NASA CR-134886
ER75-4368

NASA

MICROWAVE POWER TRANSMISSION SYSTEM STUDIES

VOLUME IV SECTIONS 9 THROUGH 14 WITH APPENDICES

RAYTHEON COMPANY
EQUIPMENT DIVISION
ADVANCED DEVELOPMENT LABORATORY
SUDBURY, MASS. 01776

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3-17835

(NASA-CR-134886-Vol-4) MICROWAVE POWER TRANSMISSION SYSTEM STUDIES. VOLUME 4: SECTIONS 9 THROUGH 14 WITH APPENDICES (Raytheon Co.) 235 p HC $8.00 CSCL 10B
N76-15597
Unclas
G3/44 07455

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-134886		

4. Title and Subtitle
MICROWAVE POWER TRANSMISSION SYSTEM STUDIES
Volume IV - Sections 9 through 14 with Appendices

5. Report Date
December 1975

6. Performing Organization Code

7. Author(s)
O. E. Maynard, W. C. Brown, A. Edwards, J. T. Haley, G. Meltz, J. M. Howell - Raytheon Co.; A. Nathan - Grumman Aerospace Corp.

8. Performing Organization Report No.
ER75-4368

9. Performing Organization Name and Address
Raytheon Company
Equipment Division
528 Boston Post Road
Sudbury, Massachusetts 01776

10. Work Unit No.

11. Contract or Grant No.
NAS 3-17835

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D. C. 20546

13. Type of Report and Period Covered
Contractor Report

14. Sponsoring Agency Code

15. Supplementary Notes
Mr. Richard M. Schuh
NASA Lewis Research Center
Cleveland, Ohio 44135

16. Abstract -- A study of microwave power generation, transmission, reception and control was conducted as a part of the NASA Office of Applications' joint Lewis Research Center/Jet Propulsion Laboratory five-year program to demonstrate the feasibility of power transmission from geosynchronous orbit. This volume (4 of 4) is comprised of Sections 9 through 14 which present receiving antenna, frequency interference and allocation, risk assessment, system analysis and evaluation, critical technology and ground test program, critical technology and orbital test program. Section 9 reviews and discusses the microwave rectifier technology, approaches to the receiving antenna, topology of rectenna circuits, assembly and construction, with ROM cost estimates. It includes analyses and cost estimates for the equipment required to transmit the ground power to an external user. Section 10 presents the analyses and discussion associated with radio frequency interference and allocation. Noise and harmonic considerations are presented for both the amplitron and klystron. Interference limits are identified and evaluated. Section 11 presents the risk assessment discussion wherein technology risks are rated and ranked with regard to their importance in impacting the microwave power transmission system. Section 12 presents the system analyses and evaluation of parametric studies of system relationships pertaining to geometry, materials, specific cost, specific weight, efficiency, converter packing, frequency selection, power distribution, power density, power output magnitude, power source, transportation and assembly. Capital costs per kW and energy costs as a function of rate of return, power source and transportation costs as well as build cycle time are presented. Appendices include estimated annual operations and maintenance cost for 5 and 10 GW systems, systems analysis examples and format for the readers use. Section 13 presents the critical technology and ground test program including objectives, configurations, definition of test Phases I through III and critical technology development with ROM costs and schedule. Section 14 presents the orbital test program with associated critical technology and ground based program based on full implementation of the defined objectives. ROM costs and schedule estimates are included. An appendix is included which provides further detail of the ground and orbital test programs such that the reader may readily modify configurations as studies and technology developments mature leading to modification of the driving objectives.

17. Key Words (Suggested by Author(s))
Microwave power transmission; power from space; satellite power transmission; phased array power transmission; rectifying antenna (rectenna).

18. Distribution Statement
Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	234	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22161

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LIST OF NON-STANDARD TERMS

AFCRL	Air Force Cambridge Research Laboratory
ATC	Air Traffic Control
ATS	Applications Technology Satellite
CFA	Crossed Field Amplifier
CPU	Central Processor Unit
GaAs	Gallium Arsenide
HLLV	Heavy Lift Launch Vehicle
Met	Meteorological
MPTS	Microwave Power Transmission System
MW	Microwave
N. F.	noise factor
PPM	periodic permanent magnet
ROM	Rough Order of Magnitude
SCR	Silicon Controlled Rectifier
SEPS	Solar Electric Propulsion Stage
Sm-Co(SMCO)	Samarium Cobalt
SPS	Satellite Power System
SSPS	Satellite Solar Power Station
TDRS	Tracking and Data Relay Satellite
TEC	Total Electron Content

SECTION 9

RECEIVING ANTENNA

The collection and rectification of microwave power from space is conceptually a two step process and in the early stages of development of microwave power transmission it was treated in this fashion. However, it was determined early that the individual requirements placed upon the collection of microwave power and upon the rectification of microwave power in a two step process could not be met by any available technology or any forseeable technology development. The rectenna concept, however, which in effect combined collection and rectification into a one-step process was found to meet all of the requirements for the collection and rectification of the power in a free-space microwave beam. Furthermore, it was found that the concept could be experimentally established immediately from available components and technology.

