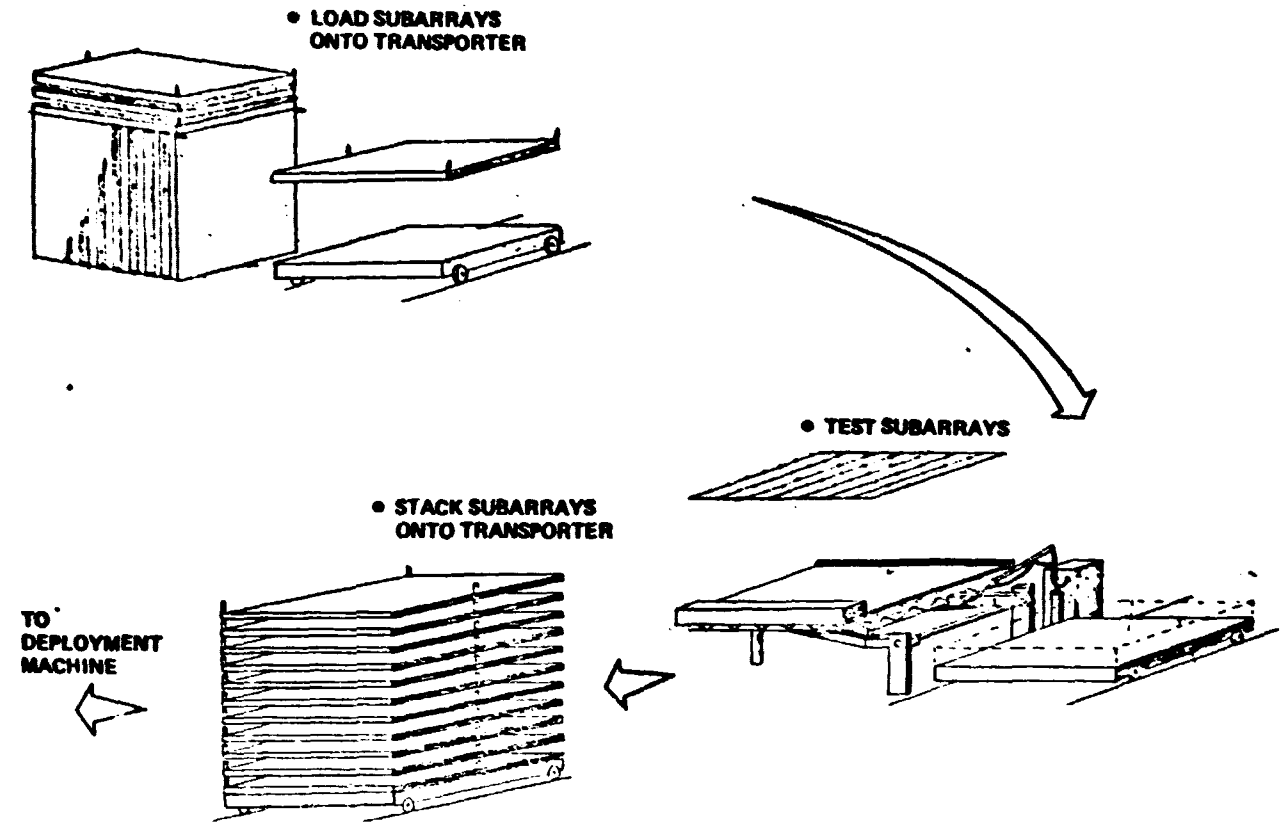

Figure 1.2.1-21 Subarray Preparation Process

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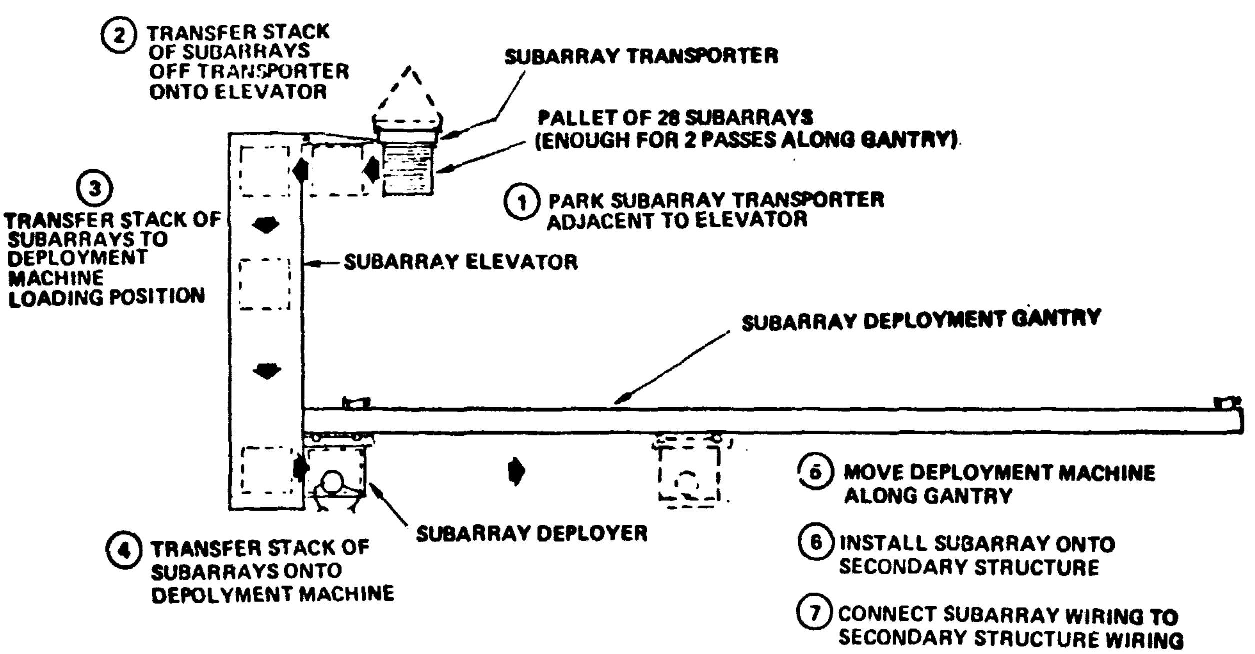

Figure 1.2.1-22 Subarray Deployment Sequence

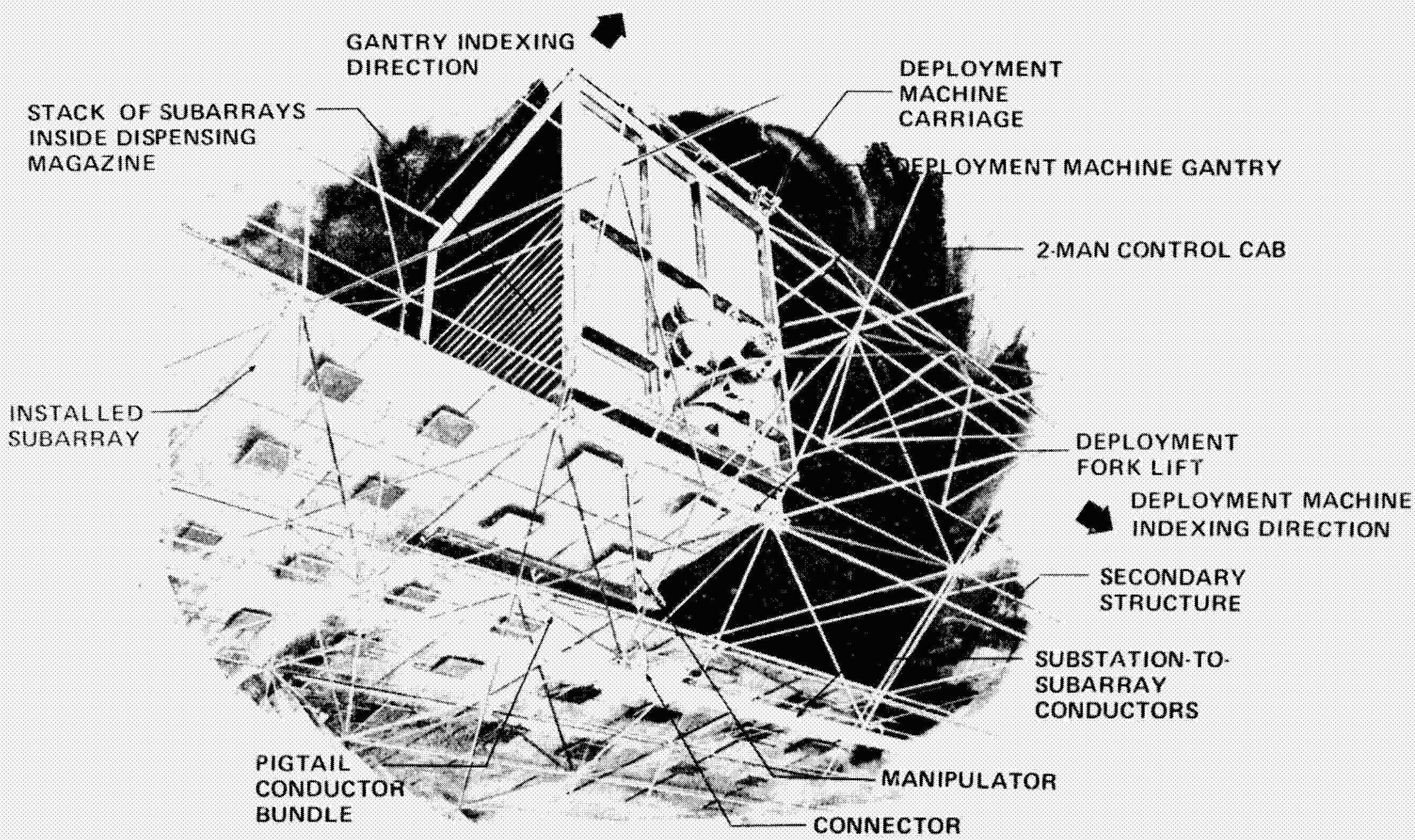

Figure 1.2.1-23 Subarray Deployment Machine Details

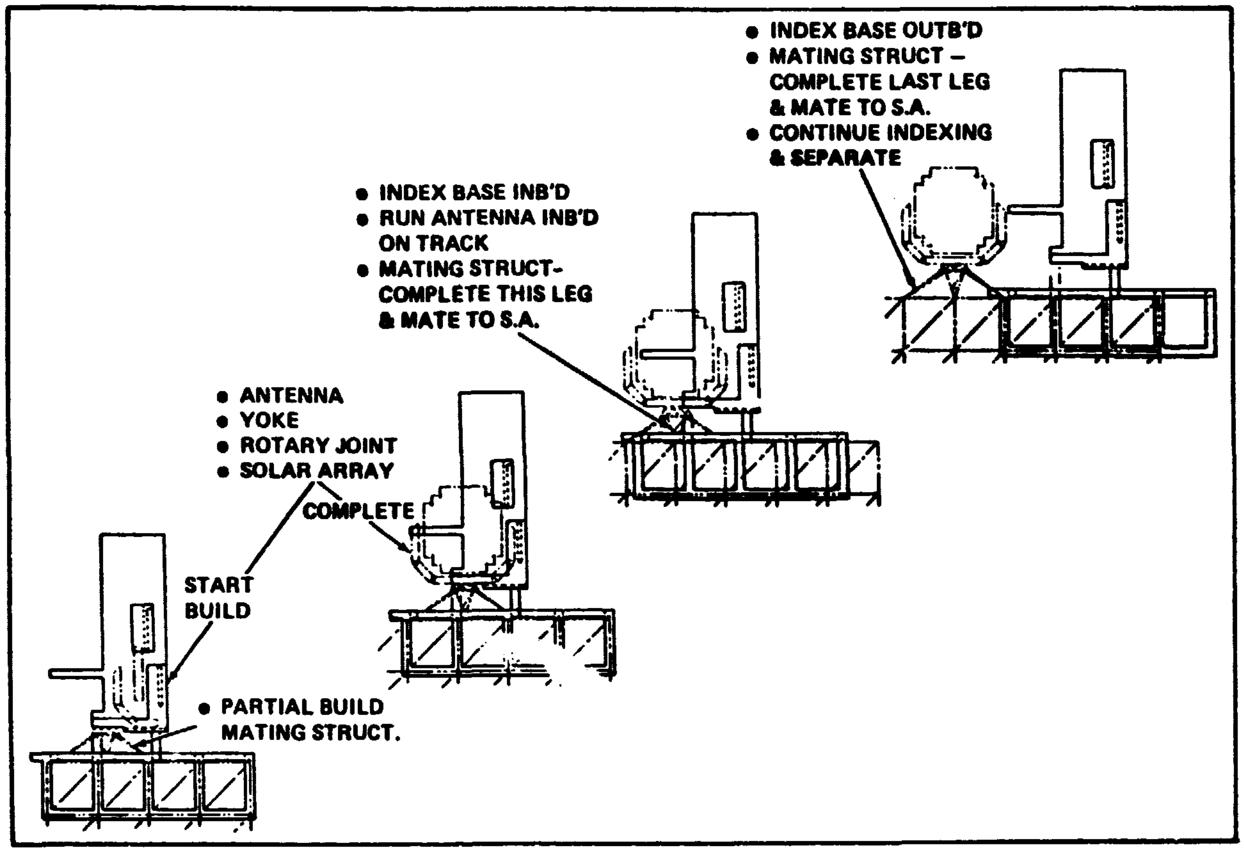

Figure 1.2.1-24 Interface System (Yoke) Construction and Mating Operation

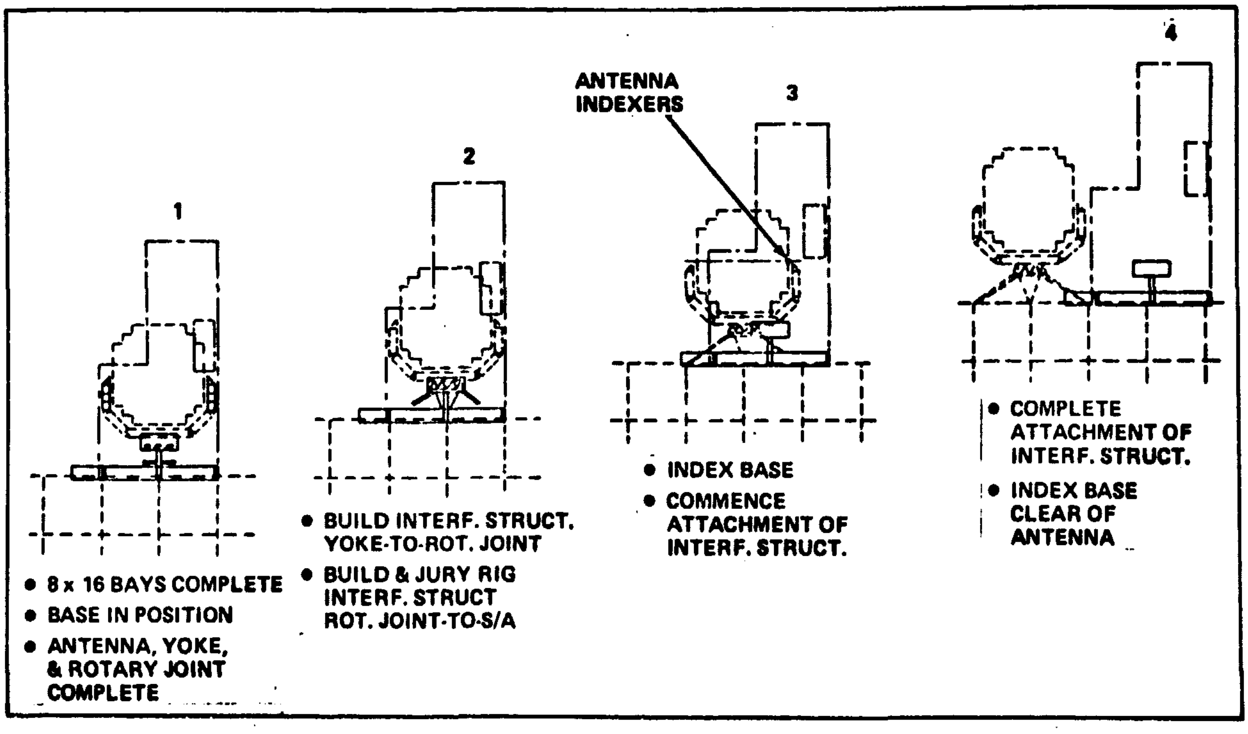

Figure 1.2.1-25 Yoke Construction/Antenna Mating (Option)

it self away from, and clear of, the antenna. The start of the final mating operation is illustrated in step 3. The array is indexed laterally along the base so that the appropriate structural nodal point is in the base overhang. The antenna assembly is also indexed on rails until it is positioned for completing assembly of the mating interface structure legs. Subsequently the base is indexed outboard to position the next pair of mating points in the base overhang. The center legs of the interface structure are then completed. Step 4 illustrates the final mating of the power transmission system to the energy conversion system. When the mating operation is completed, final test and checkout will be automatically performed on the major satellite systems (e.g., attitude control, dc power distribution, and RF phase control). At the conclusion of these tests, the base will be separated from the satellite and transferred to the next satellite GEO construction location. Subsequent satellite power build-up operations will be controlled from the ground.

Equipment Description Summaries

WBS 1.2.1.1.2.1 Beam Machines

WBS Dictionary

This element includes all machines dedicated to fabricating structural beams. Beam machines are used in construction of the solar array and power transmission system.

Element Description

Requirements for three types of beam machines have been identified, as summarized in Table 1.2.1-4. Figure 1.2.1-26 shows a conceptual configuration.

WBS 1.2.1.1.2.2 Cherrypickers

WBS Dictionary

This element includes the mobile equipment that has crew cabins equipped with dextrous manipulators. Cherrypickers are general-purpose construction equipment used in many ways.

Element Description

Requirements for four types of cherrypickers have been identified, see Table 1.2.1-5. Figure 1.2.1-27 shows one conceptual configuration.

Table 1.2.1-4 Beam Machine Description Sheet

ITEM BEAM MACHINES WBS NO. 1.2.1.1.2.1

SUBITEMS	7.5m Synchronized	7.5m Gimbled/Mobile Manned Beam Machine	12.5m Gimbled/Mobile/ Manned Beam Machine
FUNCTIONAL REQUIREMENTS	o Fabricate 7.5 m beam o 10 Machines operated synchronously o Remotely controlled o Traverse in one dimension	o Fabricate 7.5 m beam o traverse o tilt 0-90° o Rotate ± 90° o Controlled by on-board operator	o Fabricate 12.5 m beam o traverse o Rotates ± 90° o controlled by on-board operator
	(Common to all types) o Fabricate composite material beam o Install beam end fittings o Install batten end caps o Support beam as it is fabricated o Support beam while beam end fitting installed o Quick-change component magazines o Material reload by cherrypickers		
WHERE USED	Solar Array Longitudinals	All other beams	Solar Array lateral Beams
MAJOR SUBELEMENTS	o 7.5mBeam fabricator	o 7.5mbeam fabricator o Gimble o 1 man control cabin	o 12.5m beam fabricator o Gimble o 1 man control cabin
	(Common to all types) o Carriage (Self-propelled) o Beam End Fitting installation system o Beam holder/indexers		
OPERATING RATES AND TIMES	1 m/min	5 m/min	5 m/min
QTY	10	4	1
MASS EA.	11000kg	15000kg	21000kg
MASS TOTAL	110,000kg	60,000kg	21000kg
COST EA.	$35M TFU/$26.9mAVE	$65M TFU/$49.8m AVE	$75m TFU/$75m AVE
COST TOTAL	$269M	$199M	$75M
MANNING	1 operator per 8 machines	1 operator per machine each shift	1 operator per machine each shift

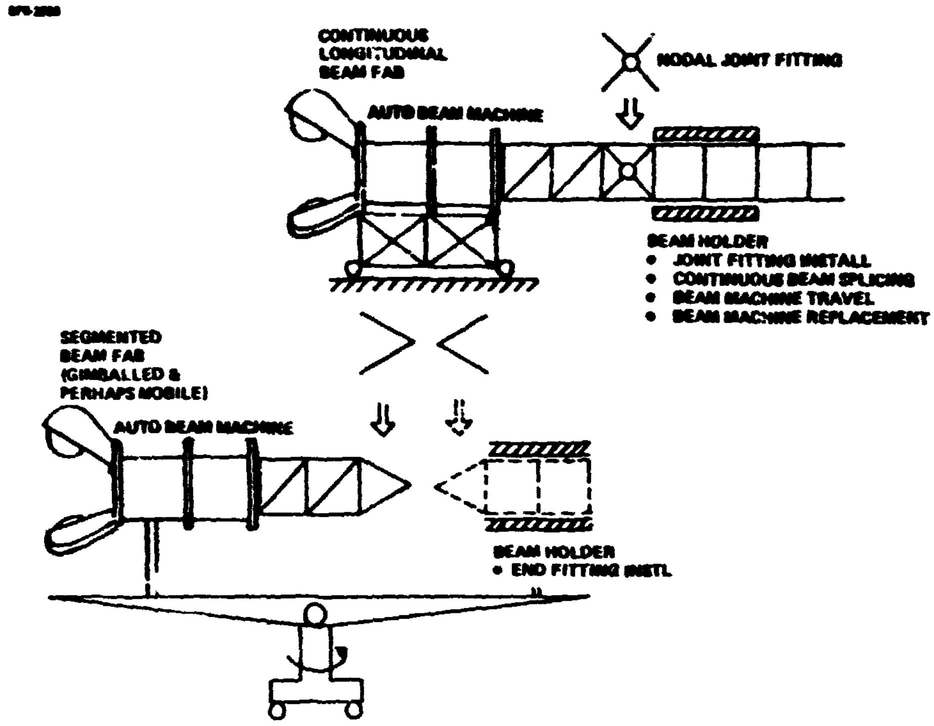

Figure 1.2.1-26 Beam Machine Concepts

Table 1.2.1-5 Cherrypicker Description Sheet

ITEM CHERRYPICKERS WBS NO 1.2.1.1.2.2

	20M CHERRYPICKER	90M CHERRYPICKER	120M CHERRYPICKER	250M CHERRYPICKER
FUNCTIONAL REQUIREMENTS	MANIPULATOR TASKS o cargo pallet latching o bus bar handling o SW gear handling o Electrical connections o MECH connections o Thruster panel handling o small beam handling o Piping connections o Radiator handling o Subarray handling o Equip loading o Maint ops o solar array cont. handling o Beam end fitting handling	MANIPULATOR TASKS o frame assy o Thruster subassy installation o SW Gear subassy installation o Bus support struct installation o Equip loading o Maint ops	MANIPULATOR TASKS	MANIPULATOR TASKS
		(COMMON TO ALL TYPES) o Traverse along facility tracks o controlled by on-board operator		
WHERE USED	SOLAR ARRAY/SUBASSY	SOLAR ARRAY/ANT	ANT	ANT
MAJOR SUBELEMENTS	o 20M Boom (Elbow type)	o 90M Boom (Telescoping type) o Stabilizer legs	o 120M Boom (Telescoping type) o Stabilizer legs	o 250m Boom (Telescoping type) o Stabilizer legs
		(COMMON TO ALL TYPES)		
	o Carriage (self-propelled) o 1-man control cab			
OPERATING RATES AND TIMES				
QTY	7	6	7	1
MASS EA	2500 kg	5000kg	7000 kg	9000 kg
MASS TOTAL	17500 kg	30000 kg	14000 kg	9000 kg
COST EA	$26M TFU	$36M TFU	$38M TFU	$41M TFU
COST TOTAL	$131.04	$131M	$59M	$32M
MANNING	1 operator per machine	1 operator per machine	1 operator per machine	1 operator per machine

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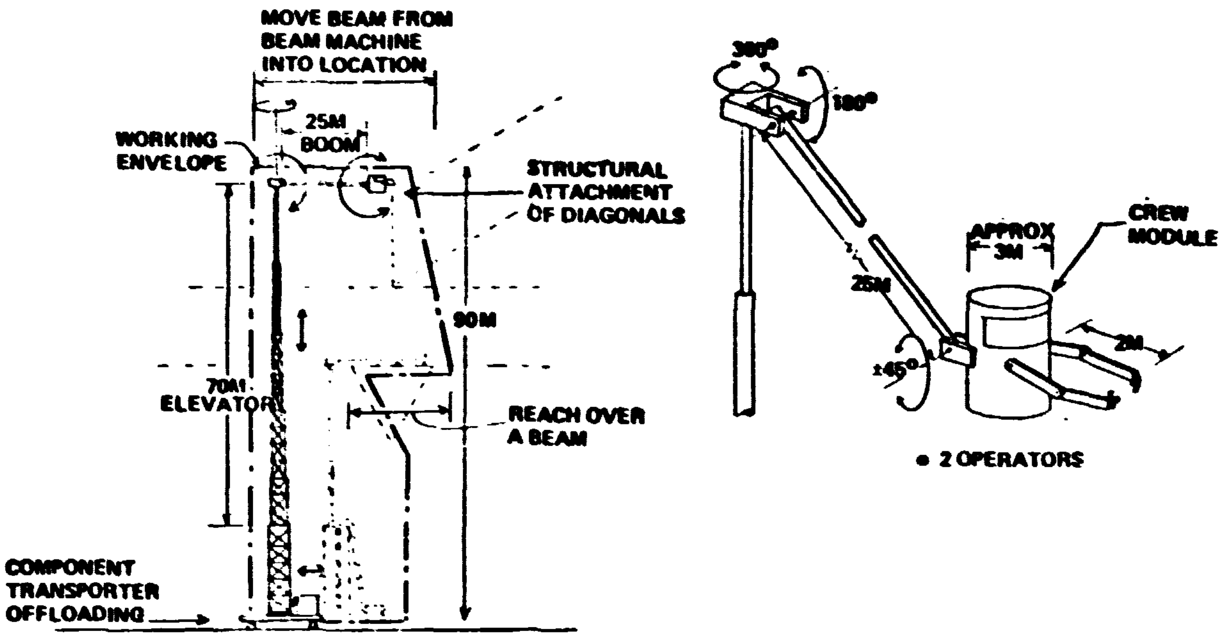

Figure 1.2.1-27 110M Crane/Manipulator

WBS 1.2.1.1.2.3 Indexers

WBS Dictionary

This element includes the equipment items used to support and move the SPS major end items during construction.

Element Description

Four sizes of indexers have been identified, see Table 1.2.1-6. A conceptual configuration for an indexer is shown in Figure 1.2.1-28.

WBS 1.2.1.1.2.4 Bus Deployment Machines

WBS Dictionary

This element includes the construction equipment used to deploy the sheetmetal power busses.

Element Description

Three types of bus deployment machines have been identified, see Table 1.2.1-7. A conceptual design for the bus deployment machine used on the solar array module is shown in Figure 1.2.1-29.

WBS 1.2.1.1.2.5 Solar Array Deployment Equipment

WBS Dictionary

This element includes the equipment dedicated to deployment of solar array blankets, with the exception of cherrypickers.

Element Description

The solar array deployment equipment that has been identified is described in Table 1.2.1-8.

WBS 1.2.1.1.2.6 Antenna Deployment System (Platform)

WBS Dictionary

This element includes the equipment used to deploy and install the antenna secondary structure, to install phase control and power distribution wiring on the secondary structure, and to install the antenna subarrays.

Table 1.2.1-6 Indexer Description Sheet

ITEM INDEXER WBS NO. 1.2.1.1.2.5

SUBITEMS	20M Indexer	130M Indexer	200m Indexer	230m Indexer
FUNCTIONAL REQUIREMENTS	o Support, indexes solar array module	o Supports/indexes antenna	o supports/indexes antenna	o support/indexes yoke
	(COMMON TO ALL TYPES) o Remotely controlled in unison o Traverse along facility tracks (orthogonal directions) o Independently controlled o Tightly controlled syncronization of indexing speed o Attach/detach from structured attached points on satellite			
WHERE USED	Solar array facility	Antenna facility	Antenna facility	Yoke facility
MAJOR SUBELEMENTS	o 20M Tower	o 130M Tower	o 200M Tower	o 230M Tower
	(COMMON TO ALL TYPES) o Carriage (self-propelled) o Latch/unlatch mechanism o Remote control avionics			
OPERATING RATES AND TIMES	10 m/min	10m/min	10m/min	10m/min
QTY	7	6	2	2
MASS EA. / TOTAL	1300 kg 9100 kg	3000 kg 18000 kg	5000 kg 10000 kg	5500 kg 11000 kg
COST EA. / TOTAL	$3.8m $27m	$6m $30m	$10m $20m	$10.5m $21m
MANNING				

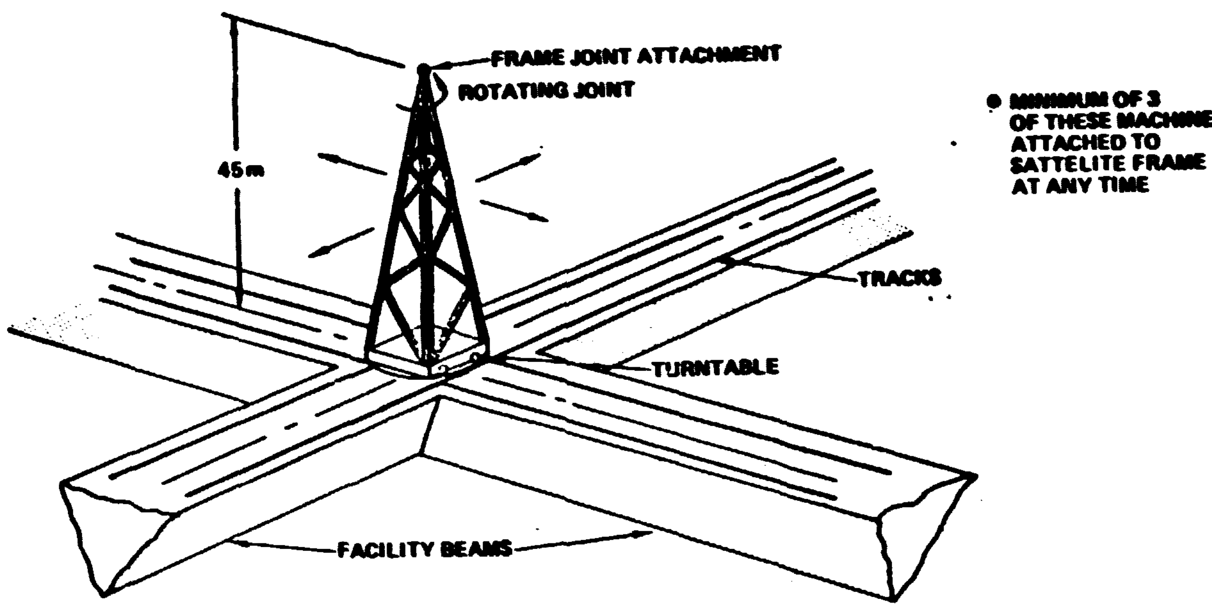

Figure 1.2.1-28 Satellite Support/Indexing Machine

Table 1.2.1-7 Bus Deployment Machine Description Sheet

ITEM BUS DEPLOYMENT MACHINES WBS NO. 1.2.1.1.2.3

SUBITEMS	SOLAR ARRAY BUS DEPLOYMENT MACHINE	ANTENNA BUS DEPLOYMENT MACHINE	YOKE BUS DEPLOYMENT MACHINE
FUNCTIONAL REQUIREMENTS	o Retract acquisition bus dispenser to clear beams	o Connect busses to switch gear subass'y	o Dispensers can be articulated so that busses can be directed to the slip ring subass'y
	(COMMON TO ALL TYPES) o Traverse along facility tracks (orthoronal direction) o Weld bus to bus connections o Dispense and flatten 1 mm thick sheet metal conductors o Quick change bus material magazines		
WHERE USED	Solar array mod.	Antenna	Yoke
MAJOR SUBELEMENTS	o Acquisition bus dispenser o A bus dispenser o B bus dispenser o C bus dispenser o 60m Boom	o A bus dispenser o B bus dispenser o C bus dispenser o 110m Bus boom	o A bus dispenser o B bus dispenser o C bus dispenser o Articulating/elevating boom
	(COMMON TO ALL TYPES) o Self-propelled carriage o 20m cherrypicker o Built-in tracks for cherrypicker o Control cab		
OPERATING RATES AND TIMES	TBD	TBD	TBD
QTY	1	1	1
MASS EA. / TOTAL	8000 kg 8000 kg	8000 kg 8000 kg	8000 kg 8000 kg
COST EA. / TOTAL	$25m	$25m	$25m
MANNING	2 operators per machine	2 operators per machine	2 operators per machine

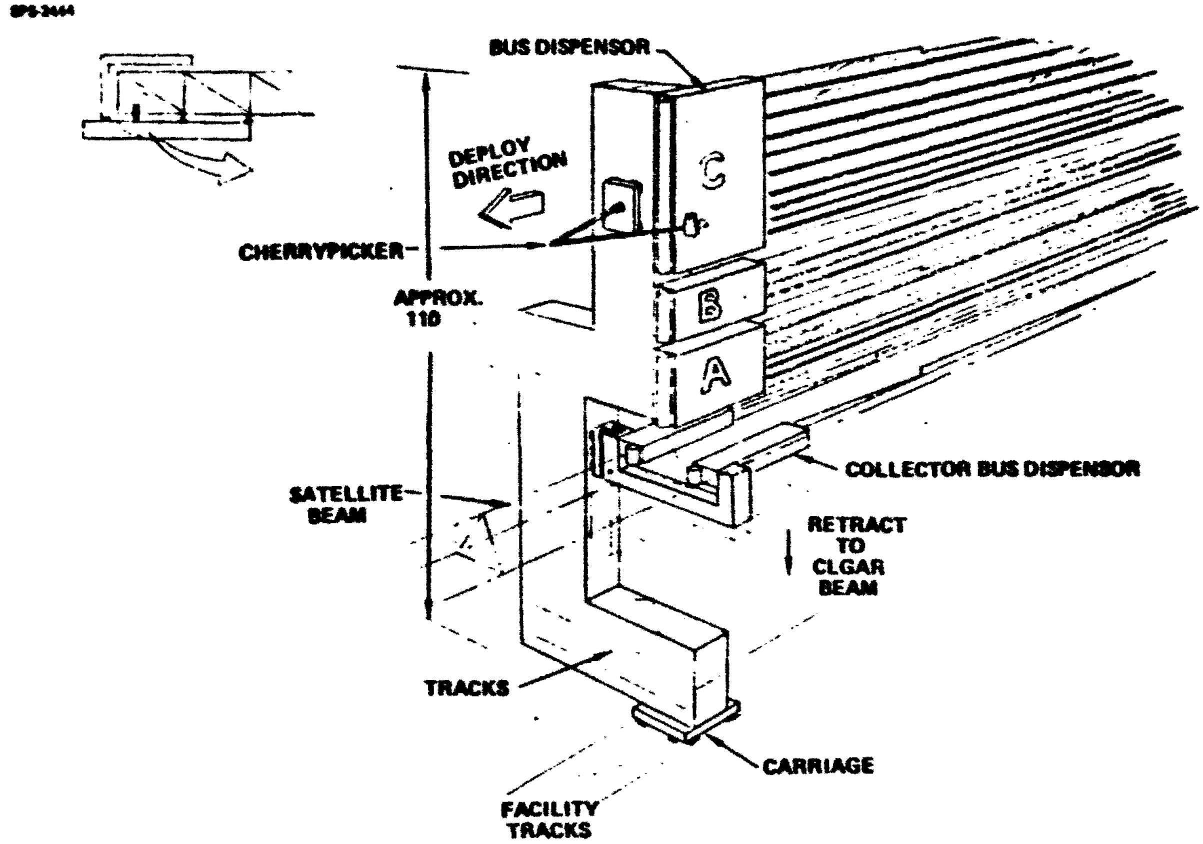

Figure 1.2.1-29 Bus Deployment Machine

Table 1.2.1-8 Solar Array Deployment Equipment Description Sheet

ITEM SOLAR ARRAY DEPLOYMENT EQUIPMENT WBS NO. 1.2.1.1.2.4

SUBITEMS	SOLAR ARRAY ANCHORS	SOLAR ARRAY CONTAINER HANDLING JIGS	SOLAR ARRAY CONTAINER TRANSPORTERS
FUNCTIONAL REQUIREMENTS	o Holds solar array container during deployment sequence	o Interface between containers and cherrypicker manipulators	o Stores TBD Solar array containers . o Transports containers
WHERE USED	Solar array facility	cherrypickers	Solar array facility
MAJOR SUBELEMENTS	o Frame o Hinge ass'y o container support bracket o tension sensors	o strongback beam o manipulator interface brackets o container interface mechanism	o container holdown mechanisms o carriage ass'y
OPERATING RATES AND TIMES			
QTY	176	4	4
MASS EA. TOTAL	TBD	TBD	TBD
COST EA. TOTAL	TBD	TBD	TBD
MANNING			

Element Description

The operation of the antenna deployment system was described on page previously. System characteristics are summarized in Table 1.2.1-9.

WBS 1.2.1.1.3 Cargo Handling/Distribution System

WBS Dictionary

This element includes the hardware used for docking the various cargo and crew vehicles, the systems used to offload/reload these vehicles, the cargo and crew transporters, the cargo sorting and storage systems, and the track network used to move the cargo, crews, and equipment around the base.

Operational Description

As an EOTV or chem OTV approaches the GEO base, the controller at the Earth-based Space Traffic Control Center would handoff control of the vehicle to a local traffic controller, who is stationed in the GEO base o, ·ations module. This local traffic controller issues verbal commands to the pilot oı he OTV or issues data commands to the unpiloted EOTV. The EOTV is brought into a stationkeeping position where it will remain until the cargo is offloaded. The chem OTV's are guided into a docking port on the base.

The EOTV transports the cargo on a free-flying "cargo pallet vehicle" (CPV) that is attached to the EOTV during orbit transfer. After the EOTV achieves its station-keeping position, the local space traffic controller (or another specialist) would issue the necessary command and control to activate the CPV and launch it away from the EOTV. The CPV is then guided into a dedicated docking system on the GEO base. There would be dedicated crew members who would be located at the docking systems area, who would control the docking of the vehicles.

When the CPV, EOTV, or chem OTV is ready for departure, the local traffic controller directs their departure until the ground-based traffic controller takes over command.

If space vehicles need refurbishment or repair prior to departure from the GEO base, there would be a crew of vehicle maintenance people who would handle the problem.

Table 1.2.1-9 Antenna Deployment System Description Sheet

ITEM ANTENNA DEPLOYMENT SYSTEM WBS NO. 1.2.1.1 2.6

SUBITEMS	DEPLOYMENT PLATFORM	PHASE CONTROL SYSTEM INSTALLOR
FUNCTIONAL REQUIREMENTS	o Provides the structural base upon which the following mobile equipment operators o Subarray deployment gantry o Secondary Structure assembly gantry o Secondary Structure telescoping installation system	o Provide capability to maneuver a 20m cherrypicker anywhere beneath a secondary structure o Provide means to install a phase control wiring (or fiber optics) distribution harness o Assists in deployment of secondary structure
WHERE USED	Antenna const. facility	Beneath deployment platform
MAJOR SUBELEMENTS	o Structure o Tracks for gantry carriages o Power distribution system	o Gantry o Mobile 20m cherrypicker o Harness storage o Work illumination system
OPERATING RATES AND TIMES		TBD
QTY	1	1
MASS EA. TOTAL	(Total including all attached equip) 28000 kg	TBD
COST EA. TOTAL	(Total including all attached equip) $80m	TBD
MANNING		1 man/shift

Table 1.2.1-9 Antenna Deployment System Description Sheet (Continued)

ITEM ______ WBS NO. 1.2.1.1.2.6

SUBITEMS	SECONDARY STRUCTURE ASSEMBLY EQUIPMENT	SUBARRAY DEPLOYMENT GANTRY
FUNCTIONAL REQUIREMENTS	o Provides capability to maneuver a cherrypicker anywhere over the top surface of the secondary structure o Provide means to install power distribution wiring harness o Assists in secondary structure deployment op.	o Provides capability to maneuver the subarray deployer anywhere under a secondary structure o Provide means to transfer pallets of subarrays from cargo transporter to the subarray deployer o Provide tracks for subarray deployer
WHERE USED	Deployment Platform	Deployment Platform
MAJOR SUBELEMENTS	o Gantry o Mobile 20m cherrypicker o Mobile Secondary structure De-telescoper o Harness storage o Work illumination system	o Gantry o Elevator system
OPERATING RATES AND TIMES		
QTY	1	1
MASS EA. TOTAL	TBD	TBD
COST EA. TOTAL	TBD	TBD
MANNING	1 op/shift	0

Table 1.2.1-9 Antenna Deployment System Description Sheet (Continued)

ITEM ______ WBS NO. 1.2.1.1.2.t

SUBITEMS	Subarray Deployer	Secondary Structure teelscoping installation system
FUNCTIONAL REQUIREMENTS	o Provide capability to load/ offload subarray pallets o Provide means to extract single subarrays from o Provide means to raise subarray o Provide means to attach subarray leveling jacks to secondary structure o Provide means to level the subarray o Provide means to attach subarray phase control and power distribution pig tails to connectors on secondary structure	o Provide means to support secondary structure while it is being worked o Provide means to raise secondary structure into contact with primary structure o Provide means to make secondary structure-to-primary structure interface
WHERE USED	Subarray deployment gantry	Deployment platform
MAJOR SUBELEMENTS	o Pallet conainer o Subarray feed mechanism o Subarray elevator o Subarray screw jack actuator o Leveling sensor/control sytem o Dextrous manipulator o 2 man control cab o Carriage	o Telescoping actuators (4) o Interface attatchment mechanisms
OPERATING RATES AND TIMES	install one subarray within 20 minutes	TBD
QTY	1	1
MASS EA. TOTAL	TBD	TBD
COST EA. TOTAL	TBD	TBD
MANNING	2 operators/shift	Controlled by subarray deployment machine operator.

There would also be a requirement for some GEO-based crew who would handle the OTV's and their cargo or crew payload modules.

After a crew OTV is docked in the OTV operations area, Figure 1.2.1-30, a crew bus (concept illustrated in Figure 1.2.1-31) drives up to the crew module and achieves an airlock. The passengers and crew are then moved out of the OTV into the crew bus. The passengers are then transported to the crew habitat modules by the bus.

The crew supply module attached to the OTV is taken off by cherrypickers and placed on cargo transporter vehicles which then move the supply module to the crew quarters.

After a cargo pallet vehicle (CPV) is docked, cherrypickers with a pallet handling jig attached, remove the cargo pallets and place them onto cargo transporter vehicles. There are 10 cargo pallets to be removed from each CPV.

The cargo pallets are transported to the Cargo Sorting Facility (Figure 1.2.1-32) where a pair of cherrypickers place the pallet onto a pallet holdown fixture. These cherrypickers assist a component handling gantry/manipulator in removing the component containers from the pallet. The gantry/manipulator then transports the containers to a nearby storage rack.

This operation is repeated until the cargo pallet is emptied. If there are empty containers that are to be recycled, these are placed into the cargo pallet. Eventually, the cargo pallet is returned and reloaded onto the CPV.

The component handling gantry/manipulator is used to remove containers from the storage racks and to place them onto transporters. These transporters then take the containers either directly to construction equipment or to subassembly factories.

At the construction equipment, such as a beam machine or bus deployment machine, a cherrypicker is employed to changeout empty containers from the machine and replace them with the loaded containers.

At the subassembly factories (refer to figures 1.2.1-33 and -34), the component containers are removed from the transporters by cherrypickers and placed on storage racks near the work spaces.

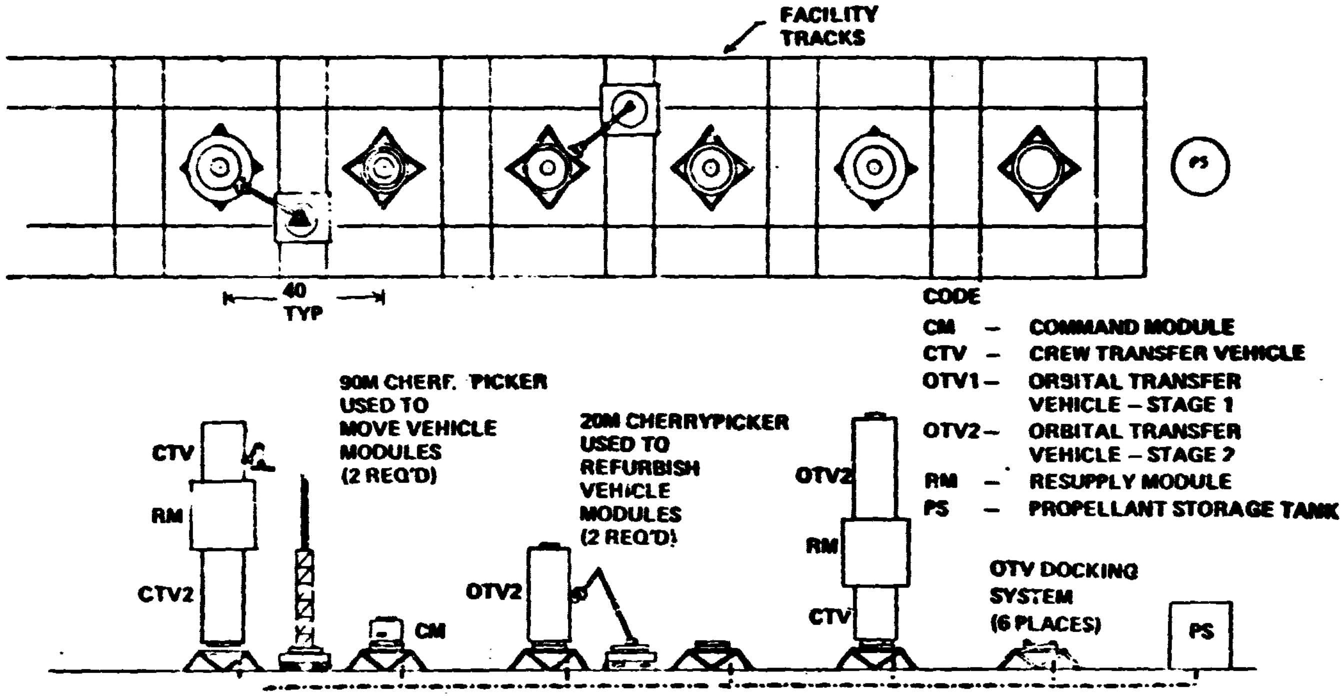

Figure 1.2.1-30 OTV Operations Area

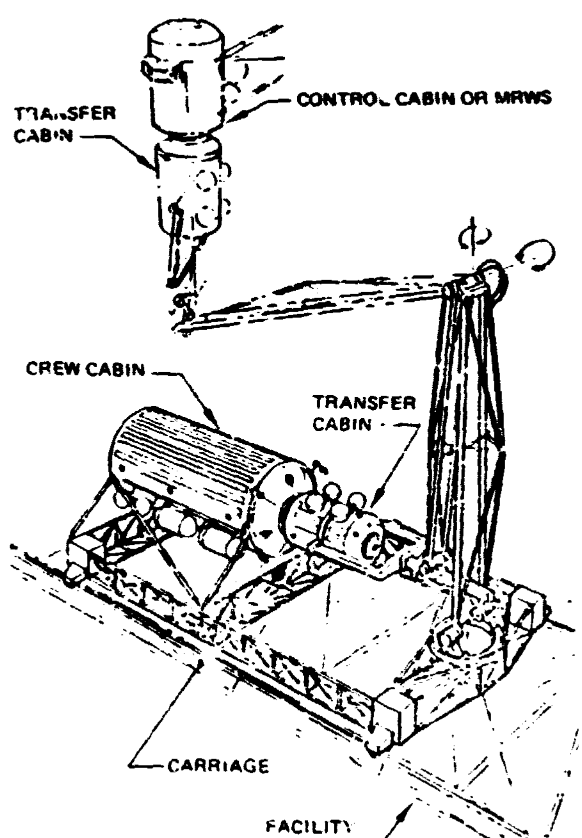

Figure 1.2.1-31 Crew Bus

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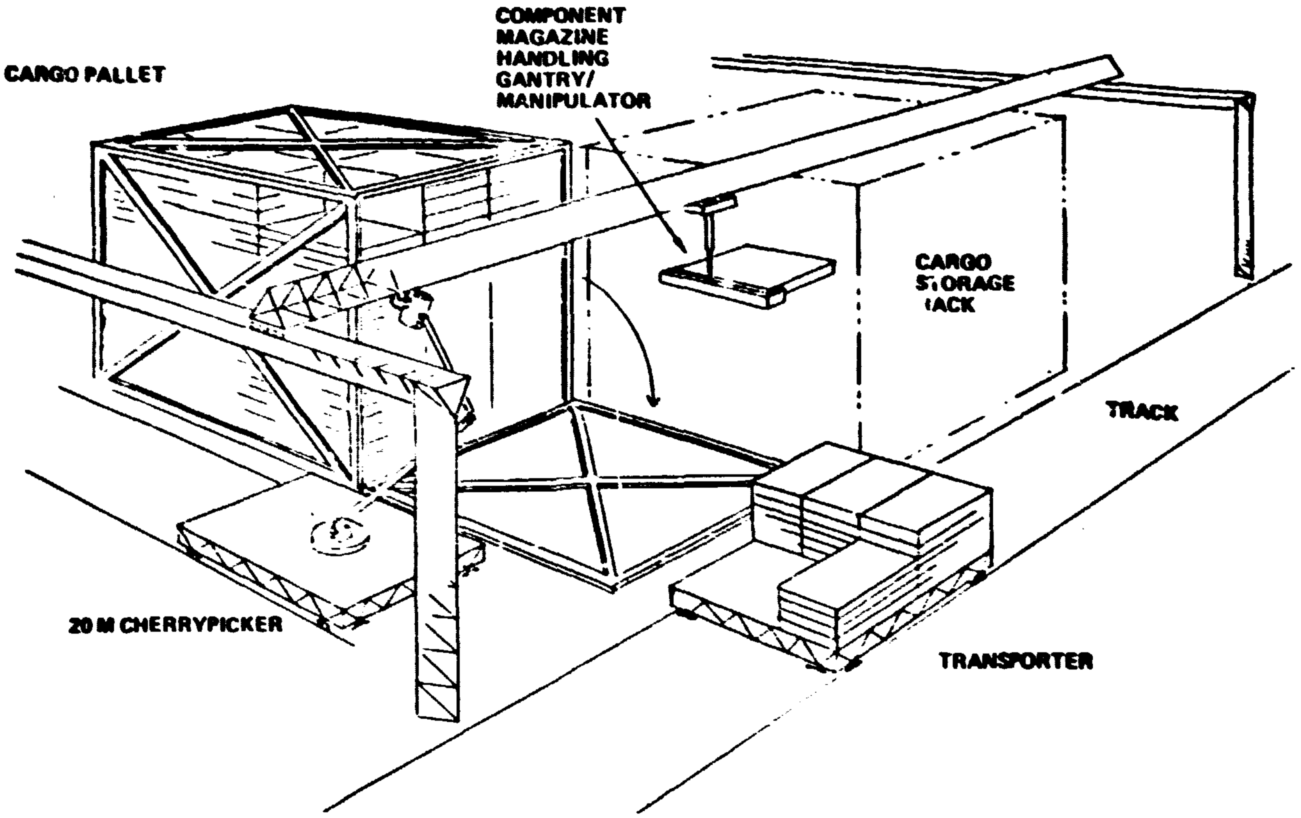

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Figure 1.2.1-32 Cargo Sorting/Storage Area

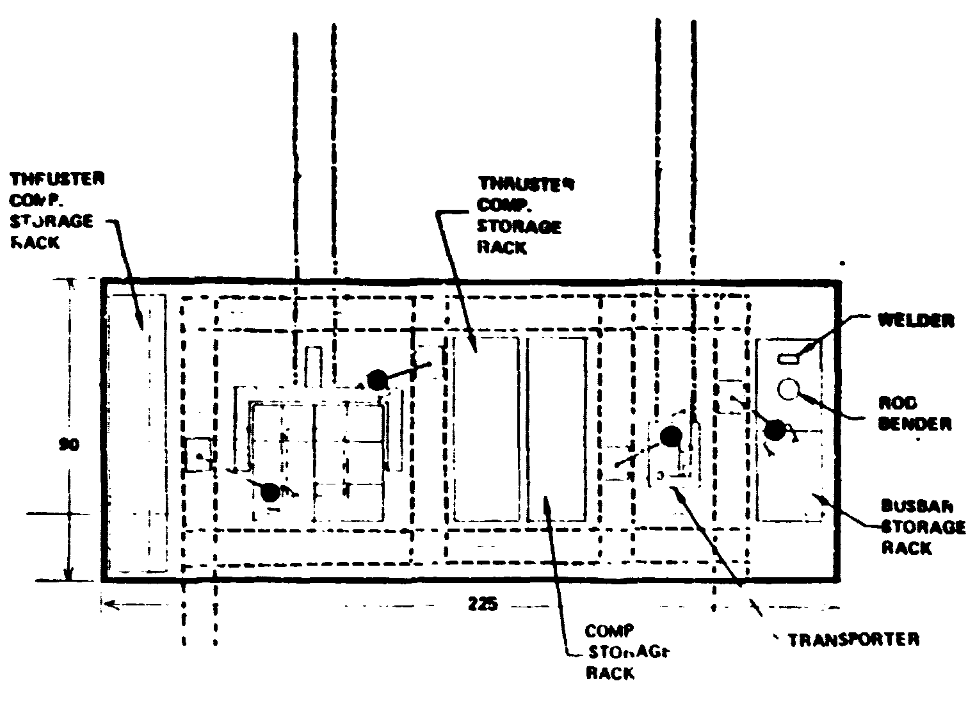

Figure 1.2.1-33 Level A Subassembly Factory

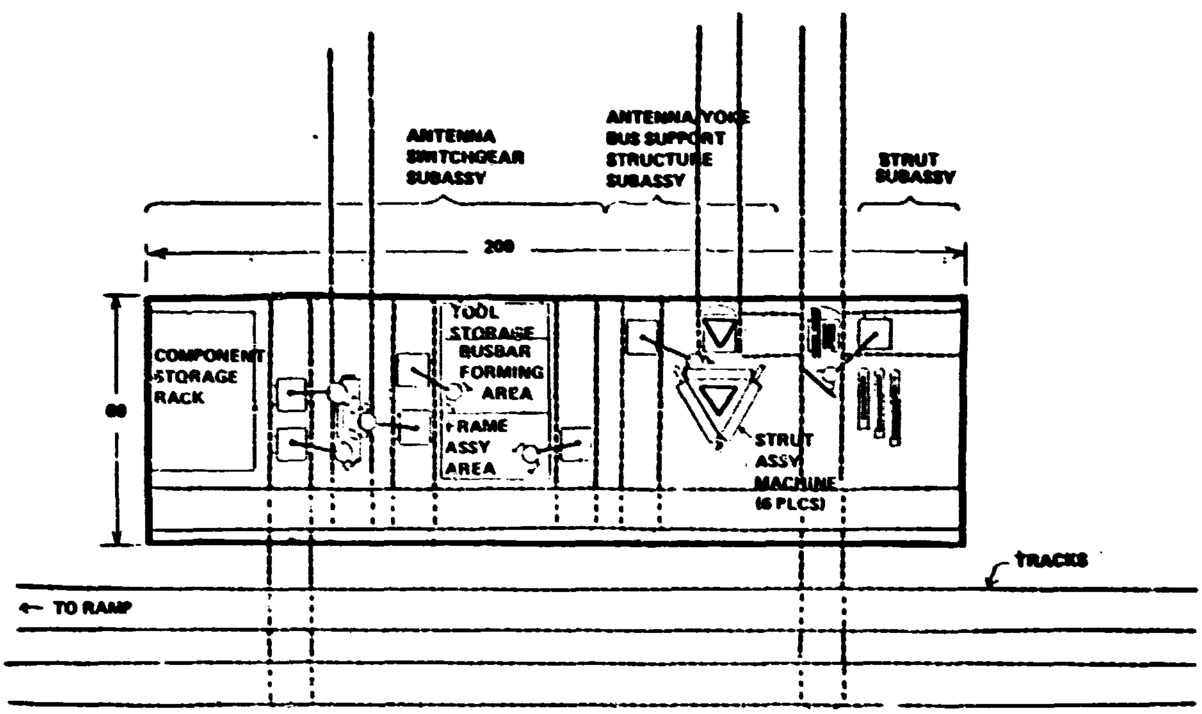

Figure 1.2.1-34 Level B Subassembly Factory

The transporters, either empty or loaded with empty containers, are then returned to the warehouse to pick up another load.

The movement of the transporters around the facility track network would be controlled from a central track traffic management center in the operations module. All of these transporters are self-propelled but are remotely controlled. The central track traffic management center controllers also keep track of the construction equipment and crew busses that are operating on the track network.

WBS 1.2.1.1.3.1 Vehicle Docking Systems

WBS Dictionary

This element includes the systems dedicated to docking of chem OTV's and the EOTV cargo pallet vechicles.

Element Description

Requirements for two types of vehicle docking sytems are identified. in Table 1.2.1-10. Figure 1.2.1-30 showed the chem OTV docking facilities.

The vehicle docking operations were discussed in WBS 1.2.1.3.1.

WBS 1.2.1.1.3.2 Vehicle Loading/Unloading Systems

WBS Dictionary

This element includes the hardware systems used to load/off-load the chem OTV and cargo pallet vechicle.

Element Description

The equipment associated with loading/off-loading the transportation vehicles is described in Table 1.2.1-11.

Table 1.2.1-10 Vehicle Docking System Description Sheet

ITEM VEHICLE DOCKING SYSTEMS WBS NO. 1.2.1.1.3.1

SUBITEMS		OTV DOCKING SYSTEM	CARGO PALLET VEHICLE DOCKING SYSTEM
FUNCTIONAL REQUIREMENTS		o Provide docking interface with chem OTV stages, command module, crew transfer vehicles, and tankers.	o Provide docking, interface with cargo pallet vehicle
WHERE USED		Vehicle docking area	Vehicle docking area
MAJOR SUBELEMENTS		o Frame o Docking mechanism	o Frame o "Short" docking arms (2) o "Long" docking arms
OPERATING RATES AND TIMES			
QTY		6	2
MASS	EA	TBD	TBD
	TOTAL		
COST	EA	TBD	TBD
	TOTAL		
MANNING			

Table 1.2.1-11 Vehicle Loading/Offloading System Description Sheet

ITEM VEHICLE LOADING/OFFLOADING SYSTEMS WBS NO. 1.2.1.1.3.2

SUBITEMS		OTV CARGO HANDLING CHARRYPICKERS	PROPELLANT TRANSFER SYSTEM	CARGO PALLET VEHICLE CARGO HANDLING CHERRYPICKERS
FUNCTIONAL REQUIREMENTS		o Stack/unstack OTV stages and payload modules	o Transfer Propellants between OTV docking systems and the propellant storage tank	o Offload loaded HLLV cargo pallets o Reload empty pallets
WHERE USED		OTV docking area	OTV docking area	Vehicle docking area
MAJOR SUBELEMENTS		o 90m cherrypicker o Handling jig	o pump system o piping	o 90m cherrypicker o handling jig
OPERATING RATES AND TIMES				
QTY		2		2
MASS	EA TOTAL	5000 KG 10000 kg	TBD	5000 kg 10000 kg
COST	EA TOTAL	$36m TFU $55.7 m	TBD	$36m TFU $55.7m
MANNING		2/shift	TBD	2/shift

WBS 1.2.1.1.3.3 Transporters

WBS Dictionary

This element includes the GEO base track-mounted unit used as the prime mover for construction equipment and the units used to transport cargo within the base.

Element Description

The basis for every piece of moving equipment is a machine called a "Standard Carriage Unit," see Figure 1.2.1-35. Additional details of the "bogey units" used on these carriages are shown in Figures 1.2.1-36 and -37. Table 1.2.1-12 shows that there are four major classes of carriage units that will be required.

The carriages associated with construction equipment items have already been accounted for. There are some transporters that are used for moving cargo between the receiving area, cargo sorting area, subassembly areas, and final assembly areas. The mass and cost estimates for these cargo transporters are listed in Table 1.2.1-13.

WBS 1.2.1.1.3.4 Cargo Sorting Systems

WBS Dictionary

This element includes the hardware systems dedicated to the cargo pallet contents off-loading into component storage, and component loading onto cargo transporters.

Element Description

A requirement for dedicated cargo sorting equipment has been identified. Figures 1.2.1-32 and 1.2.1-38 show the cargo sorting area. Table 1.2.1-14 describes this equipment.

WBS 1.2.1.1.3.5 Cargo Storage Systems

WBS Dictionary

This element includes the hardware systems used to store (warehouse) the SPS components and propellants.

Element Description

The cargo storage systems that have been identified are described in Table 1.2.1-15.

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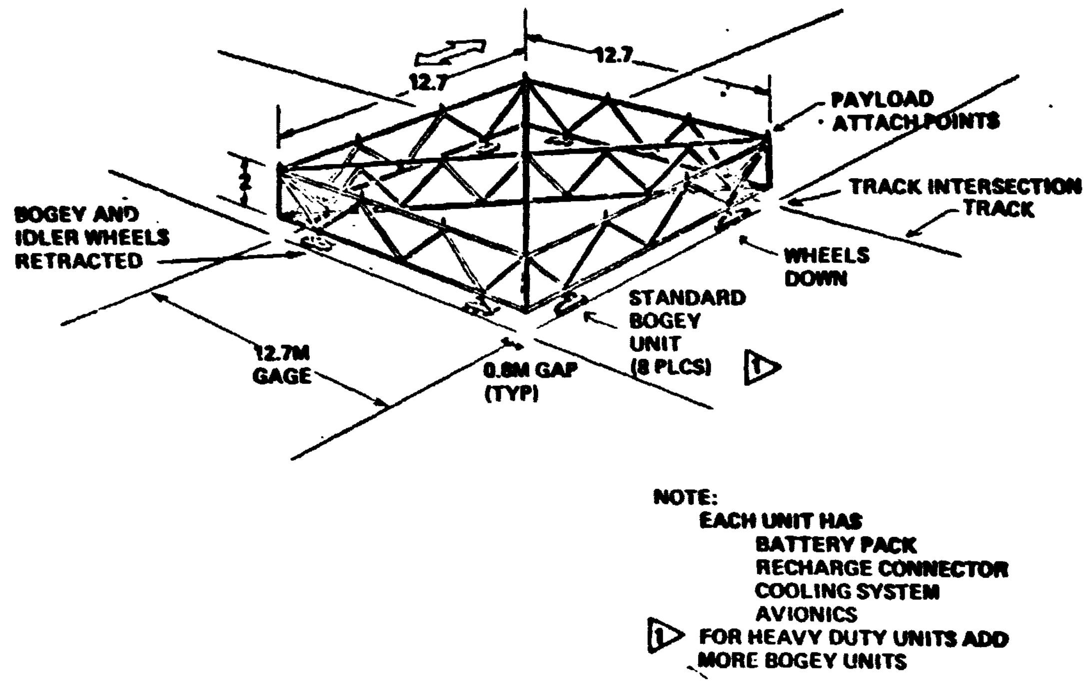

Figure 1.2.1-35 Standard Carriage Unit

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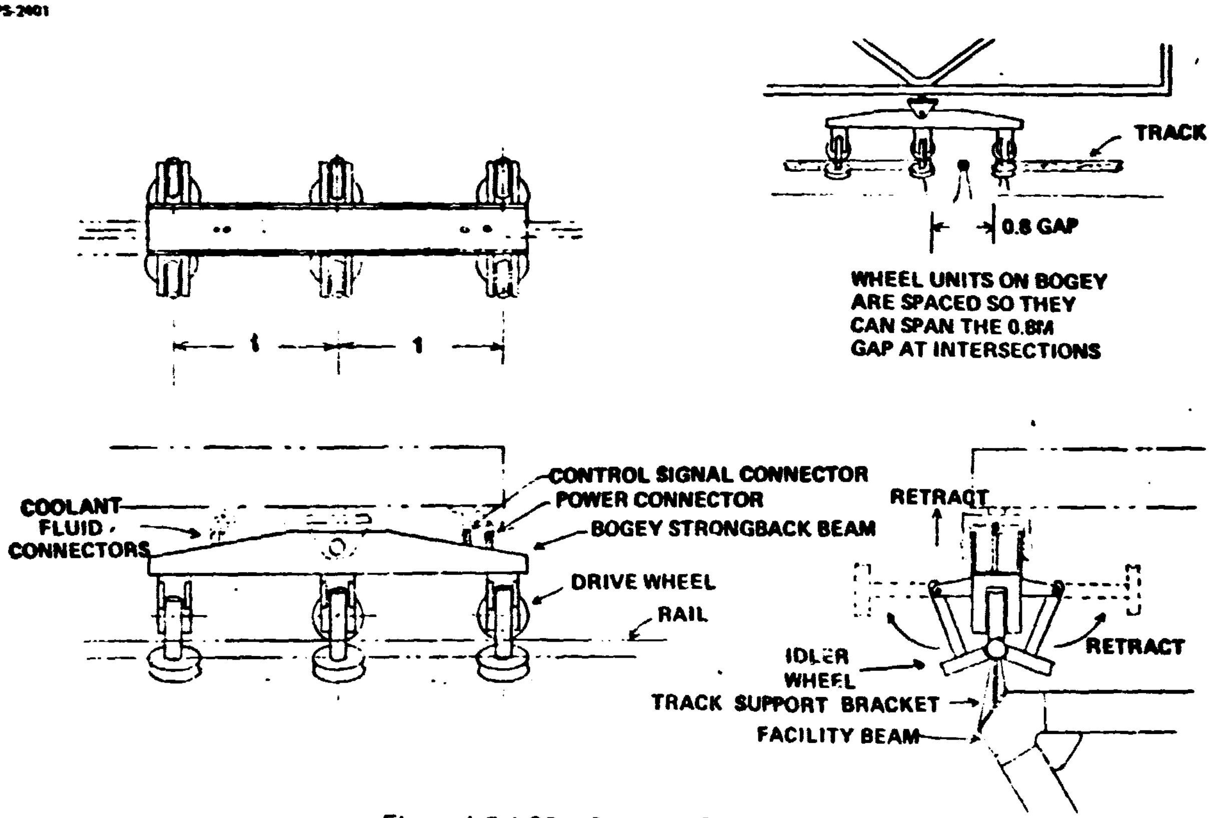

Figure 1.2.1-36 Standard Bogey Unit

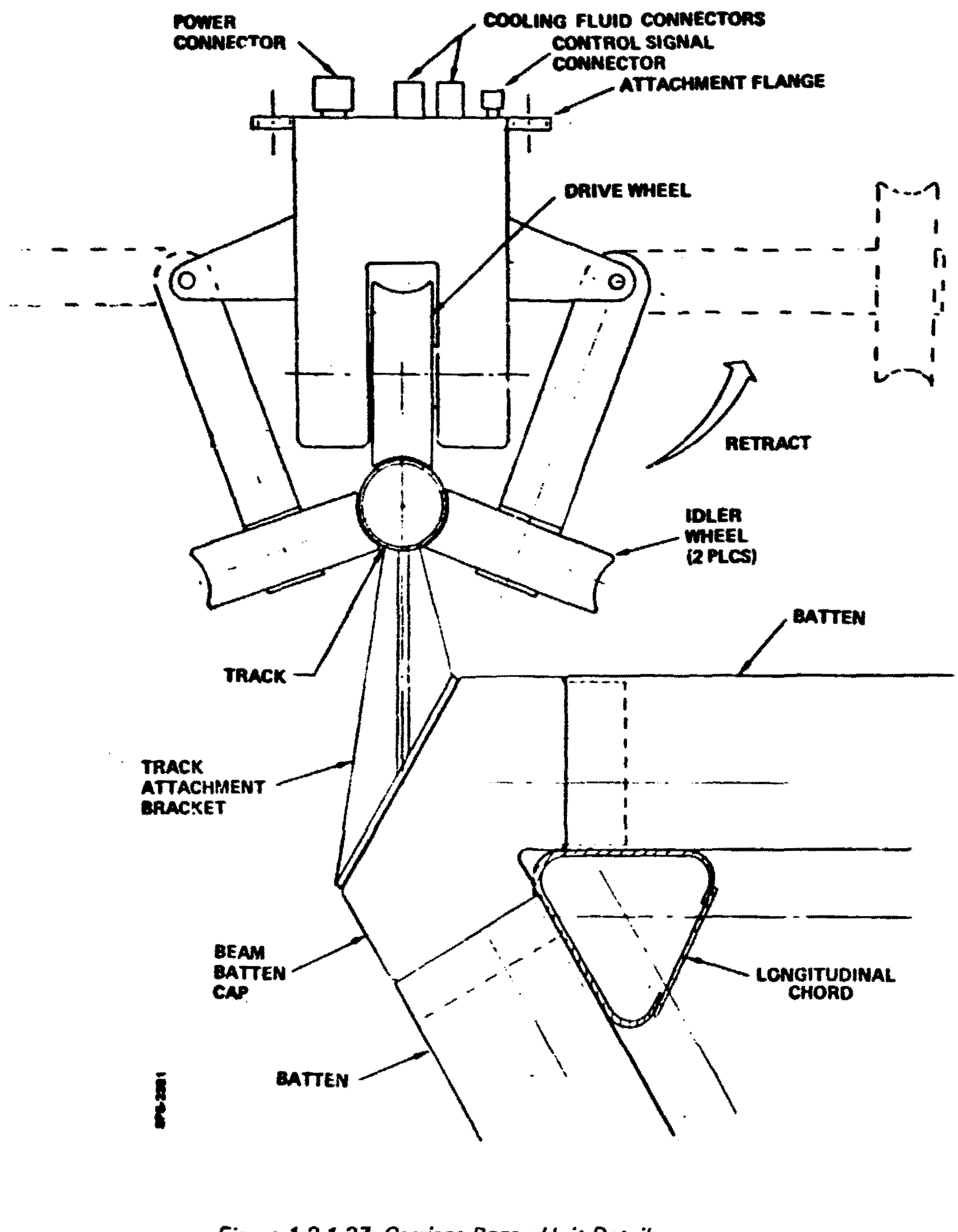

Figure 1.2.1-37 Carriage Bogey Unit Details

Table 1.2.1-12 Transporter Classifications

UNDER 20,000 KG CLASS

- o Crew Bus Carriage
- o Slipring Transporter
- o Turntable Cart
- o Ant. Sw. Gear Transporter
- o 110 m Crane/Manipulator
- o Module SW Gear Transporter
- o Component Platform Carriage
- o Small Beam Machine Carriage
- o Wiring Deployer Carriage
- o Strut Transporter Carriage
- o Ant. Bus Support Struct. Transp.

40,000 KG CLASS

- o Large Beam Machine Carriage
- o Strut Magazine Transporter
- o Conductor Roll Transporter
- o Bus Deployment Machine Carriage
- o Secondary Structure Deployer Carriage

80,000 KG CLASS

- o Subarray Deployment Machine Carriage
- o Solar Array Magazine Transporter
- o Solar Array Deployer Carriages

SPECIAL PURPOSE CLASS

- o Thruster Module Transporter (700,000 KG)
- o Module Indexing/Support Machine (3×10^6 KG)
- o Antenna Indexing/Support Machine (12×10^6 KG)

Table 1.2.1-13 Cargo Transporter Description Sheet

ITEM CARGO TRANSPORTERS WBS NO. 1.2.1.1.3.3

SUBITEMS	
FUNCTIONAL REQUIREMENTS	o Transport cargo
WHERE USED	Throughout the GEO base
MAJOR SUBELEMENTS	o Frame o Bogey units o Power supply o Avionics
OPERATING RATES AND TIMES	10 - 20m/min
QTY	20
MASS EA. / TOTAL	500 K· 10000 KG
COST EA. / TOTAL	$3m $60m
MANNING	REMOTELY CONTROLLED

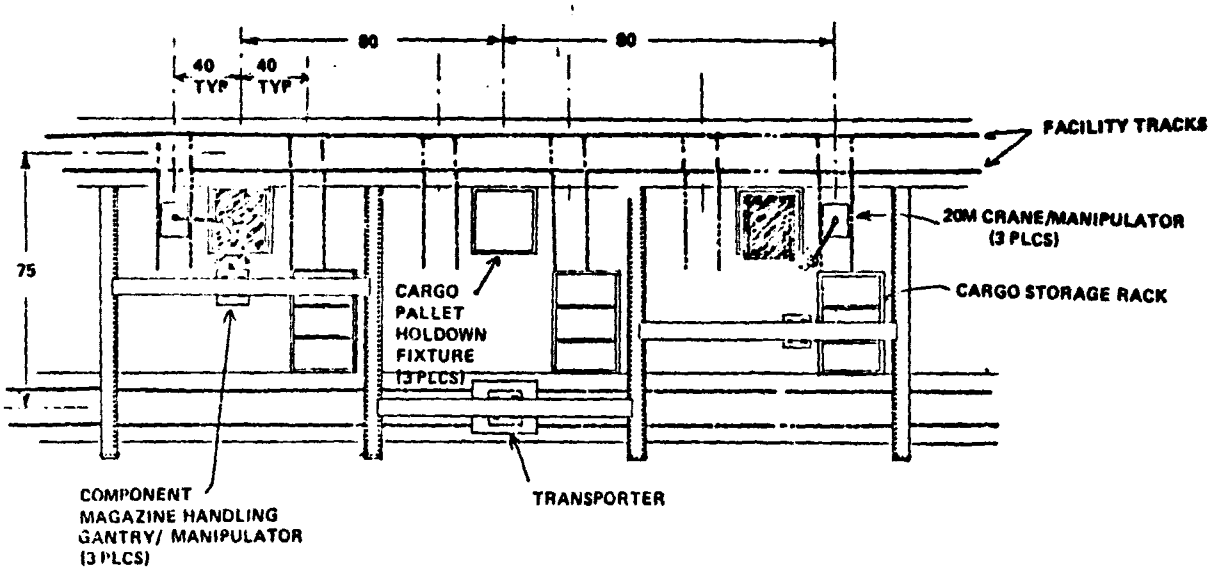

Figure 1.2.1-38 Central Cargo Receiving and Warehousing Area (Level A)

Table 1.2.1-14 Cargo Sorting System Description Sheet

ITEM CARGO SORTING SYSTEM WBS NO. 1.2.1.1.3.4

SUBITEMS	Cargo Pallet holddown fixture	Component magazine handling gantry/manip	20 m cherrypicker
FUNCTIONAL REQUIREMENTS	o Latches cargo pallet to base structure o Remotely controlled	o Transfers cargo magazine from pallets to storage racks o Remotely controlled o Transfers cargo magazines from storage racks to transporters	o Unlatches cargo pallet magazines o Assists in removing magazines from pallet o Configures empty pallet for return to vehicle o Removes pallet from transporter and places on holdown fixture
WHERE USED	Warehouse	Warehouse	Warehouse
MAJOR SUBELEMENTS	o Frame o Latch mechanisms	o Gantry o Manipulator o Avionics	
OPERATING RATES AND TIMES			
QTY	3	3	3
MASS EA. / TOTAL	TBD	TBD	2500 kg 7500 kg
COST EA. / TOTAL	TBD	TBD	$26m TFU $56.16m
MANNING		1 operator	1 operator

Table 1.2.1-15 Cargo Storage System Description Sheet

ITEM CARGO STORAGE SYSTEMS WBS NO. 1.2.1.1.3.5

SUBITEMS	Cargo Storage Racks	Propellant storage tank
FUNCTIONAL REQUIREMENTS	o Restrain cargo magazines, pallets, subassemblies, etc. o Self-latching interfaces between racks and cargo.	o Store propellants that will be used on the maintenance OTV's, sateilite transfer systems, and base thruster systems
WHERE USED	Warehousing area	Warehousing area
MAJOR SUBELEMENTS	o Framework o Latches	
OPERATING RATES AND TIMES		
QTY	TBD	TBD
MASS EA. / TOTAL	TBD	TBD
COST EA. / TOTAL	TBD	TBD
MANNING		

WBS 1.2.1.1.3.6 Cargo Distribution System

WBS Dictionary

This element includes the GEO base track network that is used for mounting movable equipment.

Element Description

The cargo distribution system is a track network that is built into the base. This track system is mounted on the facility structural beams as shown in Figure 1.2.1-39. This network provides pathways for moving and cargo transporters, construction equipment, and crew transporters throughout the base. Figures 1.2.1-40 and -41 show the track networks in the antenna construction facility. (The track network in the solar array construction facility has not been defined). Table 1.2.1-16 summarizes the estimated characteristics of the track system.

WBS 1.2.1.1.3.7 Crew Transporters

WBS Dictionary

This element includes the vehicles that are used on the GEO base track network for transporting crew.

Element Description

Requirements for two types of crew transport vehicles have been identified. Table 1.2.1-17 describes these vehicles (also see Figure 1.2.1-31).

WBS 1.2.1.1.4 Subassembly Factories

WBS Dictionary

This element includes the facilities and equipment dedicated to preassembly of SPS subassemblies prior to delivery to the final installation facilities.

Element Description

There are several SPS subassemblies that cannot be shipped in a volume/mass efficient manner. Subsequently, it will be necessary to preassemble some items at the GEO base in dedicated facilities prior to delivering the subassemblies to the final assembly areas. (The subassembly areas were shown in Figures 1.2.1-33 and 1.2.1.34). The

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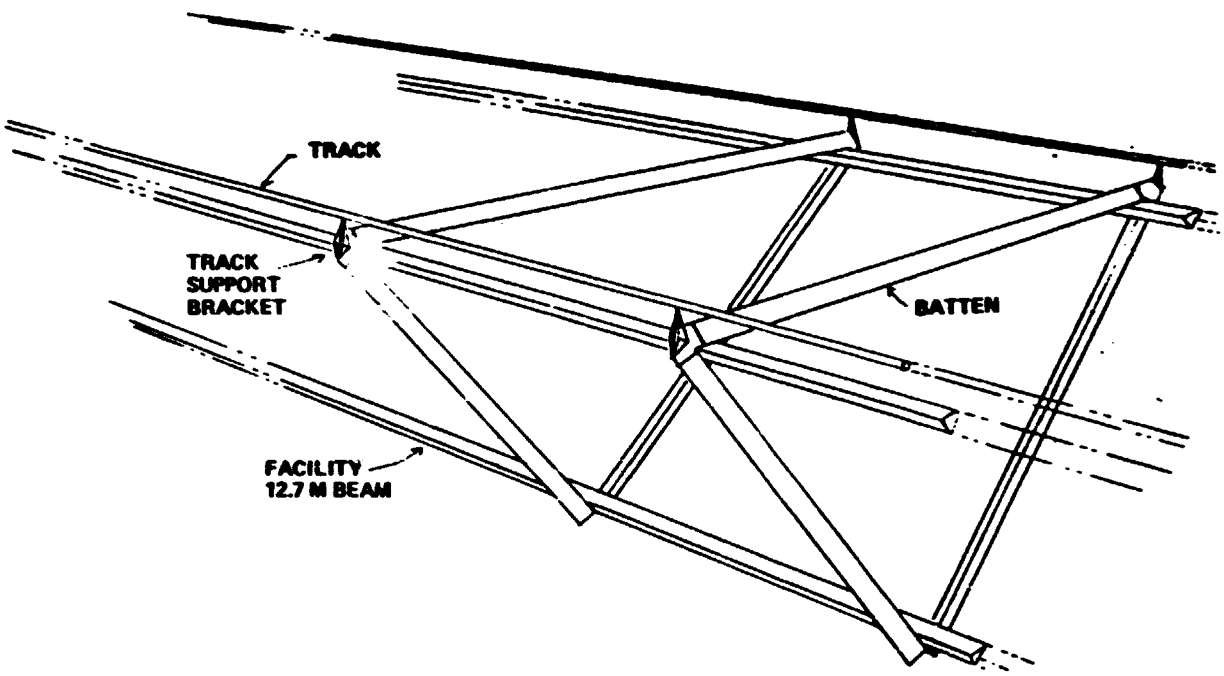

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Figure 1.2.1-39 Facility and Satellite Track Concept

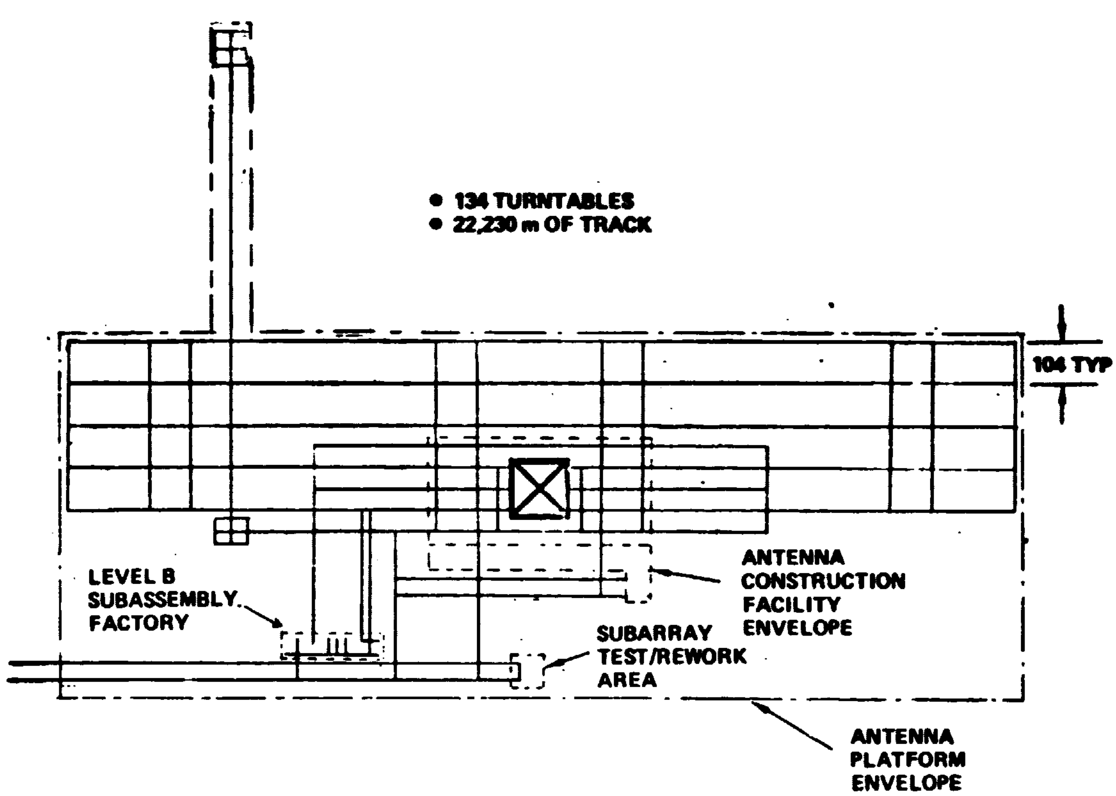


Figure 1.2.1-40 Antenna Platform (Level B) Track Pattern

C-3

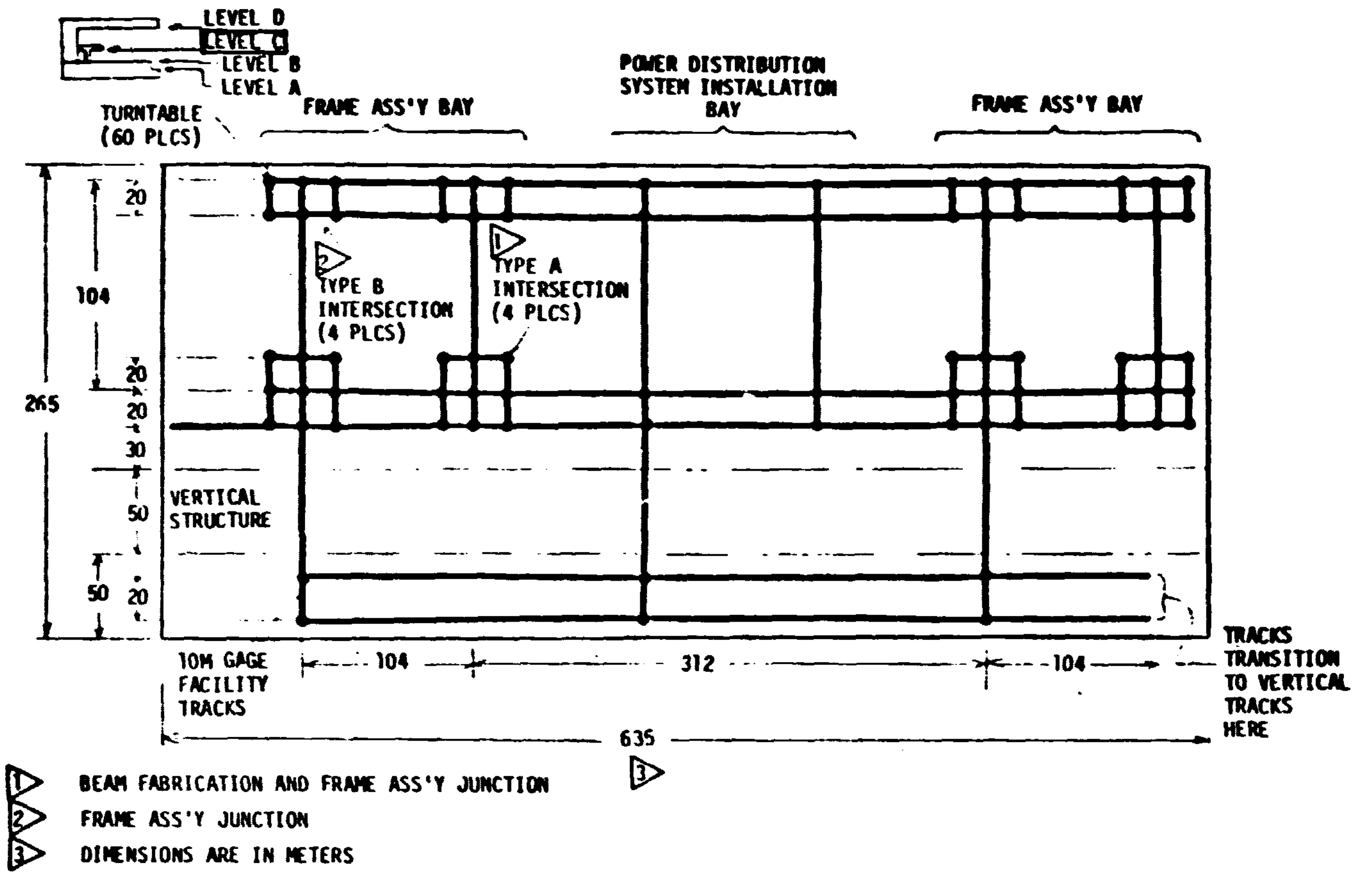


Figure 1.2.1-41 Logistic Network Level C

Table 1.2.1-16 Cargo Distribution System Description Sheet

ITEM: CARGO DISTRIBUITON SYSTEM

WBS NO.: 1.2.1.1.3.6

SUBITEMS		Track network
FUNCTIONAL REQUIREMENTS		o Provide interface between equipment carriages and the base structure o Provide orthogaral pathways for vehicle movement
WHERE USED		Throughout the GEO base
MAJOR SUBELEMENTS		o Attachment brackets o Rail o Vehicle command and control o Central command and control center
OPERATING RATES AND TIMES		
QTY		77696 meters (double rail)
MASS	EA. TOTAL	155,392 kg
COST	EA. TOTAL	$31.1m
MANNING		

Table 1.2.1-17 Crew Transporter Description Sheet

ITEM CREW TRANSPORTERS WBS NO. 1.2.1.1.3.7

SUBITEMS	10 man crew bus	24 man crew bus
FUNCTIONAL REQUIREMENTS	o 10 man capacity	o Transfer crew to const. equip control cabs o 2 man capacity
	(COMMON TO BOTH) o Provide pressurized, shirt-sleeve environment o Provide airlocks at each end o Provide personnel restraint system	
WHERE USED	Throughout base	Throughout base
MAJOR SUBELEMENTS		o Transfer capsule o Capsule manipulator
	(COMMON TO BOTH) o Carriage o Pressurized container with ECLSS o Avioncs	
OPERATING RATES AND TIMES	0-20m/min	0-20 m/min
QTY	3	2
MASS EA. / TOTAL	5000 kg 15000 kg	12000 kg 24000 kg
COST EA. / TOTAL	$4m $12m	$7M $14m
MANNING	1 operator	1 operator

Level A subassembly factory puts together the subassemblies used on the solar array module. The Level B subassembly factory puts together the subassemblies used on the antenna and yoke. Table 1.2.1-18 summarizes the equipment that has been identified to date.

WBS 1.2.1.1.5 Test/Checkout Facilities

WBS Dictionary

This element includes all facilties and equipment on the GEO base that are dedicated to test and checkout of SPS components or subassemblies.

Element Description

The major test and checkout facilities/equipment that have been identified are the following:

- Subarrays test system
- Thruster test system
- Slipring assembly test system

There has been no configuration concept or mass, cost, or crew size estimates developed for these elements.

WBS 1.2.1.1.6 Transportation Vehicle Maintenance Facilities

WBS Dictionary

This element includes special facilities and equipment dedicated to chem OTV or EOTV maintenance operations at the GEO base.

Element Description

These facilities have not been identified at this time.

WBS 1.2.1.1.7 SPS Maintenance Support Facilities

WBS Dictionary

This element includes equipment items stationed at the GEO base that are dedicated to the refurbishment of the SPS failed components that have been returned from SPS's.

Table 1.2.1-18 Subassembly Factory Equipment Description Sheet

ITEM SUBASSEMBLY FACTORY EQUIPMENT WBS NO. 1.2.1.1.4

SUBITEMS	Subassembly Factory A	Subassembly Factory B
FUNCTIONAL REQUIREMENTS	o Preassemble o Thruster subass'y o Solar array module switch gear subass'y o Beam end fittings o Beam battens	o Preassemble o Antenna switch gear subass'y o Antenna/yoke bus support structures o Beam end fittings o Beam battens
WHERE USED		
MAJOR SUBELEMENTS	o component stroage racks o 20m cherrypickers (6) o Bus bar welder o Bus bar rod bender o Strut assembly machines o Beam end fitting assy. jigs. o Batten fabricators	o component storage racks o 20m cherrypickers (9) o Beam end fitting ass'y jigs o Batten fabricators
OPERATING RATES AND TIMES		
QTY		
MASS EA. / TOTAL	(cherrypickers only) 2500 kg 15000 kg	(cherrypickers only) 2500 kg 22500 kg
COST EA. / TOTAL	(cherrypickers only) $112m	(cherrypickers only) $168.5m
MANNING	7 per shift	7 per shift

The maintenance crew living and working modules and the dedicated maintenance vehicles are addressed in other sections.

Element Description

The refurbishment facility equipment provisions have not been defined at this time.

WBS 1.2.1.1.8 Base Subsystems

WBS Dictionary

This element includes the base electrical power and flight control systems.

Element Description

Several subsystems do not relate specifically to any one of the crew modules, but instead are associated with operating the base as a total entity. Such subsystems include primary power and flight control.

Electrical Power. Basic operating power requirements have been grouped into the categories associated with crew modules, construction equipment and external lighting as shown in Table 1.2.1-19. The average operating power level required is estimated at over 1600 KW. This load does not include recharging of the secondary power supply or losses.

Crew module, power requirements were based on estimates for a 12 man space station defined by Rockwell, scaled up to account for the difference in crew size and the number of modules involved.

Construction equipment power estimates relied on Boeing data and data from recent space station studies. Typical examples per machine include the 12.5m beam machine at 5 KW, and crane/manipulator at 3 KW. All of these estimates include the power for a two man control cabin.

External lighting estimates are based on providing 216 lumens/m^2 as specified by McDonnell Douglas in the Space Station Systems study (NAS9-14958). Typical construction areas in this study covered 2000 m^2 and required 10 KW to provide the specified illumination. A total of 32 areas of this size were identified.

Table 1.2.1-19 Base Operating Power Requirements

OPERATING POWER		KW
CREW MODULES		(1175)
ENVIRONMENT CONT/LIFE SUPPORT	750	
INTERNAL LIGHTING	350	
INFORMATION SYSTEM	70	
GUID. & CONT.	5	
CONSTRUCTION EQUIPMENT		(150)
SATELLITE EQUIPMENT	50	
ANTENNA EQUIPMENT	50	
SUBASSEMBLY	50	
EXTERNAL LIGHTING		(320)
SATELLITE CONST.	120	
ANTENNA CONST.	120	
SUBASSY/WAREHOUSE	80	
	TOTAL	1645

Table 1.2.1-20 Solar Array Sizing

• REQUIREMENTS (KW)		(3645)
• OPERATING LOAD		1645
• SECONDARY POWER SUPPLY RECHARGING		960
• POWER CONDITIONING		330
• POWER DISTRIBUTION		540
• RADIATION DEGRADATION (5%)		170
• SIZING		
• CONTINUOUSLY SUN ORIENTED ARRAY: (SATELLITE TYPE CELLS, 140 w/m^2)	26000 m^2	
• FIXED BODY MOUNTED ARRAY WITH EARTH ORIENTED CONST. BASE		
• ARRAYS ON 3 SIDES OF BASE		
• MAX SUN INCIDENCE ANGLE OF 54.5 DEG		
• TOTAL ARRAY SIZE:	≈130000 m^2 205m x 205m FOR EACH OF (3) ARRAYS	

The total power requirement to be used in sizing the primary power supply is 2985 KW as noted in Table 1.2.1-20. The secondary power recharging load is for a nickel hydrogen system that produces the operating loads during 10% of the orbit. The allowance for oversizing is that associated with 50 μm cells and 75 μm cover slips. No thermal annealing is assumed.

The primary power generation system is solar arrays similar to those used in the satellite, with a nickel hydrogen battery system used for occultation periods. An array voltage of 1500 volts has been selected.

The selected installation approach for the array is a fixed body mounted concept, with an array located on three sides of the construction base so that the necessary power can be generated by any one array with the base at any location in orbit. Each array also has been sized to account for sun incidence angle penalties so the combined net affect is a total array that is approximately five times as large as an array that was always PEP. By past space system standards, this excess would be prohibitive. However, in the era of power satellite with low mass and low cost cells, the penalty is quite small.

Flight Control

Included under the category of flight control are the guidance/navigation/attitude type sensors such as IRU, star trackers and horizon sensors and the propulsion system to perform attitude and orbit maintenance maneuvers.

This system has not been defined at this time.

WBS 1.2.1.2 Crew Support Facilities

WBS Dictionary

This element includes the facilities and equipment required for the life support and well-being of the crew members. Included are living quarters, central control facilities, recreation facilities, and health facilities.

Element Description

A total of fifteen primary crew modules have been included in the GEO construction base. The modules have an Earth atmosphere environment and have been sized to fit within the HLLV cargo bay. Accordingly, the modules have dimensions of 17m diameter and up to 23m length.

A summary listing of these modules and their functions are presented in Table 1.2.1-21. All modules are self-sufficient in terms of environmental control provisions and emergency power. Primary power is obtained through a common power supply provided by the base. The mass and cost summary for the crew support facilities is presented in Table 1.2.1-22.

WBS 1.2.1.2.1 Crew Quarters Module

WBS Dictionary

This element includes the crew modules designated as crew living quarters.

Element Description

Eight crew quarter modules have been provided with each sized for a crew of 100. Four of the modules house construction crew and 4 modules house maintenance crew. These modules provide all of the offwork functions associated with living.

A transient crew quarters has been provided. This module is used during crew rotation periods to accommodate overlapping of the crews, preventing overcrowding of the crew quarters and allowing time to clean up the crew quarters between crew changes. This transient crew quarters also provides for redundancy in the event a primary crew quarters module had a massive failure. The transient crew quarters further provides temporary housing for crews that cannot be returned to LEO in the event of vehicle troubles.

Floor area requirements associated with a 100 person module and the division of functions among the decks of the module are shown in Figure 1.2.1-42. The indicated area allocations are based to a large degree on the Rockwell Integral Space Station Study (NAS9-9953). The indicated areas are sized for all 100 people present; this occurs one day per week when both shifts are off-duty.

The module is 17m in diameter and approximately 20m in length including the end domes. The module is divided into seven decks with the indicated functions performed on each deck. General arrangement within each deck has not been defined.

Table 1.2.1-21 Construction Base Crew Modules

MODULE	QUANTITY	FUNCTION (PROVISIONS)
• CREW QUARTERS	5	• PERSONAL QUARTERS/HYGIENE • PHYSICAL FITNESS/RECREATION • DINING
• TRANSIENT CREW QUARTERS	1	• USED DURING CREW ROTATION PERIODS • HOUSE VIP'S • EMERGENCY QUARTERS
• OPERATIONS CENTER	1	• BASE OPERATIONS • CONSTRUCTION OPERATIONS
• MAINTENANCE, TEST AND CHECKOUT	1	• CONSTRUCTION EQUIPMENT • SATELLITE COMPONENTS
• TRAINING & SIMULATION	1	• NEW PERSONNEL • NEW CONSTRUCTION OPERATIONS
• UNDEFINED	1	• CLINIC

NOTE: ALL MODULES SELF-SUFFICIENT EXCEPT PRIMARY POWER AND FLIGHT CONTROL.

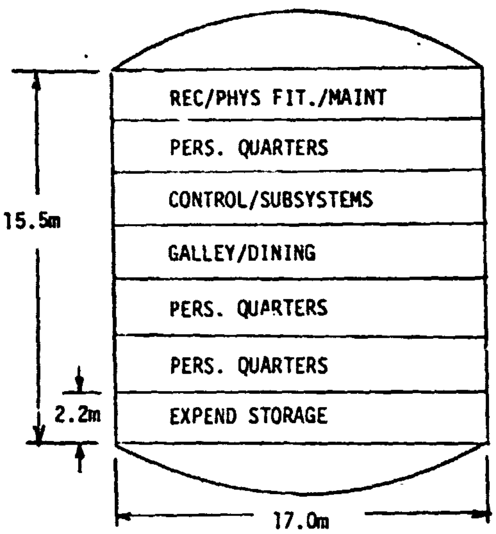
Table 1.2.1-22 4-Bay GEO Base Crew Module Mass and Cost Summary

SPS 2685

4-BAY CONCEPT

ITEM	QTY	MASS		COST	
		MASS EA, KG	SUBTOTAL	COST EA $	SUBTOTAL
CREW QUARTERS	8	375×10^3	3000×10^3	$325 X 10^6	$2600 X 10^6
OPERATIONS MODULE	1	218×10^3	218×10^3	$347 X 10^6	$347 X 10^6
MAINTENANCE MODULE	3	164×10^3	492×10^3	$193 X 10^6	$579 X 10^6
TRAINING MODULE	1	143×10^3	143×10^3	$158 X 10^6	$158 X 10^6
TRANSIENT CREW QTRS.	1	375×10^3	375×10^3	$325 X 10^6	$325 X 10^6
MISC.	1	146×10^3	146×10^3	$236 X 10^6	$236 X 10^6
TOTAL MASS			4374×10^3		
TOTAL COST					$4245 X 10^6

- SIZED FOR 100
- FLOOR AREAS SCALED FROM 12 MAN UNITARY SPACE STATION (BASED ON ROCKWELL 1970 STUDY - NAS 9-9953)
- AREAS BASED ON ENTIRE CREW BEING PRESENT



- GEO MODULE MODIF
  - ADD 1 DECK FOR RADIATION SHELTER

ALLOCATIONS PER MODULE

FUNCTION	FLOOR AREA M^2	(FT^2)
o PERSONAL QTRS	512	(5500)
o PHYSICAL HYGIENE	89	(960)
o RECREATION	107	(1150)
o PHYSICAL FITNESS	53	(570
o GALLEY	53	(570
o DINING	116	(1250)
o CONTROL CENTER	37	(400)
o SUBSYSTEMS	149	(1600)
o MAINTENANCE SHOP	9	(100)
o EXPENDABLE STORAGE (90 DAYS)	193	(2080)
o TUNNELS/AISLES	163	(1750)
TOTAL	1480	15930
MARGIN	71	760

Figure 1.2.1-42 Crew Quarters Sizing

Crew Module Subsystem Definition. The design approach used for each subsystem was generally the same as defined by Rockwell in their solar powered integral Earth orbit space station study (NAS9-9953) for JSC in 1970. A summary of these subsystems is provided in Table 1.2.1-23.

Structure. The crew module primary structure is aluminum alloy. The pressure compartment is designed for an operating pressure of 14.7 psia. The outer shell of each module consists of a double bumper micrometeroroid protection system that was designed to give a 0.9 probability of no penetration in 10 years. Also included in the outer bumper system is the thermal radiator for internal heat rejection. An aerothermal shroud for the crew modules is not required since they will be launched within the payload shroud of the launch vehicle. One deck of each crew module incorporates radiation shielding to provide a refuge for the crew during solar flare activity.

Electrical Power. The primary electrical power system is diiscussed under the Base Subsystem Section 1.3.1.1.5. Each crew module incorporates an emergency power system of fuel cells. Distribution, wiring and special power conditioning equipment are also included in each module.

Environmental Control. All modules have an independent ECS. The system provides an Earth atmosphere environment. Oxygen makeup for leakage and usage is provided through electrolysis of water which is obtained by reduction of CO_2 using a Sabatier reactor while CO_2 itself is removed using molecular sieves.

Nitrogen to supply leakage and repressurization is stored as a cryogenic. Oxygen for repressurization is stored as a cryogenic while the emergency oxygen system uses high pressure storage. Thermal control of the modules makes use of water and freon loops.

Life Support

Both urine and wash water are recovered. The urine is reprocessed using vapor compression while wash water recovery utilizes reverse osmosis. Dried and frozen food was used. Also included under life support are the waste management and personal hygiene systems.

Table 1.2.1-23 Subsystem Summary

CREW MODULES

• STRUCTURE	• ALUMINUM ALLOY
	• METEOROID PROTECTION
	• $P_{(O)}$ = 0 FOR 10 YRS.
	• DOUBLE BUMPER
	• PRESSURE COMPARTMENT
	• 101000 n/m^2 (14.7 psia)
• ELECTRICAL POWER	• EMERGENCY - FUEL CELLS
• ENVIRONMENTAL CONTROL	• EACH INDEPENDENT
	• LEAKAGE
	• OXYGEN - WATER ELECTROLYSIS
	• NITROGEN - CRYOGENIC
	• REPRESSURIZATION
	• OXYGEN - HIGH PRESS
	• NITROGEN - CRYOGENIC
	• WATER - SABATIER REACTOR
	• CO_2 REMOVAL - MOLECULAR SIEVES
	• THERMAL - WATER AND FREON LOOPS
• LIFE SUPPORT	• URINE AND WASH WATER RECOVERY
	• DRIED AND FROZEN FOOD
	• WASTE MANAGEMENT
	• PERSONAL HYGIENE
• CREW ACCOMMODATIONS	• PERSONAL EQUIPMENT
	• FURNISHINGS
	• RECREATION
	• PHYSICAL FITNESS
• INFORMATION SYSTEM	• COMMUNICATIONS - S BAND
	• DATA PROCESSING
	• DISPLAYS AND CONTROLS

Crew Accommodations

Included under this category are the personal equipment, furnishings, recreation and physical fitness equipment. These are located only in the crew quarters.

Information System

The principal systems included are communications, data processing and displays and controls. Each module will have its own internal communication system as well as contact with the main communication center located in the operations module. The principal link between the base and Earth or transportation vehicles is S-band. Each module has data processing capability suitable for its needs. Each module also has an appropriate set of displays and controls.

Guidance and Control

Displays and controls for these systems are located in the Operations module although the equipment itself is located throughout the base.

Reaction Control

This is a base level subsystem.

Special Equipment

This equipment is peculiar to the maintenance/test/checkout and training/simulation modules.

Element Mass

The mass of the crew modules are summarized in Table 1.2.1-24.

WBS 1.2.1.2.2 Work Modules

WBS Definition

This element includes the crew modules used for operations, maintenance and training.

Element Description

The work modules have the same general configuration and subsystems described for the crew modules.

The operations module serves as the control center for all base operations and construction operations. Typical base operations to be controlled from this module

Table 1.2.1-24 Crew Module Mass Summary – Mass in 10^3 kg

SYSTEM	CREW QUARTERS (EA)
STRUCTURE	80
ELEC. POWER	5
ENVIRON. CONT./ LIFE SUPPORT	60
CREW ACCOMMODATIONS	11
INFORMATION	6
GUID & CONT	0
REACTION CONT	0
SPECIAL EQUIPMENT	0
SUBTOTAL	162
GROWTH/ CONTINGENCY	53
TOTAL DRY	215
CONSUMABLES (90 DAYS)	45
TOTAL	260

include that associated with the primary power supply and flight control system (attitude and stationkeeping), communication system within the base as well as that with Earth, other bases and transportation vehicles in transit.

Overall crew scheduling and consumables management functions are also included under base operations. Construction operations controlled from the module include those functions associated with scheduling, briefings, troubleshooting or identifying workarounds, monitoring of construction operations and the operations associated with cargo handling and distribution. The operations module also houses the central data management and processing center.

The maintenance, test and checkout module provides the capability to work on large pieces of construction or base equipment or satellite components while in an Earth atmosphere environment.

The training and simulation module provides a facility for training new personnel and for development construction task procedures in a controlled environment.

An additional module has been included to provide for functions not included in other modules. Examples include medical, dental and sickbay provisions, as well as a temporary morgue for personnel who have died in space. Isolation of sickbay and morgue areas from the other base crew quarters was deemed important.

Element Mass

The mass of the work modules are summarized in Table 1.2.1-25.

WBS 1.2.1.3 Operations

WBS Dictionary

This element includes the planning, development, and conduct of operations at the construction facility. It includes both the direct and support personnel and the expendable maintenance supplies required for satellite assembly and checkout.

The operations work element is used to collect the direct ongoing costs of operations. The foregoing items (WBS 1.2.1.1 and 1.2.1.2) represent construction base hardware and equipment and thus represent the capital cost of the construction base.

Table 1.2.1-25 Work Module Mass Summary – Mass in 10^3 kg

SYSTEM	OPERATIONS CENTER	MAINTENANCE TEST & C/O	TRAINING & SIMUL.	MISC.
STRUCTURE	80	80	80	
ELEC. POWER	7	3	7	
ENVIRON. CONT./ LIFE SUPPORT	42	24	11	
CREW ACCOMMODATIONS	4	3	3	
INFORMATION	30	5	0	
GUID & CONT	1	0	0	
REACTION CONT	0	0	0	
SPECIAL EQUIPMENT	0	5	0	
SUBTOTAL	164	120	108	110
GROWTH/ CONTINGENCY	54	40	35	36
TOTAL DRY	218	164	143	146
CONSUMABLES (90 DAYS)	0	0	0	0
TOTAL	218	164	143	146

The operations descriptions were included with the base hardware descriptions to provide an integrated exposition of the hardware elements and their roles in constructing SPS's.

Element Description

The operations conducted at the GEO base include the following major categories of operations:

- Transportation Vehicle Operations
- Cargo Handling/Distribution Operations
- Construction Operations
  - Solar Collector Construction Operations
  - Antenna Construction Operations
  - Yoke Construction Operations
- Command and Control Operations
- Base Maintenance Operations
- SPS Maintenance Operations
- Base Support Operations

Each of these operations were addressed in the preceding sections.

Table 1.2.1-26 summarizes the crew requirements that have been identified. The cost summary for WBS 1.2.1.3 is shown in Table 1.2.1-27. Figure 1.2.1-43 presents the crew organizational relationships that were used to determine crew size.

Table 1.2.1-26 GEO Construction Base Personnel

• Base Directors and Managers------------------------		10
• Construction Management Operation------------------		267
- Construction Management Staff------------------	22	
- Energy Conversion System Construction Crew------	40	
- Power Transmission System Construction Crew-----	40	
- Subassembly Construction Support----------------	46	
- Construction System Maintenance-----------------	37	
- Construction Logistic Support-------------------	42	
- Test and Quality Control-----------------------	40	
• Base Operations Mangement--------------------------		41
• Base Support Management----------------------------		67
	Total Personnel	385

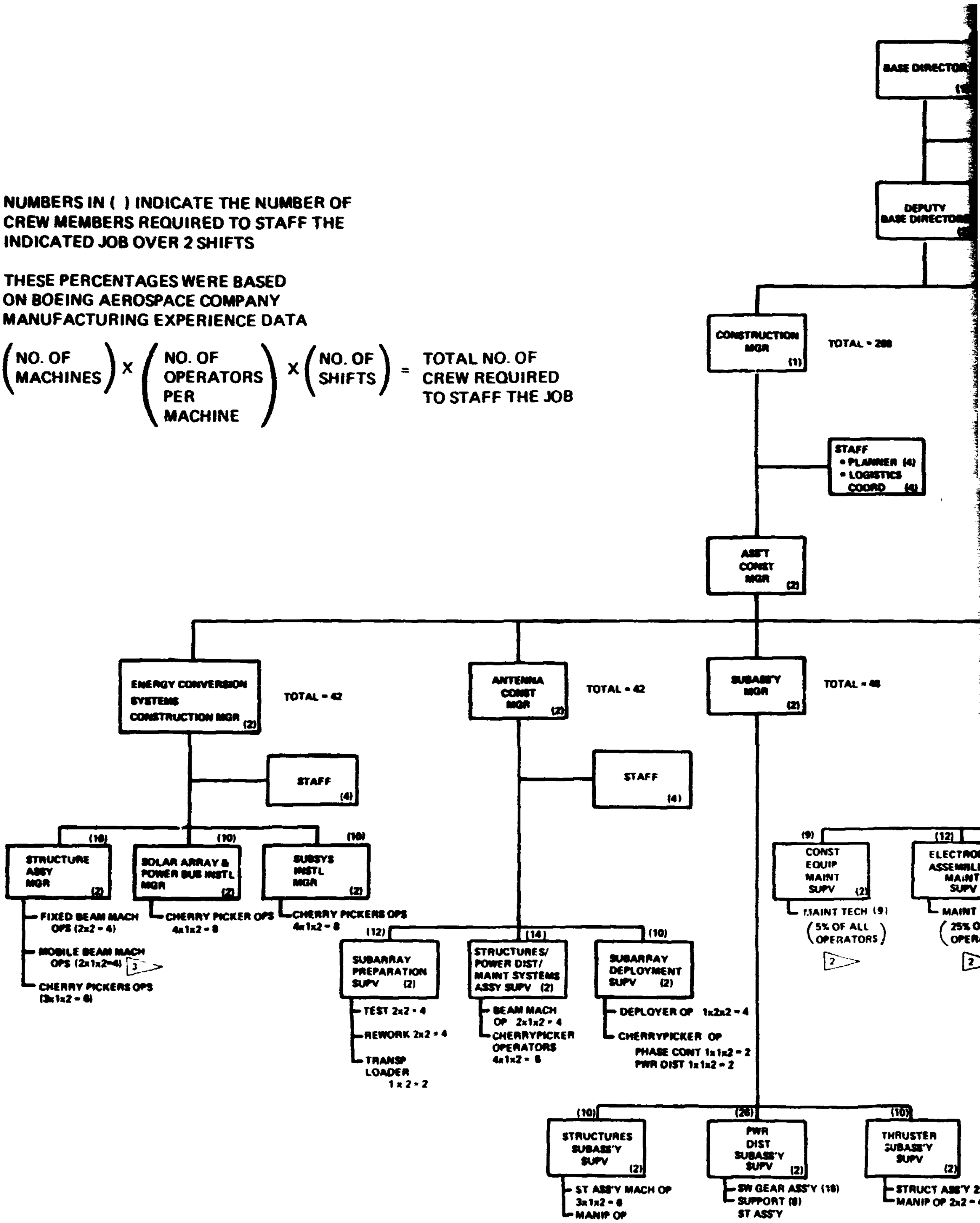
Table 1.2.1-27 WBS 1.2.1.3 Mass and Cost Summary

WBS SUB-ITEMS		MASS, 10^3 kg	COST, $\$10^6$
1.2.1.3.1	TRANSPORTATION VEHICLE OPERATIONS		2.64
1.2.1.3.2	CARGO HANDLING/DISTRIBUTION OPERATIONS		5.04
1.2.1.3.3	CONSTRUCTION OPERATIONS		27.0
1.2.1.3.4	COMMAND AND CONTROL OPERATIONS		3.6
1.2.1.3.5	BASE MAINTENANCE OPERATIONS		TBD
1.2.1.3.6	SPS MAINTENANCE SUPPORT OPERATIONS		28.8
1.2.1.3.7	BASE SUPPORT OPERATIONS		8.04
	(ALLOWANCE FOR CONSUMMABLES)		7.5
1.2.1.3	OPERATIONS		82.62

1. NUMBERS IN ( ) INDICATE THE NUMBER OF CREW MEMBERS REQUIRED TO STAFF THE INDICATED JOB OVER 2 SHIFTS

2. THESE PERCENTAGES WERE BASED ON BOEING AEROSPACE COMPANY MANUFACTURING EXPERIENCE DATA

3. (NO. OF MACHINES) X (NO. OF OPERATORS PER MACHINE) X (NO. OF SHIFTS) = TOTAL NO. OF CREW REQUIRED TO STAFF THE JOB



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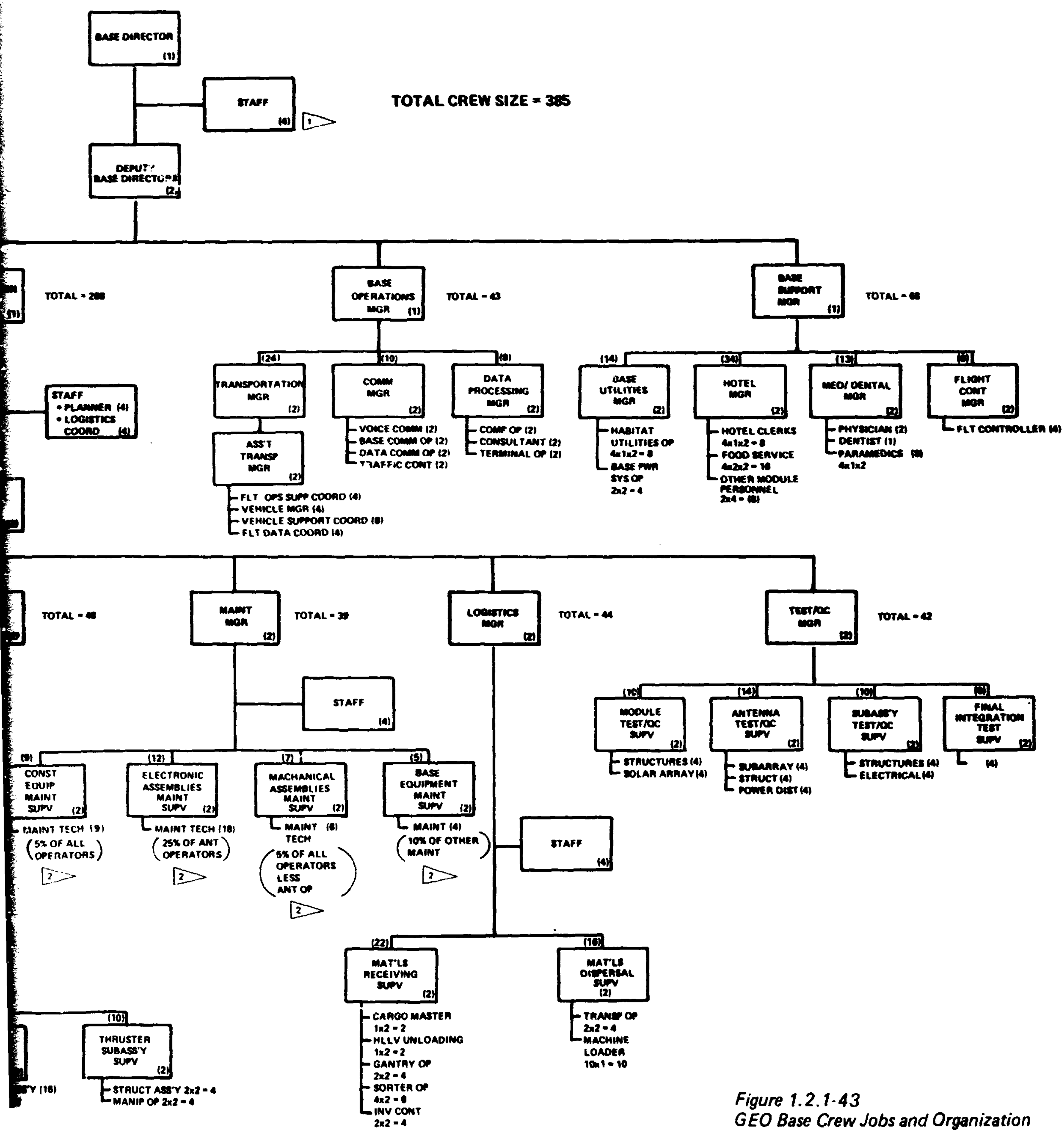

Figure 1.2.1-43
GEO Base Crew Jobs and Organization

WBS 1.2.2 Logistics Support Facility (LEO Base)

WBS Dictionary

This element 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 receiving, storage, and transfer of cargo and personnel destined for a construction base or operational satellite located in GEO.

Element Description

Development of the LEO base description was not carried to as great a level of detail as that for the GEO base. Additional definition will be accomplished during Phase II of the study. The LEO base is shown in Figure 1.2.2-1. It has three primary operational functions: EOTV construction, orbit transfer vehicle servicing, and staging depot for cargo and crews.

Early in the SPS program, the LEO base will be used to construct a fleet of EOTV's. The base gets its configuration from the requirements imposed by the EOTV construction operations. The main deck size is approximately the size of the EOTV bay.

The outriggers provide the capability for indexing 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 HLLV's to EOTV's. The EOTV's will stationkeep with the LEO base during the cargo transfer operations. Inter-orbit vehicles (IOTV's) shuttle between the base and the EOTV.

The LEO base also serves as a temporary quarters for the crews on their way between Earth and the GEO base. This requires transient crew quarters and the docking facilities for the Earth-to-LEO crew vehicles and the crew OTV's.

Table 1.2.2-1 lists the mass and cost summary for this WBS element.

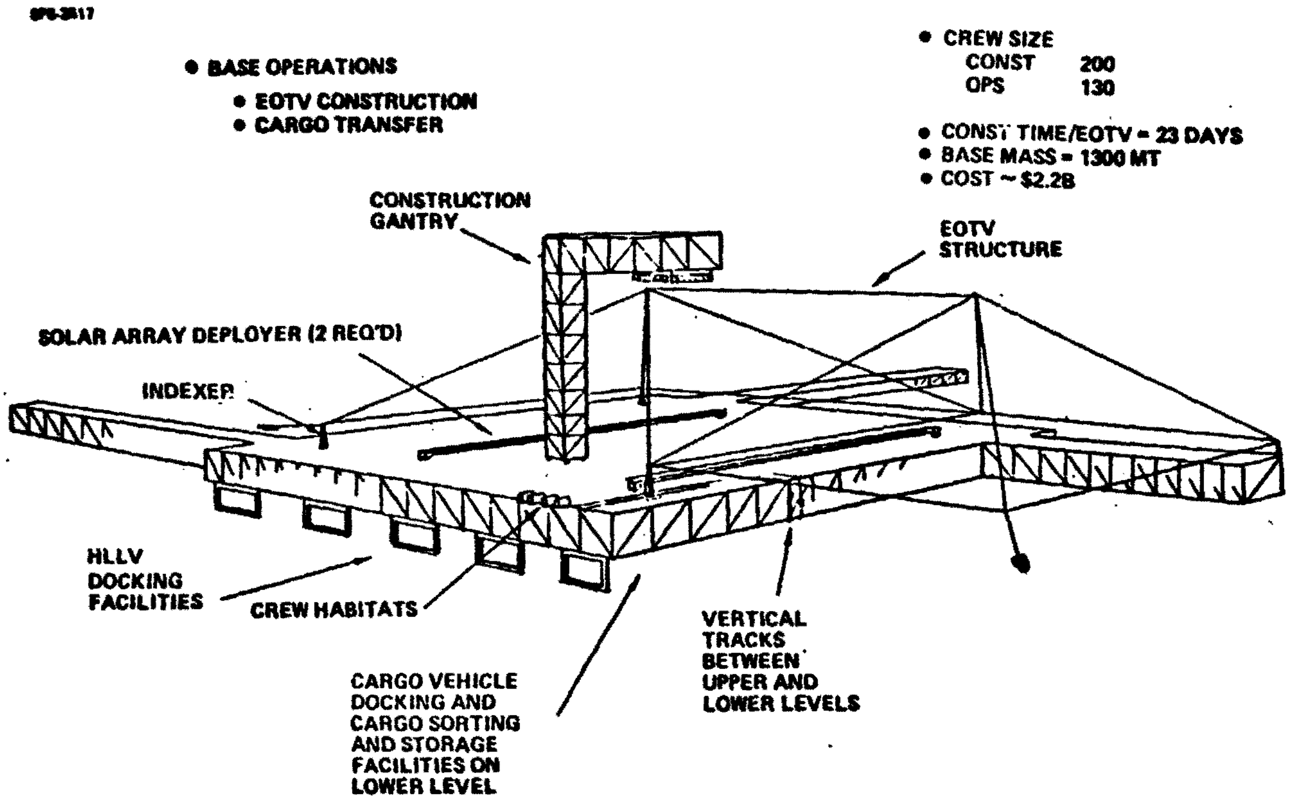

Figure 1.2.2-1. LEO Base For GEO Construction/EOTV Concept

Table 1.2.2-1. Mass and Cost Summary LEO Logistics Support Facility (WBS 1.2.2)

SPS-2687

WBS NUMBER	ITEM	MASS, 10^3 kg	COST, $\$10^6$
1.2.2	LEO LOGISTICS SUPPORT FACILITY	1260	2186
1.2.2.1	WORK SUPPORT FACILITIES	450	337
1.2.2.1.1	STRUCTURES	200	20
1.2.2.1.2	CONSTRUCTION EQUIPMENT FOR (SEE TABLE DETAILS)	115	257
1.2.2.1.3	CARGO HANDLING/DISTRIBUTION SYSTEM	50	40
1.2.2.1.4	SUBASSEMBLY FACTORIES	TBD	TBD
1.2.2.1.5	TEST AND CHECKOUT FACILITIES	TBD	TBD
1.2.2.1.6	TRANSPORTATION SUPPORT SYSTEMS	35	15
1.2.2.1.7	BASE MAINTENANCE SYSTEMS	TBD	TBD
1.2.2.1.8	BASE SUBSYSTEMS	50	5
1.2.2.2	CREW SUPPORT FACILITIES	810	1150
1.2.2.2.1	CREW QUARTERS MODULES	660	900
1.2.2.2.2	WORK MODULES	150	250
	(BASIC HARDWARE)	(1260)	(1487)
	INDIRECT COST FACTORS (BASED ON BASIC HARDWARE TOTAL)		699
	SPARES (15%)		223
	ASSEMBLY AND CHECKOUT (16%)		238
	SE&I (7%)		104
	PROJECT MANAGEMENT (2%)		30
	SYSTEM TEST (3%)		45
	GSE (4%)		59

WBS 1.2.2.1 Work Support Facilities

WBS Dictionary

This element includes the facilities and equipment required to provide logistics support in LEO. Included are EOTV construction facilities and equipment, HLLV and OTV docking stations, payloads handling equipment, and cargo and propellant storage depots. Excluded are facilities related to crew element support.

Element Description

This element describes the configurations of the LEO base structure, construction equipment, cargo handling/distribution equipment, subassembly factories, test/checkout facilities, transportation vehicle support equipment, base subsystem and base maintenance system. The operational interface between the LEO base and orbit transfer systems is similar to that described for the GEO base. Figure 1.2.2-2 shows a preliminary concept of docking an HLLV orbited to the LEO base. Figure 1.2.2-3 shows a representative flight schedule.

WBS 1.2.2.1.1 Structure

WBS Description.

This element includes the primary and secondary structure of the LEO base.

Element Description.

The LEO base structural configuration lis shown in Figure 1.2.2-4.

The structural mass is estimated to be 200000 Kg and the cost $20M.

WBS 1.2.2.1.2 Construction Equipment

WBS Dictionary

This element includes all equipment items dedicated to construction of the EOTV with the exception of equipment utilized in subassembly operations (the latter are included in WBS 1.2.2.1.4).

Element Description

Table 1.2.2-2 provides a summary of the equipment types, quantities, mass, and cost.

The general location of the construction equipment is shown in Figure 1.2.2-5. The integrated construction operation encompasses solar array deployment, power bus installation, thruster system installation, payload pallet assembly, and the associated

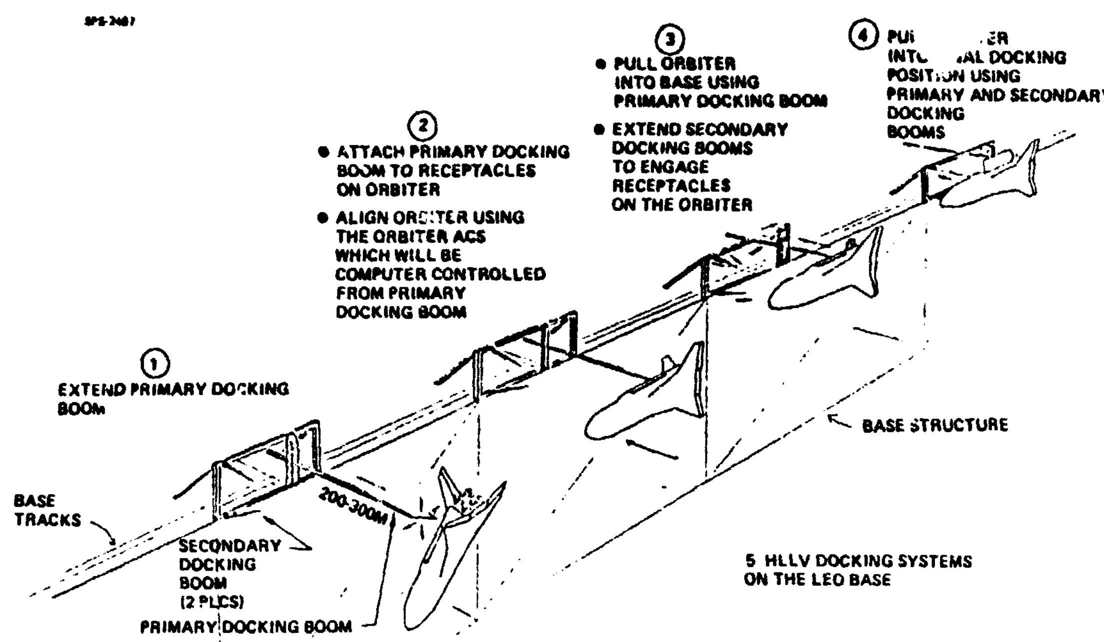

Figure 1.2.2-2. HLLV Docking Operations

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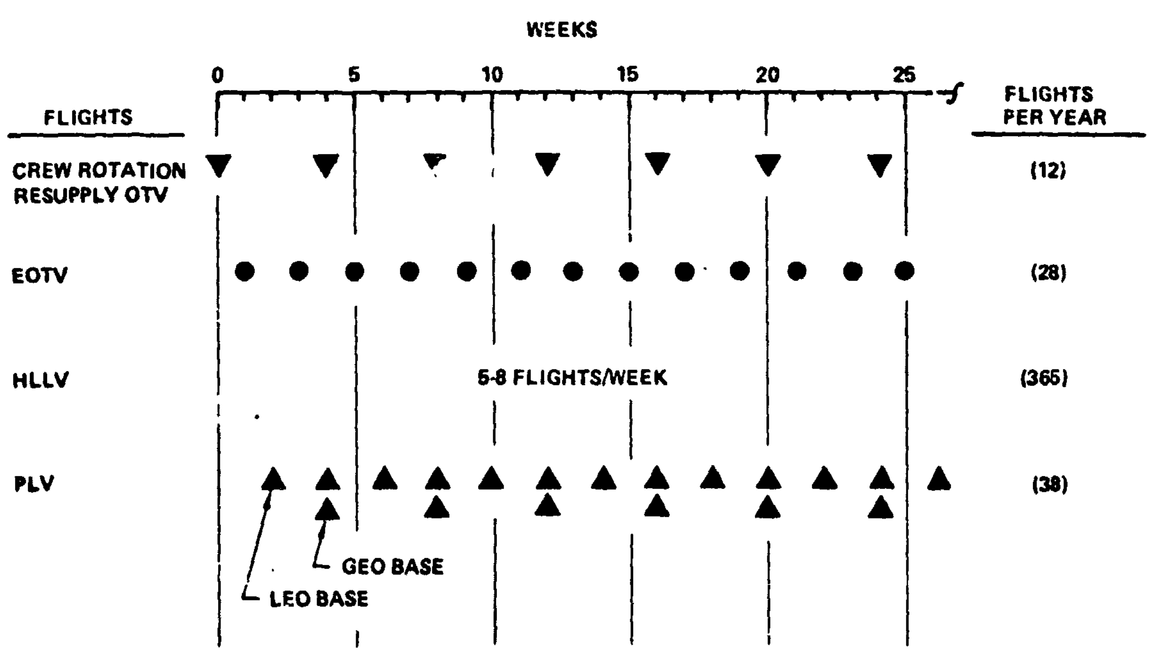

Figure 1.2.2-3. LEO Base Depot Operations Flight Support Schedule

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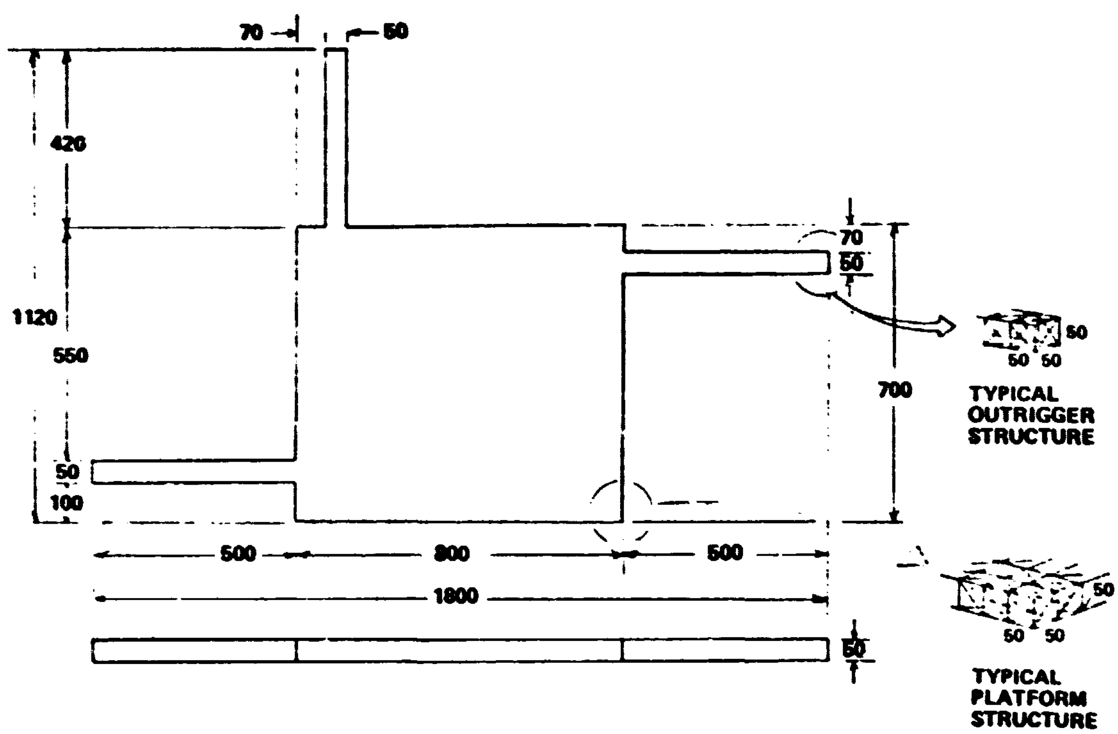

Figure 1.2.2-4. LEO Base Structure

Table 1.2.2-2. Construction Equipment Mass and Cost Summary

SPS-2044

ITEM	QUANITITY	MASS, 10^3 kg		COST $10^6	
		EACH	SUBTOTAL	EACH	SUBTOTAL
BEAM MACHINES	2	15	30	50	100
CHERRYPICKERS					
20m	2	4	8	4	8
50m	4	6	24	5	20
230m	1	11	11	11	11
INDEXERS					
45m	6	1.3	8	3	18
BUS DEPLOYER	1	4	4	20	20
SOLAR ARRAY DEPLOYER	2	11	22	40	80
TOTAL CONST. EQUIPMENT MASS			115		
TOTAL CONST. EQUIP. COST					257

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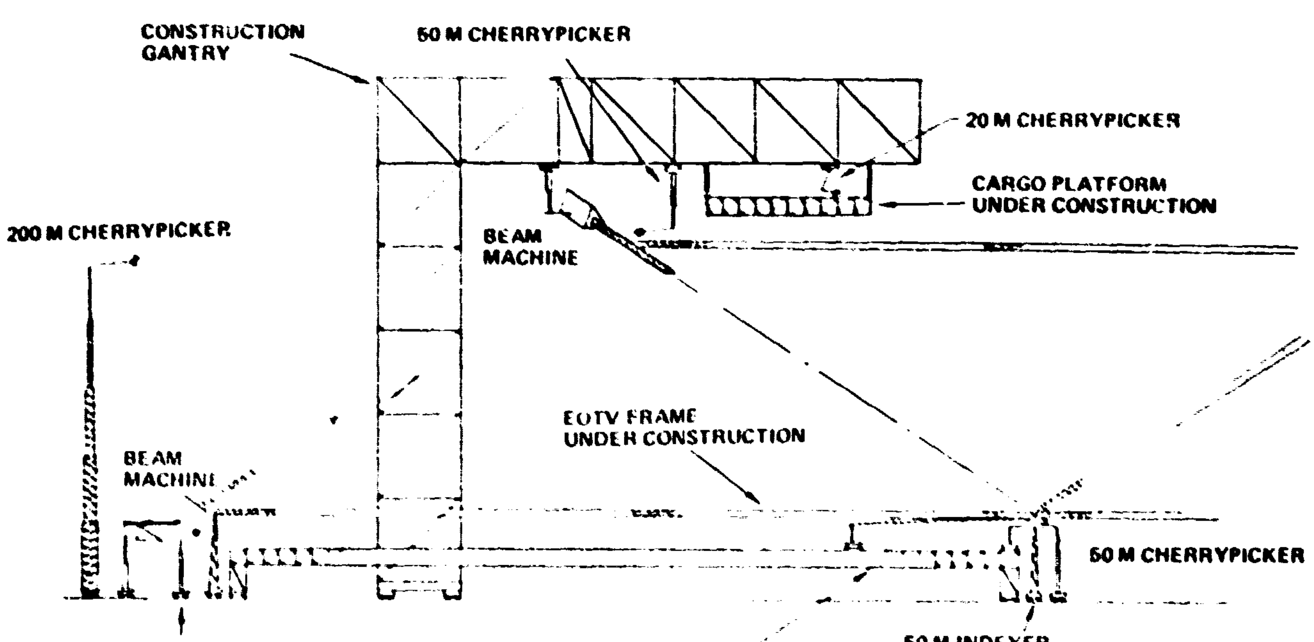


Figure 1.2.2-5. Construction Equipment Locations

subassembly operations. Each of the above operations are described in subelement descriptions. Figure 1.2.2-6 shows the integrated construction sequence. It is estimated that 23 days are required to construct each EOTV. The timeline to construct one bay of the EOTV is shown in figure 1.2.2-7. A fleet of 23 vehicles would be constructed.

WBS 1.2.2.1.2.1 Beam Machine System

The beam machines used in the construction of the EOTV are similar in design to those used in the construction of the satellite and defined in WBS 1.2.1.1.2. The two machines required produce 5 meter beams.

WBS 1.2.2.1.2.2 Cherry Pickers

The cherry pickers used in the construction of the EOTV are similar in design to those used to constructing the satellite (defined in WBS 1.2.1.1.2). Two 50 m and one 200 m cherry pickers are required.

WBS 1.2.2.1.2.3 Bus Deployment Machines

The bus deployment machines used in the construction of the EOTV are similar to those used in constructing the satellite as defined in WBS 1.2.1.1.2. The primary differences between the machines is that the buses will be smaller in depth.

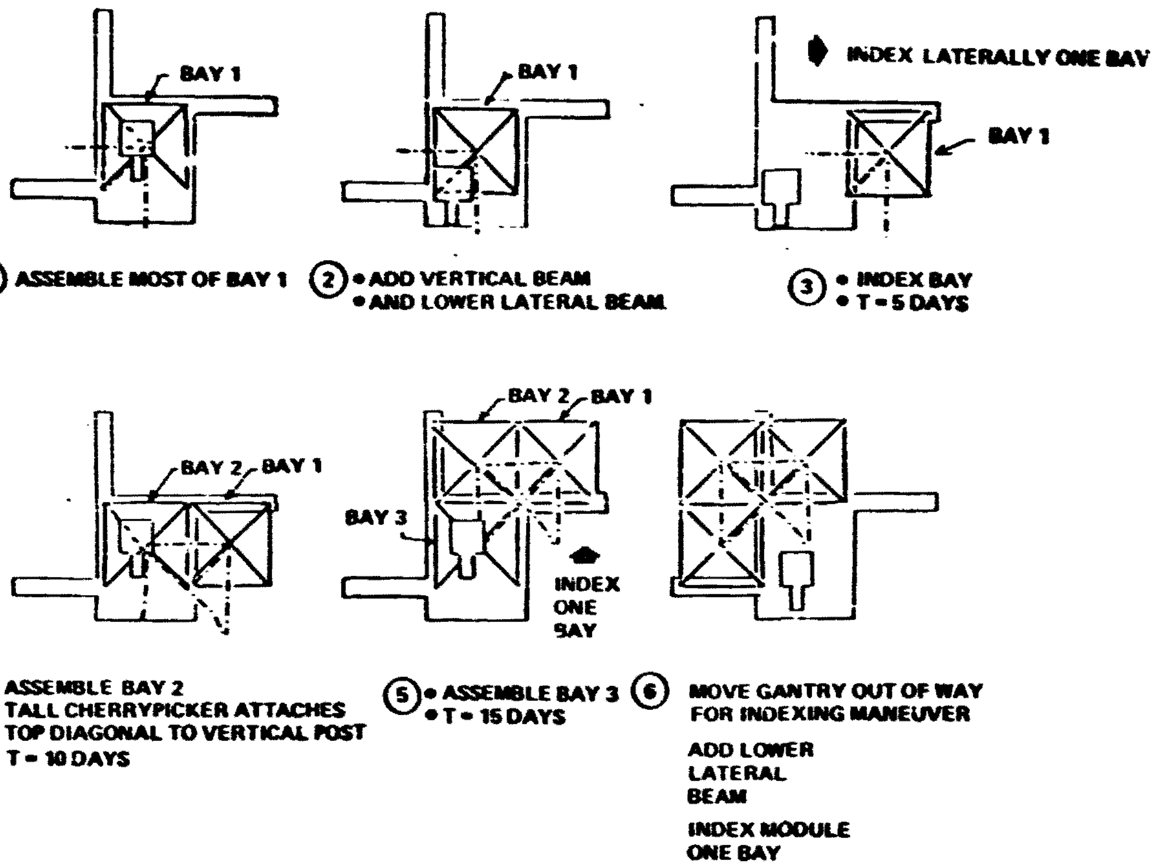
WBS 1.2.2.1.2.4 Indexers

The indexers used for EOTV construction will be similar to those used in construction of the satellite and defined in WBS 1.2.1.1.2.

Frame Assembly Operations

The primary frame is constructed by a team of 2 beam machines, 4 50m cherry pickers, and a 230m cherry picker. The location of these equipment items was shown in Figure 1.2.2-5.

The beams are fabricated by the beam machines. The beam end fittings and the battens are fabricated in the subassembly factory and delivered to the beam machines for assembly. The 50m cherry pickers take the fabricated beams from the beam machines and assembles them to indexers or to previously assembled structure.
It is necessary to use the 230m cherry picker to join the ends of some of the upper surface beams after the beam nodal joint is indexed away from the search of the 90m cherry pickers on the construction gantry.



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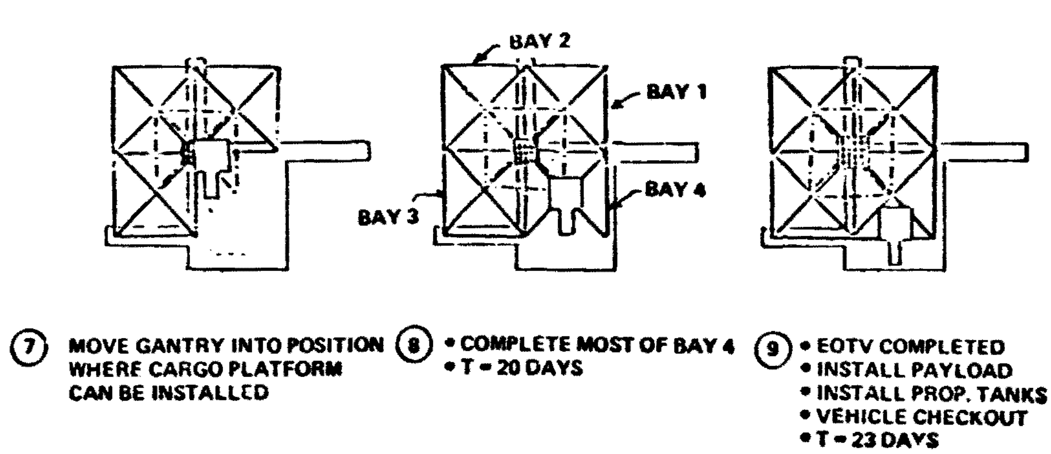

Figure 1.2.2-6. EOTV Construction Sequence

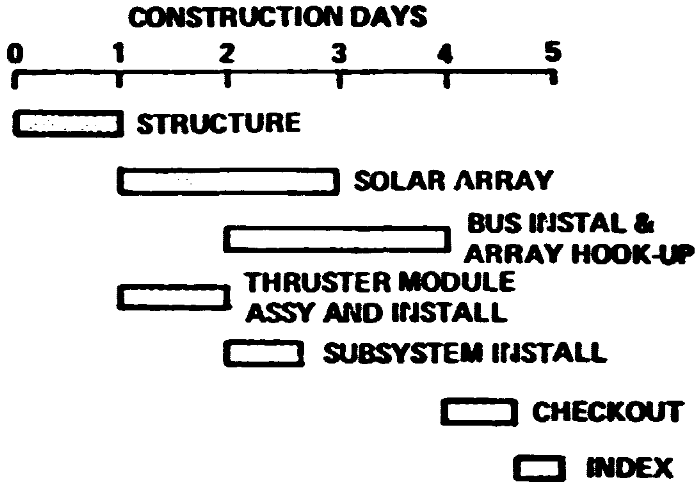

Figure 1.2.2-7. EOTV Bay Construction Timeline

WBS 1.2.2.1.2.5 Solar Array Deployment System

WBS Dictionary

This element includes the equipment dedicated to deployment of solar array blankets.

Element Description

There are two independent types of solar array deployment equipment: (1) the solar array deployment machine which incorporates several pieces of equipment, and (2) the distal end installation machine.

The solar array deployer subelements are described in Table 1.2.2-3. This machine installs the solar array containers onto the EOTV structure, deploys the array across the structural bay, and installs the proximal end electrical inter-bay jumpers. Figure 1.2.2-8 shows the configuration of the machine.

The distal end installer, see Figure 1.2.2-9, is used to make the solar array distal end structural and electrical connections. Table 1.2.2-4 describes the machine.

After the frame for a bay is completed and the construction gantry moved out of the way, the solar array deployment operations are initiated.

Prior to the initiation of the solar array deployment, containers of solar array are delivered to the solar array deployers. These containers are loaded into the solar array container magazines by the 50m cherry pickers.

The solar array deployer gantry is moved into position. The container manipulator grasps each container and lifts it into position where the container can be installed on hardpoints on the EOTV beam. The manipulator then unlatches the front cover of the container. The manipulator then retracts and recycles after the gantry is indexed one solar array blanket width (15m).

The leading edge deployer then moves into position where the catenary handling mechanisms can grasp the handling rings on the solar array catenary cables. The leading edge deployer traverses along the gantry pulling the accordion-folded solar array blanket out of the container. When the leading edge deployer reaches the far end of the gantry, the catenary cable ends are handed off to the distal end deployer. The leading edge deployer then traverses back along the gantry to its starting position.

Table 1.2.2-3. Equipment Description Sheet

ITEM: SOLAR ARRAY DEPLOYER WBS NO. 1.2.2.1.2.1

SUBITEMS	GANTRY	SOLAR ARRAY CONTAINER MAGAZINE	CONTAINER MANIPULATOR
FUNCTIONAL REQUIREMENTS	o Provides track surface for the leading edge deployer and proximal end installer o Provides mounting surface for container manipulator, container magazine, and the control cab. o Provides means for indexing the equipment across the base	o Provides storage for 20 solar array containers o Provide a container feed mechanism o Configured to allow container loading via cherrypickers	o Extract container from container feed mechanism o Raise container to EOTV structure o Attach container to structure o Unlatch container front cover
WHERE USED	LEVEL A	GANTRY	GANTRY
MAJOR SUBELEMENTS	o Carriages o Structure o Tracks o Power Supply	o Feed mechanism o Container storage rack o Structure o Avionics	o Horizontal actuator o Elevator o Container manipulator o Latch actuator o TV camera and lights
OPERATING RATES AND TIMES	Index at 10 m/min	-	Install container in 5 min
QTY	1	1	1
MASS EA / TOTAL	(Total for entire mach) 12000 kg	TBD	TBD
COST EA / TOTAL	(Total for entire mach) $45 M	TBD	TBD
MANNING	2 operators/mach/shift	-	-

Table 1.2.2-3. (Cont'd.) Equipment Description Sheet

ITEM SOLAR ARRAY DEPLOYER WBS NO. 1.2.2.1.2.1

SUBITEMS		LEADING EDGE DEPLOYER	PROXIMAL END INSTALLER	CONTROL CAB
FUNCTIONAL REQUIREMENTS		o Attach to solar array leading edge catenary cable ends o Traverse along gantry tracks o Handoff catenary cable ends to distal end installer	o Attach proximal catenary cable ends to EOTV structure o Install electrical pigtail connectors	o Provide work station for two operators o Control all gantry-attached equipment operations
WHERE USED		GANTRY	GANTRY	GANTRY
MAJOR SUBELEMENTS		o Carriage o Elevator o Catenary attachment mechanisms o TV camera and lights	o Carriage o Elevator o Catenary attachment mechanism o Pigtail manipulator o TV camera and lights	o Structure o ECLSS o Ingress/egress
OPERATING RATES AND TIMES		o Attach to catenary in 3.5 min o Deploy at 12.5 m/min o Handoff in 3.5 min	o Attach proximal catenary in 3.0 min	-
QTY		1	1	1
MASS	EA. TOTAL	TBD	TBD	-
COST	EA. TOTAL	TBD	TBD	-
MANNING		-	-	2 operators

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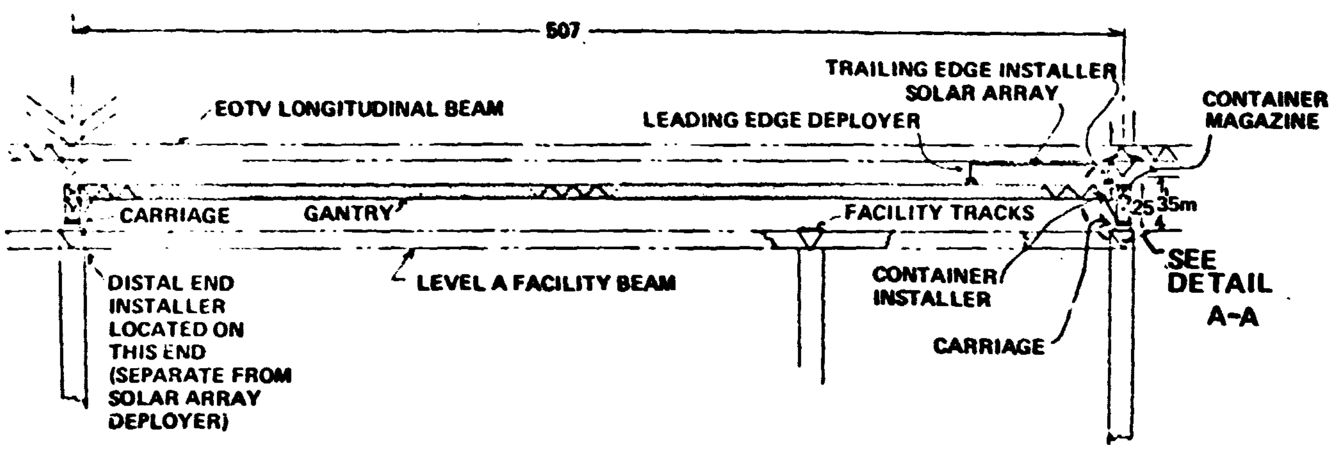

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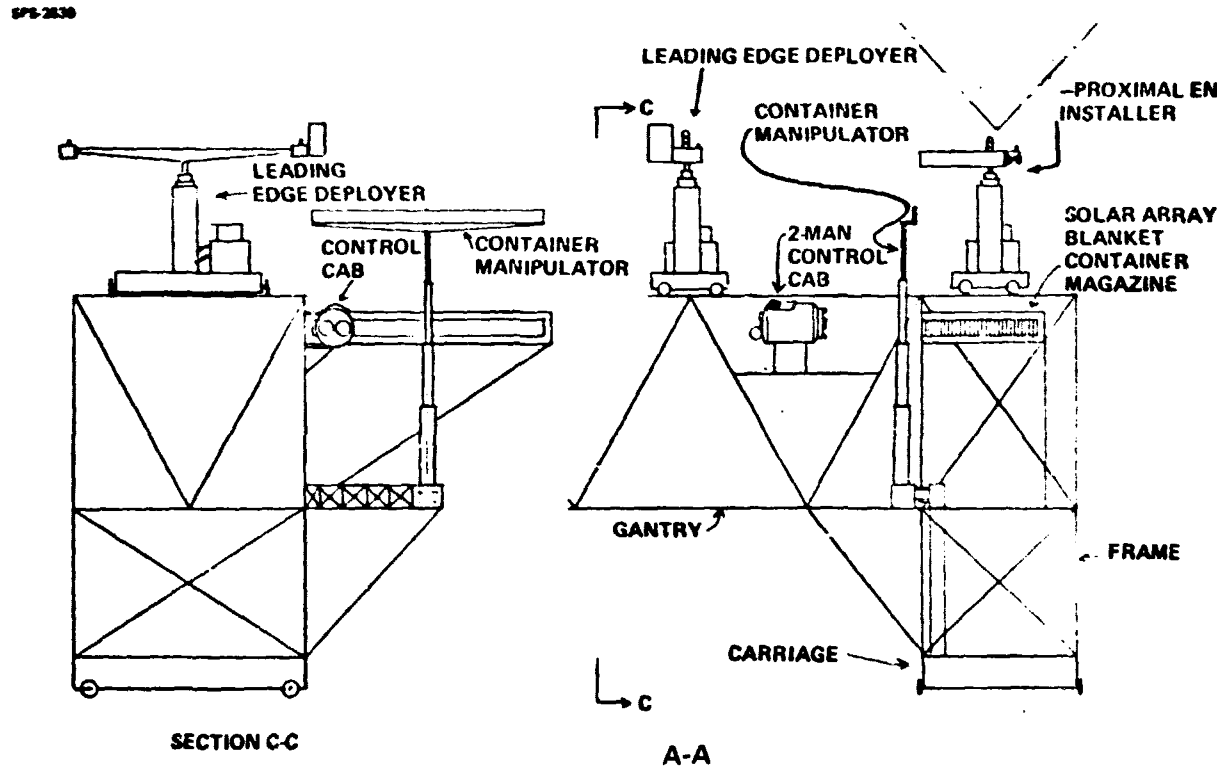

Figure 1.2.2-8. Solar Array Deployer

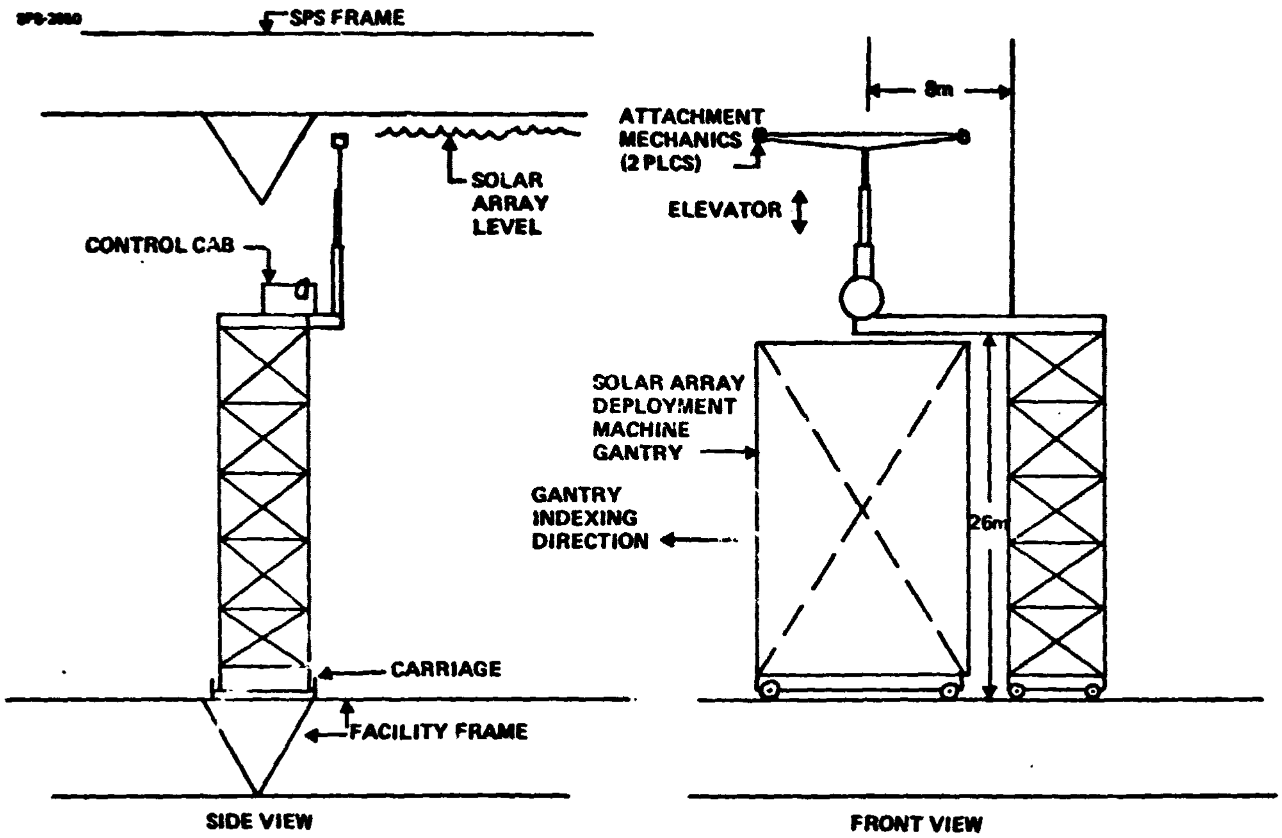

Figure 1.2.2-9. Distal End Installer

Table 1.2.2-4. Equipment Description Sheet

ITEM SOLAR ARRAY DISTAL END INSTALLER WBS NO. 1.2.2.1.2.1

SUBITEMS		
FUNCTIONAL REQUIREMENTS		(See Figure 1.2.2-9) o Receive blanket catenary ends from cross-bay deployer o Attach catenary ends to EOTV structure o Attach electrical pigtail
WHERE USED		LEVEL A
MAJOR SUBELEMENTS		o Carriage o Control cab o Structure o Elevator o Catenary manipulator o Pigtail manipulator
OPERATING RATES AND TIMES		
QTY		1
MASS	EA. TOTAL	TBD
COST	EA. TOTAL	TBD
MANNING		1 operator/shift

After the leading edge deployer has started down the gantry, the proximal end installer moves into position where it can grasp the proximal solar array catenary. It then installs the catenary and makes the necessary interbay electrical connections.

At the end of the installation sequences, the gantry is reindexed 15 meters and the operations repeated until the solar array is installed in a bay. The gantries are then indexed out of the way so that the EOTV frame can be indexed as sequenced.

WBS 1.2.2.1.2.6 Construction Gantry

WBS Dictionary

This element includes the mobile construction gantry used to construct the EOTV's.

Element Description

The consruction gantry is shown in Figure 1.2.2-10. It is described in Table 1.2.2-5.

WBS 1.2.2.1.3 Cargo Handling/Distribution Systems

WBS Dictionary

This element includes the hardware used to load/offload these vehicles, the cargo and crew transporters, the cargo sorting and storage systems, and the track network used to move the cargo, crew, and equipment around the base in any detail. This system was not defined. It includes the following subelements:

WBS 1.2.2.1.3.1 Cargo Loading/Unloading Systems

WBS Dictionary

This element includes the hardware systems used to load/off-load the various transportation vehicles.

Element Description

The equipment used to load/off-load the vehicles is described in Table 1.2.2-6.

WBS 1.2.2.1.3.2 Cargo Transporters

WBS Dictionary

This element includes the LEO base track-mounted unit used to move construction equipment and the units used to transport cargo within the base.

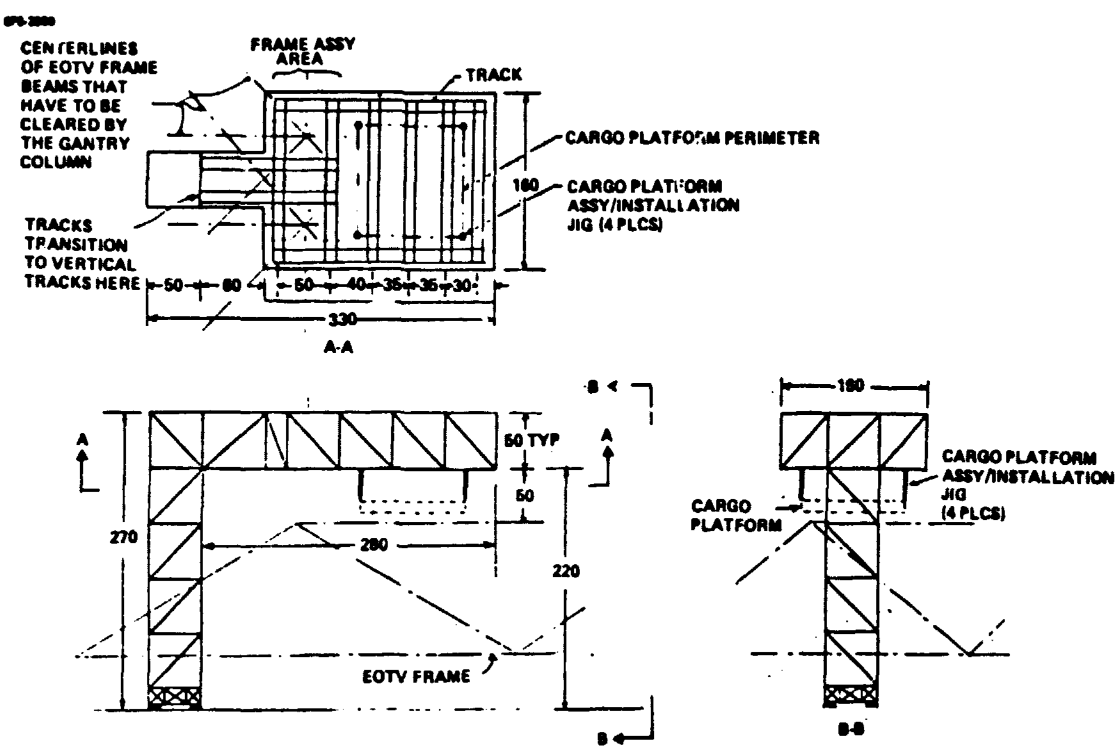

Figure 1.2.2-10. Construction Gantry Configuration (LEO Base)

Table 1.2.2-5. Equipment Description Sheet

ITEM CONSTRUCTION GANTRY WBS NO. 1.2.2.1.2.2

SUBITEMS	
FUNCTIONAL REQUIREMENTS	o Provides track network for the beam machines and cherrypickers used to fabricate EOTV frame and cargo platform o Capable of traversing about the Level A track network
WHERE USED	LEVEL A
MAJOR SUBELEMENTS	o Carriage o Structure o Track network o Cargo platform installation jig
OPERATING RATES AND TIMES	-
QTY	1
MASS EA. / TOTAL	
COST EA. / TOTAL	
MANNING	-

Table 1.2.2-6. Equipment Description Sheet

ITEM CARGO LOADING/UNLOADING SYSTEMS WBS NO 1.2.2.1.3.2

SUBITEMS	HLLV CARGO HANDLING SYSTEM	SEE TABLE 1.2.1-13 FOR OTHER EQUIPMENT
FUNCTIONAL REQUIREMENTS	o Extract cargo pallet from HLLV orbiter cargo bay o Deposit cargo pallet onto transporter o Reload empty cargo pallet into cargo bay	(same as described in Table 1.2.1-13)
WHERE USED	HLLV DOCKING AREA	
MAJOR SUBELEMENTS	o Pallet manipulator o Carriage o Control cab	
OPERATING RATES AND TIMES		
QTY	3	
MASS EA / TOTAL	TBD	
COST EA / TOTAL	TBD	
MANNING	1 operator/shift	

Element Description

Refer to WBS 1.2.1.1.2.2 for a description of this type of hardware. The number of cargo transporters required at the LEO base has not been determined.

WBS 1.2.2.1.3.3 Cargo Sorting Systems

WBS Dictionary

This element includes the hardware systems dedicated to the cargo pallet contents off-loading into component storage and component loading onto cargo transporters.

Element Description

Refer to WBS 1.2.1.1.3.2 for a description of this type of hardware. The quantity of equipment required for this element has not been determined.

WBS 1.2.2.1.3.4 Cargo Storage Systems

WBS Dictionary

This element includes the systems used to store (warehouse) the SS and EOTV components and propellants.

Element Description

Refer to Table 1.2.1-17 in WBS 1.2.1.1.3.5 for descriptions of this type of hardware. The quantities, mass, and cost of the LEO base elements have not ben determined.

WBS 1.2.2.1.3.5 Cargo Distribution System

WBS Dictionary

This element includes the LEO base track network that is used for mounting movable equipment.

Element Description

The track design approach is described in WBS 1.2.1.1.3.6. The LEO base track network is shown in figures 1.2.2-11 and -12. A total of 18085 meters of track is required. The mass and cost were not estimated.

WBS 1.2.2.1.2.6 Crew Transporters

WBS Dictionary

This element includes the vehicles that are used on the LEO base track network for transporting crew.

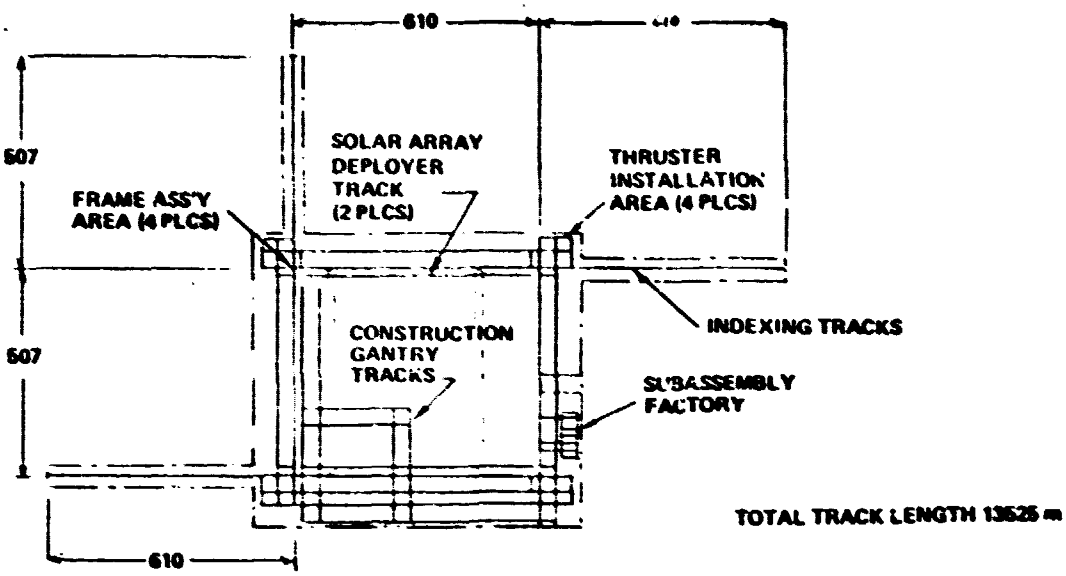

Figure 1.2.2-11. Level A Track Network

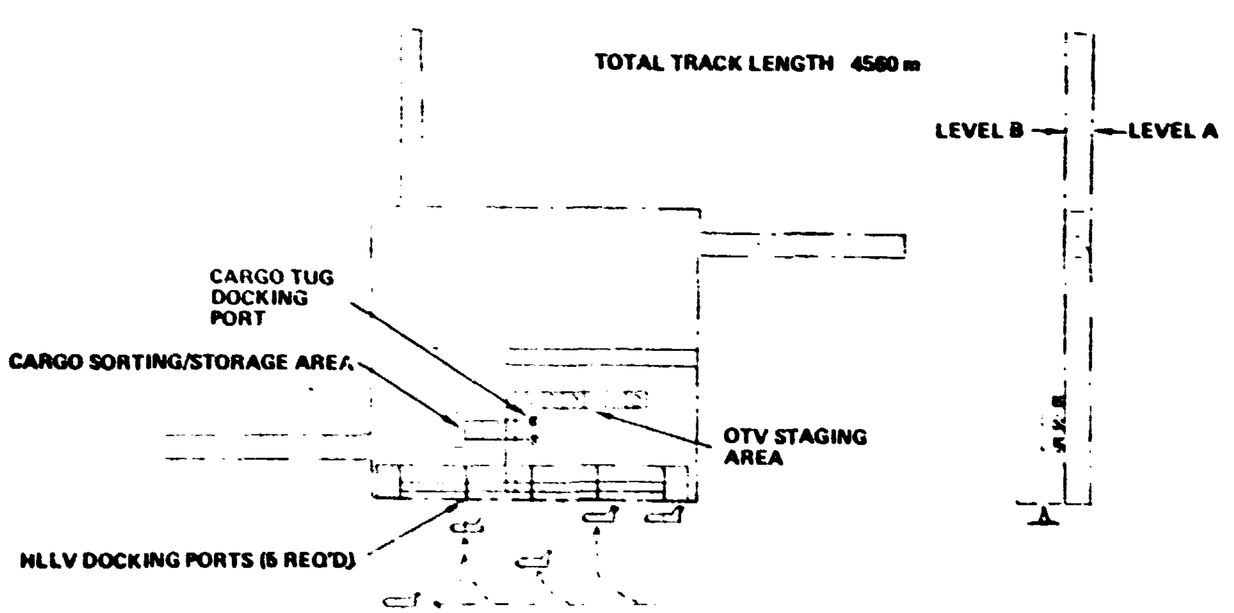

Figure 1.2.2-12. Level B Track Network

Element Description

A representative crew bus concept was described under WBS 1.2.1.1.3.7. Quantities, mass, and cost for the LEO base have not been determined.

WBS 1.2.2.1.4 Subassembly Factories

WBS Dictionary

This element includes the facilities and equipment dedicated to preassembly of EOTV subassemblies prior to delivery to the final installation facilities.

Element Description

The following subassemblies have been identified:

- o Beam end fittings
- o Beam battens
- o Thrusters
- o Switchgear subassemblies
- o Bus support structures

The subassembly facilities and equipment have not been defined.

WBS 1.2.2.1.5 Test/Checkout Faciities

WBS Dictionary

This element includes the faciities and equipment on the LEO base that are dedicated to test and checkout of EOTV components or subassemblies.

Element Description

The facilities and equipment have not been defined.

WBS 1.2.2.1.6 Space Transportation Support Systems

WBS Dictionary

This element includes facilities and equipment dedicated to support space transportation vehicles that interface with the LEO base. These items included are docking systems, assembly systems, propellant storage and distribution system and maintenance systems.

Element Description

The subelements of the transportation support systems are described in the following subsections.

WBS 1.2.2.1.6.1 Vehicle Docking Systems

WBS Dictionary

This element includes the systems dedicated to docking of the OTV's, HLLV's, PLV's and IOTV's.

Element Description

Requirements for three types of vehicle docking systems have been identifies as indicated in table 1.2.2-7. Figure 1.2.2-13 shows the location of these systems.

WBS 1.2.2.1.6.2 Assembly System

WBS Dictionary

This element includes the systems necessary to handle and assemble elements that make up the orbit to orbit crew/supply vehicles.

Element Description

The principal equipment includes 110m cherry pickers (number not determined) that are used to move and assemble crew transfer vehicles, resupply modules and the LO_2/LH_2 orbit transfer vehicle.

WBS 1.2.2.1.6.3 Propellant Storage and Distribution System

WBS Dictionary

This element includes the systems used to store and distribute propellant to be used by space transportation vehicles.

Element Description

Storage is provided for LO_2, LH_2, helium and argon propellants. A distribution system provides the capability to more propellant from the storage systems to the required vehicles or to tanks that will be transported to vehicles. The quantity and size of storage tanks has not been determined at this time.

Table 1.2.2-7. Equipment Description Sheet

ITEM VEHICLE DOCKING SYSTEMS WBS NO. 1.2.2.1.6.1

SUBITEMS		HLLV DOCKING SYSTEM	CARGO PALLET VEHICLE DOCKING SYSTEM	OTV DOCKING SYSTEM
FUNCTIONAL REQUIREMENTS		o Provide means to dock to HLLV orbitor	(Refer to Table 1.2.1-12)	
WHERE USED		LEVEL B		
MAJOR SUBELEMENTS		o Structure o Primary docking boom o Secondary docking booms (2)		
OPERATING RATES AND TIMES				
QTY		5	2	6
MASS	EA. TOTAL	TBD		
COST	EA. TOTAL	TBD		
MANNING				

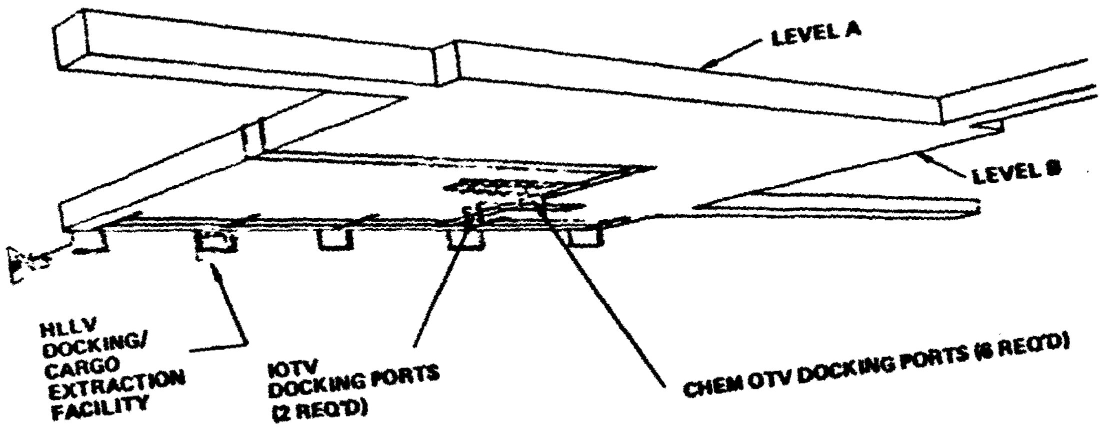

Figure 1.2.2-13. Vehicle Docking Facilities

WBS 1.2.2.1.6.4 Maintenance Systems

WBS Dictionary

This element includes all systems necessary to maintain space vehicles that are periodically based at the LEO base such as LO_2/LH_2 OTV's or those that station keep near the base such as the EOTV's.

Element Discription

Maintenance systems for the LO_2/LH_2 OTV have not been defined as yet.

One type of equipment used in maintaining the EOTV's is that associated with the electric propulsion system. A concept for the maintenance vehicle is shown in figure 1.2.2-14. Four of these EOTV maintenance vehicles are provided. Mass and cost have not been determined.

WBS 1.2.2.1.7 Base Maintenance Systems

WBS Dictionary

This element will include all systems and facilities necessary to conduct maintenance on all elements permanently associated with the base.

Element Description

This element has not been defined at this time.

WBS 1.2.2.1.8 Base Subsystems

WBS Dictionary

This element includes the base electrical power and flight control systems.

Element Description

The LEO base subsystem elements are described in the following subsections. The mass for the base subsystems is estimated as 50,000 KG and the cost estimated to be $5M based on scale-ups from other systems.

WBS 1.2.2.1.8.1 Electrical Power System

WBS Dictionary

This element includes all systems necessary to generate and distribute electric power to be used by the LEO base.

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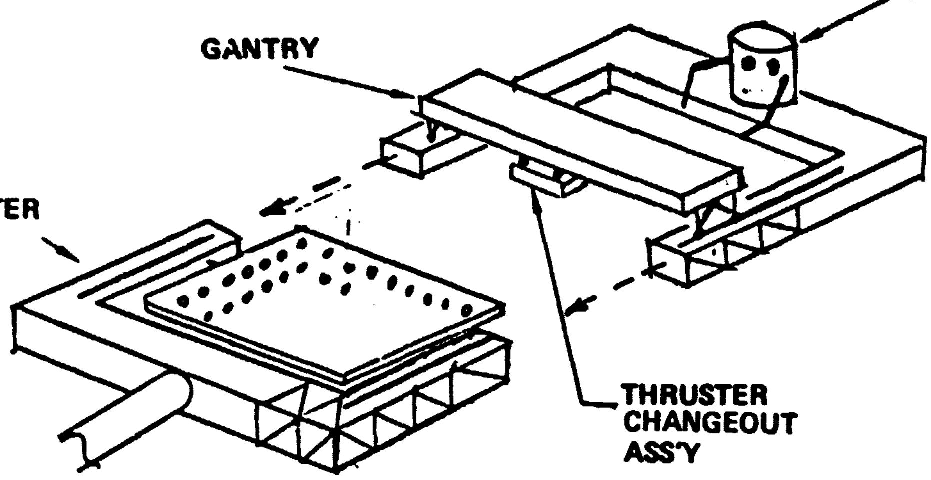


Figure 1.2.2-14. EOTV OTS Maintenance Vehicle

Element Description

Primary power is provided by body mounted solar array blankets. Nickel hydrogen batteries provide power during occultations. Power requirements for the presently defined LEO base have not been estimated.

WBS 1.2.2.1.8.2 Flight Control Systems

WBS Dictionary

This element includes all systems necessary to determine, maintain and change the orbital position and attitude of the base.

Element Description

Included under the category of flight control are the guidance/navigation/attitude type sensors such as IRU, star trackers and horizon sensors and a LO_2/LH_2 propulsion system to perform attitude and orbit maintenance maneuvers. The orbit altitude to be maintained is 477 ± 1 Km. Sizing of the propulsion system for the present base has not been accomplished.

WBS 1.2.2.2 Crew Support Facilities

WBS Dictionary

This element includes the facilities and equipment required for the life support and well-being of the crew members. Included are living quarters and work modules.

Element Description. A total of four crew modules have been included in the LEO base:

2 permanent crew quarters modules

1 transient crew quarters modules

1 work module (operations and maintenance)

The configurations of these modules are identical to those described inWBS 1.2.1.2 except that the radiation shelter is not referenced. Table 1.2.2-8 gives the mass and cost summary for the crew support facilities.

WBS 1.2.2.3 Operations

WBS Dictionary

This element includes the planning, development, and conduct of operations at the logistics support facility. It includes both the direct and support personnel and the expendable maintenance supplies required for logistics support.

Table 1.2.2-8. WBS 1.2.2.2 Mass and Cost Summary

WBS SUB-ITEMS		MASS, 10^3 kg	COST, $\$10^6$
1.2.2.2.1	CREW QUARTERS MODULES	660	900
1.2.2.2.2	WORK MODULES	150	250
1.2.2.2	CREW SUPPORT FACILITIES	810	1150

Element Description

The operations conducted at the LEO base include an integration of the following categories of operations:

- o Transportation vehicle opertions
- o Cargo handling/distribution operations
- o EOTV construction operations
- o Command and control operations
- o Base maintenance operations
- o Base support operations

These operations are discussed in following subelements. Table 1.2.2-9 summarizes the LEO base crew size.

WBS 1.2.3 Operations and Maintenance Support Facilities

Introduction

The operations and maintenance support facilities description is based on the partial maintenance analysis conducted as a part of Part III of Contract NAS0-15196, in which periodic replacement of Klystron tubes was analyzed. The definition is incomplete. A complete maintenance analysis will be conduted during Phase II of the present study and this description will be revised and completed at that time.

WBS Dictionary

Note: This WBS definition has been modified from the NASA WBS Dictionary to include mobile maintenance systems.

This element includes the mobile maintenance systems (crew habitats, crew supply modules, and cargo modules) that are flown between the GEO base and operational satellites by chemical OTV's.

Other SPS maintenance systems are described in the following sections:

WBS 1.1.1.6	Energy Conversion System Maintenance Systems
WBS 1.1.2.6	Power Transmission System Maintenance Systems
WBS 1.1.6.5	Interface System Maintenance Systems
WBS 1.2.1.1.7	GEO Base SPS Maintenance Support Facilities

Table 1.2.2-9. LEO Staging Depot Crew Size

SPS-2227

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

Element Description

A crew of maintenance personnel will visit each SPS twice a year to remove and replace failed hardware and perform scheduled maintenance and replenishment of consumables. This will require a fleet of OTV's and mobile crew habitats, crew supply modules, and cargo modules. The OTV's are described under WBS 1.3.4 (POTV). The cargo pallet modules are discussed under WBS 1.2.3.1. The crew habitats and supply modules are discussed under WBS 1.2.3.2. The SPS maintenance operations are described under WBS 1.2.3.3.

WBS 1.2.3.1 Work Support Facilities

WBS Dictionary

This element includes the cargo pallets used to transport SPS components between the SPS and the GEO base.

Element Description

The only item that belongs to this WBS element that has been defined to date is the klystron tube module cargo pallet, see Figure 1.2.3-1. A set of pallets is required, but the number, mass and cost have not been determined.

WBS 1.2.3.2 Crew Support Facilities

WBS Dictionary

This element includes the facilities and equipment required for the life support and well being of the crew members. Included are living quarters, recreation facilities, and health facilities.

Element Description

The mobile crew habitat shown in Figure 1.2.3-2 has been defined. Four of these crew modules are required to repair a 10 GW_e satellite by the reference maintenance operations plan defined in 1.2.3.3. (This plan does not provide a comprehensive maintenance capability.) The mass and cost of each module are estimated to be 240,000 kg and $240 M, respectively.

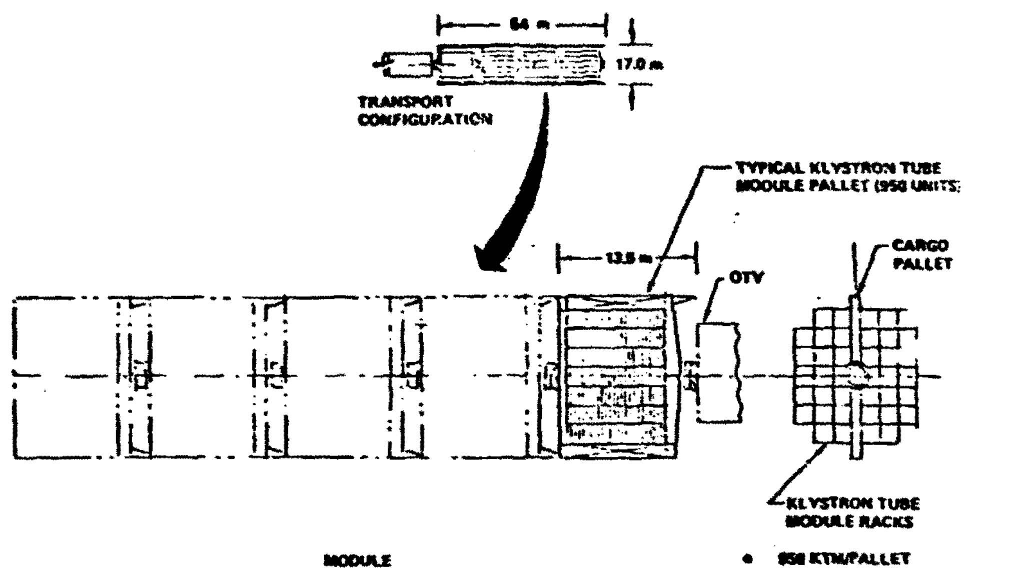


Figure 1.2.3-1. Mobile Maintenance System Equipment Transport Configuration

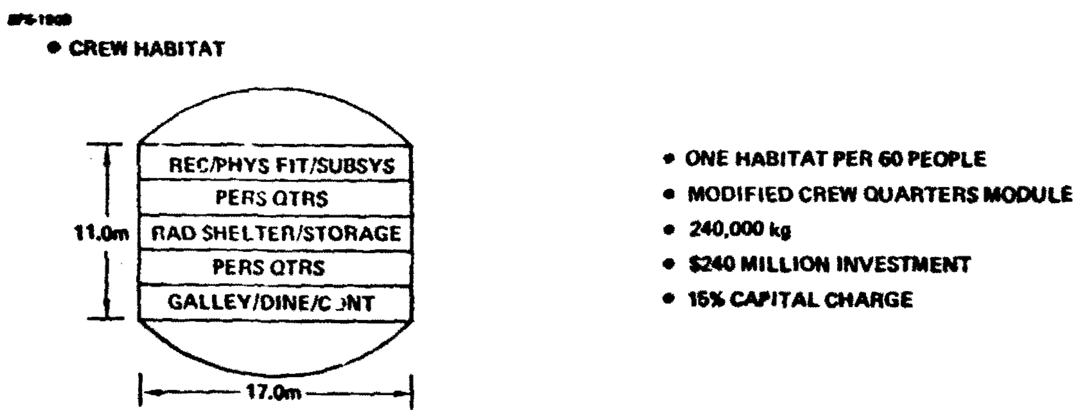


Figure 1.2.3-2. Mobile Crew Habitat Module

1.2.3.3 Operations

WBS Dictionary

This element includes the planning, development, and conduct of operations at the O&M support facility. It includes both the direct and support personnel and the expendable maintenance supplies required in GEO for satellite operations and maintenance.

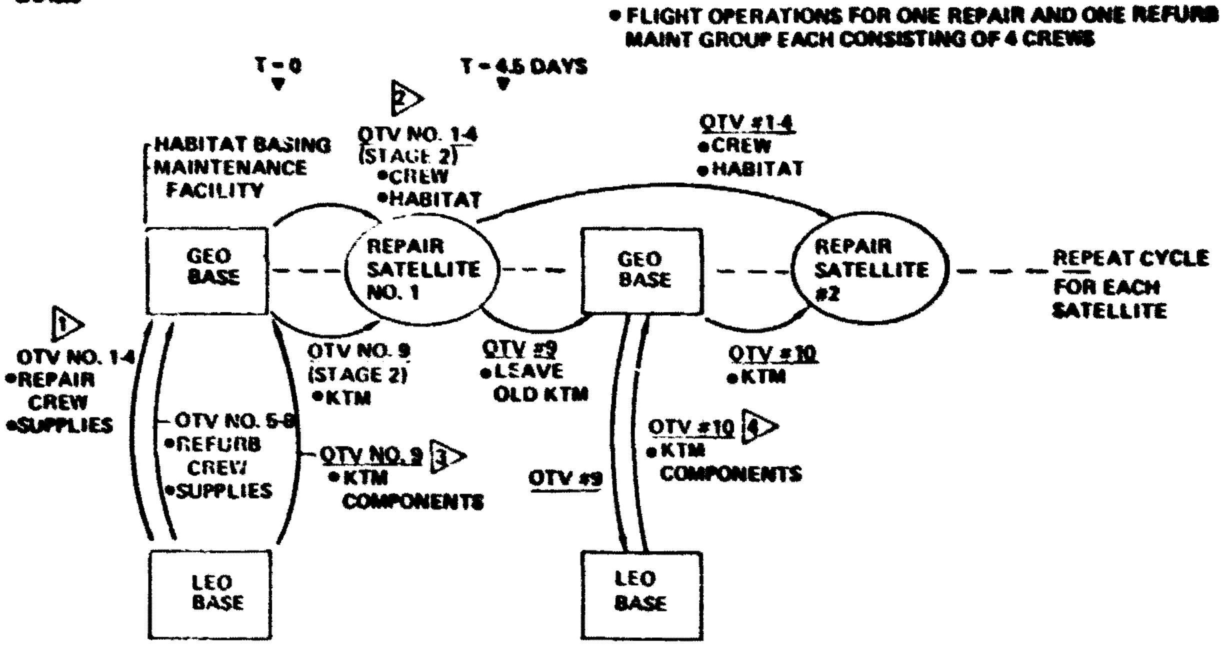
Element Description

The reference satellite maintenance mission includes semi-annual visits to each 5 GW_e satellite by two repair crews, each with 50 people, that work continuously for 3½ days until a satellite is repaired. A two shift operation is employed. Each repair group can service 20 satellites per 90 days allowing one day for transfer operations between satellites. The maintenance operations associated with the first visit to the satellites is initated at the beginning of one equinox (e.g., spring), with the second visit to the satellites beginning at the start of the autumn equinox.

The plan to be described provides only for klystron power amplifier replacement. According to present estimates, this is the dominant SPS maintenance workload requirement, but other nontrivial requirements exist. These are to be analyzed during Phase II of the present study.

Typical flight operations associated with one GEO base and the operations associated with one repair group and one refurbishment group assigned to the base are described under the assumption that 40, 5-GW SPS's are in orbit.

Once maintenance operations are begun, the GEO construction base serves as a major staging depot for the maintenance crews and their hardware in addition to its role of constructing the satellites. The initial operations associated with a typical 90 day period are shown in Figure 1.2.3-3. Four repair crews and four refurbishment crews are transported to the GEO base. Each crew is provided with its own LO_2/LH_2 orbit transfer vehicle. At approximately the same time another orbit transfer vehicle delivers klystron tube module components to be used in the refurbishment of failed tubes. This vehicle would also transfer other replacement components.



KTM = KLYSTRON TUBE MODULE

1. ALL OTV'S HAVE W_p = 460k kg. NO PROP TRANSFER REQUIRED AT GEO
2. 1 deg SEPARATION BETWEEN SATELLITES
3. COMPONENTS COULD BE DELIVERED VIA EOTV
4. CAN BE DELIVERED BEFORE OTV NO. 9 RETURNS

Figure 1.2.3-3. Selected Maintenance Mission Concept

Refurbishment crews remain at the GEO base, repairing failed klystron tube modules that have previously been delivered by other repair crews. Repair crews transfer to the satellite designated for repair taking with them their habitat. The second stage of the orbit transfer vehicle which brought the crew to GEO is used for the transfer to the satellite. The second stage of the orbit transfer vehicle used to deliver the klystron tube components to the GEO final assembly base is then loaded with refurbished klystron tube modules and transferred to the first satellite to be repaired.

At the completion of repairs on the first satellite, the crew and habitat transfer to the next satellite to be repaired. The other orbit transfer vehicle returns the failed klystron tubve modules back to the GEO base where they will be refurbished. The OTV then returns back to the LEO base. Prior to this time, however, another orbit transfer vehicle has come from LEO base to the GEO base delivering additional klystron tube components and is then dispatched with completely refurbished klystron tube modules to the second satellite that is to be repaired.

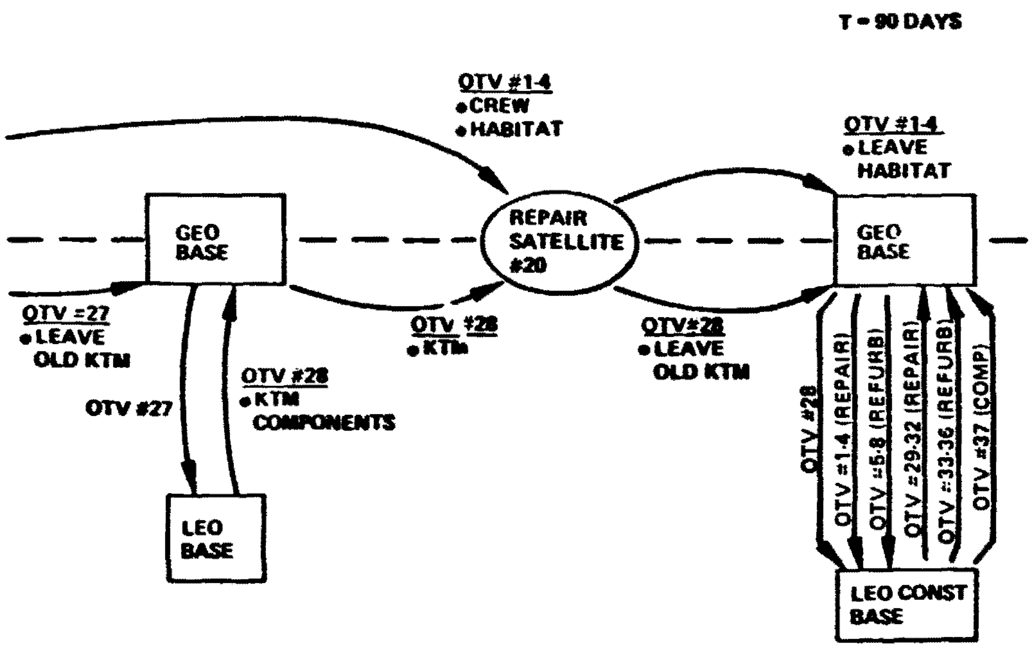
This cycle is repeated for each satellite to be repaired.

The final operations associated with a typical 90-day period are illustrated in Figure 1.2.3-4. After the 20th satellite hs been repaired, the crew and habitat return to the GEO base where the habitat is left for the next repair crew. The initial crew then returns back to the LEO base and eventually back to Earth. The refurbishment crew has also completed their 90 day stay time and also returns back to Earth. Four new crews and four new refurbishment crews are then transferred to the GEO base. The complete cycle is repeated again.

The annual number of orbit transfer vehicles and launch vehicles flights which occur in the maintenance of 40 satellites are also indicated.

Crew Summary

The maintenance crew size estimate is summarized in Table 1.2.3-2.



ANNUAL FLT SUMMARY (100 SATELLITES)

- 280 OTV FLTS TO GEO
- 400 OTV FLTS GEO TO GEO
- 350 HLLV FLTS TO LEO
- 80 SHUTTLE GROWTH FLTS TO LEO

Figure 1.2.3-4. Selected Maintenance Mission Concept

Table 1.2.3-2 Maintenance Crew Size Estimate [1]

Repair Group [2]	
Direct	160
Indirect	80
Refurbishment Group [3]	
Direct	160
Indirect	80
	480

[1] Maintenance crew assigned to a typical GEO base. This crew can repair and refurb SPS's two times per year.

[2] Consists of four repair crews which would be at operational SPS's except when at the GEO base at the time of crew rotation.

[3] Consists of four crews normally stationed at the GEO base.

WBS 1.2.3.3.1 Energy Conversion Maintenance Operations

WBS Dictionary

This element includes the description of the energy conversion equipment requiring maintenance and the operations required to perform the maintenance. Energy conversion maintenance operations were not analyzed.

WBS 1.2.3.3.2 Antenna Maintenance Operations

WBS Dictionary

This element includes the description of the antenna items requiring maintenance, the level of replacement, the replacement concept, logistics provisions, and the maintenance equipment. Maintenance operations were analyzed only for klystron power amplifier replacement.

Level of Replacement. The level of replacement selected is that of the klystron tube module plus its thermal control system as shown in Figure 1.2.3-5. Actual removal of the tube module involves access through holes in the radiator to reach the distribution wave guide attachment bracket which secures the module to the distribution wave guide. Once this attachment is released the module is free to be removed.

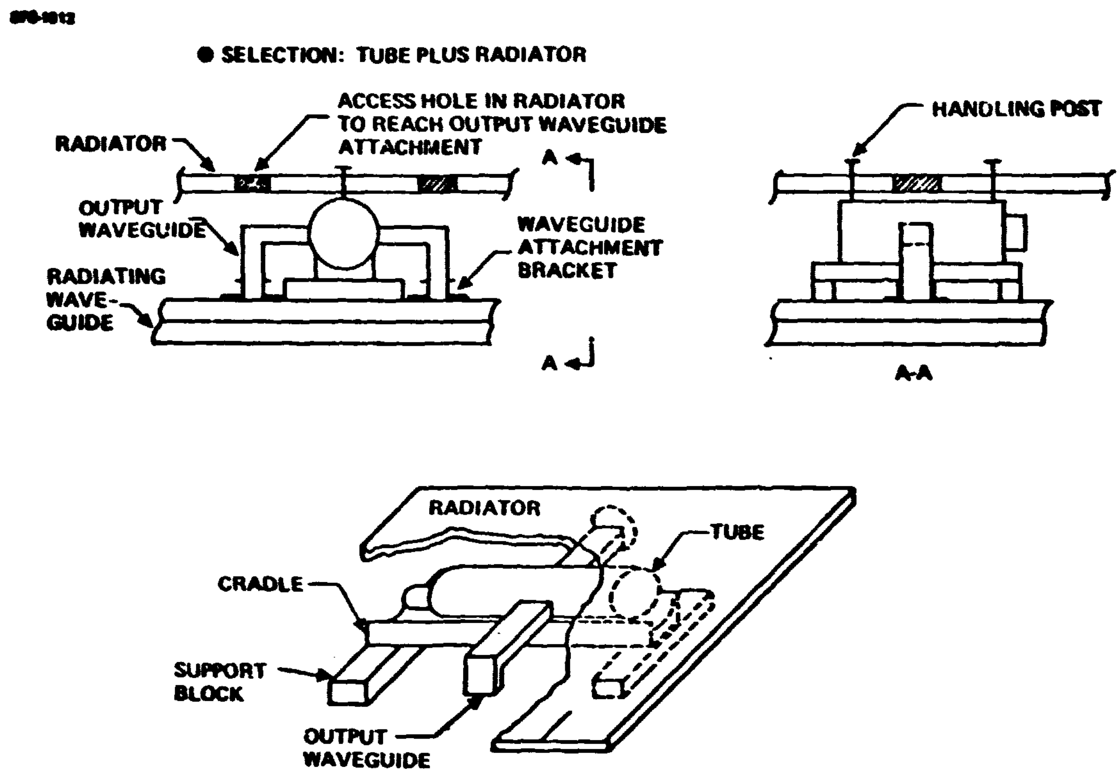


Figure 1.2.3-5. Level of Replacement Selection

Concept

The selected klystron tube module replacement concept uses vertical access through the cubic secondary structure which is attached to the A-frame primary structure. The overall concept is illustrated in Figure 1.2.3-6. The primary structure is an A-frame design forming ridges that allows free unobstructed movement of the maintenance gantry moving horizontally across the antenna.

The antenna will have a total of 10 channels in which maintenance gantries can be mounted. 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 1.2.3-7.

Additional detail of the cubic secondary structure and the maintenance vehicle is presented in Figure 1.2.3-8 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-man 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 repaired. In the case of a 36 tube subarray as many as three tubes may require replacement.

Using this concept a tube replacement time of 45 minutes is expected, which includes removal and replacement of two diagonals (in lower and upper surface of secondary structure), removal and replacement of one klystron tube module, and movement to the next failed klystron tube estimated at a distance of 2 subarrays away or 20 meters.

The Satellite based maintenance systems will be installed during satellite construction. The systems are shown as they relate to one side of one antenna in Figures 1.2.3-9 and 1.2.3-10. Since two crews work on each satellite, these same systems are present on both sides of both antennas.

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 maintained and supplied with new klystron tube modules. These items are included under "antenna maintenance provisions," WBS 1.1.2.6.

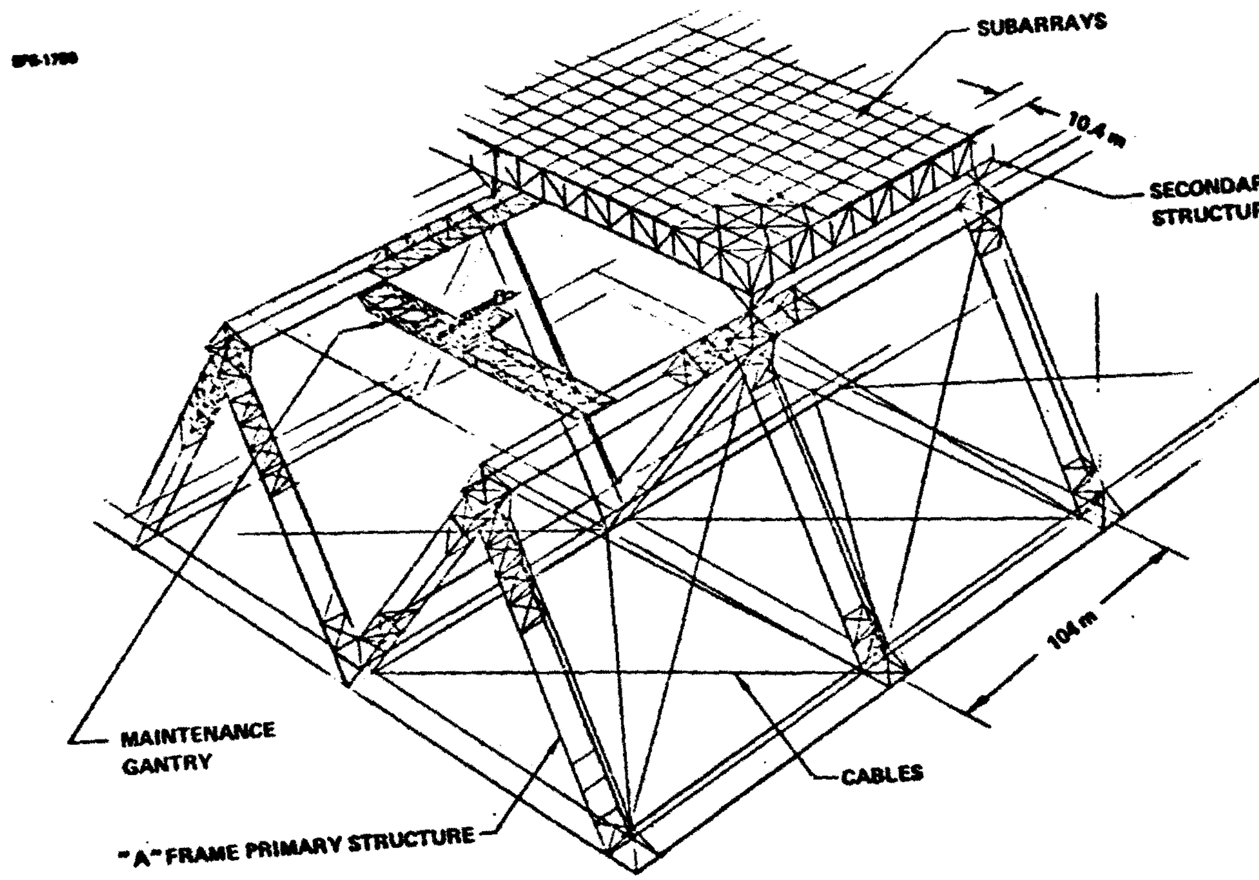


Figure 1.2.3-6. Vertical Access For Tube Maintenance

SPS-1701

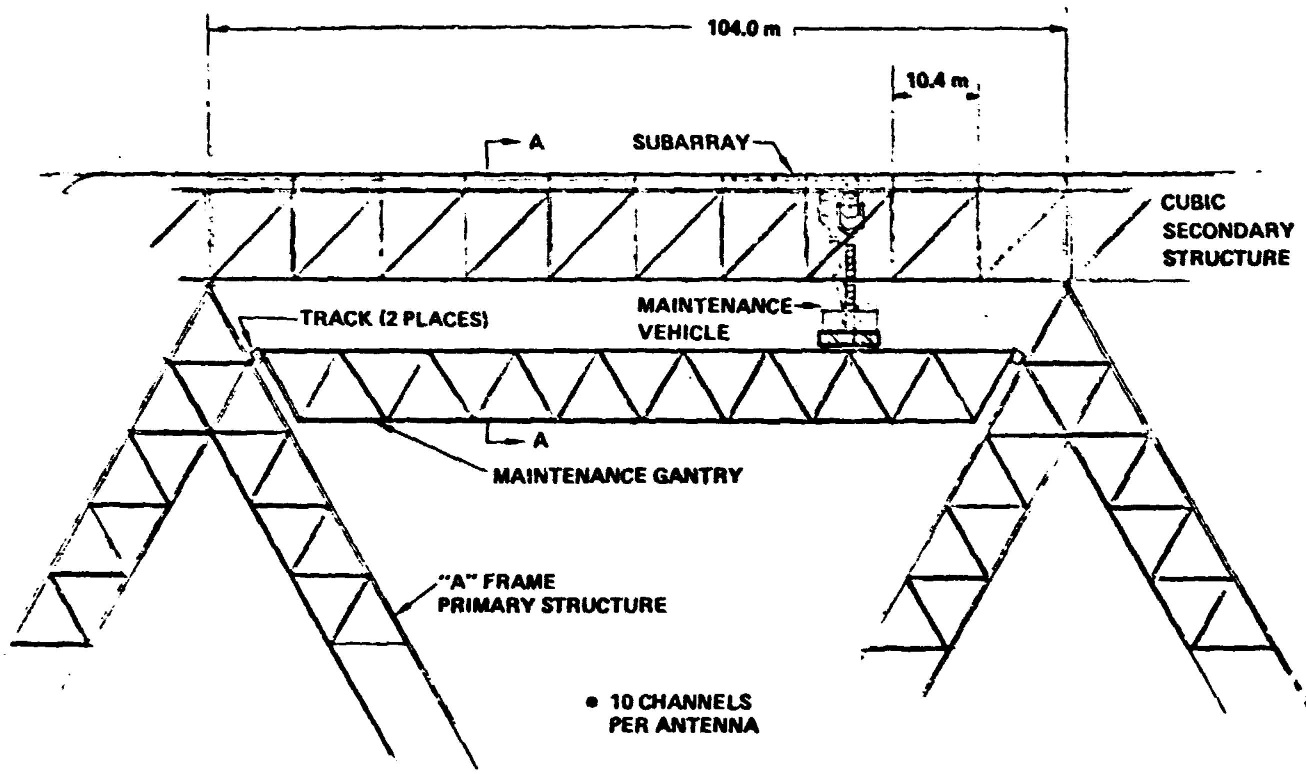


Figure 1.2.3-7. Vertical Access For Tube Maintenance

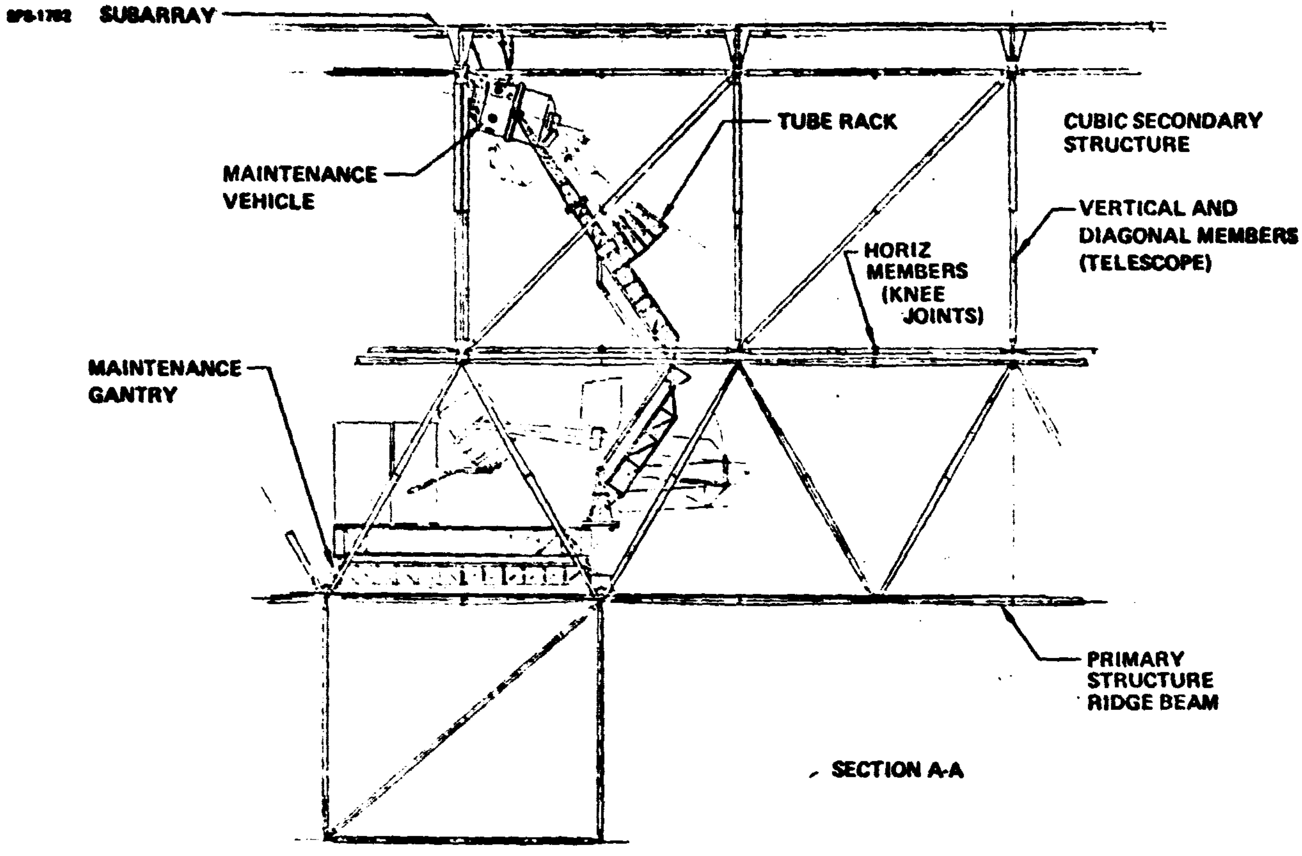


Figure 1.2.3-8. Vertical Access Maintenance Vehicle

SPS-1940

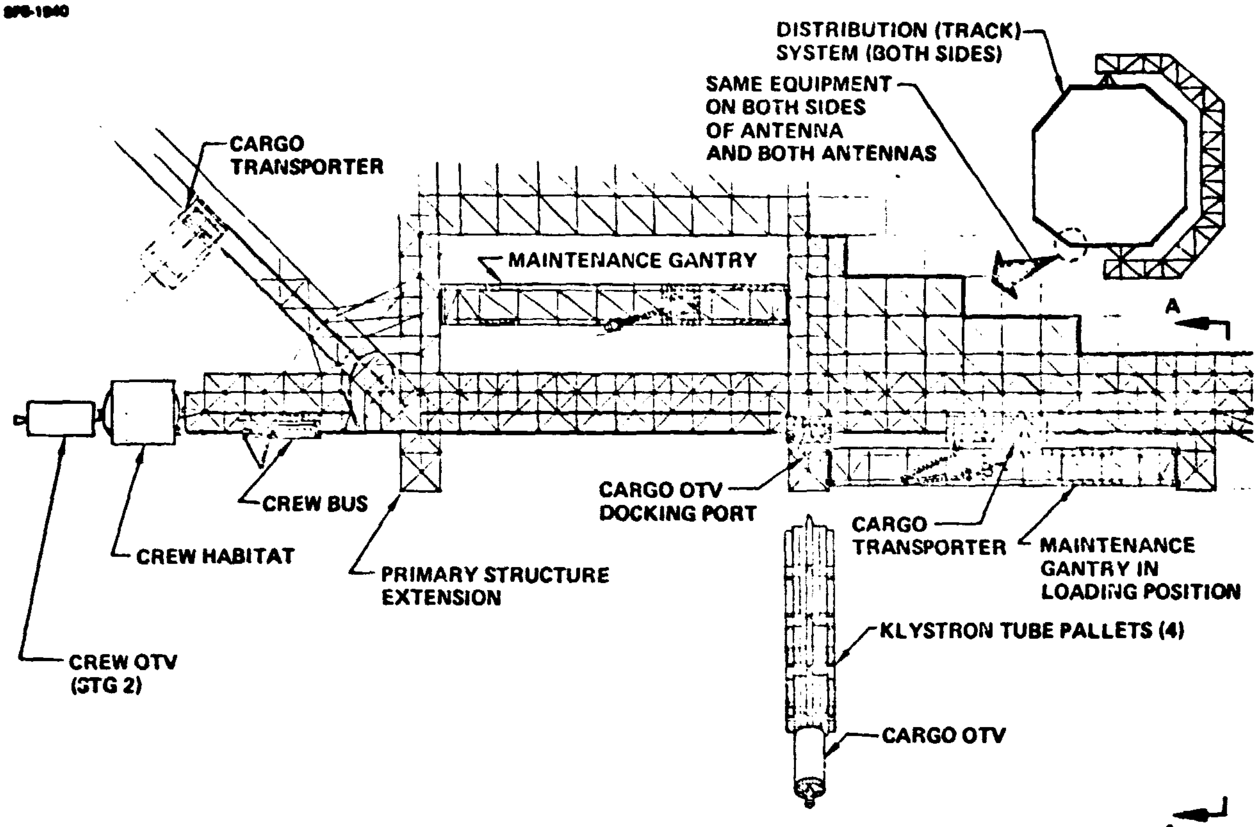


Figure 1.2.3-9. Satellite Maintenance Systems

SPS-1941

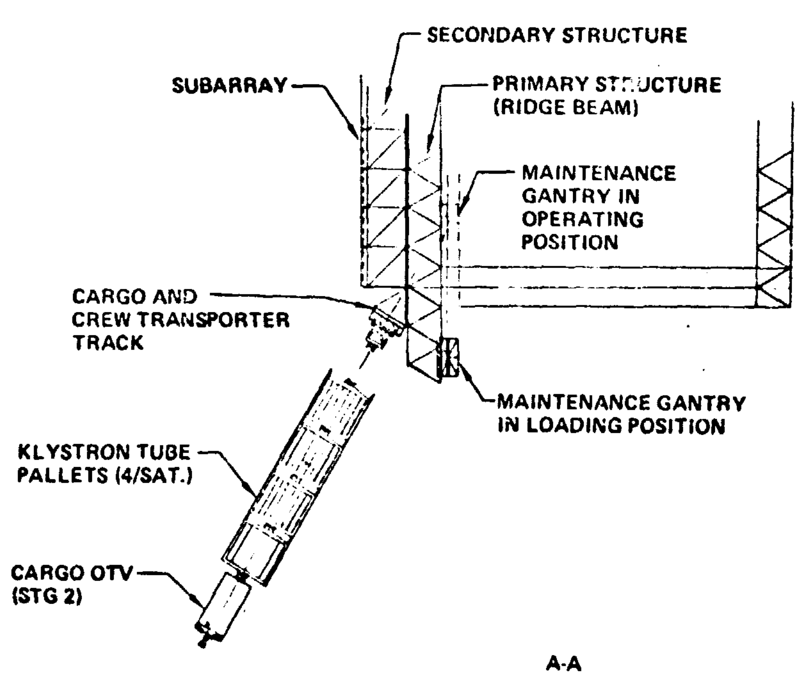


Figure 1.2.3-10. Satellite Maintenance Systems

The 60-person crew is delivered to the satellite in the crew habitat using the second stage of the OTV that initially brought the crew from the LEO construction base to the GEO final assembly base. Once at the satellite (antenna), a crew bus is used to transfer persons between the habitat and the maintenance repair vehicles.

Cargo, primarily in the form of klystron tube modules is also delivered to the satellite using a dedicated OTV (stage 2) that had initially brought klystron components to the GEO final assembly base for refurbishment of "failed" klystron tubes. The operations associated with an OTV include docking and release of one klystron tube pallet on one side of the antenna and then free-flying to the other side of the antenna leaving another pallet. At the completion of the repair operation, the pallets are loaded with "failed" klystron tubes. The OTV then moves to the four docking locations collecting the pallets with failed tube modules and then returns them back to the GEO final assembly base where they will be refurbished. Following the release of the pallets, the OTV returns to the LEO construction base where it is made ready to deliver another load of klystron components.

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 each 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 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 have been removed. The train system 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.

The installation location of the maintenance equipment on an antenna being repaired by two crews is shown in Figure 1.2.3-11.

The number of maintenance vehicles (machines) installed in each channel of the antenna is a function of the estimated number of tube failures. This value is larger in the middle channels of the antenna since the center of the antenna has subarrays containing 36 and 30 klystron tube modules while near the edge of the antenna, the

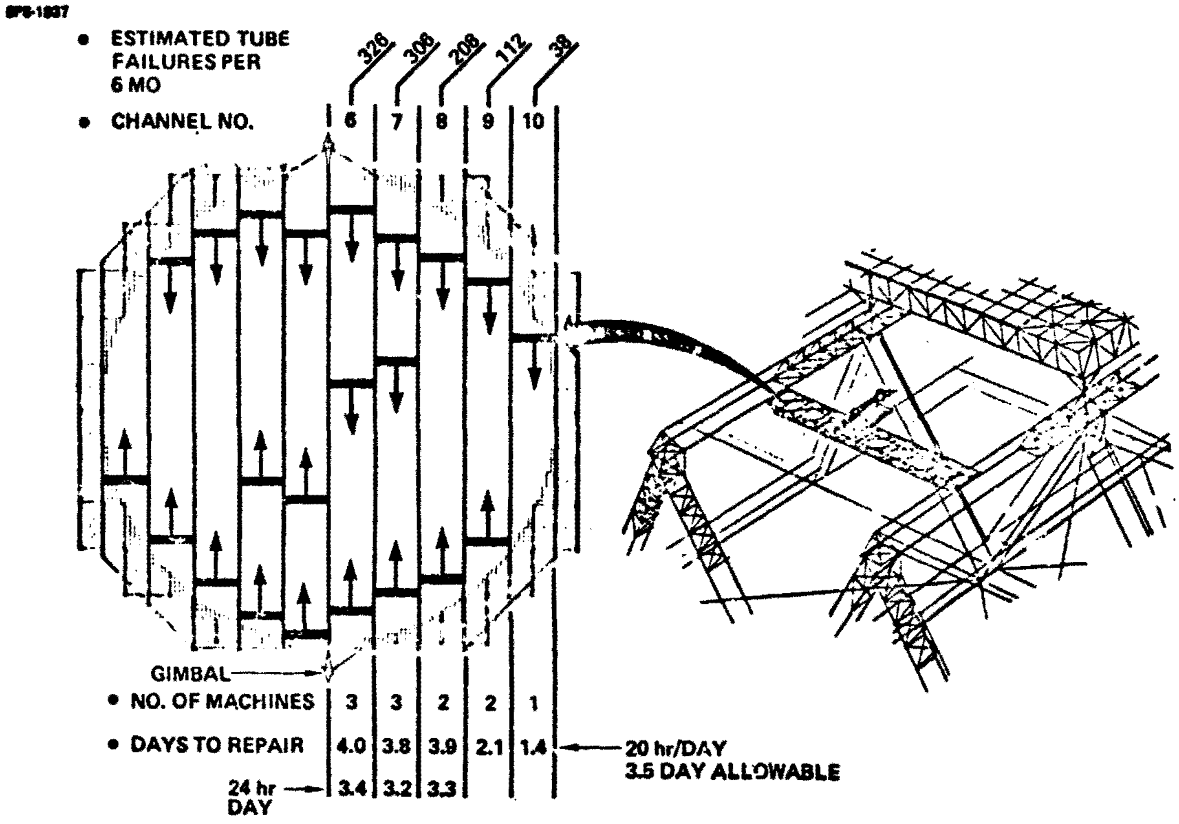


Figure 1.2.3-11. Antenna Maintenance System Installation

subarrays have 4 to 6 tubes per subarray. Consequently it will be noted that the middle channel has three maintenance systems consisting of a gantry and repair vehicle.

With this equipment distribution and working 20 hours per day, the middle channels require slightly more time than previously identified for repair—3½ days per satellite. The addition of 1/2 day to the schedule, however, will not appreciably alter the prior analysis.

It should also be noted, the outside channels require far less time to repair and less equipment due to fewer failed tubes. Consequently when the crews assigned to this particular equipment are finished, they can then be used to repair other components on the satellite such as the dc-dc converters mentioned earlier in the discussion.

WBS 1.2.3.3.3 Interface System Maintenance Operations

To be added.

WBS 1.3 Space Transportation

This section of the document addresses the description of the space transportation system. Both launch and orbit transfer vehicles for cargo and personnel are included. In addition, launch facility requirements, propellant production and delivery systems, and operations/support are discussed in the following sub-sections.

Transportation Summary

The space transportation system includes a heavy lift launch vehicle (HLLV), a modified shuttle personnel launch vehicle (PLV), a personnel and supplies high-thrust orbit transfer vehicle (OTV), and low-thrust electric orbit transfer vehicle (EOTV). The low-thrust EOTV systems are reusable and are returned to LEO after delivery of cargo to GEO. A vehicle flight utilization and cost summary is presented in Table 1.3.0-1.

WBS 1.3.1 Cargo Launch Vehicle

The launch configuration of the SPS cargo vehicle is shown in Figure 1.3.1-1 with the overall geometry noted. This series burn concept uses 16 LCH_4/LO_2 engines on the booster and 14 standard SSME's on the orbiter. The LCH_4/LO_2 booster engines employ a gas generator cycle and provide a vacuum thrust of 9.79×10^6 newtons each. The SSME's on the orbiter provide a vacuum thrust of 2.09×10^6 newtons (100% power level). The nominal 100% power level for the SSME's was selected based on engine life considerations which indicated about a 3 factor reduction in life if the 109% power level is used.

An airbreather propulsion system has been provided on the booster for flyback capability to simplify the booster operational mode. The reference wing area for both stages is:

S_W (Orbiter) = $1446 m^2$ ($15{,}560\ ft^2$)
S_W (Orbiter) = $2330 m^2$ ($25{,}080\ ft^2$)

Heat sink thermal protection system is provided on the booster and the Shuttle's Reusable Surface Insulation (RSI) is used on the orbiter.

WBS 1.3.1.1 Launch Vehicle Characteristics

WBS 1.3.1.1.1 Vehicle Design Characteristics

The vehicle design characteristics are noted in Table 1.3.1-1. The net delivered payload is 424,000 A return payload of 15% (63,500 kg) of the delivered payload was assumed for the orbiter entry and landing conditions. The resulting mass fraction is 0.875 for the booster and 0.841 for the orbiter.

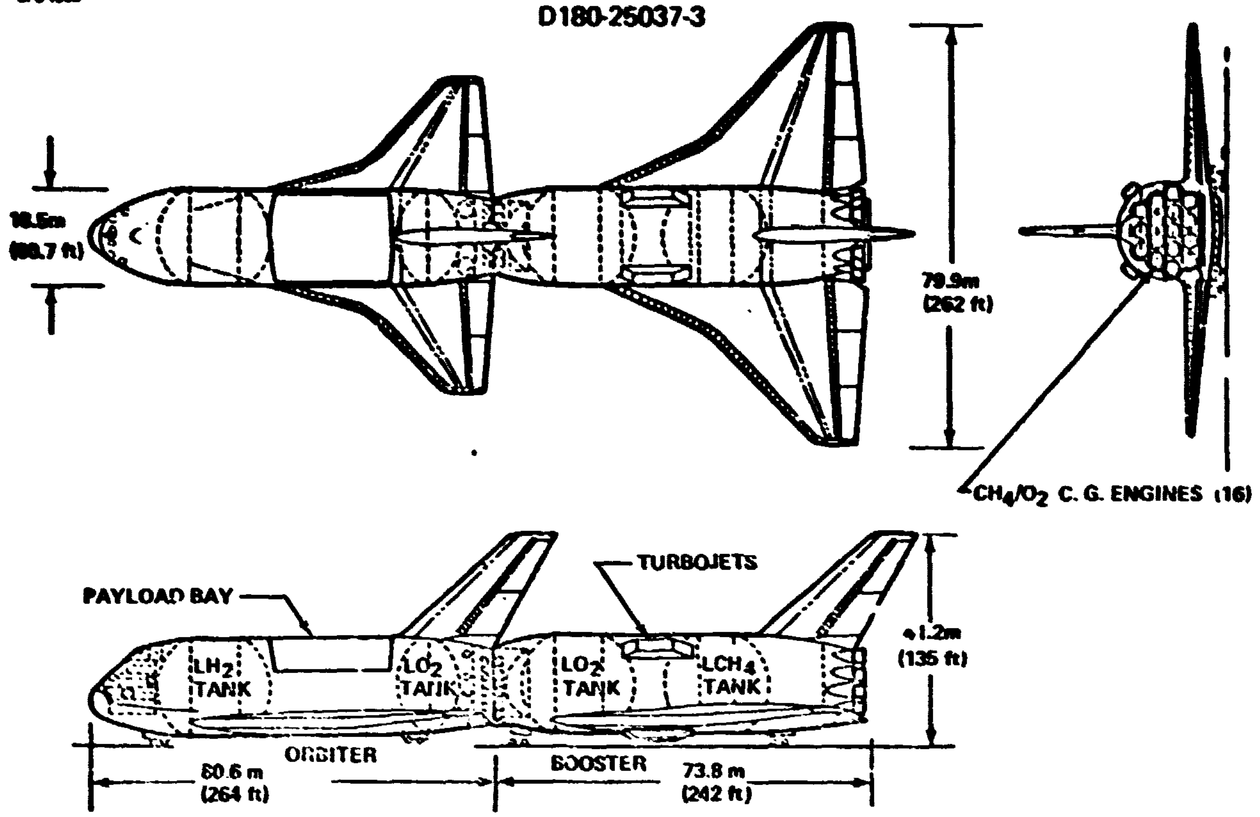


Figure 1.3.1-1 Two-Stage Winged SPS Launch Vehicle (Fully Reusable Cargo Carrier)

Table 1.3.1-1 Two-Stage Winged Vehicle Design Characteristics

	ORBITER		BOOSTER
GLOW		10,978,400	
BLOW	—		7,813,700
BOOSTER FUEL (LCH4)	—		1,708,900
BOOSTER OXIDIZER (LO2)	—		5,126,700
BOOSTER INERTS	—		978,100
OLOW–LESS PAYLOAD	2,740,700		—
ORBITIER FUEL (LH2)	329,400 *		—
ORIBITER OXIDIZER (LO2)	1,976,200 *		—
ORBITER INERTS	435,100		—
ASCENT PAYLOAD	424,000		—
RETURN PAYLOAD ~ 15%	63,600		—
MASS FRACTION	0.841		0.875
ENTRY WEIGHT–NO PAYLOAD	395,200		936,600
–WITH RETURN P/L	456,000		—
START CRUISE WEIGHT–NO P/L	—		932,900
–WITH RETURN P/L	—		—
LANDING WEIGHT–NO PAYLOAD	391,800		846,700
–WITH RETURN P/L	452,600		—

(ALL MASS DATA IN kg)

*MAINSTAGE + FLIGHT PERFORMANCE RESERVE

WBS 1.3.1.1.2 Ascent Performance Characteristics

The SPS launch vehicle ascent performance characteristics are noted in Table 1.3.1-2. A '3g' maximum acceleration thrust profile was used due to the manned capability and also to minimize the load conditions on the orbiter. The booster staging velocity of 2170 m/sec is well within the "heat sink" capability of the aluminum/titanium airframe.

1.3.1.1.3 Reentry Characteristics

The reentry characteristics for the booster and orbiter are noted in Table 1.3.1-3. The maximum deceleration for the booster is 4.27 g's and the subsonic transition altitude is 17.86 km. The orbiter reentry has been limited to a normal load factor of 1.41 g's until the subsonic transition which occurs at an altitude of 13.62 km.

1.3.1.2 Booster Stage

1.3.1.2.1 System Description

The booster stage of the 2-stage winged vehicle consists of the following subsystems:

- Structures
- Induced Environmental Protection
- Landing and Auxiliary Systems
- Ascent Propulsion
- Flyback Propulsion
- RCS Propulsion
- Prime Power
- Electrical Conversion and Distribution
- Hydraulic Conversion and Distribution
- Surface Controls
- Avionics
- Environmental Control

Each of these subsystems is discussed in the following sections including definition of the rationale for the mass and cost estimates.

1.3.1.2.1.1 Structures—The booster stage structures subsystem consists of the wing, vertical tail, and body group. The body group consists of the nose section, oxidizer (LO_2) tank, intertank, fuel (LCH_4) tank, base skirt, thrust structure, aft body flap, and fairing structures. A preliminary sizing analysis was conducted to determine the individual structural element masses exclusive of heat skin requirements. The additional materials required to satisfy heat sink requirements are incorporated into the induced environmental protection subsystem.

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Table 1.3.1-2 Ascent Performance Characteristics

FIRST STAGE

T/W AT IGNITION	=	1.30	
MAXIMUM DYNAMIC PRESSURE	=	35.91 kPa	(750 psf)
MAXIMUM ACCELERATION	=	3.0g	
STAGE BURN TIME	=	155.24 sec	
RELATIVE STAGING VELOCITY	=	2170 m/sec	(7,120 fps)
DYNAMIC PRESSURE AT STAGING	=	1.16 kPa	(24 psf)

SECOND STAGE

INITIAL T/W	=	0.94
MAXIMUM ACCELERATION	=	3.0 g
STAGE BURN TIME	=	350.24 sec

SPS-1854

Table 1.3.1-3 SPS Winged Vehicle Reenetry Characteristics

BOOSTER

APOGEE CONDITIONS
h = 80.82 km
V_{rel} = 1955 m/sec

MAXIMUM DECELERATION CONDITION
q = 10.77 kPa
h = 32.61 km
V_{rel} = 1327 m/sec
NORMAL LOAD FACTOR = 4.27 g's

MAXIMUM DYNAMIC PRESSURE CONDITION
q = 13.29 kPa
h = 22.96 km
V_{rel} = 686 m/sec
NORMAL LOAD FACTOR = 1.49 g's

SUBSONIC TRANSITION CONDITION
h = 17.86 km
α = 15 deg

ORBITER

MAXIMUM DYNAMIC PRESSURE CONDITION
q = 13.17 kpa
h = 15.55 km
V_{rel} = 361 m/sec
NORMAL LOAD FACTOR = 1.41

SUBSONIC TRANSITION CONDITION
h = 13.62 km
α = 6.4 deg

Wing–The wing box is constructed of 7075-T73 aluminum and the leading edge, trailing edge, and elevons are constructed of 6AL-4V titanium. A 4g entry condition and a 2.5g subsonic maneuver condition were considered in sizing the wing structure. A constant t/c = 10% was used. The wing mass is 129,700 kg.

Vertical Tail–The vertical tail was sized for a boost max $q\beta$ condition of 177 kpa. The box structure is 7075-T73 aluminum and the remaining tail structure is 6AL-4V titanium. The mass of the vertical tail is 14,000 kg.

Nose Section–The nose section consists of a fixed shell structure plus a deployable nose cap. The shell structure experiences maximum compressive loadings of 35,200 N/cm forward and 24,000 N/cm aft during the boost 3g condition. The smeared thickness of the 7075 aluminum skin-stringer panels is 0.82 cm forward and 0.68 cm aft. The smeared thickness of the 7075 aluminum nose cap is 0.38 cm. The nose section mass is 26,800 kg.

Oxidizer (LO_2) Tank–The oxidizer tank is an all welded 2219-T87 aluminum pressure vessel with integral sidewall stiffening in the cylindrical section. The smeared thickness of the sidewall panels varied from 0.79 cm forward to 0.93 cm aft. The dome membrane thickness varies between 0.28 cm and 0.40 cm for the upper dome and between 0.47 cm and 0.81 cm for the lower dome. The tank mass including slosh baffles is 36 100 kg.

Intertank–The intertank is approximately 18.5 meters long and is constructed of 7075 aluminum. The intertank experiences a maximum compressive loading of 30,160 N/cm at the boost 3g onset condition. The smeared thickness of the skin-stringer panels is 0.76 cm. The mass of the intertank, which incorporates the airbreather engine support structures, is 38,000 kg.

Fuel (LCH_4) Tank–The fuel tank is an all welded 2219-T87 aluminum pressure vessel with integral sidewall stiffening in the cylindrical section. The smeared thickness of the sidewall panels is 0.89 cm. The dome membrane thickness varies between 0.28 cm and 0.40 cm for the upper dome and between 0.28 and 0.46 cm for the lower dome. The tank mass including slosh baffles is 32,600 kg.

Base Skirt–The base skirt is approximately 19.7 meters long and is constructed of 7075 aluminum. The upper 14.4 meters experiences maximum compressive loadings of 40,000 N/cm forward and 44,500 N/cm aft at the boost 3g onset condition. The smeared thickness of the skin-stringer panels is 0.88 cm forward and 0.94 cm aft. The lower 5.3 meters experiences a maximum combined compressive loading of 31,100 N/cm and shear flow of 18,900 N/cm during the tanked pre-ignition condition. The smeared thickness of the skin-stringer panels is 1.50 cm in the shear-out region and 0.64 cm outside the shear-out region. The base skirt mass is 47,200 kg.

Thrust Structure–The thrust structure consists of four major beam assemblies plus interbeam stabilizing members. Sixteen thrust posts are incorporated into the beam assemblies. 7075 aluminum is used throughout. The structural elements are sized for the ignition condition using a dynamic magnification factor of 1.25. Shear flows in the individual plates vary from 15,300 N/cm to 61,300 N/cm and the web plate thicknesses vary from 0.46 cm to 1.85 cm. The average cross area of a thrust post is 186 square centimeters. The thrust structure mass is 23,900 kg.

Aft Body Flap–The constant chord body flap provides the booster stage with pitch trim control and thermally shields the main engines during entry. The flap is constructed of 6AL-4V titanium and has a mass of 2100 kg.

Fairing Structures–Fairing structures consist o the wing-to-body fairings located both forward and aft of the box carry-thru section, the tail-to-body fairing, and the engine shroud/base region fairings. The fairings are constructed of 6AL-4V titanium and have an estimated mass of 8500 kg.

1.3.1.2.1.2 **Induced Environmental Protection**–The induced environmental protection subsystem system consists of the heat sink additions required to maintain the airframe outer skin within acceptable temperature limits, plus the base heat shield. Reusable Surface Insulation is the thermal protection system on the base heat shield. The heat sink additions weigh 38,300 kg and the base heat shield 8100 kg for a total system mass of 46,400 kg.

1.3.1.2.1.3 **Landing and Auxiliary Systems**–In addition to landing gear, this subsystem includes a includes a landing drag device and auxiliary systems for upper stage separation and nose cap deployment/latching. The landing gear weight is estimated at 3.2% of design landing weight. Total subsystem mass is 34,500 kg.

1.3.1.2.1.4 **Ascent Propulsion**–The ascent propulsion subsystem consists of the main engines, engines, accessories, gimbal provisions, and the fuel and oxidizer systems. Main propulsion is provided by sixteen (16) high pressure LO_2/LCH_4 gas generator cycle engines and the associated tank pressurization and propellant delivery system. The following engine characteristics were used in the analysis:

Propellant	LO_2/LCH_4
Chamber Pressure	34,500 kpa
Area Ratio	60:1
Mixture Ratio	3:1
Thrust (S.L./Vac.)	8.76×10^6N/9.68×10^6N
Specific Impulse (S.L./Vac.)	318.5 sec/352 sec

The mass of the sixteen engines and associated accessories plus gimbal provisions (for eleven engines) is 162,400 kg.

Pressurization gases are heated GO_2 for the LO_2 tank and heated GCH_4 for the LCH_4 tank. The total mass of the tank pressurization and propellant delivery systems is 42,200 kg.

1.3.1.2.1.5 **Flyback Propulsion**—The flyback propulsion subsystem consists of the airbreathing engines, accessories, fuel system, tankage, and engine installation nacelles, ducts, and doors. Flyback thrust is provided by twelve (12) turbojet engines, each having a S.L. static thrust of 356,000 N. The flyback fuel is RP-1. The dry mass of the subsystem is 57,400 kg.

1.3.1.2.1.6 **Other Subsystems**—The remaining subsystem masses have been estimated using historical or Shuttle predicted weights. These subsystems include RCS propulsion, prime power, electrical conversion and distribution, hydraulic conversion and distribution, aerosurface controls, avionics, and environmental control.

RCS Propulsion—The reaction control system is required for stage orientation prior to entry and for control during entry. The subsystem dry mass is 5100 kg.

Prime Power—Major power sources consist of batteries and airbreather engine driven generators for electrical power, and a hydrazine powered APU for hydraulic power. The subsystem mass is 4300 kg.

Electrical Conversion and Distribution—The power conversion conditioning, and cabling elements are included in this category. The subsystem mass is 4200 kg.

Hydraulic Conversion and Distribution—All stage functions requiring hydraulic power are serviced by the hydraulic conversion and distribution subsystem. The hydraulic power for rocket engine thrust vector control and valve actuation is included in this category. The subsystem mass is 10,900 kg.

Surface Controls—The actuation system for the aerodynamic control surfaces are included in this category. The subsystem mass is 10,300 kg.

Avionics—The avionics subsystem includes elements for guidance, navigation and control, tracking, instrumentation, and data processing and software. The subsystem mass is 1500 kg.

Environmental Control—The environmental control subsystem maintains a conditioned thermal environment for the avionics. The subsystem mass is 200 kg.

1.3.1.2.2 Booster Mass Characteristics

The flyback booster mass characteristics are shown in Table 1.3.1-4. The structure, induced environment protection, ascent and auxiliary propulsion, and landing subsystems account for 89% of the dry mass. The induced environment protection subsystem mass includes the additional structural thickness required for the "heat sink capability" and the base heat shield.

1.3.1.3 Orbiter Stage

1.3.1.3.1 System Description

The Orbiter of the 2-stage winged vehicle consists of the following subsystems:

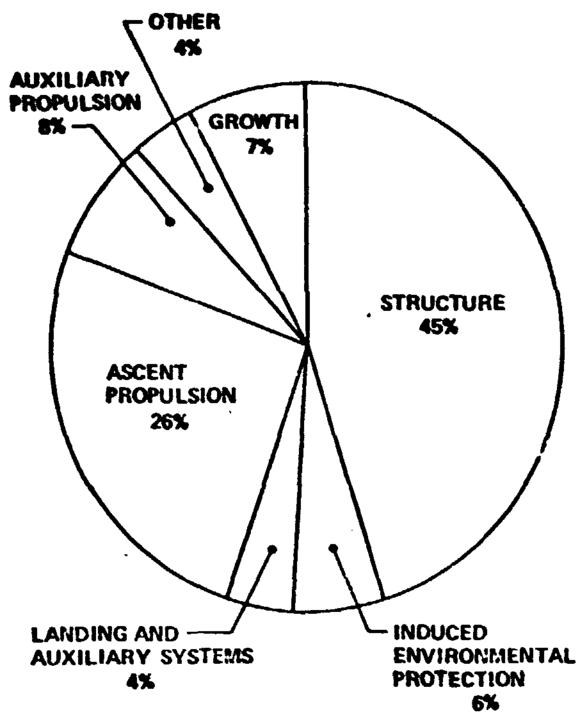
- Structures
- Induced Environmental Protection
- Landing and Auxiliary Systems
- Ascent Propulsion
- OMS Propulsion
- RCS Propulsion
- Prime Power
- Electrical Conversion and Distribution
- Hydraulic Conversion and Distribution
- Surface Controls
- Avionics
- Environmental Control
- Personnel Provisions
- Personnel
- Payload Accommodations

Each of these subsystems will be discussed in the following sections including definition of the rationale for the mass and cost estimates.

1.3.1.3.1.1 Structures—The Orbiter structures subsystem consists of the wing, vertical tail, and body group. The body group consists of the nose section, crew module, fuel (LH_2) tank, intertank, P/L bay doors, oxidizer (LO_2) tank, aft skirt, thrust structure, aft body flap, and fairing structures. A preliminary sizing analysis was conducted to determine the individual structural element masses.

Wing—The wing is constructed from 6AL-4V titanium. A 2.5g entry condition and a 2.5g subsonic maneuver condition were considered in sizing the wing structure. A constant t/c = 10% was used. The wing mass is 51,800 kg.

Table 1.3.1-4 Booster Mass Statement



DRY MASS BREAKDOWN

	MASS (kg)
STRUCTURE	360 800
INDUCED ENVIRONMENTAL PROTECTION	46 400
LANDING AND AUXILIARY SYSTEMS	34 500
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	1 500
ENVIRONMENTAL CONTROL	200
GROWTH	58 600
DRY MASS =	796 900
RESIDUALS AND RESERVES	49 800
LANDING MASS =	846 700
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

Vertical Tail–The vertical tail was sized for a boost max $q\beta$ condition of 177 kpa. It is constructed of 6AL-4V titanium. The mass of the vertical tail is 12,300 kg.

Nose Section–The nose section is constructed of 6AL-4V stiffened sandwich construction. Included in the nose section are the exterior windshields and the nose landing gear support bulkhead, wheel well and doors. The titanium sandwich is 3 cm thick and has a smeared thickness of 0.13 cm. The total mass of the nose section is 9200 kg.

Crew Module–The crew module is an all welded 2219-T87 aluminum pressure-tight vessel with integral stiffening. Included in the crew module are the interior (redundant) windshields, hatches for ingress and egress, and support provisions for other subsystem elements located within the module. The module accommodates a 4-man flight crew plus a 6-man passenger group. The crew module mass is 2800 kg.

Fuel (LH_2) Tank–The fuel tank is an all welded 6AL-4V titanium sandwich pressure vessel. The core thickness is 3 cm. The smeared thickness of the sidewall sandwich is 0.41 cm. The dome sandwich smeared thickness varies between 0.21 cm and 0.26 cm for the upper dome and between 0.22 cm and 0.28 cm for the lower dome. The tank mass is 21,200 kg.

Intertank–The intertank is constructed primarily of 6AL-4V titanium sandwich. It provides support for second stage payloads and the payload bay doors. The smeared thickness of the sidewall sandwich varies from 0.13 cm to 0.25 cm. The intertank mass is 25,900 kg.

Payload Bay Doors–The payload bay door is 24 meters long and has a surface area of 553 square meters. It consists of two panels that open at the upper centerline. Each panel consists of four equal length segments. The forward 6-meter segment incorporates deployable radiators. The door primary structure is of honeycomb and frame construction employing composite materials. The door mass is 5100 kg.

Oxidizer (LO_2) Tank–The oxidizer tank is an all welded 2219-T87 aluminum pressure vessel consisting of two elliptical domes. The dome membrane thickness varies between 0.53 cm and 0.63 cm for the upper dome and between 0.62 cm and 1.00 cm for the lower dome. The tank mass including slosh baffles is 20,300 kg.

Aft Skirt–The aft skirt is approximately 12.2 meters long and is constructed of 7075 aluminum. The skirt experiences maximum compressive loadings of 26,200 N/cm forward and 33,800 N/cm aft during the booster 3g condition. The smeared thickness of the skin-stringer panels is 0.71 cm forward and 0.81 cm aft. The aft skirt mass is 19,600 kg.

Thrust Structure—The thrust structure consists of an internal cone frustum with a cruciform beam system at its lower end. Ten thrust posts are incorporated into the lower section of the cone frustiom and four thrust posts are incorporated into the cruciform beam system. A combination 7075 aluminum/6AL-4V titanium structure is used. The structural elements are sized for the ignition condition using a dynamic magnification factor of 1.25. The average compressive loading in the upper section of the cone frustum is 12,900 N/cm and the average smeared thickness of the aluminum skin panel is 0.49 cm. The average cross section area of a titanium thrust post is 23 square centimeters. The thrust structure mass is 10,100 kg.

Aft Body Flap—The constant chord body flap provides the Orbiter with pitch trim control and thermally shields the main engines during entry. The flap is an aluminum structure with honeycomb skin panels. The flap mass is 640 kg.

Fairing Structures—Fairing structures consist of a forward wing-to-body fairing located in the transition region between the circular fuel tank and the "boxey" intertank, a wing-to-body fairing located under the lower half of the circular aft skirt, and a tail-to-body fairing. The fairings are aluminum structures with honeycomb skin panels. The total mass of the fairings is 3960 kg.

1.3.1.3.1.2 **Induced Environmental Protection**—The induced environmental protection sub system consists of (1) Reusable Surface Insulation (RSI) on the exterior surfaces of the wing, tail, and body, (2) a base heat shield incorporating RSI, (3) internal insulation for thermal control of pertinent components, and (4) purge, vent, and drain provisions. The masses of the foregoing are 44,800 kg, 1400 kg, 1100 kg, and 100 kg, respectively, yielding a total subsystem mass of 48,300 kg.

1.3.1.3.1.3 **Landing and Auxiliary Systems**—The subsystem consists of the landing gear and payload handling manipulator arms. The landing gear weight is estimated at 3.2% of design landing weight. Total subsystem mass is 15,800 kg.

1.3.1.3.1.4 **Ascent Propulsion**—The ascent propulsion subsystem consists of the main engines, accessories, gimbal provisions, and the fuel and oxidizer systems. Main propulsion is provided by fourteen (14) standard SSME's and the associated tank pressurization and propellant delivery systems. The following engine characteristics were used in the analysis:

Propellant	LO_2/LH_2
Chamber Pressure	20,700 kpa
Area Ratio	77.5:1
Mixture Ratio	6:1
Specific Impulse (Vac)	473 sec

The mass of the fourteen engines and associated accessories plus gimbal provisions (for ten engines) is 43,540 kg.

Pressurization gases are heated GO_2 for the LO_2 tank and heated GH_2 for the LH_2 tank. The dry mass of the tank pressurization and propellant delivery system is 17,260 kg.

1.3.1.3.1.5 OMS Propulsion—The orbital maneuver system consists of four (4) ASE engines and accessories, and associated tank pressurization and propellant delivery and storage elements. The following engine characteristics were used in the analysis:

Propellant	LO_2/LH_2
Chamber Pressure	13,800 kpa
Area Ratio	200:1/400:1
Mixture Ratio	6:1
Thrust (Vac)	89,000 N
Specific Impulse (Vac)	473 sec

The mass of the four engines and accessories is 770 kg.

Tank pressurization is provided by a high-pressure low-temperature hellium gas system. The dry mass of the tank pressurization and propellant delivery and storage elements is 4830 kg.

1.3.1.3.1.6 Other Systems--The remaining subsystem masses have been estimated using historical or Shuttle predicted weights. These subsystems include RCS propulsion, prime power, electrical conversion and distribution, hydraulic conversion and distribution, aerosurfaces controls, avionics, environmental control, personnel provisions, personnel, and payload accommodations.

RCS Propulsion—The reaction control system provides for stage orientation on-orbit and prior to entry, and for control during entry. The subsystem dry mass is 3900 kg.

Prime Power—Major power sources consist of an O_2/H_2 powered fuel cell subsystem to provide electrical power, and a hydrazine powered APU subsystem to provide hydraulic power. The dry mass of the prime power subsystem is 2500 kg.

Electrical Conversion and Distribution—The power conversion, conditioning and cabling elements are included in this category. The subsystem mass is 4800 kg.

Hydraulic Conversion and Distribution—All stage functions requiring hydraulic power are serviced by the hydraulic conversion and distribution subsystem. The hydraulic power for rocket engine thrust vector control and valve actuation is included in this category. The subsystem mass is 3600 kg.

Surface Controls The actuation systems for the aerodynamic control surfaces are included in this category, as are the cockpit controls. The subsystem mass is 6800 kg.

Avionics–The avionics subsystem includes elements for guidance, navigation and control, communications and tracking, displays and controls, instrumentation, and data processing and software. The subsystem mass is 2400 kg.

Environmental Control–The environmental control subsystem maintains a habitable environment for the crew and passengers, and a conditioned thermal environment for the avionics. It provides the basic life support functions for the crew and passengers, and thermal control for several subsystems. It also provides for air lock pressurization. The subsystem mass including closed loop fluids, is 2400 kg.

Personnel Provisions–The fixed life support system and personnel accommodations for the 4-man flight crew are included in this category. The subsystem mass is 500 kg.

Personnel–The 4-man flight crew and their gear and accessories are included in this category. (The 6-man passenger group and their gear, accessories, and baggage are considered part of the payload.) The subsystem mass is 1200 kg.

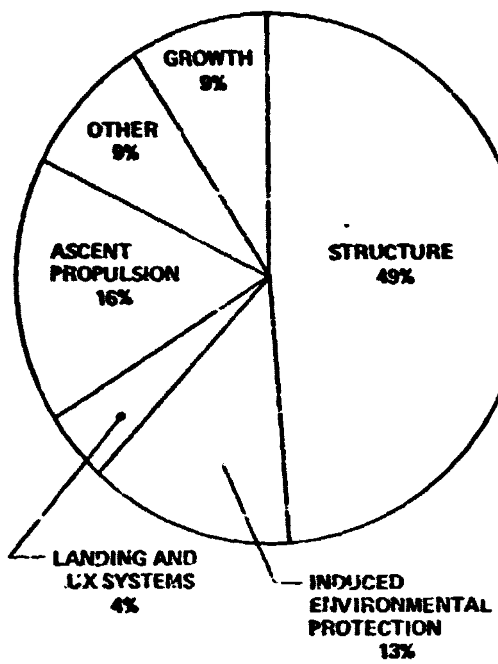
Payload Accommodations–Removable payload support equipment is included in this category. The mass allowance is 2900 kg.

1.3.1.3.2 Orbiter Mass Characteristics

The orbiter mass characteristics are shown in Table 1.3.1-5. Structure accounts for approximately 50% of the stage dry mass. The ascent propulsion and thermal protection subsystems are an additional 29% of the dry mass. The dry mass is 86% of the inert mass with the remainder including residuals and reserves, personnel and payload accommodations, and inflight losses.

SP6-1966

Table 1.3.1-5 Orbiter Mass Statement



DRY MASS BREAKDOWN

	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
ECLSS AND PERSONNEL PROV	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	38 900
INERT MASS =	435 100

1.3.1.4 Launch Vehicle Costs

Costs are presented in 1977 dollars. During Phase 2, costs will be updated to 1979 dollars.

1.3.1.4.1 DDT&E Costs

The DDT&E cost for the flight hardware and its associated ground support equipment is shown in Figure 1.3.1-2 for both the booster and orbiter stages. The total development cost for both stages is $11.2B. Systems test, which includes all the ground and flight test hardware in addition to the test labor, accounts for in excess of 50% of the total development cost. The booster DDT&E cost includes a new rocket engine and airbreather engine development. The orbiter DDT&E reflects use of the Space Shuttle's SSME's and some of the other subsystems which were modified rather than new developments. All costs quoted are in 1977 dollars.

Since "System Test" is such a large portion of the DDT&E cost a further detail breakdown is shown in Table 1.3.1-6 for both the booster and orbiter:

The "Systems Test Labor" entry includes the labor for both ground and flight test. A five (5) flight development test program is planned for the vehicle. The labor includes all the effort to modify equipment, build test fixtures, install instrumentation and to conduct the test program. Approximately 25% of the systems test labor entry is attributable to the flight test portion and the remainder is associated with the ground test activity.

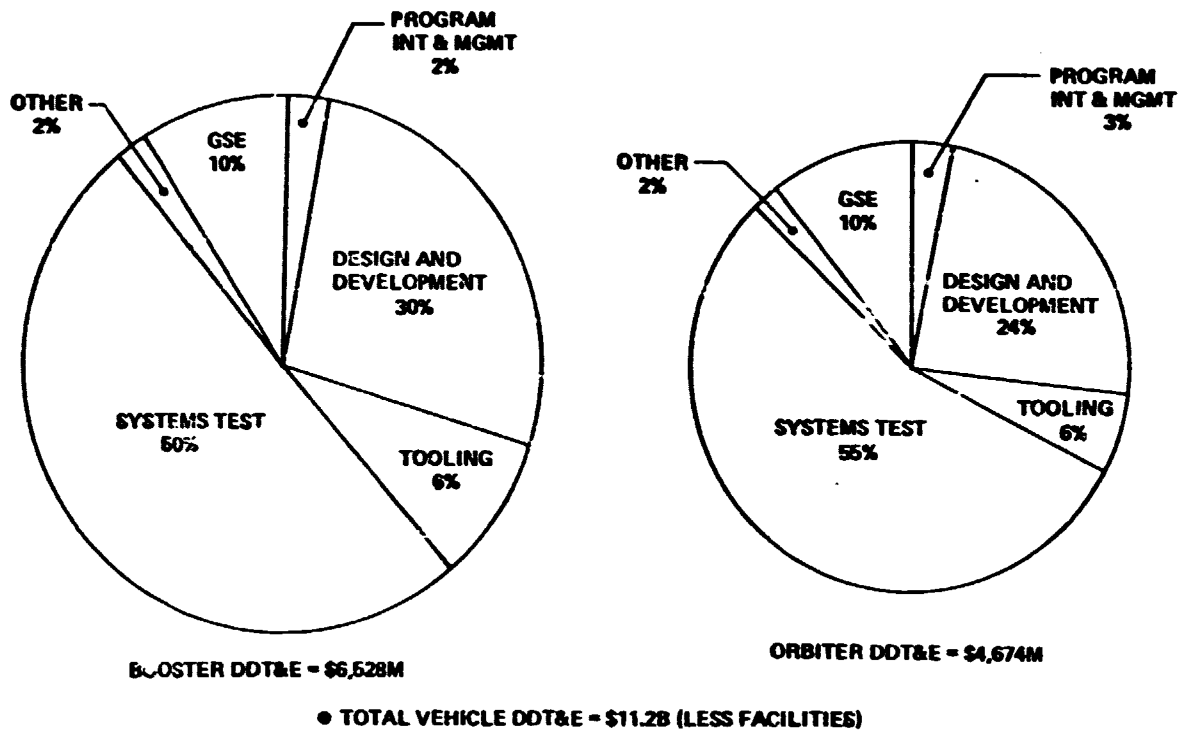


Figure 1.4.1-2 SPS Vehicle DDT&E Cost

Table 1.3.1-6 SPS Vehicle Systems Test Cost Breakdown

	BOOSTER		ORBITER	
SYSTEM TEST LABOR	$767M		$626M	
GROUND TEST HARDWARE	$1620M		$1236M	
STRUCTURAL TEST ARTICLE		($170M)		($104M)
PROPULSION TEST ARTICLE		($725M)		($566M)
DYNAMIC TEST ARTICLE		($725M)		($566M)
FLIGHT TEST HARDWARE*	$907M		$708M	
TOTAL	$3294M		$2570M	

*INCLUDES REFURBISHMENT OF DYNAMIC TEST ARTICLE INTO A FLIGHT TEST UNIT.

1.3.1.4.2 Production Cost

The initial unit production cost for both the SPS cargo vehicle booster and orbiter is shown in Figure 1.3.1-3. The theoretical first unit cost (TFU) for the booster of $821.4M and $638.5M for the orbiter were developed using the Boeing Parametric Cost Model (PCM). The following is a breakdown of the TFU cost by major subsystem:

Subsystem	Booster	Orbiter
Structure	21%	16%
TPS	N/A	10%
Main Propulsion	24%	28%
Landing and Aux. Sys.	13%	9%
Flyback Propulsion	11%	N/A
Other Subsystems	19%	26%

The ground support equipment TFU cost is estimated to be $162.8M and $126.0M for the booster and orbiter respectively.

1.3.1.4.3 Average Cost/Flight (1 Satellite/Year)

The cost/flight breakdown shown in Figure 1.3.1-4 is the average for the 400 per year launch rate and 14 years of operation. The cost/flight items follow the Shuttle User Charge Policy guidelines with the following additions.

1. Amortization of the fleet production costs
2. Inclusion of the rate tooling cost due to the hardware quantities required.

The following assumptions and criteria regarding refurbishment and replenishment spares was used to develop the average cost per flight for the vehicle:

State Element	Design Life	Refurbishment	Replenishment
Airframe	300 flights	Each 100 flights @ 30% of production cost	0.18% per flight
Rocket Engines	Indefinite	Each 50 flights @ 30% of production cost	0.50% per flight

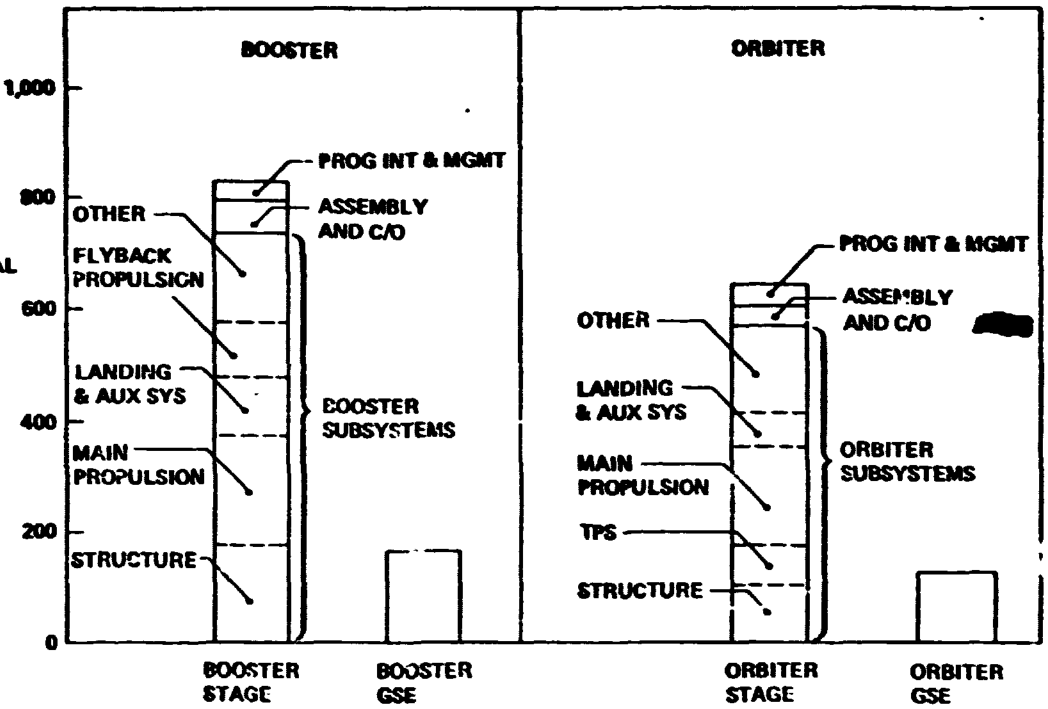
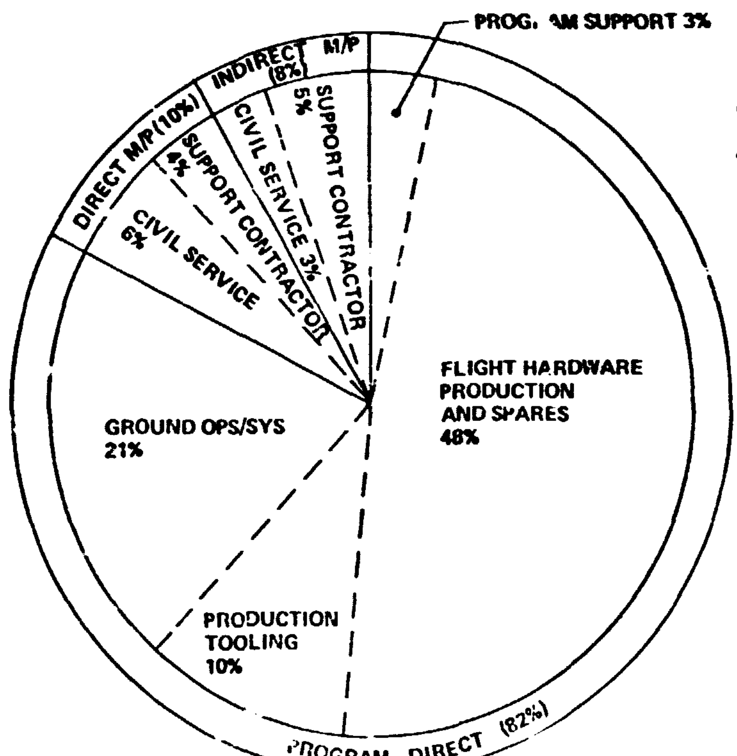


Figure 1.3.1-3 SPS Launch Vehicle Production Cost



- TWO-STAGE WINGED VEHICLE
- PLACEMENT OF 1 SATELLITE PER YEAR (400 FLIGHTS)
- 14 YEAR PROGRAM
- NO ATTRITION

AVERAGE COST/FLIGHT = $13.447M

Figure 1.3.1-4 SPS Launch Vehicle Average Cost/Flight (One Satellite/Year)

The effect of design life and attrition rate variations are shown in Figure 1.3.1-5. Based on these trends the recommended goals for design life and attrition rate are 500 flights and 0.1% respectively.

Flight Hardware production and spares is the largest single item with the booster and orbiter accounting for 55% and 45%, respectively. Propellant cost amounts to 12% of the total per flight cost.

1.3.1.4.4 Effect of Launch Rate on Cost/Flight

Figure 1.3.1-6 illustrates the effect of launch rate on the average cost/flight and the transport cost to low Earth orbit for the SPS cargo vehicle. The required launch rate of approximately 500 flights per satellite results in the following:

Annual Launch Rate	Cost/Flight	Transport Cost	
		$/kg	($/lbm)
400 Flights	$13.447M	31.71	(14.38)
1600 Flights	$10.754M	25.36	(11.50)

A 40 launch per year rate, comparable to the planned rate for Shuttle from KSC, would result in an average cost of $23M per flight for the SPS cargo launch vehicle. Also noted on the chart, are the NASA/JSC in-house cost estimates as of January 1978.

1.3.1.5 Vehicle Operations

The 2-stage winged vehicle operations plan includes prelaunch, launch, and recovery activities associated with the SPS launch vehicle. The launch site operations plan includes:

1. Both vehicles landing at the launch site.
2. Stage maintenance and checkout in dedicated facilities for both the booster and orbiter.
3. Mating, vehicle integration, and fueling at the launch pad.

A horizontal mating operation is planned on the launcher where the two stages will be joined and then rotated to the vertical. This concept is depicted in Figure 1.3.1-7. The upper portion of the launcher/erector is rotated away from the vehicle after the vehicle is in the vertical position to provide clearance for launch.

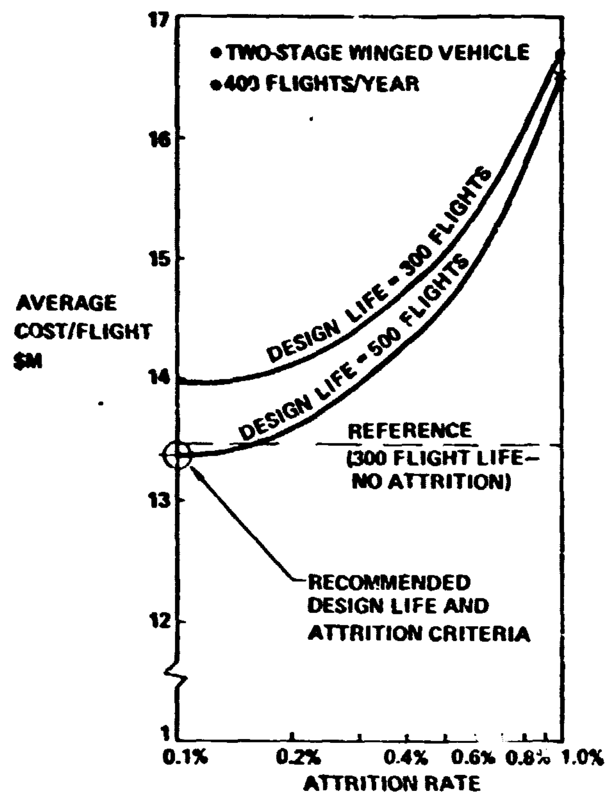


Figure 1.3.1-5 Effect of Design Life and Attrition Rate

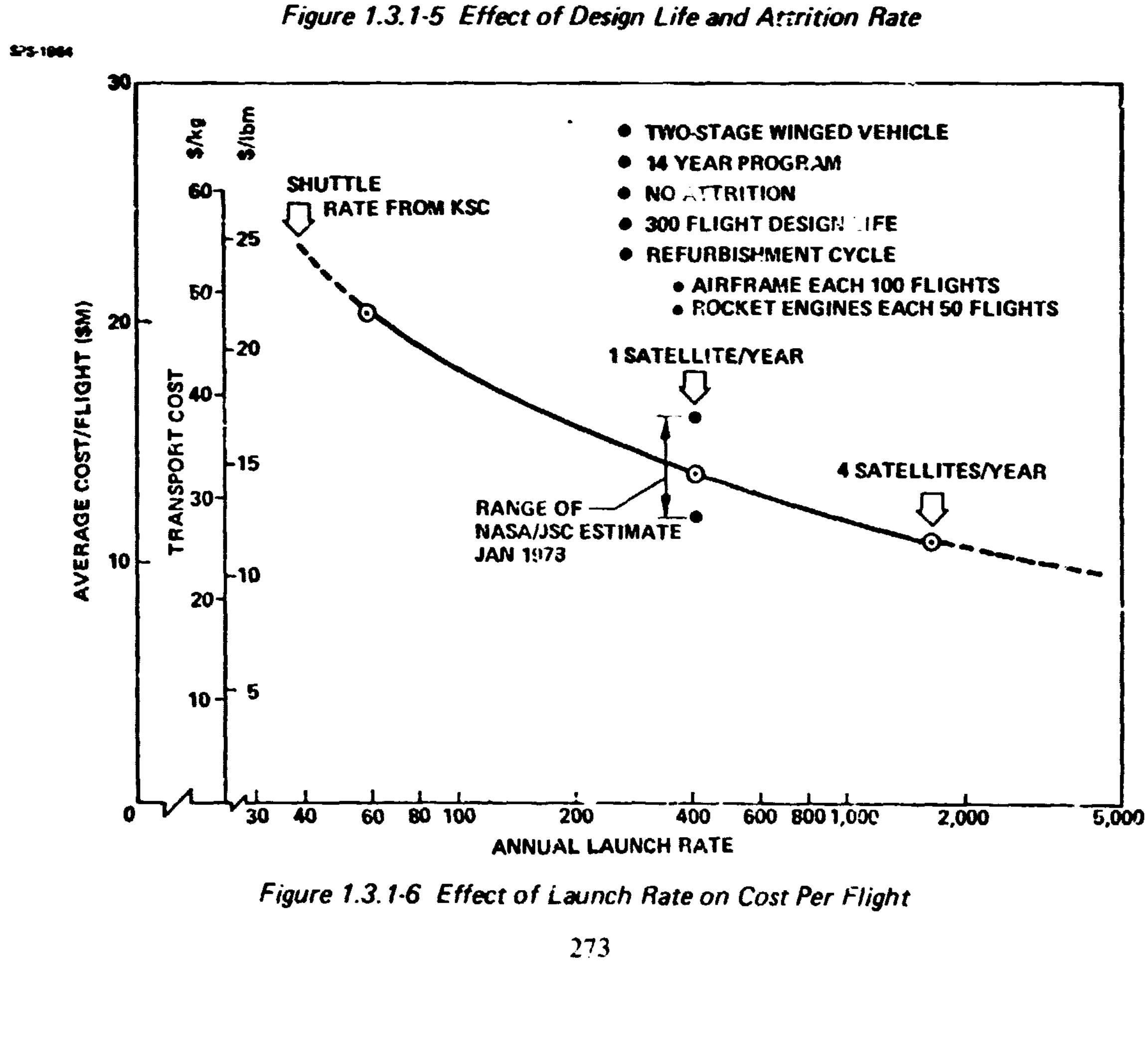


Figure 1.3.1-6 Effect of Launch Rate on Cost Per Flight

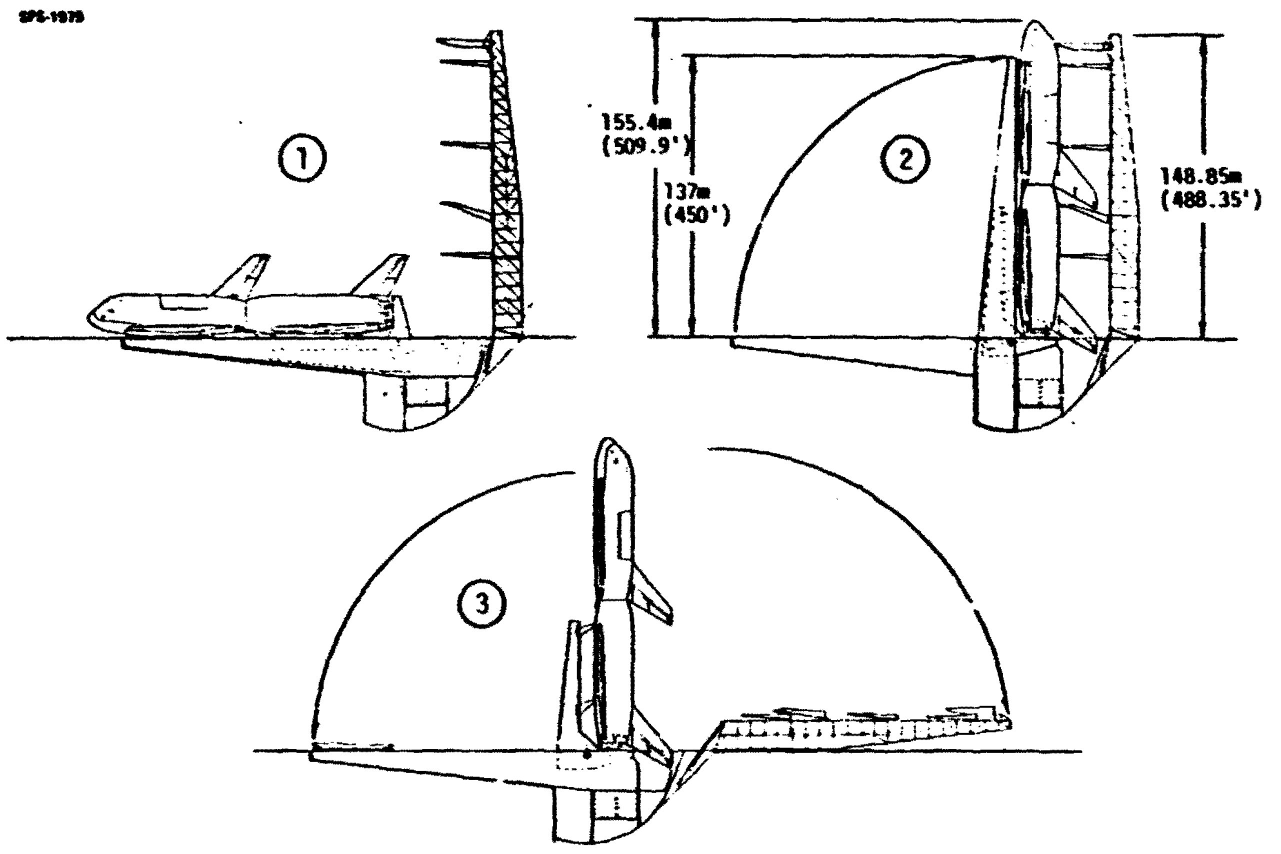


Figure 1.3.1-7 Launcher/Erector Concept

Booster Timelines

The booster timeline from launch to its move in the integration position is shown in Figure 1.3.1-8. The timelines reflect the average timelines for the operational launch vehicle system. A total of 62 hours is estimated for this portion of the turnaround with the scheduled and unscheduled maintenance activity requiring 36 hours. On-board condition monitoring equipment will enhance the operations by:

1. Providing performance monitoring of the stage subsystems.
2. Aiding in fault isolation and detection.

Rocket engine maintenance is anticipated to be the major portion of the booster operations.

Orbiter Timelines

The orbiter timeline from launch to its move to the integration position is shown on Figure 1.3.1-9. A total time of 97 hours for orbiter processing including 24 hour on-orbit staytime is estimated. The maintenance portion of the activity is estimated to require 48 hours due to the thermal protection system and the additional systems/equipment required for the manned stage. A total of 12 hours has been allocated for payload installation in a parallel operation with the orbiter maintenance.

Integrated Vehicle Timelines

The vehicle integrated operations timeline is shown on Figure 1.3.1-10. These activities are at the launch site and reflect all the operations from vehicle mating through launch. This portion of the launch operations requires 34 hours for the booster and 30 hours for the orbiter. The total turnaround times for the booster and orbiter are summarized in Table 1.3.1-7. Also shown on the table for reference is the anticipated turnaround times for the 2-stage ballistic recoverable concept studied earlier. The 2-stage winged vehicle results in turnaround times which are less than those for the ballistic vehicle.

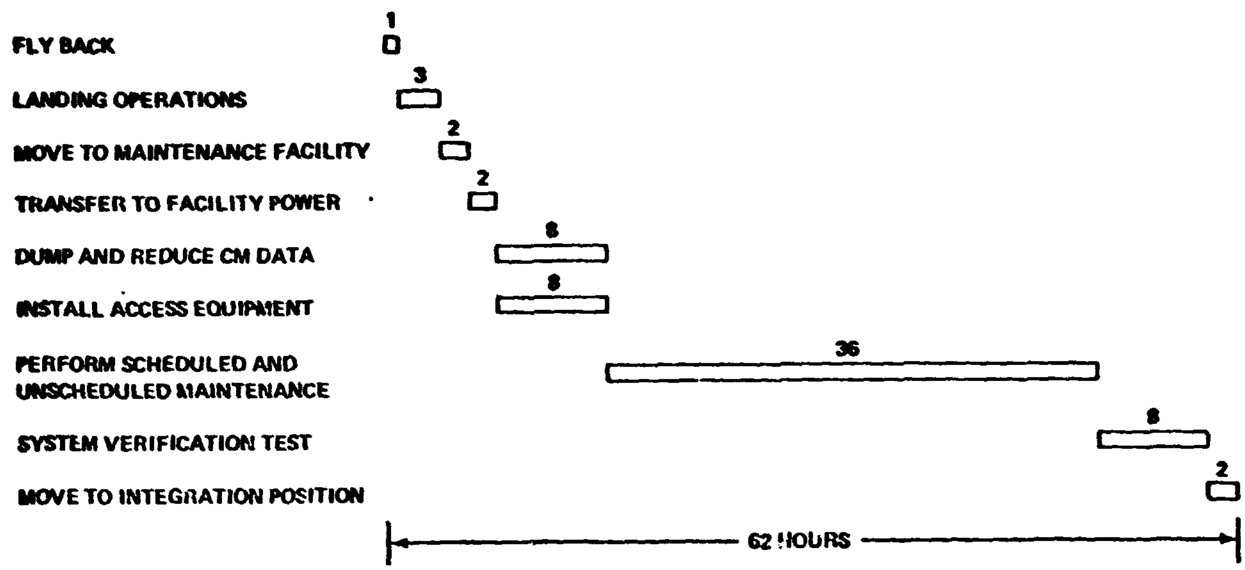


Figure 1.3.1-8 Booster Processing Timelines

SPS-1980

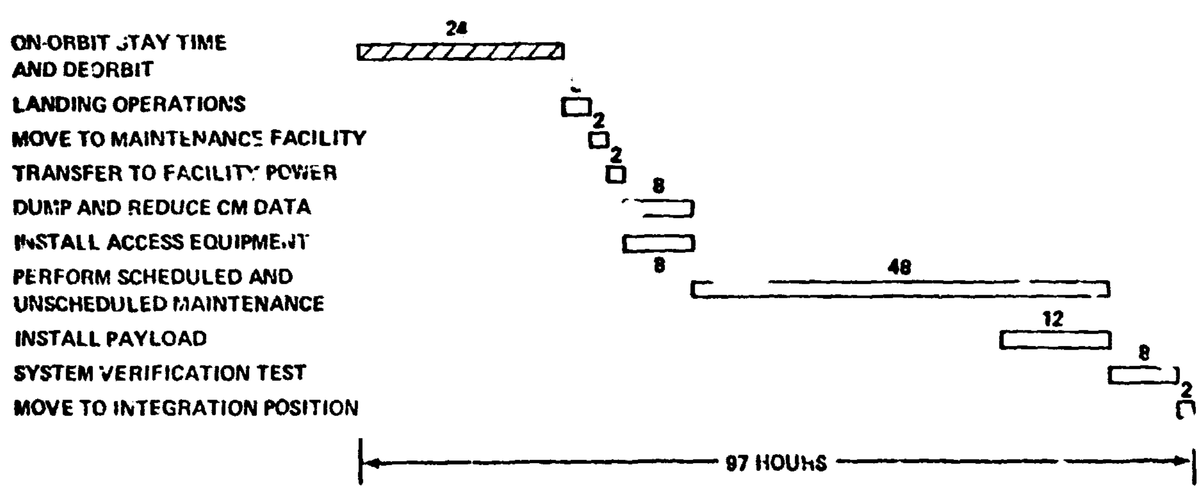


Figure 1.3.1-9 Orbiter Processing Timelines

SPS-1962

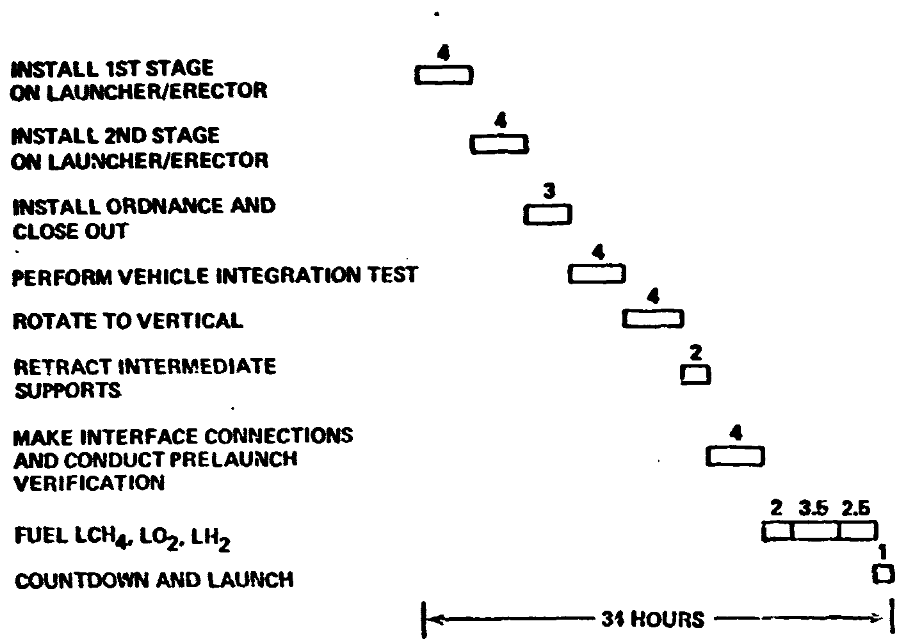


Figure 1.3.1-10 Integrated Vehicle Operations Timelines

SPS-1957

Table 1.3.1-7 Vehicle Turnaround Analysis Summary

VEHICLE CONCEPT	STAGE OPS ONLY	INTEGRATION AND LAUNCH OPS	TOTAL TURNAROUND
WING/WING			
BOOSTER	63 HOURS	34 HOURS	97 HOURS
ORBITER	97 HOURS	30 HOURS	127 HOURS
BALLISTIC/BALLISTIC			
BOOSTER	93 HOURS	34 HOURS	127 HOURS
UPPER STAGE	102 HOURS	30 HOURS	132 HOURS

WBS 1.3.2 Cargo Orbit Transfer Vehicle

The cargo Orbit Transfer Vehicle is used to transport satellite components from the LEO staging depot to the GEO construction base. This vehicle uses electric propulsion and is hereafter referred to as the electric orbit transfer vehicle (EOTV). A total of 23 vehicles are required for construction of two 5 GWE satellites in one year.

Selected Configuration

The selected EOTV configuration for cargo transportation is shown in Figures 1.3.2-1 and 1.3.2-2 and consists of four solar array bays, with each bay formed by a pentahedron. The apexes of the pentahedrons are tied together to serve as a mounting location for the payload and propellant tanks. This location provides a good moment of inertia balance to minimize gravity gradient torque control requirements and simplifies the docking of the payloads as well as propellant tankers. Thruster modules are attached to beams protruding from the four corners of the configuration. Power for the thrusters is drawn from solar arrays in the bay adjacent to the thruster module. The vehicle is sized to deliver 4000 metric tons and return 200 metric tons with an uptrip time of 180 days and down time of 40 days, with a specific impulse of 8,000 seconds. The total dry mass of the vehicle is 1462 metric tons while the total propellant loading is approximately 500 metric tons. The 1510 m dimension of the configuration reflects the change in power requirements that occurred after the Phase I midterm. The 1044 m dimension is the same as that used at the midterm and is a function cell size and voltage requirements.

1.3.2.1 Power Generation System

In terms of power generation and distribution systems, the EOTV is divided into four separate bays with each bay providing power to a thruster module as shown in Figure 1.3.2-3. Each bay is divided into fifty-four 14.5 meter segments and produces approximately 74 megawatts. The optimum voltage was found to be 2685 volts as shown in Figure 1.3.2-4. Each segment consists of 20 strings, with each string in turn consisting of 498 panels. Each of the panels include (140) 5 x 10 centimeter cells. The cell shape change is the result of compromise between a desired square satellite shape and the power and voltage requirements dictated by the propulsion system.

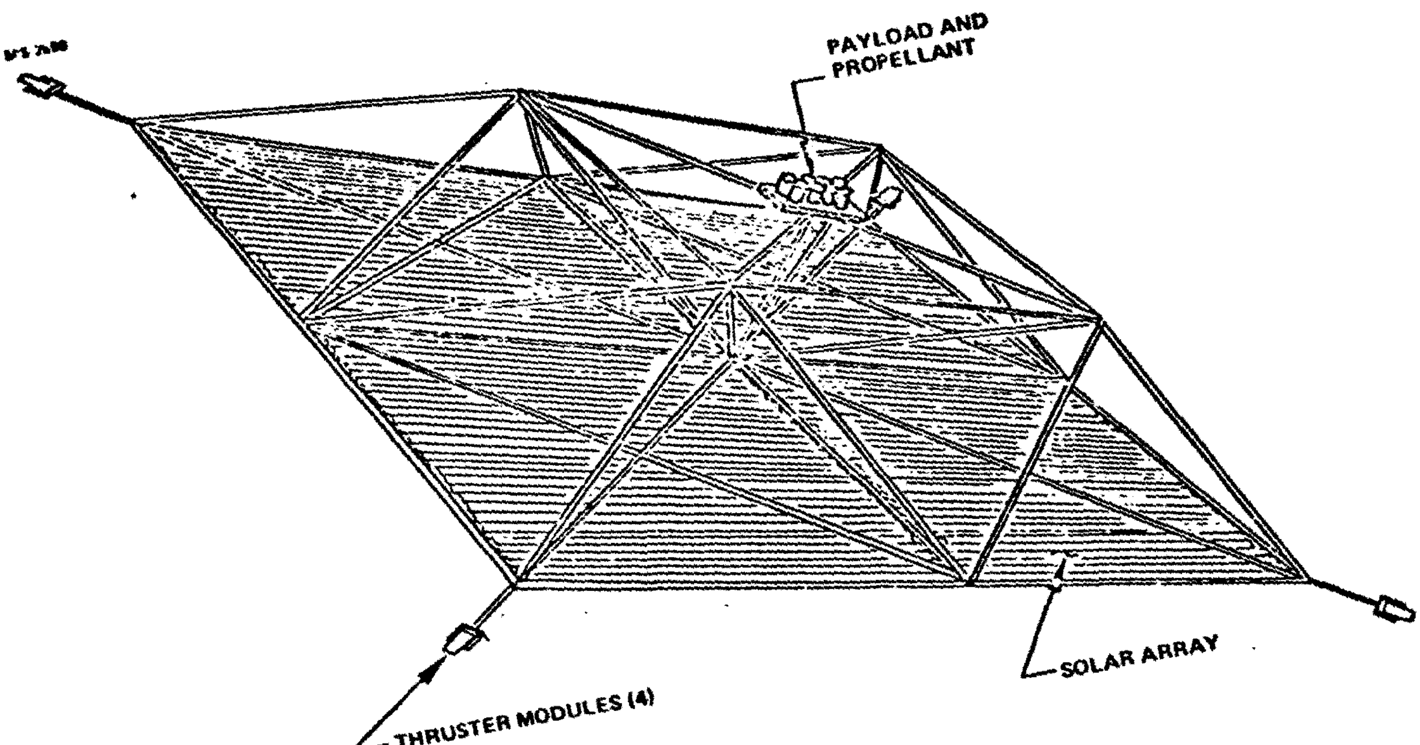


Figure 1.3.2-1 EOTV Configuration Concept

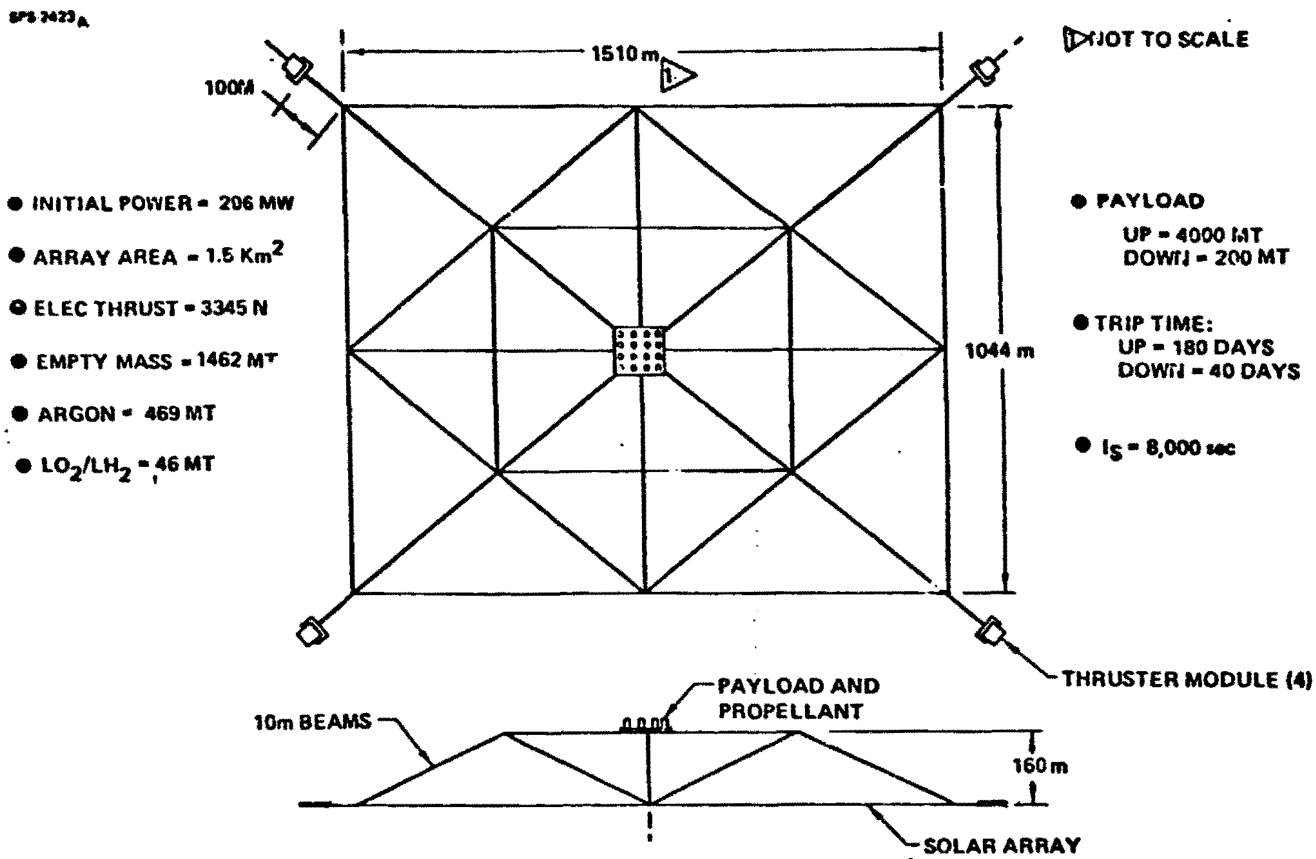


Figure 1.3.2-2 Electric OTV Configuration

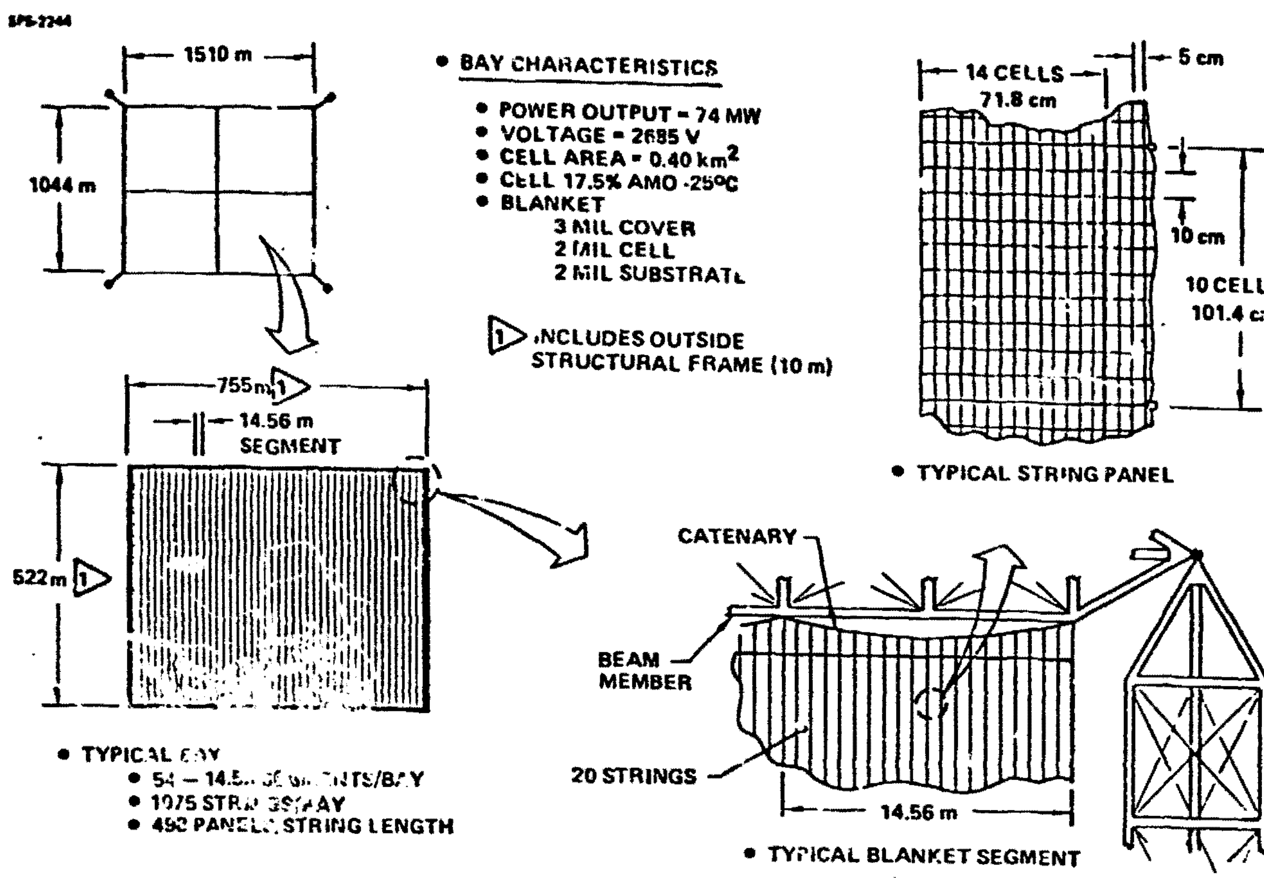


Figure 1.3.2-3 EOTV Power Generation System

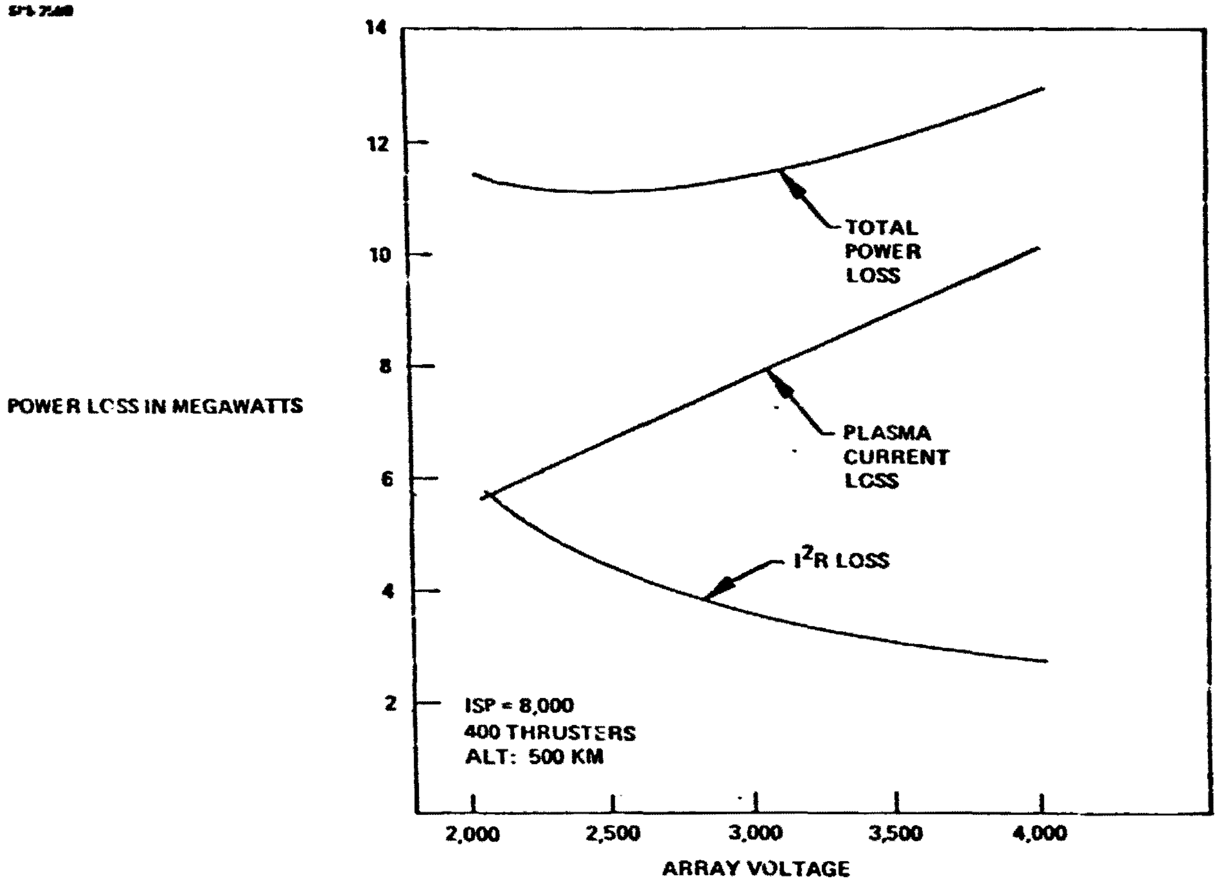


Figure 1.3.2-4 Optimum Array Voltage

1.3.2.2 Power Collection and Distribution

Power busses are located on three sides of each bay of the EOTV as illustrated in Figure 1.3.2-5. Each bay is divided into 7 sectors in order to minimize the impact on the switch gear complexity should a fault occur. Five sectors each collect power from 8 segments while two sectors collect power from 7 segments. A bus from each sector runs to the associated thruster module where the power is processed. Each of the busses is one milimeter thick by 80 centimeters deep. The optimum bus temperature was found to be 50°C as shown in Figure 1.3.2-6.

1.3.2.3 Electric Propulsion System

Electric propulsion modules are located at four corners of the EOTV. The key characteristics of each module are shown in Figure 1.3.2-7. Each module consists of a gimbal, yoke, thruster panel containing thrusters and power processing units and a thermal control system. For the reference design, 289 thrusters are used at each of the four corners. The principal components of the 1..2m diameter ion thruster and performance characteristics associated with a specific impulse of 8000 sec are shown respectively in Figure 1.3.2-8 and Table 1.3.2-1.

Several methods were considered for supplying power to the thrusters. One of these options involves obtaining power directly from the arrays with no processing or no regulation. The chief disadvantage in this option is that the voltage is decreasing at the same time the power is degrading. As the flight proceeds, the lower voltage will result in a loss of approximately 1,000 seconds of specific impulse. A second option regulates and sectionalizes the array so that as additional power is required, additional sectors can be switched into operation. The main disadvantage of this concept is the extremely complicated switch gear system. The final power supply method considered involves processing all the power. The array voltage generated in this concept is the optimum voltage from the standpoint of I^2R and plasma losses. The resulting voltage is 2685V as compared to 1700V required by the thrusters. A complete comparison was not done on these concepts, however, the all-processing method appears to be the most straightforward and since some of the power needs to be processed anyhow this method was selected for the reference. The type of processing equipment selected was solid state due to its longer MTBF. Thermal control of the processing equipment is required and is accomplished using an active radiator.

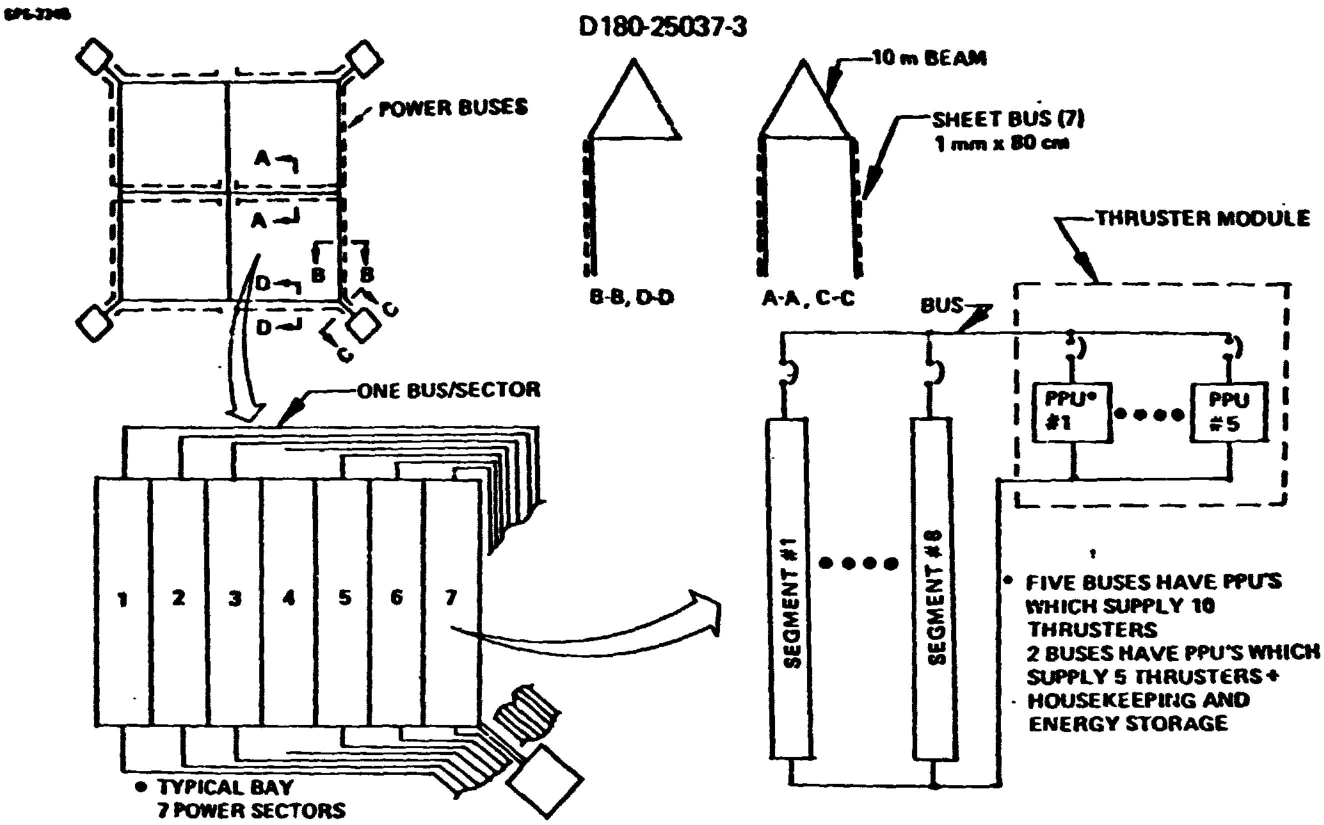


Figure 1.3.2-5 Power Collection and Distribution

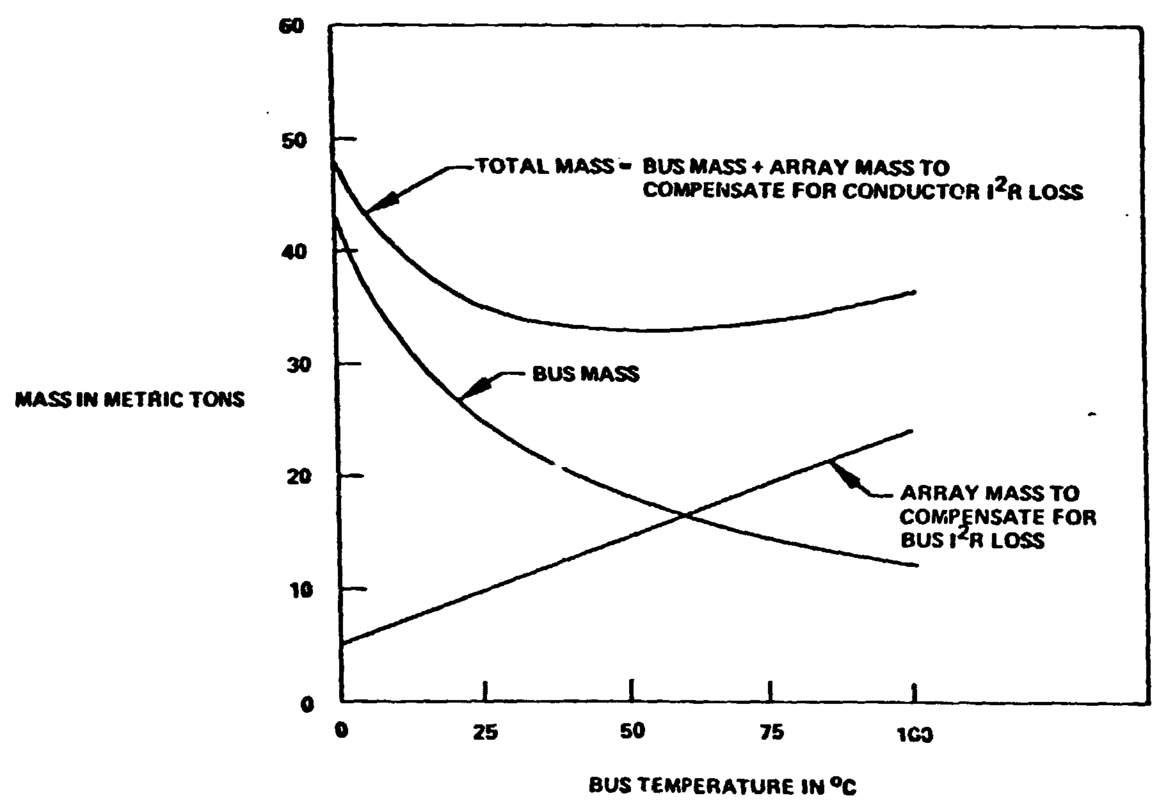
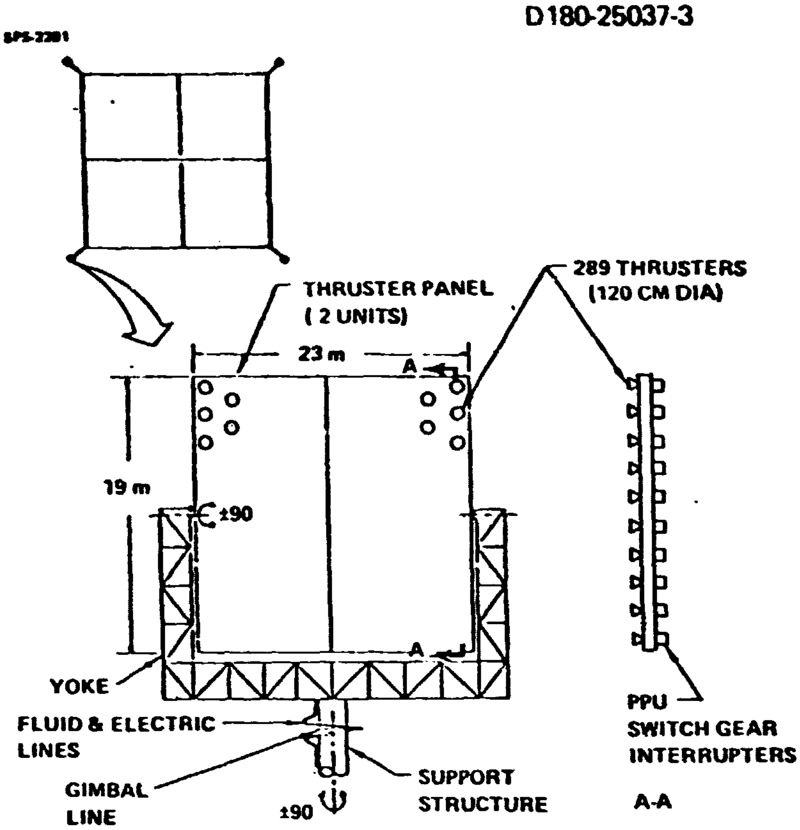


Figure 1.3.2-6 Optimum Power Bus Temperature



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

Figure 1.3.3-7 Electric Propulsion System

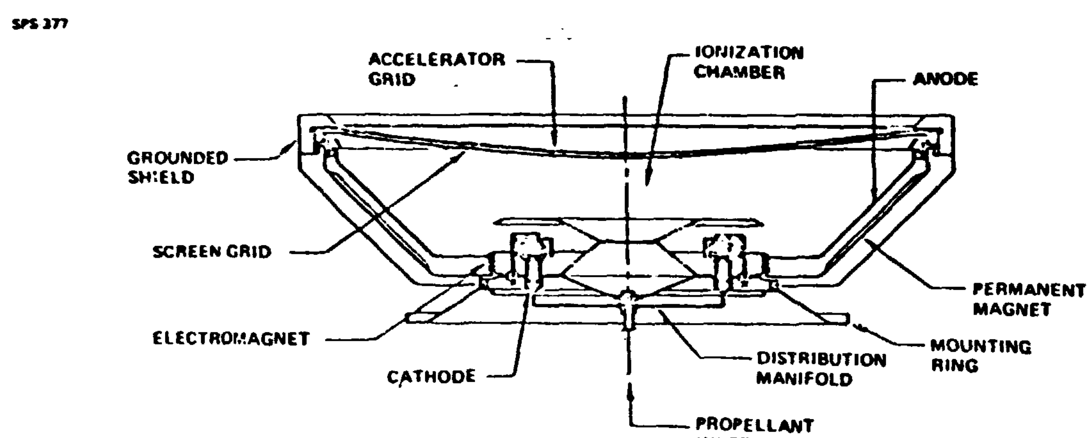


Figure 1.3.3-8 120 CM Argon Ion Thruster

Table 1.3.2-1 Selected 1.2 M Argon Ion Thruster Characteristics

SPS-2608

FIXED CHARACTERISTICS	
BEAM CURRENT:	80.0 AMPS.
ACCEL. VOLTAGE:	500.0 V.
DISCHARGE VOLTAGE:	30.0 V. (FLOATING)
COUPLING VOLTAGE:	11.0 V.
DBL. ION RATES:	0.16 (J2/J1)
NEUTRAL EFFLUX:	4.8384 AMP. EQUIV.
DIVERGENCE:	0.98
DISCHARGE LOSS:	187.3 EV/ION
OTHER LOSS:	1758.0 W.
UTILIZATION:	0.892 W.
LIFE:	8000 HR.
*WEIGHT:	50. KG.
SELECTED CHARACTERISTICS	
SCREEN (BEAM) VOLTAGE:	1700 V.
INPUT POWER:	130 KW
THRUST:	2.9 N
EFFICIENCY:	78

*WEIGHT PREDICTION COURTESY OF T. MASEK OF HRL.

1.3.2.5 Mass Summary

The mass characteristics of the EOTV are summarized in Figure 1.3.2-9. The empty mass for the configuration is shown for both mid-term and final values. The most significant change was that associated with the solar array mass, which increased as a result of using a more accurate model reflecting the power requirements for I^2R losses, storage provisions, changing power conditioning efficiencies as a result of using solid state equipment rather than motor generator equipment and also a revision in the radiation degradation analysis. These changes to the solar array, in turn, have reflected or resulted in changes in all other elements of the vehicle resulting in approximately a 300 metric ton increase over the mid-term values. Accordingly, the startburn mass also reflects a 300 metric ton increase over the mid-term value.

1.3.2.6 EOTV Cost

A preliminary cost for the EOTV was established at the mid-term of Phase I. It was indicated at that time that the estimate was probably optimistic. The guidelines used to establish more accurate EOTV costs than that shown at the mid-term are indicated in Table 1.3.2-2. The fleet size and amortization period are the same as was used for mid-term. The chief difference in costing, however, deals with the method in which the costing was done. At the mid-term, a scaling relationship was used where the power generation and distribution system cost was scaled to similar systems of the satellite and the electric propulsion system cost for the EOTV was scaled to costs associated with the selfpower orbit transfer systems. As such, this scaling method presented an optimistic cost primarily because of using a component production rate much higher than that possible when amortizing the hardware over a number of years. The final costing of the EOTV, included establishing detailed first unit costs using component mass and quantities directly associated with a single EOTV. These TFU costs were then used in conjunction with the annual production rate of the components for the entire EOTV fleet to establish the average cost of an EOTV.

As indicated earlier, amortizing or spreading out the total hardware requirements over the operating life of the system greatly influences the unit cost of the EOTV and subsequently the cost per flight. A comparison of the annual production rate for some of the EOTV and self-power components is presented in Table 1.3.2-3. In the case of the GEO construction concept, the total components for the 23 vehicles has been spread out equally over 7 years of its operating life with an additional 20%

SPS 2495

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

• STARTBURN MASS (M.T.)	
PAYLOAD	4000
EMPTY	1462
PROPELLANT	
ARGON	469
LO_2LH_2	46
	5977

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

Figure 1.3.2-9 EOTV Mass Summary

Table 1.3.2-2 EOTV Costing Guidelines

SPS-2482

	MIDTERM	FINAL
• FLEET SIZE	23	23
• AMORTIZATION PERIOD (YR)	7	7
• FLIGHT UNIT COST	SCALING	DETAILED MODELING • DETAIL TFU MASS & QUANTITY • AVG. TO REFLECT COMPONENT ANNUAL PRODUCTION RATE
• POWER GEN & DISTRIB	SCALE TO SATELLITE ($95/KG)	
ARRAY CONTRIB	$44/M^2	$53/M^2 DUE TO 5 X 10 CM CELL
• ELECTRIC PROPULSION	SCALE TO SELF POWER OTS ($117/KG)	
• PROGRAMMATIC	NOT CONSIDERED	CONSIDER

Table 1.3.2-3 Component Annual Production Rate

SPS-2481

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

added to the annual requirement to cover manufacturing problems, etc. As indicated, nearly all components for the GEO/EOTV case reflect a significant decrease in the annual production rate, which will eventually reflect in the average unit cost of the EOTV's.

The final Phase I EOTV hardware and cost per flight numbers are presented in Table 1.3.2-4. In the case of the hardware costs, both mid-term and final costs are presented. The final flight unit costs have almost doubled from that of the mid-term, reflecting the influence of the more detailed cost analysis. The output from the detailed cost analysis is presented in Table 1.3.2-5. The power generation and distribution system has not increased as much as electric propulsion system primarily because the solar array, which is the largest contributor, was and still is being costed on mature industry basis with the increase over preceding mid-term values primarily the result of the 20% penalty paid for using the 5 x 10 centimeter cell and also the 21% cost growth factor. Electric propulsion costs, are greater by almost a factor of 3 and reflect a significant difference in the cost for individual elements as a result of lower production rate. As indicated earlier, programmatic costs were not indicated in the mid-term. On a cost per flight basis, including amortization of the capital, the change from the mid-term has been approximately $30 million per flight.

Figure 1.3.2-10 presents a mass and cost summary.

1.3.2.7 Mission Operations

1.3.2.7.1 Key Mission Events

Mission events that occur whle using an EOTV for GEO construction are indicated in Table 1.3.2-6. A total of 16 days of on-orbit time has been indicated for the turnaround of the vehicle, in addition to the 219 days of time required for the up and down transfers.

Once the vehicle reaches GEO, it will be placed in a standby condition approximately 1 kilometer from the base. At that time small LO_2/LH_2 tug(s) will be used to move the cargo from the EOTV to the GEO construction base. Annealing of the solar arrays will occur at GEO and will be discussed in more detail in a subsequent chart. Once the vehicle has returned to low earth orbit, it will again be placed in a stationkeeping standby condition approximately 1 kilometer from the LEO base. Again, small tugs

Table 1.3.2-4 Silicon EOTV Cost

• COST IN MILLIONS

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

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

Table 1.3.2-5 Detailed EOTV Cost Results

CWI/WBS NO.	WBS ITEM TITLE	MASS PER SYSTEM	PRODUCT UNITS/YR	COST BASIS	FLOOR $/LB	VALUE $/LB	ELEMENT LEVEL 12345678911111 01234	COST PER ELEMENT (000)	COST PER SYSTEM (000)	COST PER YEAR (000)
1	TOTALS	1.55E+07	4	SUM	0	N/A	*	256,692	256,692	1,026,766
2	PROG INTEG & MGMT	N/A	0	G RULE	0	N/A	*	12,223	12,223	48,893
3	INITIAL SPARES	N/A	0	G RULE	0	N/A	*	4,485	4,485	17,942
4	ASSEMBLY & C/O	N/A	0	G RULE	0	N/A	*	11,214	11,214	44,856
5	PACKAGING	N/A	0	G RULE	0	N/A	*	4,485	4,485	17,942
5	IEOTV FLIGHT HDWE	1.55E+07	4	SUM	0	N/A	*	224,283	224.283	897,131
17	THRUSTER SUBPANEL	101129	32	SUM	0	N/A	*	13,180	105,444	421,776
18	PANEL STRUCT	1540	32	AVG UNIT	120	140	*	215	1,721	6,887
19	THRUSTERS	110	5600	FLOOR	100	100	*	10	15,399	61,599
20	PROCESSORS	2950	640	PROD RAT	50	107	*	316	50,658	202,634
21	SWITCHGEAR	120	640	PROD RAT	50	323	*	38	6,198	24,795
22	INTERRUPTERS	25	17504	PROD RAT	50	76	*	1	8,307	33,228
23	CABLING	3564	32	AVG UNIT	50	684	*	2,438	19,504	78,018
24	INSTRUMENTATION	200	32	AVG UNIT	100	1627	*	325	2,602	10,411
25	PROP SYSTEM	1500	32	AVG UNIT	50	88	*	131	1,050	4,201
26	THRUSTER YOKE	3660	16	AVG UNIT	100	143	*	524	2,097	8,390
27	GIMBAL ASSY	1540	16	AVG UNIT	100	916	*	1,411	5,644	22,578
28	COMPUTER	100	16	AVG UNIT	1000	9633	*	963	3,853	15,412
29	COMMUNICATIONS	100	16	AVG UNIT	1000	6760	*	676	2,704	10,816
30	STANDOFF STRUC	3330	16	AVG UNIT	100	145	*	484	1.936	7.746
31	ARGON TANKS	10300	8	AVG UNIT	100	95	*	980	1.961	7,844
32	LO2 TANKS	2640	4	AVG UNIT	100	135	*	356	356	1,426
33	LH2 TANKS	440	4	AVG UNIT	100	175	*	77	77	308
34	TANK INSUL	2200	16	AVG UNIT	25	19	*	41	164	656
35	PROP FEED SYS	5500	16	AVG UNIT	100	68	*	376	1,505	6,021
36	TCS/RADIATORS	4400	80	AVG UNIT	100	251	*	1,105	22,117	88,468
37	POWER DISTR	5900	112	FLOOR	10	10	*	58	1,651	6,607
38	ENERGY STOR	1000	256	FLOOR	100	100	*	99	6,399	25,599
39	SOLAR BLANKETS	83655	672	SUM	0	N/A	*	334	56,216	224,864
40	ARRAY PANELS	11	5110560	FLOOR	4	4	*	0	56,216	224,864
41	ARRAY STRUC	6544	128	PROD RAT	50	58	*	379	12,153	48,615

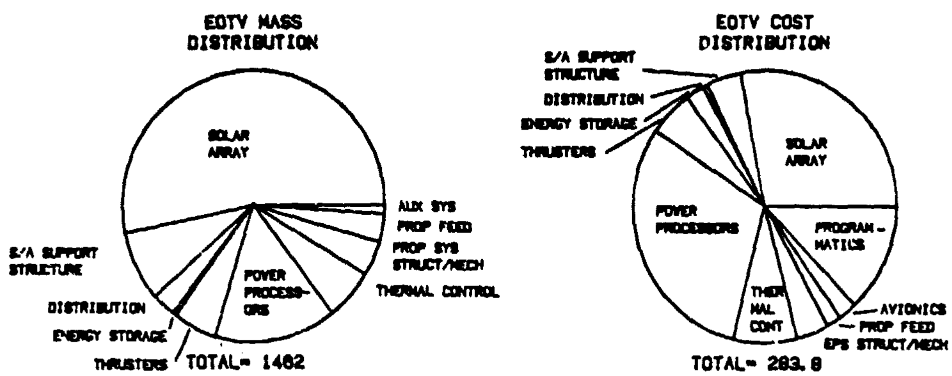


Figure 1.3.2-10 EOTV Mass & Cost Summary

Table 1.3.2-6 Mission Events

SPS-2232

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

will fly out from the LEO base to the EOTV to perform refurbishment operations on the thrusters, unload and load cargo propellant and deliver propellant. The propellant resupply will be done by tankers rather than removal of the propellant tanks.

WBS 1.3.3 Personnel Launch Vehicle (PLV)–The PLV provides for the transportation of personnel and priority cargo between earth and low earth orbit. The reference vehicle is derived from the current space shuttle system. It incorporates a winged liquid propellant fly-back booster instead of the Solid Rocket Boosters and has a personnel compartment in the Orbiter payload bay capable of transporting 50-100 passengers. The overall configuration and vehicle characteristics are shown in Figure 1.3.3-1. The passenger module is also illustrated in Figure 1.3.3-1.

The booster employs four O_2/CH_4 engines similar to those on the HLLV booster. A series burn ascent mode is utilized and the external tank (ET) is a resized, smaller version of the space shuttle tank, carrying 546 metric tons of propellant versus 715 metric tons for the current STS.

1.3.3.1 Personnel Vehicle Cost per Flight

The personnel vehicle cost per flight is based on the cost per flight work breakdown structure shown in Table 1.3.3-1. The average cost/flight is based on the cost per flight work breakdown structure amortized over 14 years of operation. Total program costs less the DDT&E and facilities portion

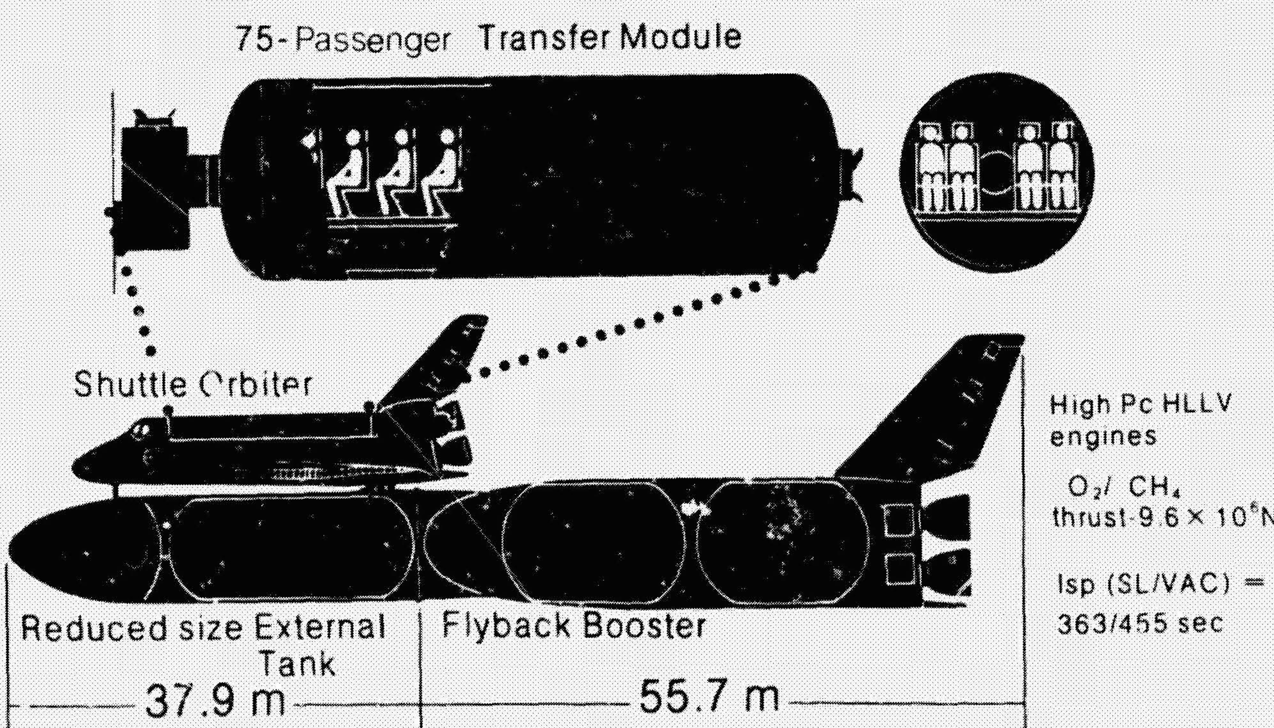


Figure 1.3.3-1 Personnel Launch Vehicle

Table 1.3.3-1 Personnel Carrier Average Cost/Flight (256 Flights/Year For 14 Years)

WBS ELEMENT	COST BY WBS LEVEL - $M (1977 $)			
	1	2	3	4
TOTAL PROGRAM OPERATING COST	12.619			
PROGRAM DIRECT		9.388		
PROGRAM SUPPORT			0.908	
PRODUCTION & SPARES			3.426	
ORBITER PRODUCTION				1.536
ORBITER SPARES				0.342
SSME'S				0.325
BOOSTER AIRFRAME				0.779
BOOSTER ENGINES				0.280
CREW RELATED GFE				0.165
EXPENDABLE HARDWARE - E.T.			1.858	
TOOLING			0.437	
GROUND OPS/SYS			2.759	
GROUND OPS				1.473
GSE SPARES				0.326
PROPELLANT				0.886
OTHER				0.074
DIRECT MANPOWER		1.568		
CIVIL SERVICE			0.861	
SUPPORT CONTRACTOR			0.707	
INDIRECT MANPOWER		1.663		
CIVIL SERVICE			0.755	
SUPPORT CONTRACTOR			0.908	

Hardware	Equivalent Units
Booster Airframe	26 units
Booster Engines	175 units
Orbiters	10 units
SSME's	140 units
ET	3584 units

The average cost of the ten orbiters was established at $ 550M each.

The average cost per flight of $12.619M includes Program Direct (75%), Direct Manpower (12%) and Indirect Manpower (13%) categories. The Program Direct element breakdown is as follows:

Program Support	10%
Production and Spares	36%
Expendable Hardware	20%
Tooling	5%
Ground Operations/Systems	29%

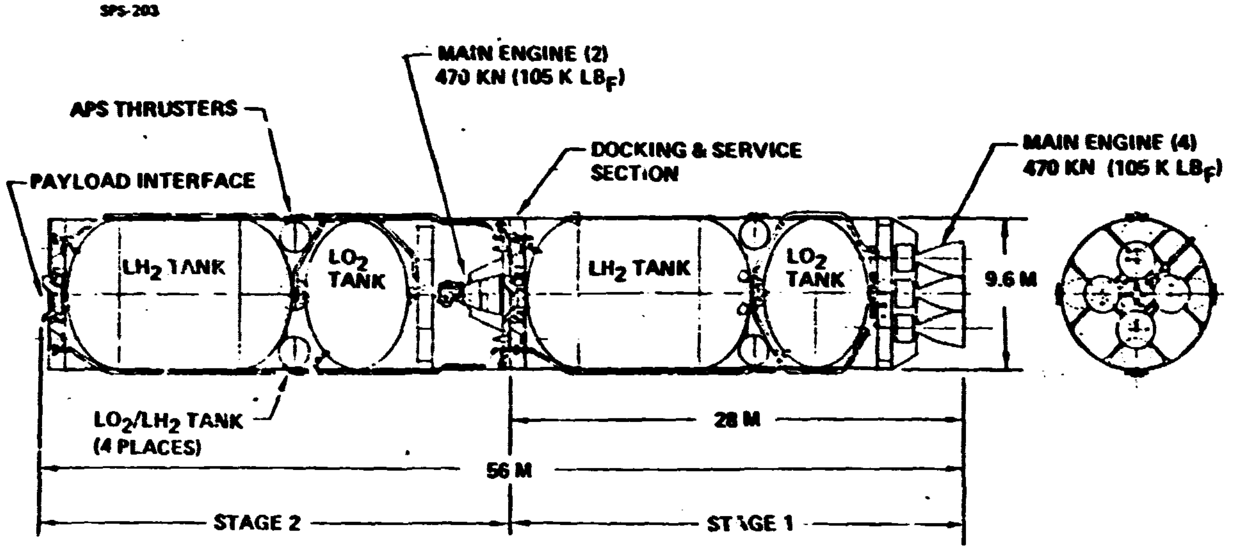
The Direct and Indirect Manpower costs reflect both extrapolation and modification of the Shuttle User charge data for the Personnel Vehicle concept.

WBS 1.3.4 Personnel Orbit Transfer Vehicle

The Personnel Orbit Transfer Vehicle (POTV) will be used to transfer personal and supplies between the LEO and GEO bases. The crew rotation/resupply mission is flown every 30 days with 160 people being transferred and one month of supplies provided for 480 people.

1.3.4.1 Configuration

The POTV configuration is a spaced-based common stage OTV is a two-stage system with both stages having identical propellant capacity as shown in Figure 1.3.4-1. The first stage provides approximately 2/3 of the delta V requirement for boost out of low Earth orbit at which point it is jettisioned for return to the low Earth orbit staging depot.



- PAYLOAD CAPABILITY = 150 000 Kg UP
  90 000 Kg DOWN
- OTV START BURN MASS = 890 000 Kg
- ONE FLIGHT PER MONTH PER CONSTRUCTION BASE

Figure 1.3.4-1. POTV for GEO Construction

The second stage completes the boost from low Earth orbit as well as the remainder of the other delta V requirements to place the payload at GEO and also provides the required delta V to return the stage to the LEO staging depot. Subsystems for each stage are identical in design approach. The primary difference is the use of four engines in the first stage due to thrust-to-weight requirements. Also, the second stage requires additional auxiliary propulsion due to its maneuvering requirements including docking of the payload to the construction base at GEO. The vehicle has been sized to deliver a payload of 150 000 kilograms and returr `0 000 Kg. As a result, the stage startburn mass without payload is approximately 890 000 kilograms with the vehicle having an overall length of 56 meters.

1.3.4.2 Subsystems

Structure and Mechanisms

Main propellant containers are welded aluminum with integral stiffening as required to carry flight loads. Intertank, forward and aft skirts, and thrust structures employ graphite/epoxy composites. An Apollo/Soyuz type docking system is provided at the front end of each stage for docking with payloads, refueling tankers and orbital bases. The stage-to-stage docking system provides for docking the stages together with flight loads carried through full-diameter structures. Propellant transfer connections allow either stage to be fueled independently with the stages either separated or docked together. Structure of the two stages is identical to the extent practicable.

Main Propulsion

Main engines are based on shuttle engine technology, operating with a staged-combustion cycle at 20 Mn/m^2 (3000 psia) chamber pressure, a LO_2/LH_2 mixture ratio of 5.5 to 1.0 and a retractable nozzle with extension expansion area ratio of 400 providing a specific impulse of 470 seconds. Advanced low NPSH pumps are used to minimize feed pressures. A 6 degree square gimbal pattern is employed. The engines are capable of operating in a tank-head idle (THI) mode (pumps not turning: mixed-phase propellants) for chill-down and self-ullaging at a specific impulse of 350 seconds; 60 seconds (time) in self-ullaging mode is assumed needed prior to bootstrapping to full thrust. Throttling between tank-head idle and full thrust is not required. Main propellant pressurization is derived from engine top off after an onboard helium prepressurization.

Auxiliary Propulsion

Auxiliary propulsion is used for attitude control and low delta V maneuvers during coast periods and for terminal docking maneuvers. An independent LO_2/LH_2 system is used and provides an Isp of 375 seconds averaged over pulsing and steady state operating modes. Thrusters are mounted in quad packages analogous to the Apollo Service Module installation. Each quad has its own propellant supply to facilitate change out. Auxiliary propulsion for the two stages uses common technology but capacities and thrust levels are tailored.

Electrical Power

Primary electric power is provided by fuel cells based on shuttle technology, tailored to the OTV requirement. Reactants are stored in vacuum-jacketed pressure vessels. Product water is assumed retained onboard to minimize payload contamination potential. Ni-Cad batteries are employed for peaking and smoothing. 28 VDC power is rough-regulated and filtered with fine regulation provided by power using subsystems as needed. A potential inert mass saving (not assumed) would use low pressure reactants provided from main propellant tanks. Electric power systems for the two stages are identical except for reactant capacity and harnesses.

Avionics

Avionics functions include onboard autonomous guidance and navigation, data management, and S-band telemetry and command communications. Navigation employs Earth horizon, star and Sun sensors with an advanced high performance inertial measurement system. Cross-strapped LSI computers provide required computational capability including data management, control and configuration control. The command and telemetry system employs remote-addressable data busing and its own multiplexing. Although the avionics systems in the two stages are identical, software for each stage is tailored to the stage functions.

Thermal/Environmental Control

Main propellant tanks arer insulated by aluminized mylar multilayer insulations contained within a purge bag. The insulation system is helium purged on the ground and during Earth launch. Environmental control of the avionics systems is accomplished using semi-active louvered radiators and cold plates. Active fluid loops and radiators are required for the fuel cell systems. Superalloy metal base heat shields are employed to protect the base areas from recirculating engine plume gas.

WBS 1.3.4.3 Performance

Performance characteristics associated with the common stage LO_2/LH_2 OTV are shown in Figure 1.3.4-2. Propellant requirements are shown as a function of the payload return and delivery capability. Performance ground rules used in these parametrics are as follows (values are main propellant quantities):

- o THI mode — Stg 1—100 kg per start
  Stg 2— 50 kg per start
- o Stop loss — Stg 1— 20 kg
  Stg 2— 10 kg
- o Boiloff rate — 6 kg/hr each stage
- o Burnout mass scaling equations:
  Stg 1 3430 kg = $0.05567\ WP_1 + 0.1725\ WP_2$
  Stg 2 3800 kg = $0.05317\ WP_1 + 0.1725\ WP_2$
  Where WP_1 and WP_2 are main and auxiliary propellant capacities respectively
- o Stage ' of 0.93
- o Staging base at 477 Km, 31 degrees

1.3.4.4 Mass

Summary level mass estimates are presented in Table 1.3.4-1 for the selected satellite OTV. A weight growth factor of 10% was used rather tnat 15% as in FSTS based on the judgment that the SPS LO_2/LH_2 OTV would be a second generation vehicle. Mass estimates for the systems reflect the design approach previously described.

1.3.4.5 Mission Profile and Flight Operations

Typical orbit transfer operations from LEO to GEO for the common stage OTV are illustrated in Figure 1.3.4-3. The majority of the delta V for boosting from LEO is provided by Stage 1. Stage 1 then separates and returns to the staging depot following an elliptical return phasing orbit. Stage 2 completes the boost and puts the payload into a GEO transfer and phasing orbit, as well as injecting the payload into GEO and performing the terminal rendezvous maneuver with the GEO construction base. Following removal of the payload, stage 2 uses two primary burns in returning to the LEO staging depot. A detailed mission profile indicating events, time and delta V is presented in Table 1.3.4-2.

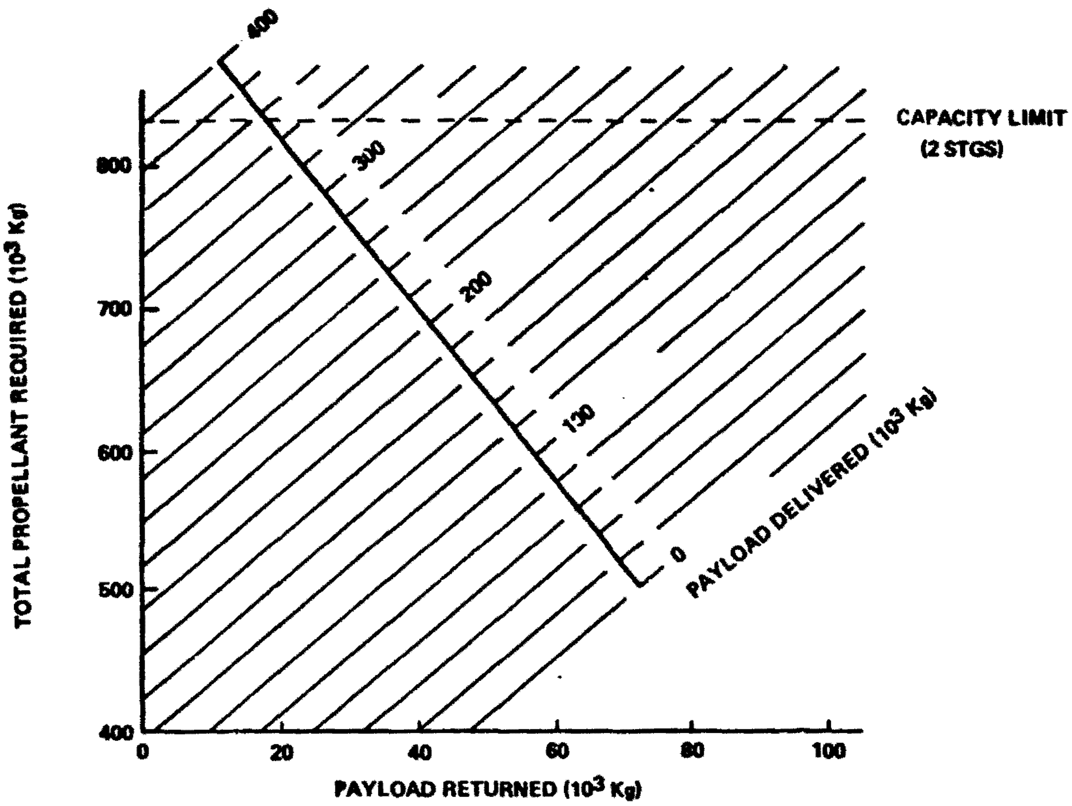


Figure 1.3.4-2 Two Stage LO_2/LH_2 OTV Performance

Table 1.3.4-1 Chemical OTV Mass Summary

	Stage 1 (KG)	Stage 2 (KG)
Struct and Mechanisms	13,300	14,780
Main Propulsion	7,090	4,020
Auxiliary Propulsion	820	1,120
Avionics	300	310
Electrical Power	850	820
Thermal Control	1,850	2,310
Weight Growth (10%)	2,420	2,340
Dry	26,630	25,790
Fuel Bias	640	640
Unusable LO_2/LH_2	1,810	1,810
Unusable and Reserve APS	290	660
Burnout	29,370	28,990
Main Impulse Prop	415,000	407,000
APS	2,700	6,100
Startburn	447,070	442,090

SPS-368

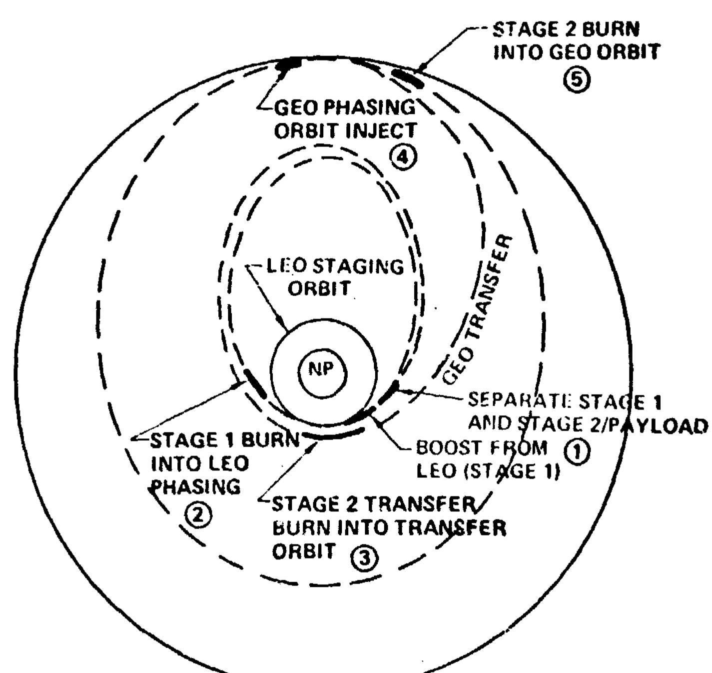


Figure 1.3.4-3 Chemical OTV Orbit Transfer Operations

Table 1.3.4-2 Mission Profile

MISSION EVENT NO. & NAME	REQUIRED TIME (HR)	DELTA V M/SEC	PROPULSION (MAIN OR AUXILIARY)	REMARK
		MISSION		
1. STANDOFF	0	3	A	PROVIDES SAFE SEPARATION DISTANCE BETWEEN FACILITY & VEHICLE
2. PHASE	12	3	A	ΔV IS ATTITUDE CONTROL
3. COAST	.5	1715	M	OTV FIRST STAGE SEPARATES AFTER THIS ΔV
4. COAST	4.2	3	A	ELLIPTIC REV
5. INJECT	.1	750	M	INCLUDES 60 M/SEC ACCUMULATED FINITE-BURN LOSS
6. COAST	5.4	3	A	TRANSFER TO GEO
7. PHASE INJ	.1	1780	M	REPRESENTATIVE FOR 15° PHASING
8. PHASE	23	3	A	
9. TPI (TERMINAL PHASE INITIATION)	.1	55	M	INCLUDES 15 M/SEC OVER IDEAL TO ALLOW FOR CORRECTIONS
10. RENDEZVOUS	2	10	A	TPI ASSUMED TO OCCUR WITHIN 50 KM OF TARGET
11. DOCK	1	10	A	
12. WAIT	8	0	-	ASSUMED DOCKED
13. STANDOFF	.1	3	A	
14. DEORBIT	.1	1820	M	
15. COAST	5.4	10	A	TRANSFER TO LEO
16. PHASE INJECT	.1	2356	M	
17. PHASE	12	3	A	ORBIT PERIGEE AT STAGING BASE ALTITUDE
18. TPI	.1	50	M	
19. RENDEZVOUS	2	20	A	
20. DOCK	1	10	A	
21. RESERVE	-	130	M	2% OF STAGE MAIN PROPULSION V BUDGET
		FIRST STAGE RECOVERY		
1. COAST	4.2	30	A	ΔV TO CORRECT DIFFERENTIAL NODAL REGRESSION BETWEEN COAST ORBIT AND STAGING BASE
2. PHASE INJECT	.1	1645	M	ELLIPTIC ORBIT - PERIGEE AT STAGING BASE ALT.
4. TPI	12	3	A	ALTITUDE CONTROL
3. PHASE	.1	50	M	
5. RENDEZVOUS	2	20	A	
6. DOCK	1	10	A	
7. RESERVE	–	85	M	2% OF STAGE MAIN PROPULSION V BUDGET

A total mission timeline for each stage is presented in Figure 1.3.4-4. Allowing approximately eight hours for refueling and refurb results in 40 hours elapsed time before a given Stage 1 can be reused. A typical Stage 2, however, has an elapsed time of 85 hours before reuse including time for assembly between stages and between OTV and payload.

1.3.4.6 Cost

DDTE cost for the common stage LO_2/LH_2 OTV with a start burn mass of approximately 900 000 kg is estimated at $950 million (1977 dollars) based on cost parametrics developed in the FSTSA study. The average TFU cost for the two stages is estimated at $82 million (1977 dollars) again using FSTSA parametrics.

Cost per flight for the LO_2/LH_2 OTV is based on the following ground rules:

- Space Based LO_2/LH_2 Common Stage OTV
- Startburn Stage Mass of 445 K kg
- Stage TFU Equal $82M (1977 Dollars)
- 1 Satellite Constructed Per Year
- 12 OTV Flights Per Year for Crew Rotation/Resupply
- 14 Year Program Life
- 50 Flight Design Life
- Stage Learning Factor of 0.88
- LO_2/LH_2 Bulk Cost of $0.10 per kg
- Spares Equal 50% of Operational Units
- Backup OTV Always Available and Assumed Used at the Same Rate as the Crew Rotation/Resupply OTV

Based on the above groundrules, a total of 16 stages are required resulting in an average cost per OTV flight of $4 million.

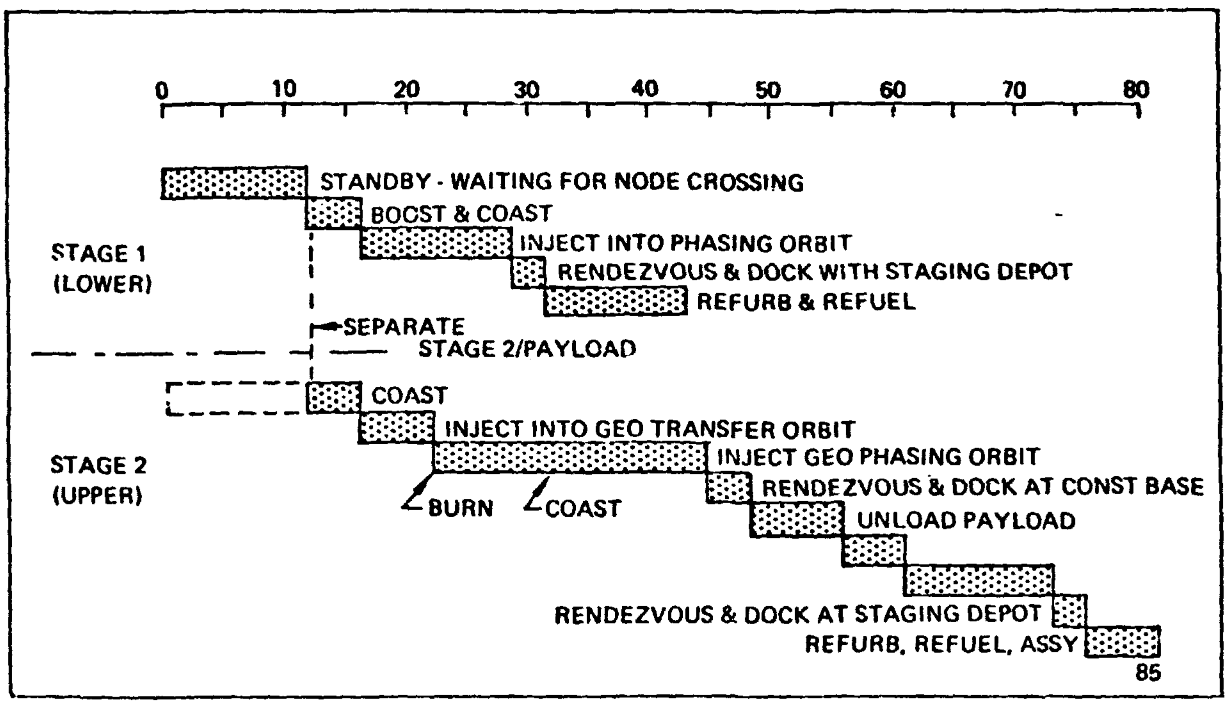


Figure 1.3.4-4 Chemical OTV Flight Operation Timeline

WBS 1.4 Ground Receiving Stations

WBS Dictionary

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 of beam formation, aiming, and power. Whether the ground receiving stations would be responsible for SPS flight control has not been determined.

Description

Each receiving station includes the land area, rectenna (rectifying antenna), grid interface equipment, and control and communications systems. The land sites are 13.18 x 18.7 km (nominal, at 35° latitude) and each rectenna proper is 9.885 x 14 km. The output power of 5000 megawatts is delivered through five 1000-megawatt transformer stations. Several rectenna configuration options were evaluated. The tilted-panel configuration shown in Figure 1.4.1 was retained as preferred concept.

Mass

Mass estimates were not made.

Cost Summary

Rectenna costs were based on General Electric Studies of rectenna construction, power collection, power processing and grid interfacing.

Land was estimated at $5000/acre for acquisition.

A summary follows:

		Cost Million of $
Land	47,800 acres	120
Structures & Installation		285
RF Assemblies & Ground Plane		834
Distribution Busses		268
Command & Control Center		61
Power Processing & Grid Interface		674
		2242

These figures are for one receiving site.

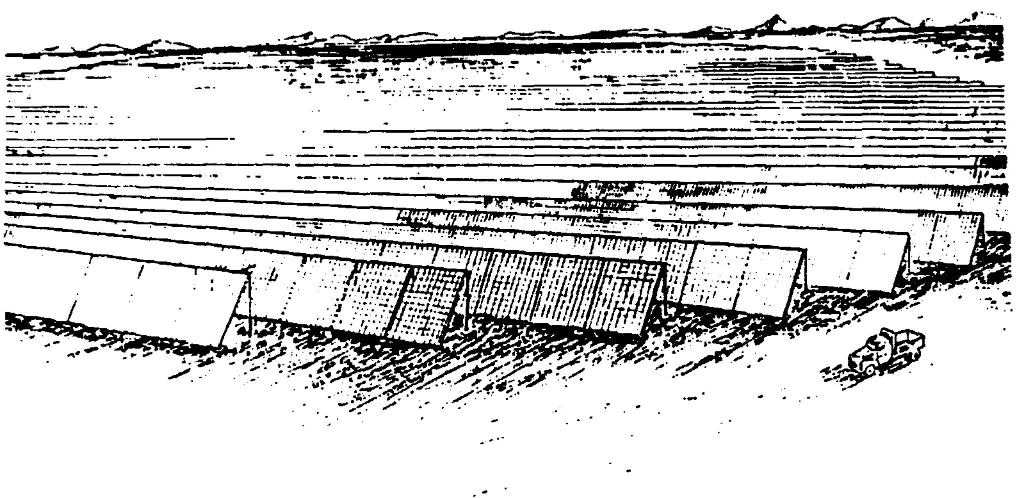


Figure 1.4-1. Tilted Panel Rectenna Configuration

WBS 1.4.1 Site and Facilities

WBS Dictionary

This element includes the land a[illegible] for the ground receiving stations and all site preparation.

Description

The land area requirement was assumed to be equivalent to the SPS power beam footprint on the ground. The size is nominally 13.8 x 18.7 km, elliptical, but varies with latitude. That portion of the land area not used for active rectenna elements may be planted in grass or forest (as is appropriate to the climate) to minimize reflection of the outer fringes of the microwave beam. The beam intensity in this region will be less than 1 mw/cm^2. The entire receiving site will be fenced.

Mass

Not applicable.

WBS 1.4.2 Rectenna Primary Structure

WBS Dictionary

This element includes all support structure for the active rectenna.

Description

The structural design selected is illustrated in Figure 1.4.2, excerpted from the General Electric Rectenna construction study.

Mass and Cost

Principal materials consumption for one rectenna is estimated as follows, based on the GE construction analysis:

Concrete*	11,145,000 metric tons
Steel	1,689,000 metric tons
Aluminum	170,000 metric tons
ceramic (probably Al_2O_3)	6,000 metric tons
plastic	12,000 metric tons
gallium arsenide (in diodes)	25 metric tons

* Indications are that this is a high estimate.

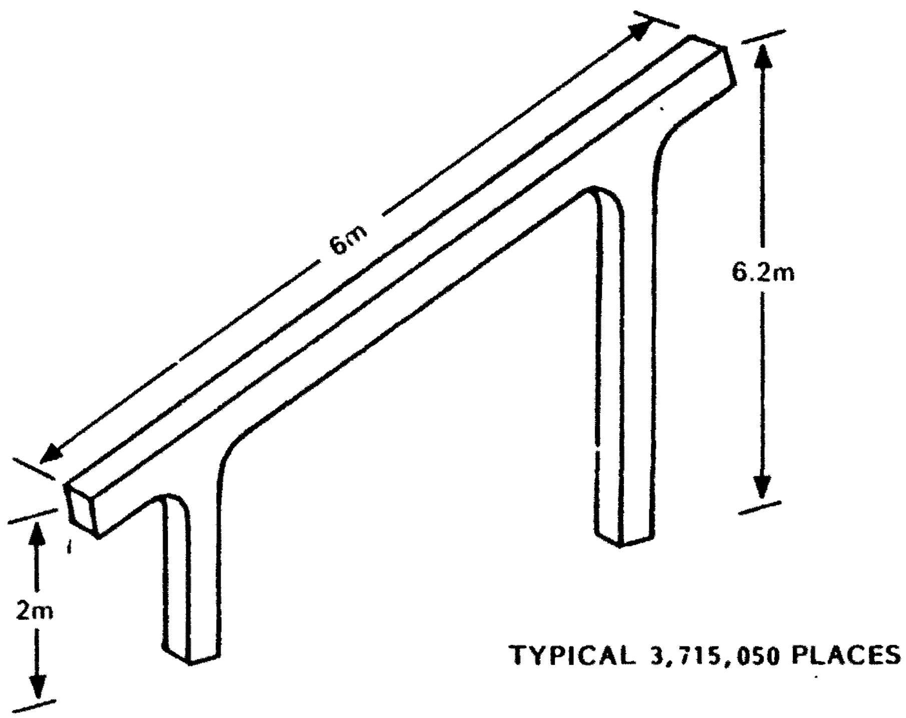


Figure 1.4-2. Pre-Stressed Concrete in Baseline Structure

Table 1.4-1 presents the summary cost estimate from the GE rectenna construction analysis.

WBS 1.4.3 Power Collection

WBS 1.4.3.1 RF-DC Conversion

Description

The rectenna concept utilizes a weather proof matched dipole configuration shown in Figure 1.4-3. All materials required are readily available and of low cost. The mechanical design is amenable to highly automated production. Using the previously proven rectennas construction methods from the JPL/Raytheon tests, a more efficient two plane design format has been developed (Fig. 1.4-4). An actual complete section has been evaluated in r.f. tests and is shown in Figure 1.4-5. The metal shield is used to provide environmental protection as well as prevent direct radiation of harmonic power. Also, the dc converting bus forms part of the filter and r.f. rectification circuit.

Ground Planes

The two-plane design consists of the active receiving elements and a reflecting plane, or ground plane. The reflecting plane need only be a metallic mesh with suitable spacing relative to the wavelenth. Refer to 1.4-4 for the form and location of the ground plane.

Use of a mesh allows passage of the wind, rain, snow, etc., to reduce structural loading.

R.F. Assemblies

The foreplane contains the half-wave dipoles the input wave filters, the rectification circuit, the smoothing capacitance, and the DC power collection and bussing function. Figure 1.4-6 shows the electrical format of the foreplane. Figure 1.4-5 showed a physical embodiment of a section of foreplane construction as defined in Figure 1.4-6 with the addition of a shield. The foreplane shown in Figure 1.4-5 has been thoroughly checked out electrically and found to be equal in efficiency to that of the three plane construction. Figure 1.4-4 showed how the foreplane can be integrated with the reflecting screen to form the major portion of the rectenna structure. It is 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.

Table 1.4-1 SPS Ground System Cost (Summary of Major Equipment, Buildings, Material and Labor)

TYPE	SENSITIVITY	TOTAL COST (M$) (1977 DOLLARS)
RECTENNA		
MATERIAL:		
DIODES	4¢/DIODE	298
STEEL IN PANELS	15.8 Kg/m²	349
ALUMINUM BUSBARS (.02" x 0.5")	165,000 METRIC TONS	267
STRUCTURE		
CONCRETE (6 x 10 METER MODULE)	9 METRIC TONS/MODULE	81
STEEL (REINFORCING)	300 Kg/MODULE (100 Kg/ARCH; 3 ARCHES/MODULE)	100
LABOR		50
CAPITAL COST	(TYPICAL MACHINE LIFE IS 5 YEARS, COST TO PROJECT ONLY DURING USE)	40
MISCELLANEOUS		175
	TOTAL RECTENNA COST	1360
GROUND POWER DISTRIBUTION AND TRANSMISSION (PER SPS PHASE III FINAL REVIEW)		630
	TOTAL SPS GROUND SYSTEM COST (EXCLUDING LAND AND DEVELOPMENT COST)	1990

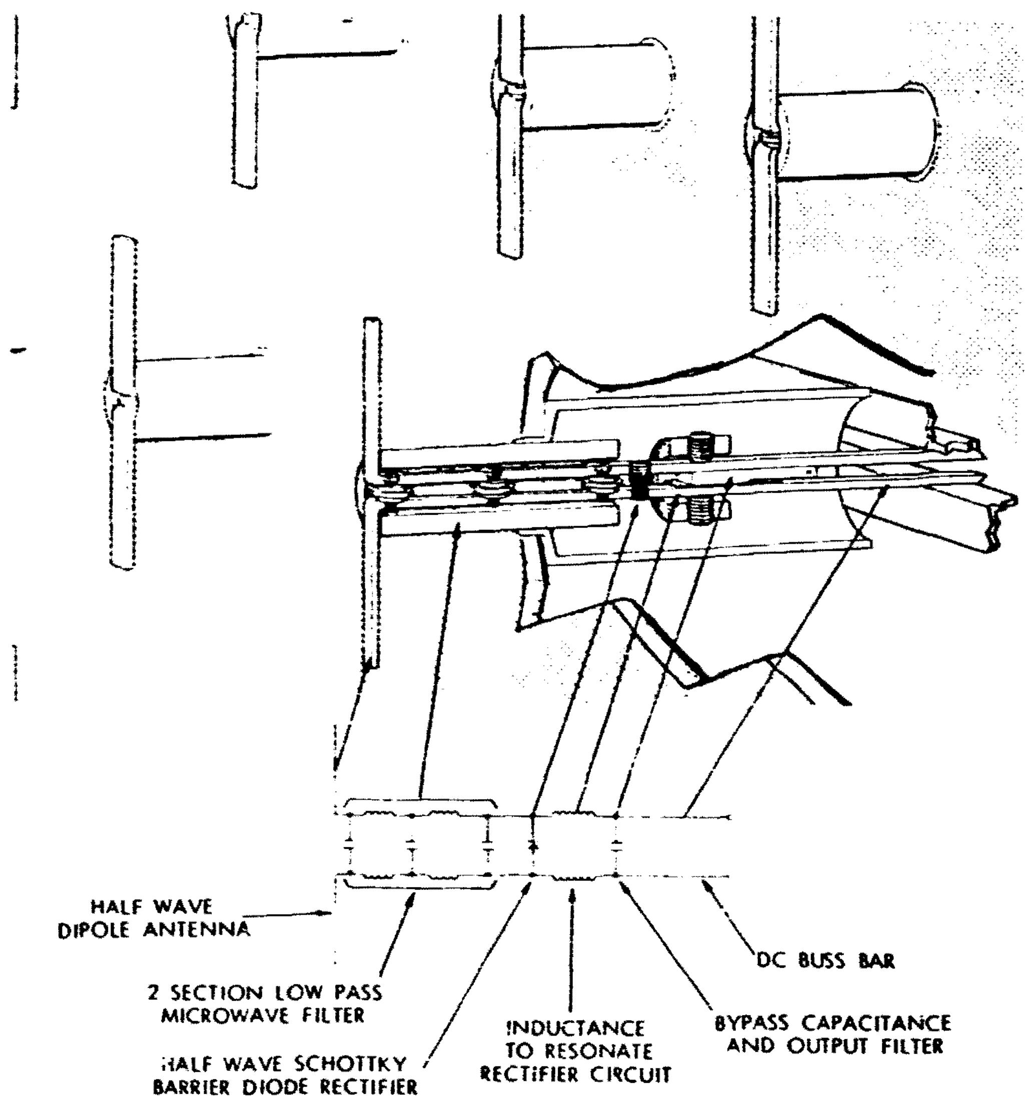


Figure 1.4-3. Cutaway section of the three-plane rectenna approach used in the RXCV at JPL's Goldstone facility showing how the rectenna elements plug into the array. Although this approach was satisfactory electrically, it is complicated from a fabrication point of view. A greatly simplified mechanical approach is the two-plane system which preserves all of the desirable electrical properties of the three-plane system.

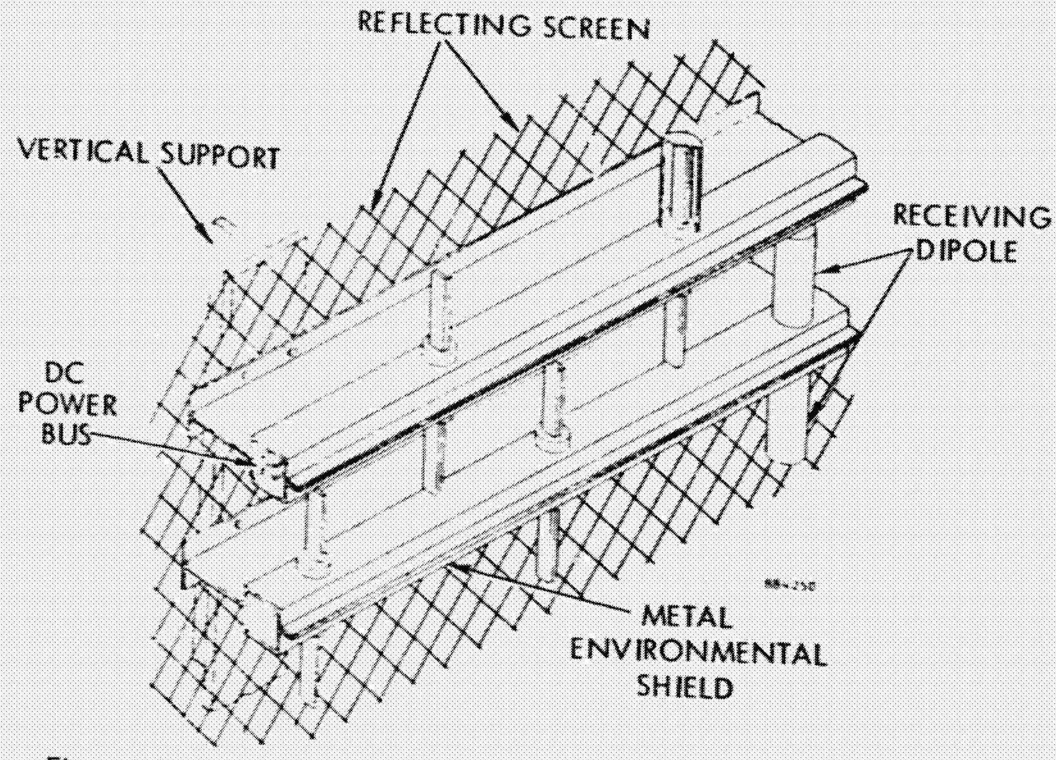


Figure 1.4-4. Drawing of the two-plane rectenna construction format consisting of a reflecting screen or ground plane and the foreplane which contains dipole antenna, wave filters, diode rectifiers, and bus bars—all protected from the environment by a metal shield.

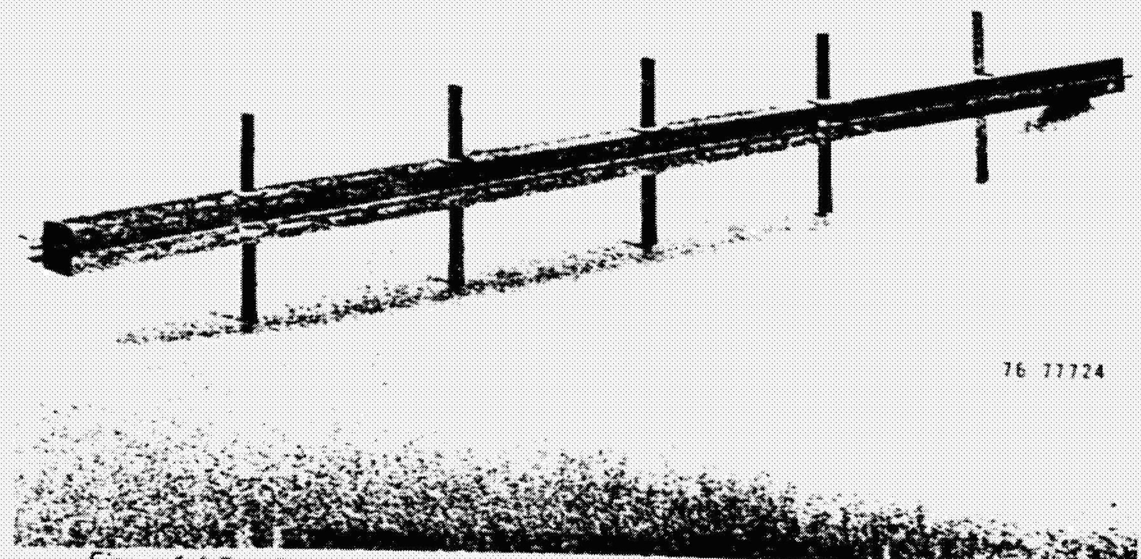


Figure 1.4-5. Completed rectenna foreplane assembly consisting of metallic shield and the core assembly of five rectenna elements. This section has been substituted for a section of the three level construction in a rectenna and found to perform as well.

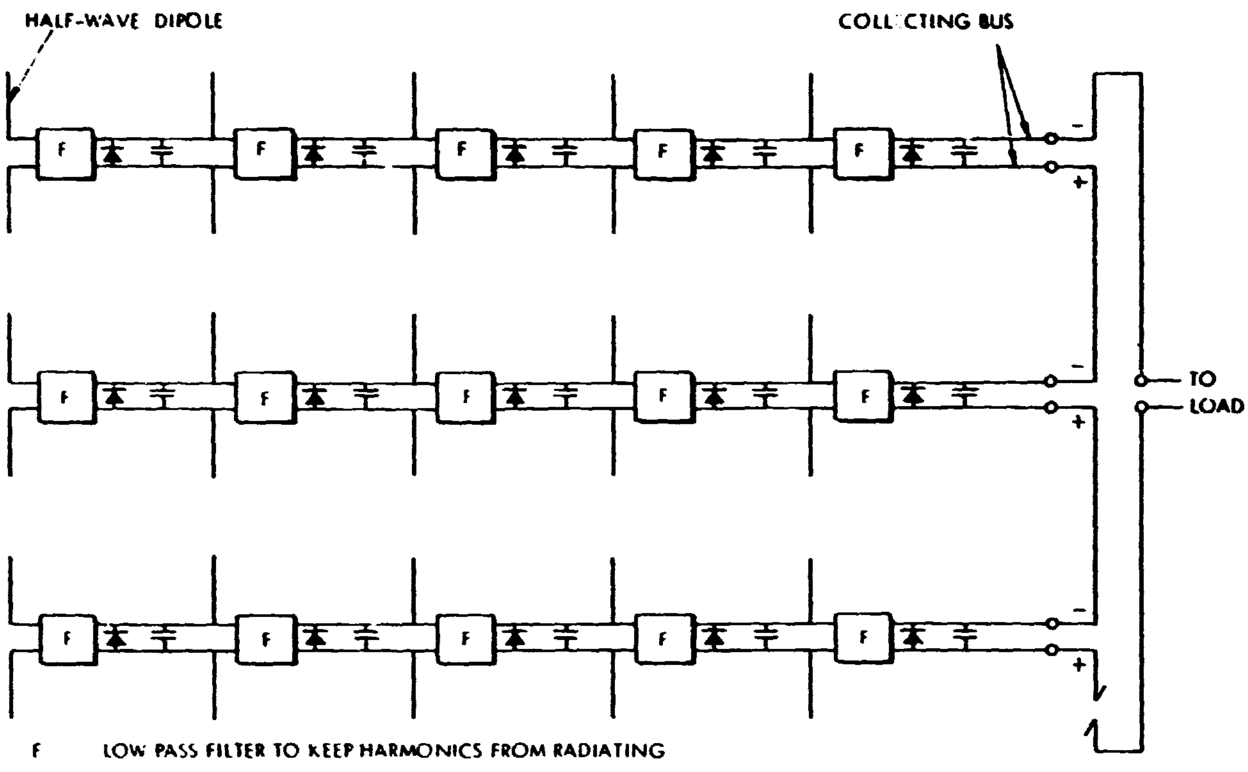


Figure 1.4-6a. Schematic of the foreplane of the two-plane rectenna showing the arrangement of half-wave dipoles, input filters, and Schottkybarrier rectifying diodes. Two-wire transmission lines are used for both microwave circuits and carrying out the DC power collected by the array.

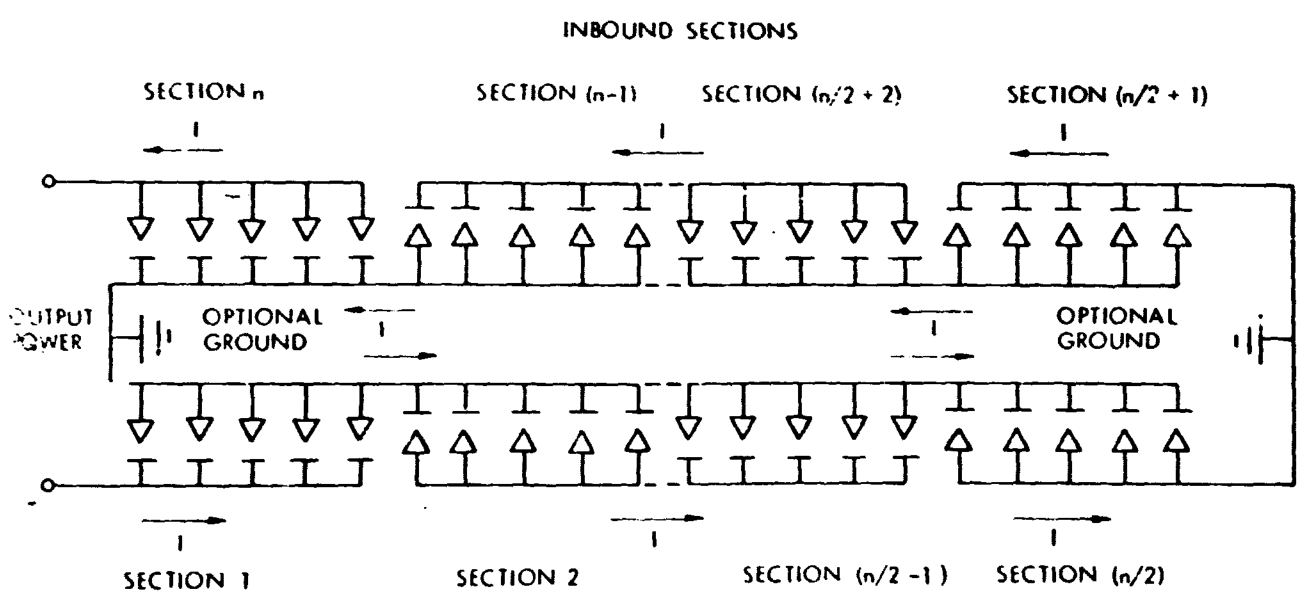


Figure 1.4-6b. Schematic electrical drawing showing how the sections of diodes representing the rectenna elements within a long length of foreplane are connected in parallel and series to build up to the desired output current and voltage levels.

Dipoles

The dipoles are formed of aluminum wire as shown in Figure 1.4-7.

Circuitry

Refer to Figure 1.4-6 for the electrical circuit of the rectenna panels. Panel interconnections are described in section 1.4.3.2.

Shields and Covers

The shape and size of the shield shown in cross section in Figure 1.4-8 is determined by a number of factors. The depth of the beam is determined by the necessary distance of about one inch between the half wave dipole antennas and the reflecting screen and the method of assembling the shield to the screen. The assembly of the beam to the screen is important but the options on how to do it are severly limited. By making the shield deeper and inserting it into folds in the screen a secure, fast, and economical assembly can result while also providing the beam with greater strength because of the greater depth. The width of the shield is largely determined by the physical size of the core assembly and the requirement for operating the core assembly at some potential removed from ground. The thicker the assembly the more will be the wind resistance. The thickness of the member is made constant throughout its depth to provide it with high torsional resistance. If the top and bottom members of the shield are quite thin, they can be given resistance to buckling under stress by forming lateral grooves in the material.

Although the dimensions assigned to Figure 1.4-8 may be somewhat arbitrary, they are quite representative of what the design will probably be with this approach. With the assumed dimensions the neutral axis is found to be at 1.043 inch and the moment of inertia I_y is found to be 2.303 t, where t is the thickness of the material.

WBS 1.4.3.2 Rectenna Power Conditioning

Introduction

In order to determine the major characteristics of a rectenna, which can be used for a failure mode and availability analysis and also to derive a realistic construction and erection concept a typical rectenna design was performed.

For this design the system parameters shown in Table 1.4-2 were assumed:

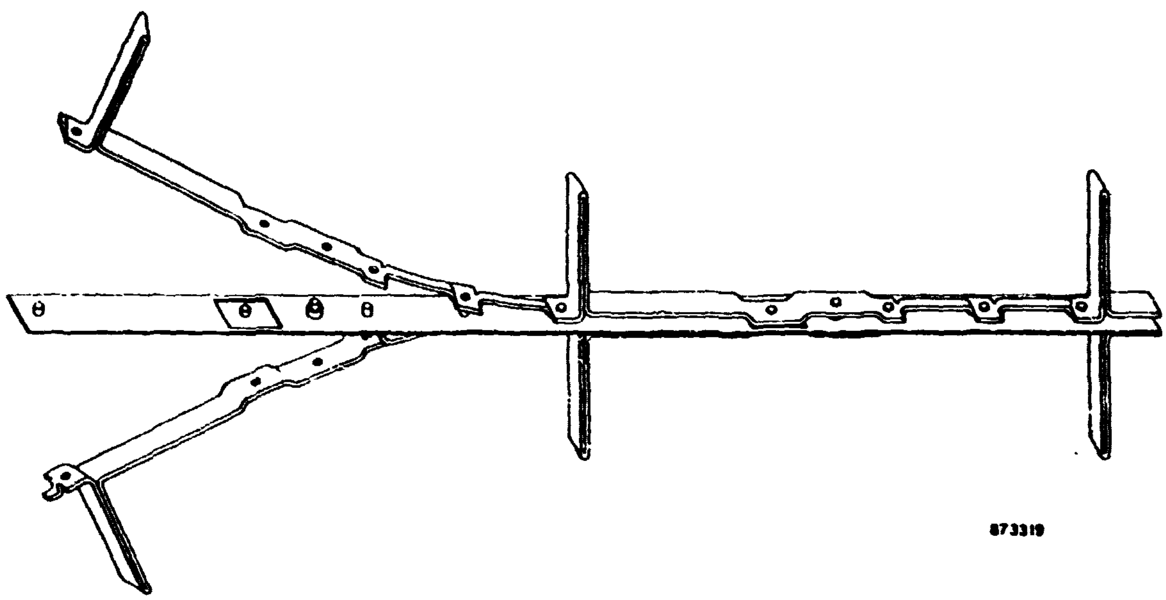


Figure 1.4-7 *Proposed method of continuous fabrication of the core assembly of rectenna elements. Top and bottom members are continuously formed from two rolls of flat wire to the left of the assembly. Details of the above drawing have been superseded by a new design shown in Figure 1.2.4-2.*

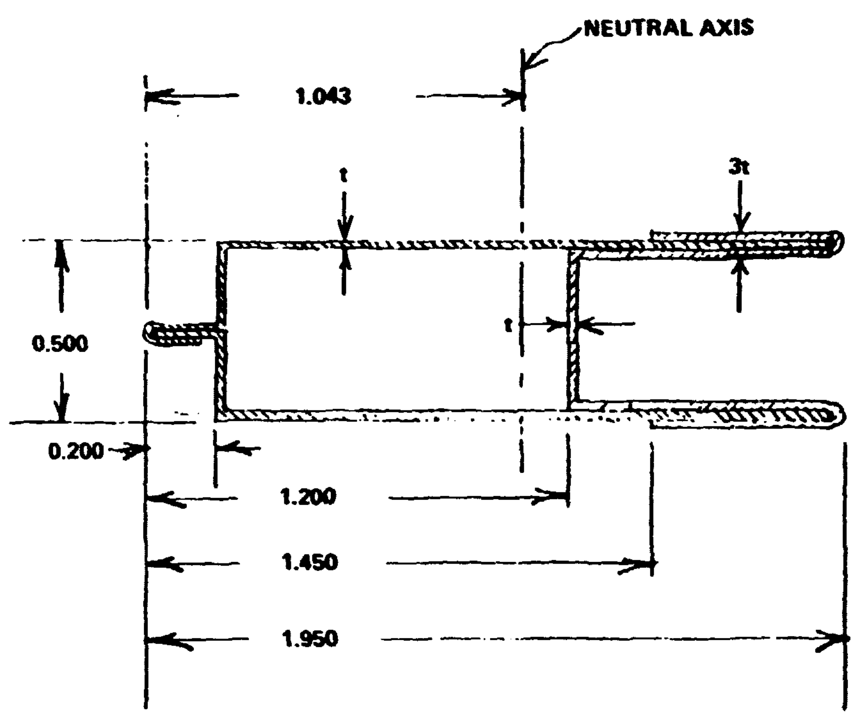


Figure 1.4-8 *Proposed design of the shield for the foreplane assembly. Design consists of three parts. The parts are continuously assembled to each other by rolling over flanges left on top and side pieces, after the parts flow around and enclose the core of the foreplane.*

Table 1.4-2. Summary of Assumptions

Space Antenna	
Equivalent diameter:	$1000m = 8153.6\lambda = D\lambda$
Power distribution:	Gaussian, approximated by 10 constant level rings with -9.5 db edge taper.
Frequency:	2450 MHz
Wavelength:	12.2449 cm
Aperture Gain:	$G_o = \pi^2 D\lambda = 88.17$ db
Aperture illumination efficiency:	$A = 88.25\%$
Antenna Gain:	$G = \eta_A G_o = 87.63$ db
3 db beamwidth:	$\frac{72.08}{D\lambda} = 8.84 \times 10^{-3}$ deg.
8.8 db beamwidth:	$\frac{119.37^o}{D\lambda} = .01464$ deg.
Number of transmitters:	101552
Transmit power out of antenna module:	70 kw
Total transmit power:	$P_T = 7.1249$ Gw
Orbit location:	-100^o long.
Northern tilt of antenna:	4.96777 deg.
Ground Antenna	
Location:	-100^o long., 30^o lat. Texas
Elevation angle to spacecraft:	55^o
Slant range:	T = 36785.3 km
Edge taper:	-8.8 db
Receive power density in middle of rectenna:	$P_R = 24.28$ mw/cm^2
Nominal N-S dimension:	11.48 km
Nominal E-W dimension:	9.4 km
Aperture shape:	Nominal elliptical, approximated by N-S and E-W straight lines.
Area:	84.75 km^2
Beam efficiency between space and rectenna:	95.33%
Beam efficienty sensitivity:	+ 1.5%/$\pm$ 12.11% antenna

variation. (beam efficiency can be increased to approximately 96.77% if antenna area is increased to 95.01 km^2)

No attempt was made to optimize the rectenna size relative to the space antenna and its aperture distribution. However, it is believed that an economical optimum is not far from the above selected antenna area. For instance if it is assumed that the rectenna represents 12% of the system cost and the rectenna costs is proportional to its area then ± 1.5% beam efficiency variation corresponds to ± 1.47% variation in the cost of the overall system. Consequently the cost of an energy unit is not sensitive to the rectenna size variation around the selected value.

Table 1.4-3 shows the power distribution that the space antenna produces on the ground relative to the center of the beam.

Figure 1.4-9 exhibits the variation of the aperture distribution and the centers of the selected "rings" over the aperture.

Table 1.4-3. Power Distribution Within the Rectenna

r_b km (E-W Plane)	r_b km (N-S Plane)	P_R db	
0	0	0	(P_o = 24.28 mw/cm^2)
1	1.22	-.37	
2	2.44	-1.50	
3	3.66	-3.8	
4	4.88	-7.9	
4.7		-8.8	

For the rectenna geometry and η_B = 95.47% the rectenna intercepts 6802 GW RF power, neglecting propagational effects. In the middle of the rectenna the power density is approximately 24.3 mw/cm^2 for the loss less atmosphere and no component failures in the space antenna. This puts the rms value of maximum power density to 21.52 mw/cm^2.

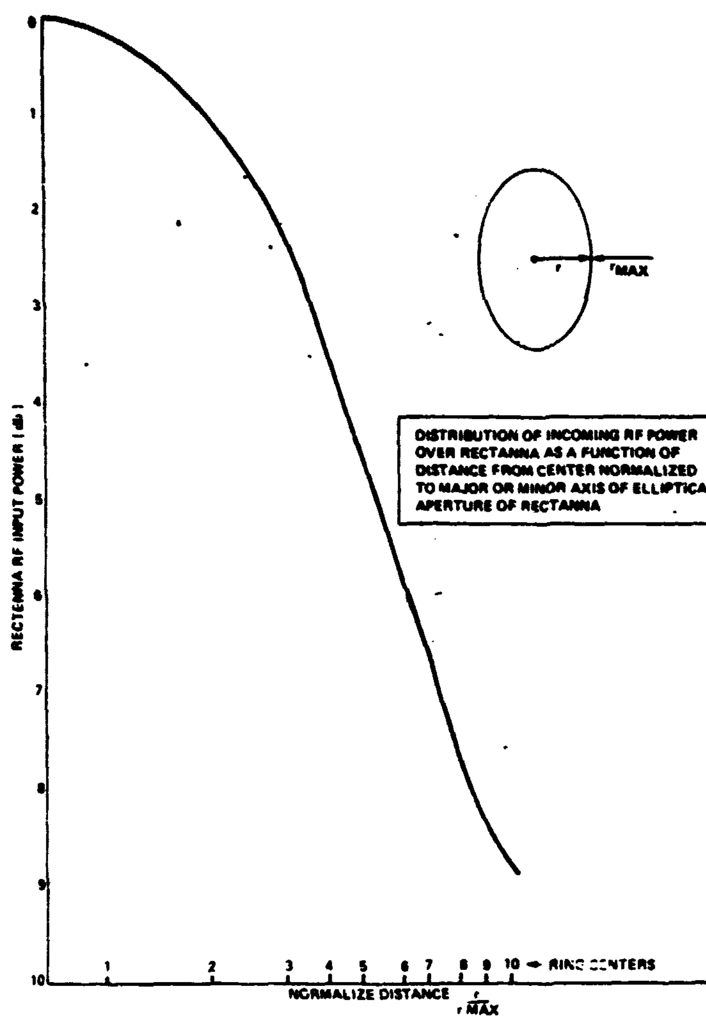


Figure 1.4-9. Distribution of Incoming RF Power over Rectenna as a Function of Distance from Center Normalized to Major or Minor Axis of Elliptical Aperture of Rectenna

In order to develop the details of the rectenna power collection network the aperture area is divided into ten approximately elliptically shaped rings. The DC 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, so-called "low voltage" design the network is connected in such a way that the line voltages remain within a nominal $\pm$ 3.25 kV range.

In the second, so-called "low current" design the network currents remain below 300A, but the range of the highest voltage increases to $\pm$ 23 kV. For safety and reliability reasons the first design was selected as the baseline. However this design results in a rectenna configuration which is 10 20% more expensive than the high voltage design, due to the larger conductor quantities necessary.

Layout and Characteristics of a Low Voltage DC System

Dipole Assembly

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

The optimum number of dipoles for a given receive area is determined by the effective receive area of a dipole. The relationship between gain, effective receive area A_{eff} and average receive area $A_{av} = \frac{\lambda^2}{4\pi}$ of an arbitrary antenna is

$$G = \frac{A_{eff}}{A_{av}} = 4\pi \frac{A_{eff}}{\lambda^2}$$

For a free space, infinitely thin half wave dipole G = 1.65, thus

$$A_{eff} = \frac{\lambda^2}{4\pi} G = 11.9316\ G = 19.6872\ cm^2.$$

For two endfire isotropic sources, $\frac{\lambda}{4}$ from each other and 90^o in phase G = 3.36 and . A_{eff} = 40.09 cm^2. When a half wave dipole is alone in the front of an infinite ground plane its gain is somewhat better than the ideal two element endfire array and its gain is G ~ 4.85 = 6.87 db. The corresponding effective area of such an antenna is $A_{eff} \simeq$ 57.86 cm. When an infinite number of such dipoles form an array the effective area per dipole decreases slightly due to mutual coupling effects, nonuniformity of the incoming wave, finite dipole thickness and dipole losses. The effective area is also a function of the dipole array layout (triangular, square, rectangular, etc.). In the following the slightly conservative A_{eff} = 54.08 cm^2 will be assumed for a dipole in an infinite array of dipoles and in the front of a ground plane. This allows the mounting of a 43 x 43 = 1849 matrix of dipole assemblies on a 10 m^2 panel. In the middle of the rectenna a single dipole ideally will receive 1.313 w power. It is assumed that all dipoles are identical throughout the rectenna. The number of dipoles in the rectenna is approximately 1.305×10^{10}. The 7.354 cm = .6λ in a square array configuration and 7.902 cm = .644 λ in a triangular array format.

In practice the triangular format is recommended due to its more even distribution of dipoles.

It may be noticed that the dipole density has some effect on the overall cost of the produced energy unit. For instance if the dipole density is reduced slightly then the cost of the dipoles is reduced proportionally, but the reduction of output power is somewhat less due to a slight increase of the effective area per dipole and an even smaller increase in conversion efficiency due to higher operating power level of the diode. However, these effects are very small and were not analyzed during the present phase of the study.

Array Assembly

Due to 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 one single type of diode is assumed which is operated with four different types of antenna elements. It is assumed that besides the dipole element already described these antenna elements are formed by using the basic dipoles in arrays containing 2, 4 or 8 dipoles. The corresponding assemblies will be called Type 1, 2, 3 and 4 receiving element or array. The array formation requires 2,4 and 8 way power combiners, which can be simple printed circuits. Table 1.4-4 shows the RF power delivered to the diode by the various type of receive elements as a function of their location in the rectenna. It is assumed that the rectenna is divided into ten rings and the power per diode shown in Table 1.4-4 is the average power within the corresponding ring. The same table also shows the estimated conversion efficiency on the basis of an analytical model as shown in Figure 1.4-10 on the basis of the Rensselaer Polytechnic Inst. Report No. N! 9-15453 by R. J. Gutman and J. M. Borrego.*

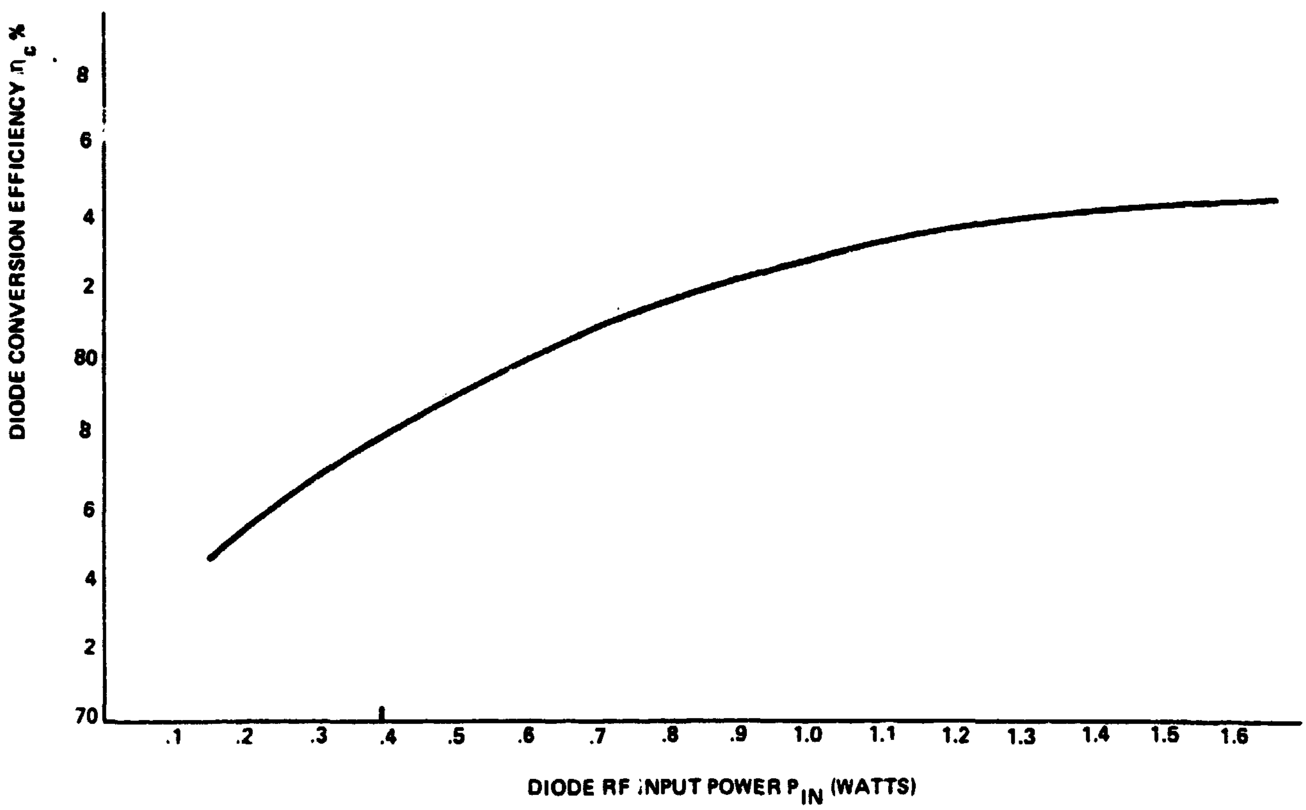


Figure 1.4-10. Assumed RF to DC Conversion Efficiency of Diode as a Function of Diode Input RF Power

* The model is conservative. Experimental results 3 to 5% better than this curve have been reported.

The "resultant" efficiency of the diode incorporates a number of factors, like

Ideal conversion efficiency
Mismatch loss
Nonuniform power variation over a long panel string caused loss
efficiency reduction caused by lower than optimum operating power level
RF combiner loss
Filter loss
Panel edge diffraction caused illumination nonuniformaity diode mount loss

The resultant efficiency shown in Table 1.4-4 refers to already demonstrated diode performance and does not include any diode technology improvement effects. It is customary to predict in the literature about 5% improvement in efficiency by diode improvement and circuit loss reduction.

On the other hand the above calculation neglects the effect of diode aging and the fact that the spacecraft and rectenna generally are not at the same longitude. For instance a 5^{o} longitude differential introduces an additional appr. 92.61% factor for the ring 10 arrays, which have relatively large directivities. At any rate a maximum 5% efficiency growth may be assumed relative to the demonstrated performance assumed in this report.

There are approximately 7.654×10^{9} arrays (diode assemblies) in the overall antenna.

Panel Assembly

From the dipole or array assemblies panels are formed. It is assumed that the panel is the smallest assembly from fabrication point of view. 10 m^2 is selected for the panel area, with a N-S plane dimension of 3 m and E-W plane dimension of 3.33 m. Figure 1.4-11 shows a typical panel assembly in the center of the rectenna. It is assumed that all panel sizes are identical and this requries 7060224 panels in the rectenna. There are four different type of panels, corresponding to the four different type of receiving arrays. Although the dipoles and diodes are identical for all panels the combining- matching-filtering circuits and the diode wiring represents four types.

Figure 1.4-12 shows the layout of the various type of panels and corresponding arrays. Table 1.4-5 summarizes the characteristics of the panels.

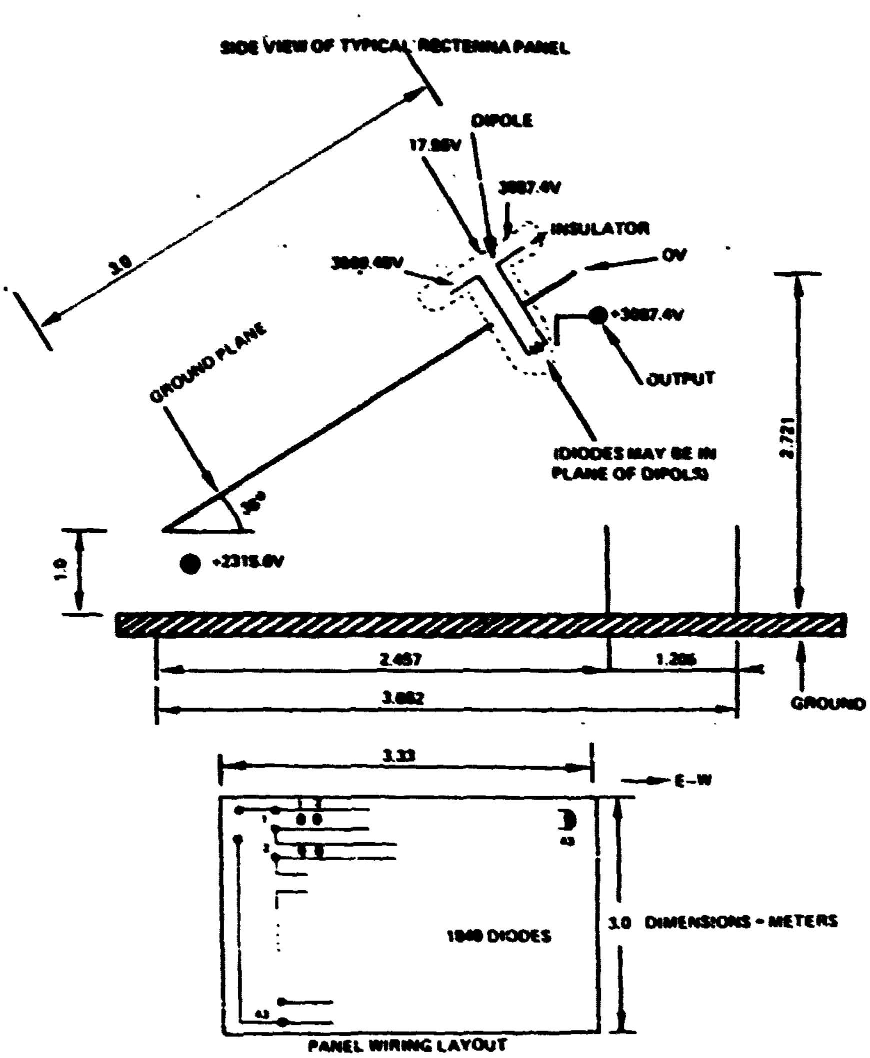


Figure 1.4-11. Conceptual Layout of Panel in the Middle of Rectenna Containing 1849 Dipoles and Diodes (Dimensions are in m.)

Table 1.4-4. Received Power and Efficiency Characteristics Associated with Various Rectenna Ring Regions

Ring Center	$P\ \frac{mw}{cm^2}$	Array Type	Received RF Power Per Diode P_D (w)	Ideal Conversion Efficiency	Circuit Loss Efficiency	Diode and Mount Resistance Loss Efficiency	Mismatch Loss Efficiency	Unequal Field Distribution Efficiency	Resultant Efficiency η_r
1	23.33	1	1.261	.836	.933	.97	.99	.955	.7453
2	18.76	1	1.014	.828	.933	.97	.99	.993	.7366
3	14.38	1	.778	.818	.933	.97	.99	.990	.7255
4	11.42	2	1.228	.836	.912	.97	.99	.988	.7251
5	8.67	2	.932	.824	.912	.97	.99	.985	.7216
6	6.72	2	.722	.810	.912	.97	.99	.982	.6966
7	5.34	2	.574	.798	.912	.97	.99	.979	.6842
8	4.24	3	.917	.825	.891	.97	.99	.976	.6889
9	3.49	3	.735	.814	.891	.97	.99	.973	.6776
10	3.14	4	1.393	.840	.871	.97	.99	.970	.6815

Table 1.4-5. Characteristics of the Panels

Ring	$P\ \frac{mw}{cm^2}$	$P_{RF}\ \frac{w}{Panel}$	η_r	$P_{DC}\ \frac{w}{Panel}$	Dipoles	Diodes	$V_{DC}\ \frac{V}{Diode}$	$P_{DC}\ \frac{w}{Diode}$	$V_{DC}\ \frac{V}{Panel}$	$I_p\ \frac{A}{Panel}$	$R_{DC}\ \frac{ohm}{Panel}$
1	23.33	2333	.7453	1738.8	43 x 43 = 1849	1849	17.96	.9398	772.3	2.25	1100
2	18.76	1876	.7366	1375.2	1849	1849	16.11	.7437	692.7	1.98	1100
3	14.38	1438	.7255	1043.3	1849	1849	14.11	.5642	606.7	1.72	1100
4	11.42	1142	.7251	828.1	2x30x31 = 1860	930	17.73	.8904	549.6	1.53	1136
5	8.67	867	.7216	625.6	1860	930	15.44	.6727	478.6	1.31	1136
6	6.72	672	.6966	468.1	1860	930	13.39	.5033	421.3	1.11	1136
7	5.34	534	.6842	365.4	1860	930	12.12	.3929	373.7	.973	1136
8	4.24	424	.6889	292.1	4x21x22 = 1848	462	15.32	.6322	337.0	.866	1232
9	3.49	349	.6776	236.5	1848	462	13.90	.5119	305.6	.773	1232
10	3.14	314	.6815	214.0	8x15x15 = 1800	225	18.90	.9511	283.5	.755	1100

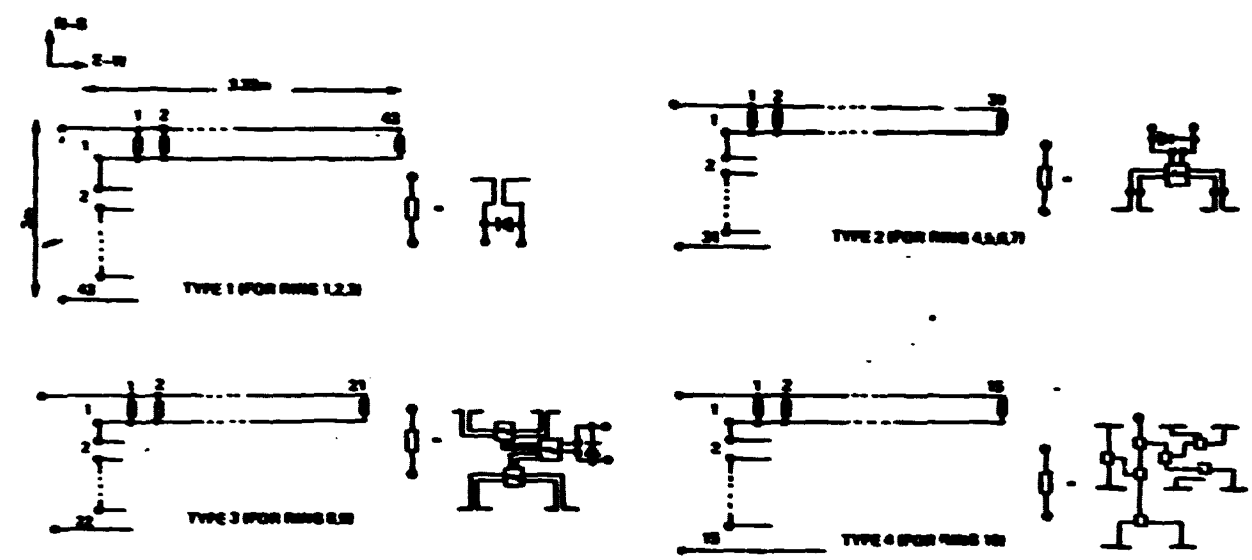


Figure 1.4-12. Wiring Layout of the Four Different Panel Designs Used in the Rectenna

Unit Assembly

From the panels unit assemblies are formed. The units are combined from panels in such a manner that nominally 1000 panels are in one unit and the N-S dimension of a unit is always 32 x 3.662 = 117.184 m, which means that the number of panel rows in the N-S plane is always 32. This allows a standardization of the unit layouts to a minimum of seven types.

Figure 1.4-13 shows the unit layouts selected for the various rings and Table 1.4-6 gives the main characteristics of the units.

Figure 1.4-14 shows the overall layout of the rectenna with the ring boundaries and the number of units within each ring. The coordinates of the ring boundaries are given in Table 1.4-7. Note, that the N-W dimension of the units are standardized to 117.8 m everywhere within the rectenna and only the E-W dimension of the units varies from ring to ring.

Group Assemblies

The last assembly which is formed at DC is called "group" and brings the power output into the 5 10 MW range. In order to keep the voltage levels relatively low the groups are formed from the units by paralled connections only.

The power from the unit output is brought to the group centers, where the DC to AC inverters are located by a relatively long transmission line and these lines are parallel connected at the group centers only. Table 1.4-8 shows the characteristics of the group assemblies.

Figure 1.4-15 presents the overall circuit diagram of group 1 in ring 1 of the rectenna on the basis of the previous calculations.

Loss Calculations

In order to determine the total loss associated with the DC power collecting network and its weight (cost) the connecting line material and cross section must be selected for the panel, unit and group assemblies. Tables 1.4-8 through 1.4-11 summarizes the results of these network loss calculations.

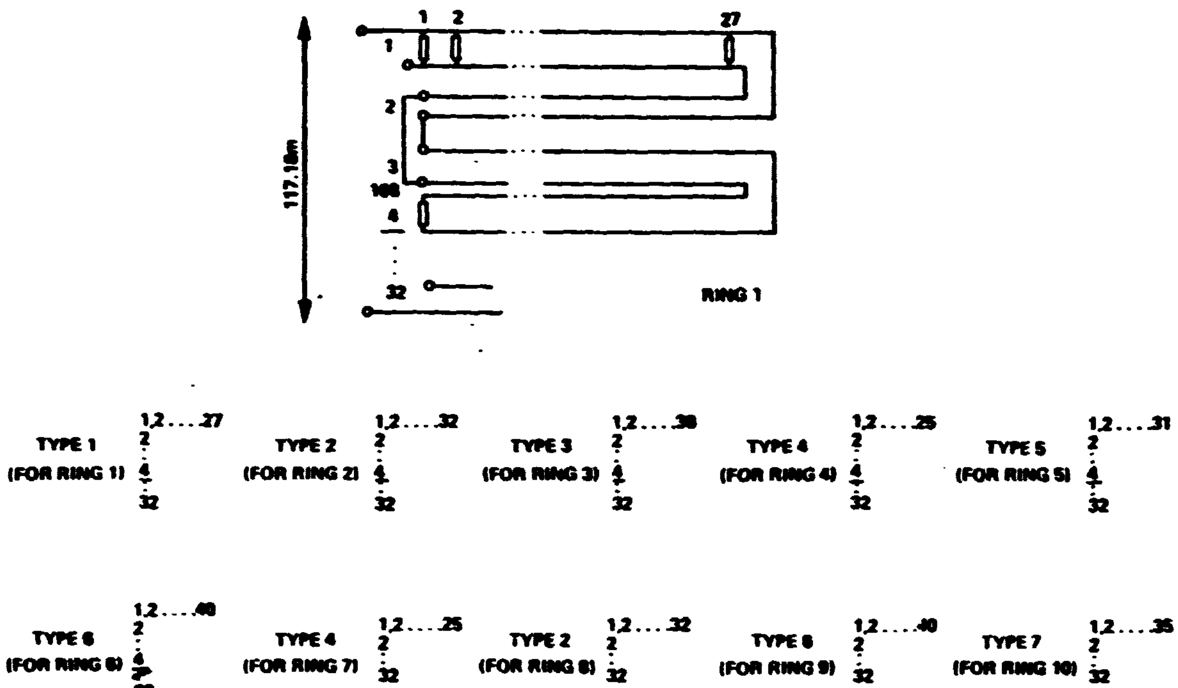


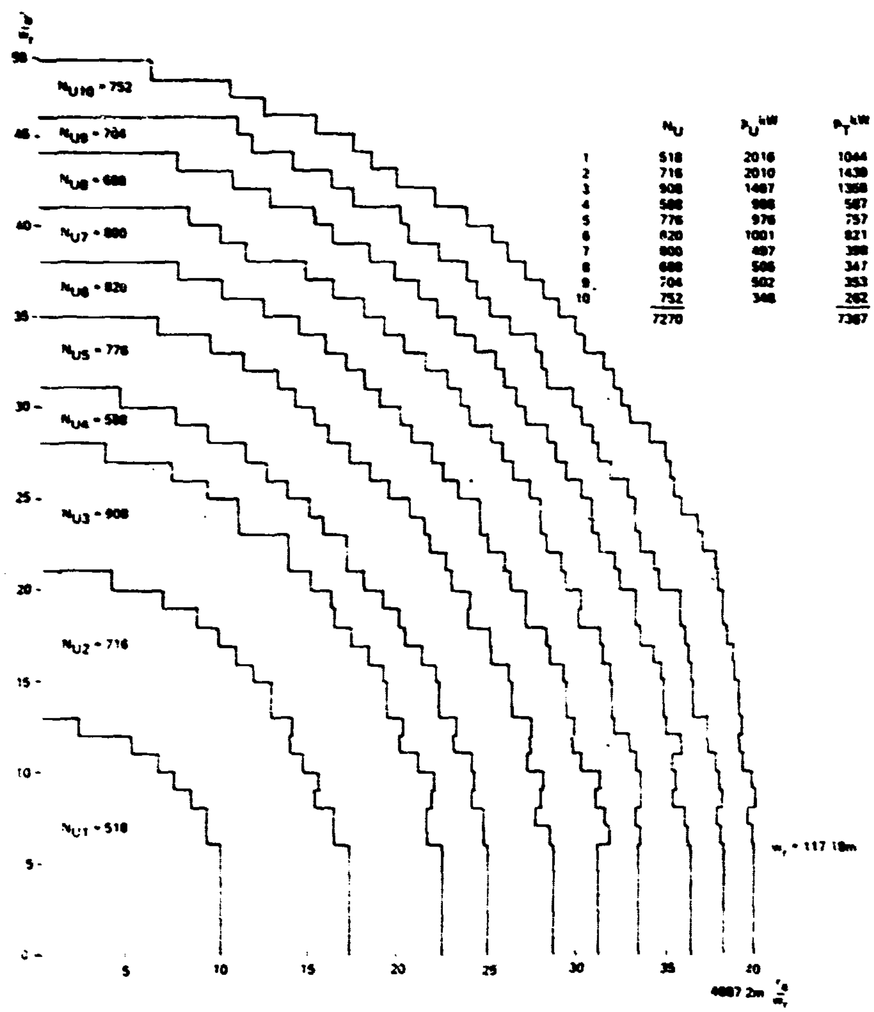
Figure 1.4-13. Wiring Layout of the Seven Different Unit Designs used in the Rectenna for the Low Voltage Configuration

Table 1.4-6. Characteristics of the Units

Ring		No. of Panels Per Unit	No. of Rows of Par. Panels	No. of Panels Per String	No. of Series Strings	V / unit	Mw / unit	A / unit	ohm / unit	No. of Units	Total Mw Power	Normalized Total Power
1		864	4	108	8	6174.8	1.502	243.2	81.48	518	778.0	.1590
2		1024	4	128	8	5541.6	1.408	254.1	68.75	716	1008.3	.2061
3		960	4	120	8	4853.6	1.002	206.4	73.33	906	909.4	.1859
4		800	4	100	8	4396.8	.6624	150.6	90.88	588	389.5	.0796
5		992	4	128	8	3828.8	.6206	162.1	71	776	481.6	.0984
6		1200	4	160	8	3370.4	.5991	177.7	56.8	820	491.3	.1004
7	*	800	2	50	16	6011.2	.2923			800		
	**	400					.5846	97.25	181.76	400	233.8	.0478
8	*	1024	2	64	16	5392	.2991			688		
	**	512					.5982	110.9	144	344	205.8	.0421
9	*	1280	2	80	16	4892.8	.3027			704		
	**	640					.6054	123.7	115.2	352	213.5	.0435
10	*	1120	2	70	16	4536	.2397			752		
	**	280					.9587	211.3	125.71	188	180.2	.0368

*Subunit
**Unit

Total DC Power Without Conductor Losses: 4891.4
Input Power to Rectenna: 6792.7
Efficiency Without Conductor Losses: 72.01%



	N_U	P_U kW	P_T kW
1	518	2016	1044
2	716	2010	1439
3	908	1487	1358
4	588	986	587
5	776	976	757
6	820	1001	821
7	800	487	398
8	688	506	347
9	704	502	353
10	752	348	262
	7270		7387

Figure 1.4-14. Geometrical Layout of Unit Boundaries in the Rectenna (Within Each of the Ten Rings of Units Different Unit Power Levels are Used)

Table 1.4-7. Coordinates for Boundaries of Rings of Units

		Ring [a]									
Row	r_b [a]	1	2	3	4	5	6	7	8	9	10
1	117.18	1186.49	2006.78	2664.76	2938.97	3392.48	3673.72	3947.93	4299.48	4486.97	4700.25
2	234.37	1186.49	2006.78	2664.76	2938.97	3392.48	3673.72	3947.93	4299.48	4486.97	4700.25
3	351.55	1186.49	2006.78	2664.76	2938.97	3392.48	3673.72	3947.93	4299.48	4486.97	4700.25
4	468.74	1186.49	2006.78	2664.76	2933.97	3392.48	3673.72	3947.93	4299.48	4486.97	4700.25
5	585.92	1186.49	2006.78	2664.76	2936.97	3392.48	3673.72	3947.93	4299.48	4486.97	4700.25
6	703.10	1186.49	2006.78	2664.76	2938.97	3392.48	3673.72	3947.93	4299.48	4486.97	4700.25
7	820.29	1087.47	1907.75	2566.33	2931.94	3385.44	3760.43	3943.24	4294.73	4482.29	4690.87
8	937.47	1087.47	1907.75	2566.33	2931.94	3271.78	3740.51	3923.32	4274.87	4462.36	4668.61
9	1054.66	1087.43	1907.69	2566.24	2931.84	3385.33	3760.31	3943.11	4294.65	4482.13	4696.57
10	1171.84	1087.43	1907.69	2566.24	2931.84	3271.66	3740.39	3923.19	4274.73	4462.21	4668.45
11	1289.02	989.00	1809.26	2577.96	2858.02	3305.64	3680.62	3954.82	4274.73	4511.43	4724.70
12	1406.21	790.96	1826.83	2595.54	2869.74	3323.22	3698.20	3972.40	4206.76	4487.99	4701.26
13	1523.39	592.93	1647.55	2416.25	2783.02	3236.51	3517.74	3883.34	4234.88	4422.37	4637.98
14	1640.58	247.25	1653.41	2422.11	2787.71	3241.20	3522.43	3796.63	4148.17	4429.40	4642.67
15	1757.76		1523.34	2292.04	2657.64	3111.13	3486.10	3760.30	4111.84	4299.33	4627.44
16	1874.94		1523.34	2292.04	2657.64	3111.13	3486.10	3760.30	4111.84	4299.33	4627.44
17	1992.13		1406.16	2285.01	2650.61	3104.10	3479.07	3753.27	4104.81	4292.30	4613.38
18	2109.31		1288.98	2167.83	2533.43	2986.92	3361.89	3727.49	4079.03	4266.52	4587.60
19	2226.50		1171.80	2050.65	2416.25	2983.40	3358.38	3723.98	3958.34	4239.57	4560.64
20	2343.68		1054.62	1933.47	2390.47	2843.96	3218.93	3584.54	3584.54	4224.34	4545.41
21	2460.86		820.26	1786.99	2283.84	2850.99	3225.96	3591.57	3943.11	4224.34	4545.41
22	2587.05		468.72	1786.99	2152.60	2719.75	3094.72	3460.32	3811.86	4093.10	4520.80
23	2695.23			1647.55	2013.15	2693.97	3068.94	3434.54	3786.08	4067.31	4495.02
24	2812.42			1647.55	2013.15	2580.30	2955.28	3320.88	3672.42	3953.55	4832.53
25	2929.60			1318.27	1775.28	2547.49	2922.47	3320.88	3641.95	3923.19	4350.89
26	3046.78			1318.27	1775.28	2456.09	2924.81	3290.41	3641.95	3923.19	4244.26
27	3163.97			1097.98	1647.55	2328.37	2797.09	3255.26	3606.80	3888.03	4209.11
28	3281.15			439.42	1354.60	2035.42	2595.54	3052.54	3404.08	3685.31	4114.19
29	3398.34				1097.98	1892.46	2454.92	3004.50	3356.03	3637.27	4064.97
30	3515.52				914.00	1822.15	2384.61	2842.79	3194.32	3569.30	3773.20
31	3623.70				548.40	1682.70	2245.17	2793.57	3145.11	3525,95	3847.02
32	3749.89					1588.96	2151.42	2699.83	3051.37	3338.46	3766.16
33	3667.07					1361.63	2017.84	2567.41	3036.13	4489.17	3745.07
34	3984.26					1134.30	1884.25	2432.66	2901.38	3276.35	3597.43
35	4101.44					794.48	1731.92	2280.32	2749.04	2655.30	3551.73
36	4218.62						1499.90	2139.70	2608.42	2983.40	3412.28
37	4335.81						1188.20	1939.33	2536.95	2911.92	3340.80
38	4452.99						937.44	1761.21	2347.11	2815.83	3243.54
39	4570.76							1373.34	2193.61	2662.33	3090.03
40	4687.36							1189.38	1892.46	2454.92	2990.43
41	4804.54							1006.57	1826.83	2369.30	2818.18
42	4921.73								1523.34	2085.80	2621.32
43	5038.91								1288.98	1945.19	2372.89
44	5156.10								937.44	1687.39	2222.90
45	5273.28									1406.16	2048.30
46	5390.46									1312.42	1847.93
47	5507.65										1499.90
48	5624.83										1285.47
49	5742.02										749.95

Table 1.4-8. Characteristics of the Groups

Ring	Parallel Units	N_G	No. of Residual Units	V^V	R^Ω	P^{Mw}	I^A
1	6	85	8	6175	13.58	9.012	1459.2
2	4	179	0	5542	17.18	5.632	1016.4
3	8	112	12	4854	9.166	8.016	1651.2
4	8	72	12	4397	11.36	5.299	1204.8
5	8	97	0	3829	8.875	4.965	1296.8
6	10	82	0	3370	5.68	5.991	1777
7	10	40	0	6011	18.18	2.923	972.5
8	8	43	0	5392	18	4.786	887.2
9	8	44	0	4893	14.4	4.843	989.6
10	8	22	4	4536	15.71	7.669	1690.4

Specials

1	4	2	0	6175	20.37	6.008	972.8
3	6	2	0	4854	12.22	6.012	1238.4
4	6	2	0	4397	15.15	3.974	903.6
10	6	2	0	4536	20.95	5.7522	1267.8

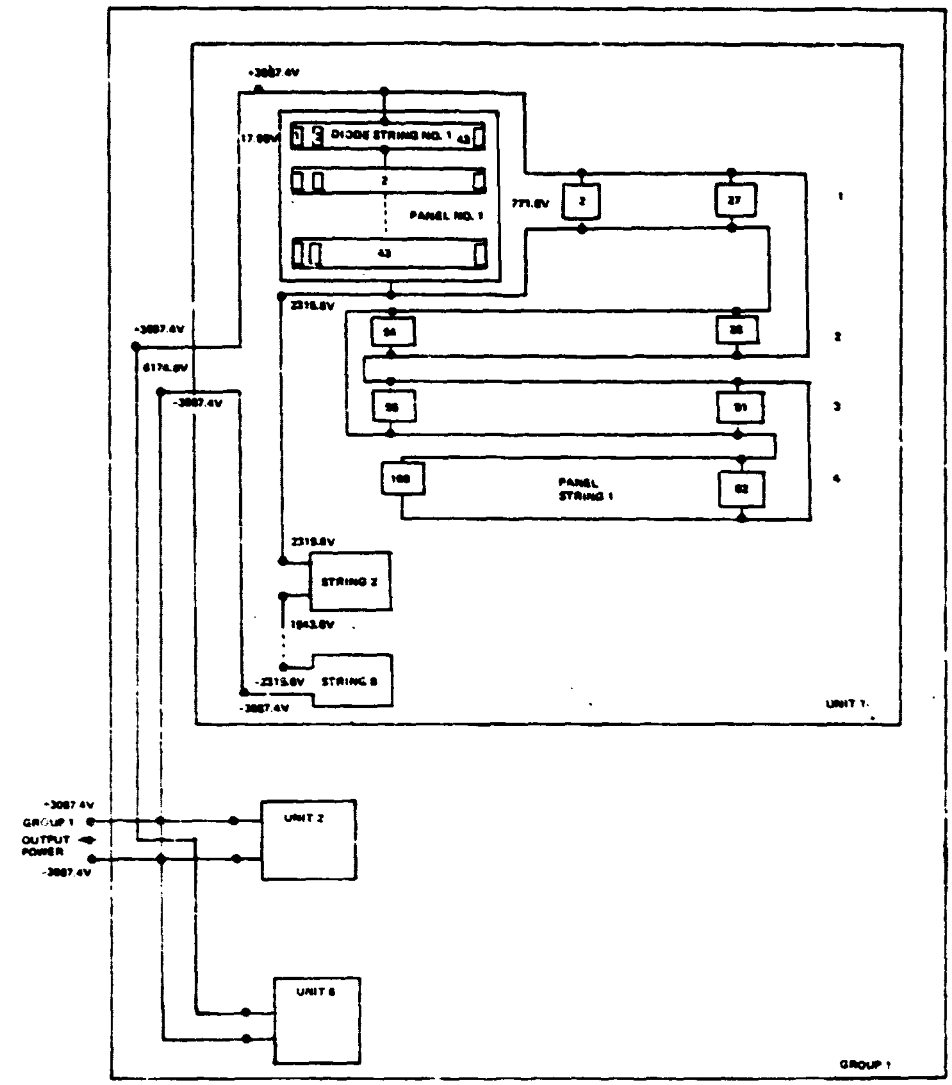


Figure 1.4-15. Block Diagram of a Typical Group for the Low Voltage Configuration. Example shows a Group within the Inner Ring (Circle) of the Rectenna Aperture

Table 1.4-8. Loss Calculation for Panel Lines (Al. Wires)

Ring	I_P^A	A^{mm}	R_o $\frac{ohm}{m}$	$\frac{1}{2}L_P^m$	R_P^{ohm}	Loss/Panel W	Loss/Panel %	M^W Total Loss	N_P	L_P^{km}	G_P $\frac{kg}{km}$	G^T
1	2.25	1.5	.02394	146.2	3.274	16.54	.953	7.40	447552	130864	4.087	534.8
2	1.98	1.5	.02394	146.2	3.274	12.83	.933	9.41	733184	214383	4.087	876.2
3	1.72	1.5	.02394	146.2	3.274	9.68	.673	8.44	871680	254879	4.087	1041.7
4	1.50	1	.0359	106.2	3.812	8.58	1.035	4.03	470400	99912	2.724	272.2
5	1.31	1	.0359	106.2	3.812	6.54	1.045	5.03	769792	163503	2.724	445.5
6	1.11	1	.0359	106.2	3.812	4.69	1.003	4.92	1049600	222935	2.724	619.6
7	.973	1	.0359	106.2	3.812	3.61	.988	2.30	640000	67968	2.724	185.1
8	.866	1	.0359	76.25	2.736	2.05	.702	1.44	704512	53719	2.724	146.3
9	.773	1	.0359	76.25	2.736	1.63	.691	1.46	901120	68710	2.724	187.2
10	.755	.5	.0718	52.95	3.802	2.16	1.012	1.80	842240	22298	1.362	30.3
						Total		46.23				4339
						Input		4891.4				
						Loss %		.945				
						Output		4845.2				

Table 1.4-9. Loss Calculation for Unit Lines

Ring	I_U^A	A^{mm^2}	R_o $\frac{ohm}{m}$	$\frac{1}{2}L_u^m$	R_u ohm	Loss/Unit kw	Loss/Unit %	Total Loss Mw	N_u	L_u^{km}	G_u $\frac{kg}{km}$	G^T
1	243.2	1600	2.243×10^{-5}	2877	.06455	3.817	.254	1.977	518	2980	4359	12991
2	254.1	1600	2.243×10^{-5}	3413	.07655	4.942	.351	3.538	716	4887	4359	21299
3	206.4	1600	2.243×10^{-5}	3199	.07175	3.056	.305	2.775	908	2905	4359	12661
4	150.6	800	4.486×10^{-5}	2666	.11959	2.712	.409	1.594	588	3135	2179	6832
5	162.1	800	4.486×10^{-5}	3306	.14831	3.897	.627	3.024	776	5131	2179	11181
6	177.7	1600	2.243×10^{-5}	4266	.09568	3.021	.504	2.477	820	6996	4359	30491
7	97.25	800	4.486×10^{-5}	5332	.23919	2.262	.386	.905	400	8531	2179	18591
8	110.9	800	4.486×10^{-5}	6826	.30621	3.766	.629	1.295	344	9393	2179	20469
9	123.7	1600	2.243×10^{-5}	8532	.19137	2.928	.447	1.030	352	12013	4359	52357
10	211.3	1600	2.243×10^{-5}	7465	.16743	7.475	.780	1.405	188	11227	4359	48931
						Total		20.02				235803
						Input		4845.2				
						Loss %		.413				
						Output		4845.2				

Table 1.4-10. Loss Calculation for Unit to Group Combining Lines

Ring	I_U	A^{mm^2}	$L_{UG}{}^{m}$	$R_{UG}{}^{ohm}$	Total Loss MW	N_U	$L_{UG}{}^{km}$	G_{UG} $\frac{kg}{km}$	G^T
1	243.2	1600	179.8	.004033	.12	518	93.1	4359	406
2	254.1	1600	106.7	.002393	.08	716	76.4	4359	333
3	206.4	1600	300	.006729	.25	908	272.4	4359	1187
4	150.6	800	250	.01121	.14	588	147.0	2179	320
5	162.1	800	310	.01391	.28	776	240.6	2179	524
6	177.7	1600	800	.01794	.46	820	656.0	4359	2859
7	97.25	800	999.8	.04485	.15	400	799.8	2179	1743
8	110.9	800	853.3	.03828	.16	344	587.1	2179	1279
9	123.7	1600	533.3	.01195	.06	352	375.4	4359	1636
10	211.3	1600	933.2	.02029	.18	188	701.8	4359	3059

Total 1.88 13348

Input 4825.2

Loss % .038

Output 4823.3

Only one iteration was made for the selection of conductor sizes and the system shown in the tables is not optimized. However, the calculation shows the sensitivity of the losses to the amount of metal used and as might be expected the losses in the units are limiting the overall system. Relatively small amount of additional conductor weight could take out some losses from the panels (about 4300 T aluminum can reduce panel losses by .48%) however the increasing conductor size increases the fabrication problems and may rule out the use of printed conductors on the panels.

The reduction of unit line weights by a factor of 2 can save about 117900 T of aluminum at the expense of deteriorating the loss by .41%, however, the associated loss of revenue probably does not justify such a reduction.

Table 1.4-12 summarizes the transfer losses for the overall SPS system.

1.4.3.3 Layout and Characteristics of a Low Current DC System

If safety and environmental considerations, and furthermore reliable high voltage insulators allow the use of larger DC voltages in the DC power collection system, then it is advantageous to increase the voltage as much as possible. This allows the reduction of conductor losses without excessive conductor weights thus may result in a lower cost rectenna.

As indicated previously, due to the uncertainties associated with this design, it was not selected as the baseline configuration. Nevertheless, because of its potential advantages a few of the calculated characteristics are included here.

The low current design is identical to the low voltage design up to the output of a panel. Furthermore the same number of panels can be used in a unit then for the low voltage

Table 1.4-11. Summary of Losses and Transmission Line Weights

Ring	Loss^{MW} Panel	Unit	Group Line	Total	Weight^{T} Panel	Unit	Group Line	Total
1	7.40	1.98	.12	9.50	535	12991	406	13932
2	9.41	3.54	.08	13.03	876	21299	333	22508
3	8.44	2.77	.25	11.46	1042	12661	1187	14890
4	4.03	1.59	.14	5.76	272	6832	320	7424
5	5.03	3.02	.28	8.33	445	11181	524	12150
6	4.92	2.48	.46	7.86	620	30491	2859	33970
7	2.30	.90	.15	3.35	185	18591	1743	20519
8	1.44	1.29	.16	2.89	146	20469	1279	21894
9	1.46	1.03	.06	5.44	187	52357	1636	54180
10	1.80	1.40	.18	3.38	30	48931	3059	52020
	46.23	20.02	1.88	66.13	4339	235803	13348	253490

Total DC Power at Diode Output	4891.4
Loss %	1.393
Total DC Power at Inverter Input	4823.3

Table 1.4-12. Summary of Power Transfer Losses without Equipment Failures and Propagation Effects in Analyzed Part of SPS System

Input Interface: Output from transmit aperture of space antenna

Output Interface: Input to power grid

	Mw	Efficiency Factors		
Satellite RF Radiated Power	7124.9	.9534 (beam)	.6769 (RF to DC)	.6667 (RF to AC)
Rectenna RF Input Power	6792.7	.7200 (resultant conversion)		
Rectenna DC Input Power		.9861 (DC transmission)		
Rectenna DC Output Power	4823.3	.985 (AC conversion and transmission)		
Rectenna AC Output Power	4750.9			

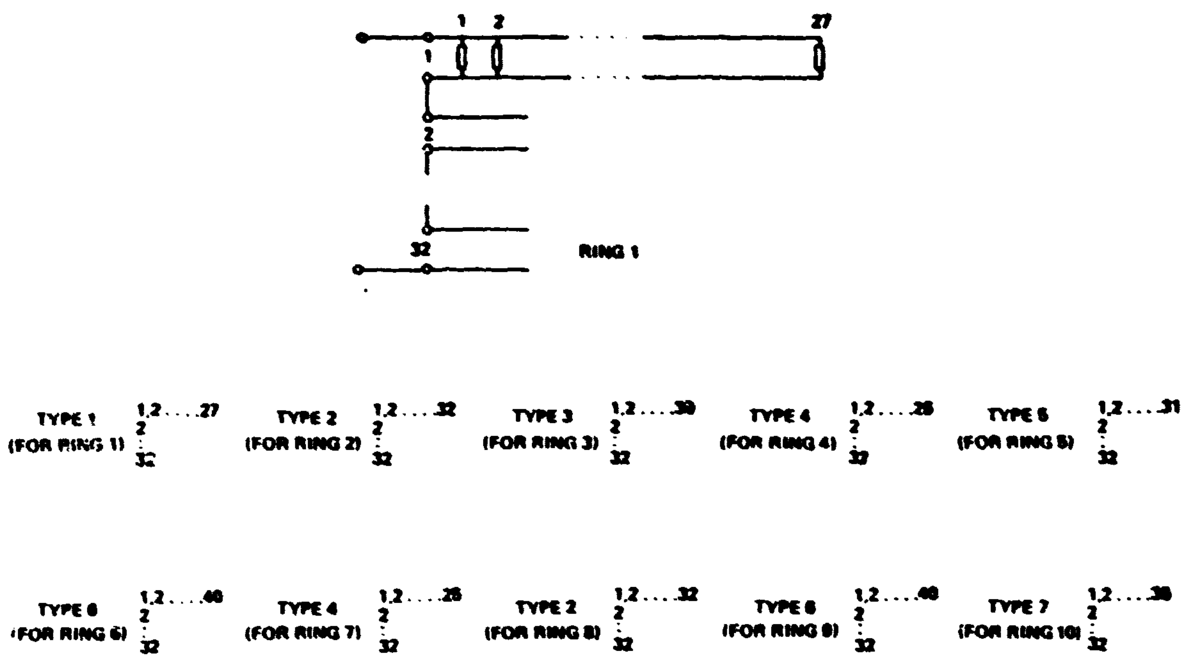


Figure 1.4-16. Wiring Layout of the Seven Different Unit Designs Used in the Rectenna for the Low Current Configuration

Table 1.4-13. Characteristics of Units in Low Current Design

Ring	Parallel Panels	No. of Series Pan. Strings	$\frac{kV}{V_{unit}}$	$\frac{A}{I_{unit}}$
1	27	32	24.69	60.80
2	32	32	22.17	63.52
3	30	32	19.41	51.60
4	25	32	17.87	37.65
5	31	32	15.31	40.52
6	40	32	13.48	44.42
7	25	32	12.02	24.31
8	32	32	10.78	27.72
9	40	32	9.78	30.92
10	35	32	9.07	52.82

design. However, in this configuration much smaller panel strings are formed and about the same number of panels are connected parallel then in series.

Figure 1.4-16 shows the unit configuration and Table 1.4-13 summarizes the applicable voltage and current levels.

From the units groups are formed in such a way that the line voltages are further increased. Table 1.4-14 shows the obtainable voltage and current levels.

A comparison between the low voltage and low current design at panel and group levels reveals, that their currents are essentially identical. However, at the most important unit level, the low current design typically has 1/4 of the current levels. Thus for identical conductors the losses will be 1/16 or for identical losses the conductor weights can be reduced by a factor of 16. On the basis of Table 1.4-10 this represents a conductor weight saving of

$$235803\,(1 - \frac{1}{16})\ T = 221065T$$

out of a total of 253490T, thus reduces the conductor weight to 32424T (a factor of 7.8!) The cost impact of such a saving could be in the order of 10 - 20% for the rectenna and 1 - 2% at the overall system level.

WBS 1.4.4 Control

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 Lincon, for JSC under separate contract.

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

WBS 1.4.5 Layout and Characteristics of AC System and Interphase with Electric Utility Systems

This selection of the layout for the rectenna AC system between the individual DC/AC converters and the bulk power levels of the DC/AC converters as well as on the needs of the bulk power transmission system. The one-line diagram for the rectenna AC system as it was developed for the previous baseline design where the DC output from the dipoles were collected into 40 MW DC/AC converter stations is shown in Figure 1.4-17. The 40 MW converter 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 interphase with the bulk transmission system. The

Table 1.4-14. Characteristics of Groups in Low Current Design

Ring	No. of Parallel Units	No. of Series Units	No. of Groups	Unit / Group	kV / V_{Group}	A / I_{Group}
1	4	2	64	8	49.38	243.2
2	4	2	89	8	44.34	254.1
3	4	2	114	8	38.82	206.4
4	4	3	49	12	53.61	150.6
5	4	3	64	12	45.93	162.1
6	6	2	68	12	26.96	266.5
7	6	3	44	18	36.06	145.8
8	8	3	28	24	32.34	221.8
9	10	4	18	40	39.12	309.2
10	5	6	24	30	54.42	264.1

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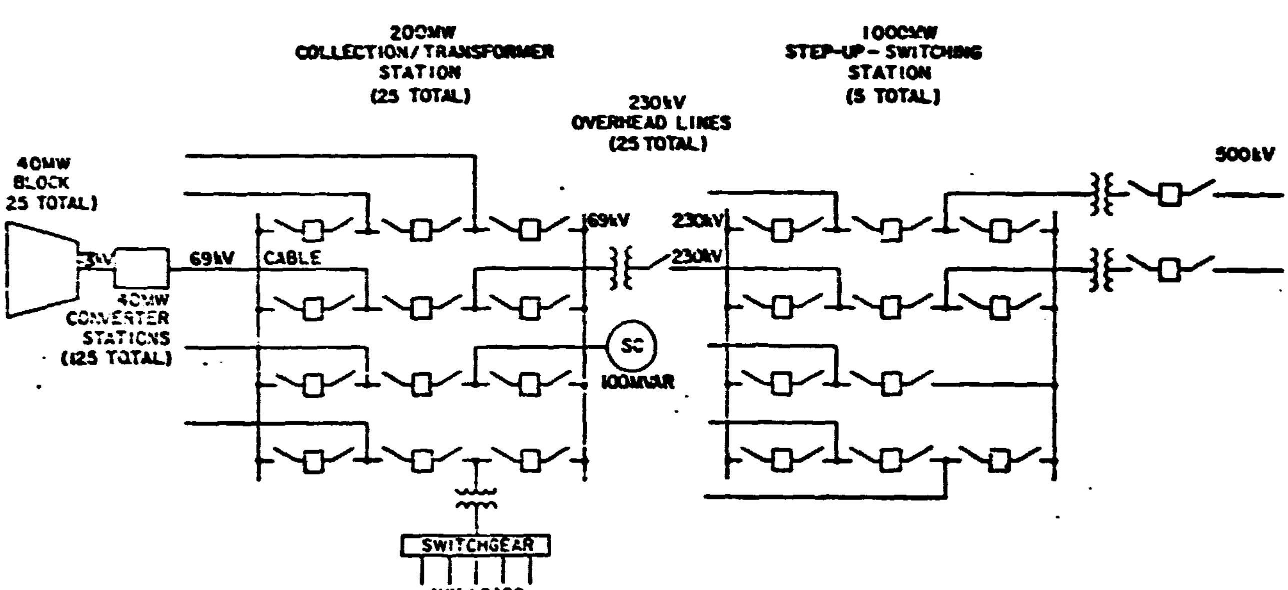

Figure 1.4-17. Ground Power Collection and Transmission System

switchyards are shown arranged as reliable "breaker and a half" schemes where single contingency outages may be sustained without loss of power output capability. The selection of the voltage level for the ultimate bulk power transmission interface with the utility grid as well as the possibility of interconnecting two or more of the 1000 MW switching stations together should be optimized based on detailed information about the connecting utility system. The solution shown in Figure 1.4-17 is one of several possible.

Further consideration of the transmission system and associated high voltage bussing arrangements has resulted in refinements which should provide both greater reliability and economy. While an arrangement as shown in Figure 1.4-17 nicely fits an assumption of symmetrically located load areas surrounding the site, it is more likely that the major portion of the output would be required at a single area geographically. For example, with location of the ground power station in the desert areas of the Southwest, one would expect that the major output would be absorbed on the West Coast.

With this in mind, it is logical to consider fewer transmission circuits from a single substation in a double bus type of arrangement.

Figure 1.4-18 shows the proposed arrangement, using a total of six 500 kV circuits, four of which are assumed direct to a single load area with the remaining two circuits directed to two additional load areas. It is anticipated that any two of the 6 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 sudden fault loss of a second circuit, or sudden loss of two circuits alone. Additional circuits would, of course, provide the ability to handle additional multiple contingency situations.

The breaker and a half arrangement shown can survive a fault in any component without load reduction. The major contingency situations are:

Bus fault	- no loss of circuits
Breaker fault	- one or two circuits lost, depending on breaker location
"stuck" breaker (i.e., failure to trip for line fault)	- one or two circuits lost (including faulted circuit) depending on location of stuck breaker

The conventional electric utility bulk transmission systems operates AC and the following paragraph will discuss system parameters on AC transmission systems to illustrate the considerations necessary when selecting AC or DC as well as voltage levels for the high voltage transmission system connecting the SPS power plant to the rest of the electric utility system.

For conventional generating stations, depending on the distance to the load center, some series capacitor compensation of the AC transmission lines would normally be expected when considering contingency line loadings. Typical line loadings versus distance and amount of series compensation for AC transmission lines is shown in Figure 1.4-19.

When considering contingency loadings as discussed above with 2 lines down and 4 lines carrying the full 5000 MW the line loadings would be 1.25 times the surge impedance loading (SIL). The surge impedance loading for various voltage levels are shown in Table 1.4-15 and for 500 kV, the SIL would be about 1000 MW. From Figure 1.4-19 it would appear that a reasonable transmission distance with no series compensation for this example would be about 200 miles, which could be increased to 350 or 400 miles with up to 70% series compensation.

To define the specific requirements for a given situation, load flow and system stability studies would be required. It is likely, however, that the SPS power system would be far more stable than a conventional power plant of the same rating. This would mean that the transmission distances could be increased for a given line loading without need for series compensation.

When substantial amounts of power are to be transported for distances of 400 miles or more, the consideration of a high-voltage DC (HVDC) as the transmission load is often indicated. The HVDC system is ideally suited for long distance bulk power transport since it does not suffer from stability effects and can even be used to improve the stability of the AC system to which it is connected. The DC system is asynchronous and can easily transmit power between independent power systems such as those of the Eastern and the Western United States.

There are, however, certain specific requirements to be met. At each of its terminals the DC transmission system absorbs reactive power which must be supplied by static capacitors, rotating machines, like synchronous condensers or from the connected AC

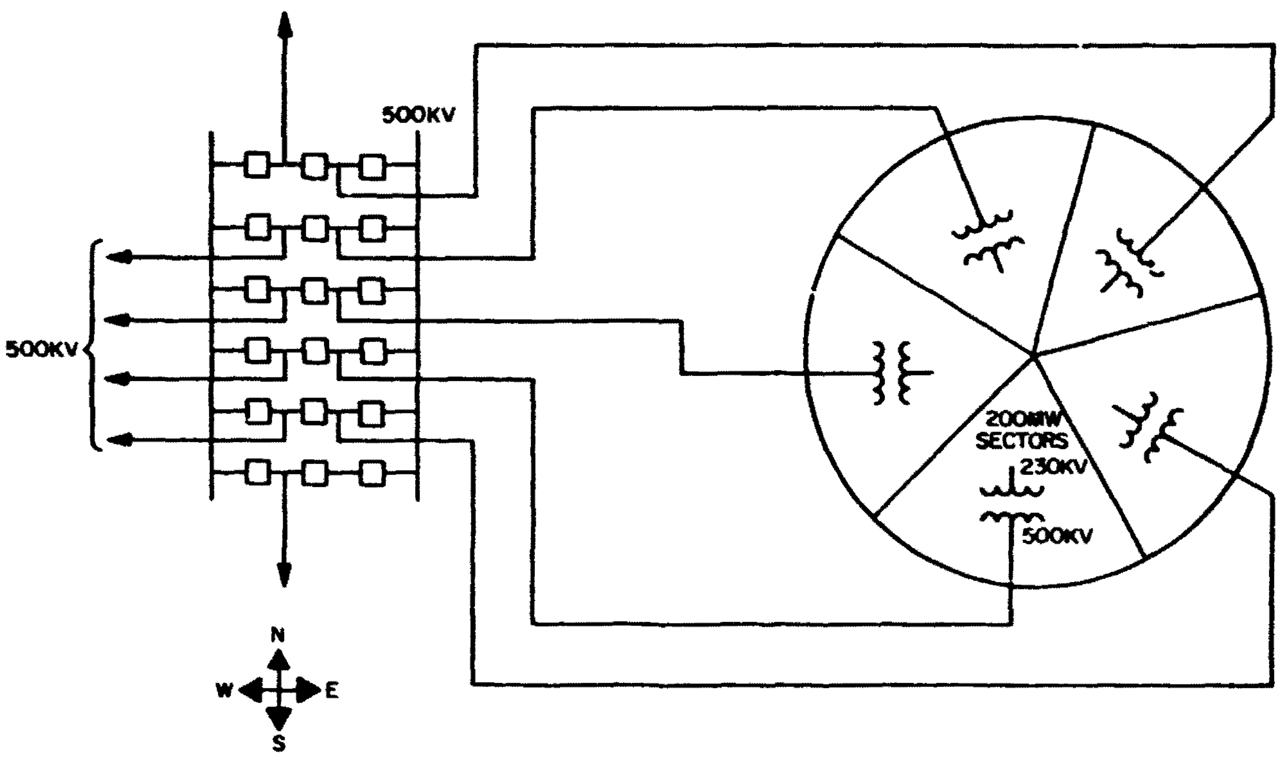

Figure 4.1-18. Transmission Requirement for Utility Interface

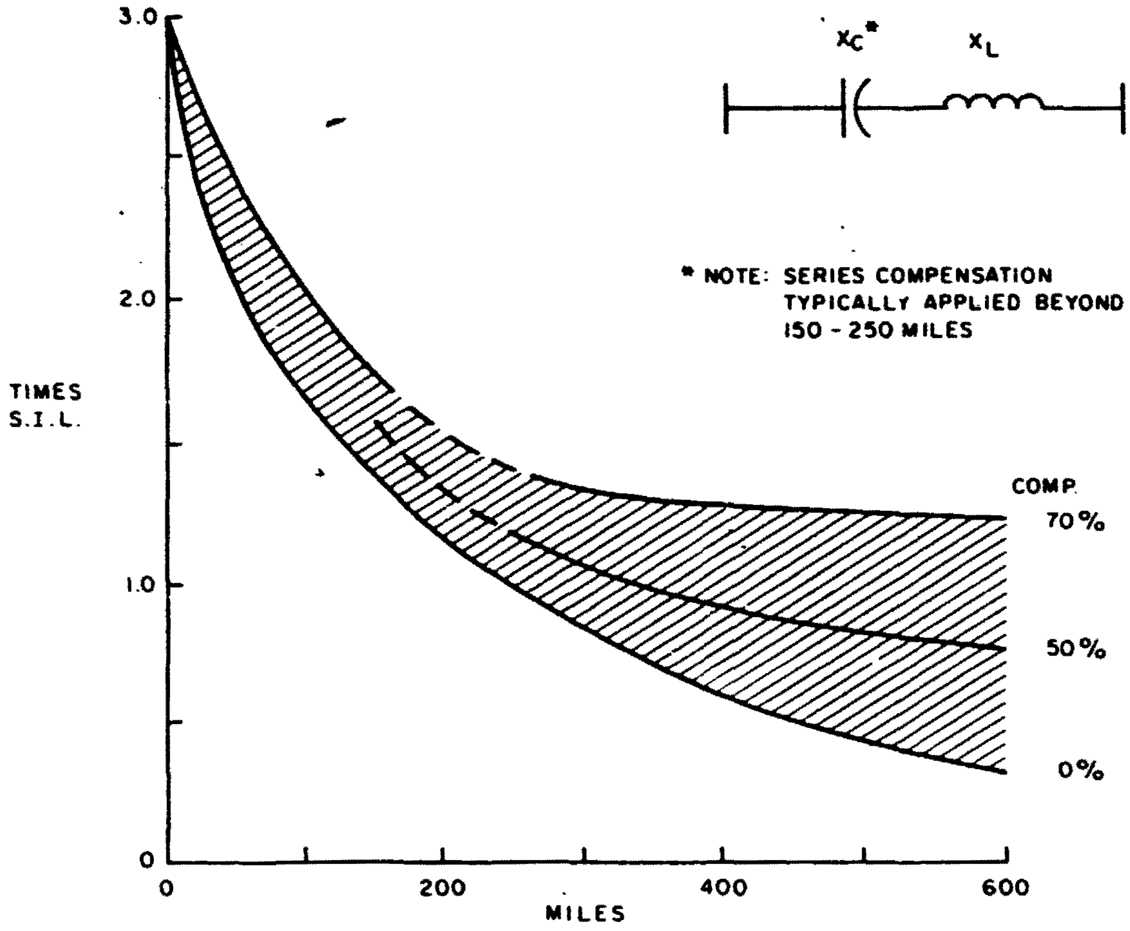

Figure 1.4-19. Typical Economic Line Loadings

network. Reactive volt-amperes equal to approximately 60% of the transmitted active power are required.

Table 1.4-15. Representative Line Surge Impedance Loadings (SIL)

Line Volt kV	One Conductor MW	Two Conductor MW	Three Conductor MW	Four Conductor MW
242	146	183	209	--
362	327	410	468	504
550	--	945	1080	1160
800	--	--	2280	2460

The current on the AC side of the terminals contains substantial harmonic components which must be removed, generally by shunt-connected tuned circuits. These filters are also large enough to provide some of the required reactive power.

Lastly, the DC terminal must be connected to an active AC network having a short circuit capacity (in volt-amperes) equal to a minimum of two times the transmitted power. If the AC system does not have the required level of short circuit capacity, which would be the case for the SPS system, synchronous condensers (also called synchronous compensators) are connected adjacent to the terminals. They will regulate the AC system voltage, provide the needed system strength, and provide the reactive power not generated by the filters. For these same reasons synchronous condensers have also been recommended for use with the DC to AC converters within the rectenna system.

When the requirements for filtering, reactive supply, and short circuit capacity are met, the HVDC system is a reliable, efficient, and readily controlled power transmission medium.

A typical HVDC power transmission circuit is shown in Figure 1.4-20. The synchronous condensers and AC filters are shown connected to the AC switchyard. The DC terminal consists of three phase bridge converters connected in parallel on the AC side and in series on the DC side. Although only two bridges are shown between ground and the DC

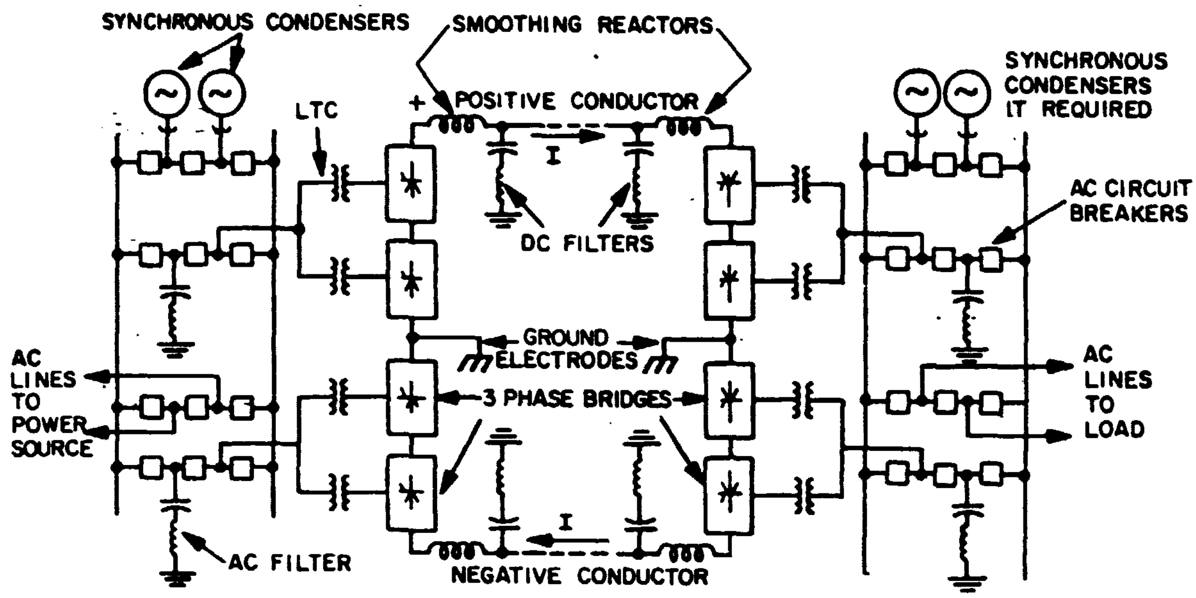

Figure 1.4-20. Elements of a HVDC Transmission System

conductor, it is not uncommon for four such bridges to be applied when the DC voltage exceeds ± 400 kV.

The DC system is balanced with respect to ground and is firmly held this way by fully rated ground electrodes. In normal operation there is no current in these ground electrodes, but in an emergency if one conductor in its converters are lost, the other conductor and the ground circuit will continue to transmit half power. Such emergency use can usually be tolerated. The transformers which couple the AC system to the bridges are shown equipped with load tap changers (LTC) which insure that the converter operates at the proper voltage and firing angle regardless of normal smaller variations in the AC system voltage.

Power flow in the DC system is subject to accurate and rapid electronic control. Power is held steady or adjusted according to source or load requirements as desired. In this respect is is ideally suited for the SPS power transmission system.

HVDC technology is advanced and the systems have been well received. A 6300 MW system in Brazil is currently in the proposal stages with full scale operation scheduled for 1985. It would appear that a DC system or a combination of DC and AC system could be applied to the Solar Power Satellite system with few difficulties using today's electric utility system's transmission design practices.

WBS 1.5 MANAGEMENT

Management systems were not defined. An allowance for program management costs was made in the cost analyses.