It is also of interest to note that the portion of a microwave power transmission system represented by the collection and rectification of microwave power has grown in the last decade from the weakest and most insecure portion of the of the system to the strongest and most secure. This has come about not only because of the soundness of the rectenna concept but also because this is the portion of the system whose development has received the most attention. The most recent portion of this development process has considered not only the efficiency and reliability aspects, but also those aspects dealing with low-cost fabrication. This has resulted in a large amount of "winnowing" of design approaches to arrive at a rather high level of design specificity. Since much of this winnowing has occurred in the period of the last three years, it is not highly documented although the general direction and the motivational influences are recorded in Reference 1. Therefore, it is desirable initially to review some of the factors which have led to the present detailed design.

9.1 MICROWAVE RECTIFIER TECHNOLOGY

The efficient conversion of microwave power directly into dc power is a technology that is specifically related to the concept of power transmission by microwaves in either a free-space or confined waveguide mode. As contrasted to dc to microwave conversion which has received broad support from many areas, there has been little support of the reverse process.

Early investigators of the use of microwaves for power transmission in the 1957-1960 time frame resorted to the conversion of microwave energy at the receiving point into heat, which was used either directly or to run a heat engine. However, this approach leads to many mechanical complications and in any event can provide an overall efficiency of at most 30%. These considerations led immediately to the desire for an efficient electronic device that would convert the microwave power directly into dc power.

The earliest known rectifier development projects in which the end use was intended for power purposes rather than information were those supported by two contracts from the laboratories of the U.S. Air Force at Wright Field. One of these contracts was awarded to Purdue University [2,3] to examine broadly the development of devices to rectify microwave power. The other was awarded to the Raytheon Company [4] for the study of a rectifier device that was the rectifier analog of the magnetron. The findings of these two investigations were important background in determining the course of subsequent investigations and in attempts to develop and operate complete systems making use of microwave power transmission.

Rectifiers may be classified in several different ways. One division of classifieation is into solid-state and electron-tube devices. Another division would be into microwave-tube analog devices and diode rectifiers. Still another classification would be into low-impedance devices and high-impedance. Microwave-tube analog devices are characterized by low-current and high-voltage output, whereas diode rectifiers of both the solid-state and electron-tube types tend to be low impedance devices.

There was considerable interest from private and industrial organizations in addition to the limited interest of the Department of Defense in the technology of microwave power rectification in the 1958 to 1962 time period. This interest is well documented in Okress, "Microwave Power Engineering", Volume I [5]. Figure 9-1 summarizes a number of these concepts and their state of development. One of these concepts, the close spaced thermionic diode rectifier [6] reached a state of development in which it could be used as a rectifier in the first known demonstration of microwave power transmission. However, it had serious reliability and life problems.

CLASS	SUBCLASS	STATUS* REACHED	MAXIMUM EXPERIMENTAL EFFICIENCY (%)	MAXIMUM EXPERIMENTAL POWER (WATTS)	FREQUENCY BAND	DEVICE IMPEDANCE
COLLINEAR BEAM	TWT	CONCEPTUAL	------	------	---	HIGH
COLLINEAR BEAM	KLYSTRON	CONCEPTUAL	------	------	---	HIGH
CROSSED-FIELD	INJECTED BEAM	EARLY DEVEL.	42	162 (CW)	S	HIGH
CROSSED-FIELD	MAGNETRON	EARLY DEVEL.	22	25,000 (PEAK)	L	MEDIUM
CROSSED-FIELD	CYCLOTRON	EARLY DEVEL.	12	12,000 (PEAK)	L	MEDIUM
DIODE	MULTIPACTOR	CONCEPTUAL	------	------	---	MEDIUM
DIODE	THERMIONIC	EARLY DEVEL.	55	900 (CW)	S	LOW
DIODE	SEMI-CONDUCTOR	ADVANCED	90	10 (CW)	S	LOW

* FROM 1966 TO PRESENT-TIME THERE HAS BEEN NO SIGNIFICANT SUPPORT OF MICROWAVE RECTIFIER DEVICE TECHNOLOGY. IMPROVEMENTS IN SEMICONDUCTOR DEVICES HAVE RESULTED AS SPIN-OFFS FROM OTHER APPLICATIONS.

** ALL OF THESE DEVICES ARE DESCRIBED IN OKRESS, MICROWAVE POWER ENGINEERING.

Figure 9-1. Microwave Rectifier Device Technology **

Although many rectifier divices which were the analogs of various microwave generators were proposed, only the development oi the rectifier analog of the magnetron was supported. This device proved to be impractical for reasons of a very basic physical nature.

The point-contact semiconductor diode was earlier demonstrated to be an efficient converter of microwaves into dc power, but its power handling capability was so low as to cause it to . nitially dismissed from serious consideration. Later, with the introduction e "rectenna" concept, its true potential as a microwave rectifier was recognized.

The limited but broad interest in microwave power rectification devices of all kinds that was initiated in the 1958 to 1962 time frame did not continue beyond that period. Residual interest was focused upon the Schottky-barrier diode because of its high demonstrated efficiency and its relationship to the rectenna concept. As a result there is today no broadly based microwave power rectification technology, and any approaches to the collection and rectification of microwave power must rely upon the semiconductor diode, whose power handling capability is limited.

The chronology of the collection and rectification of microwave power is given in Figure 9-2 and major development programs are outlined in Figure 9-3. The introduction of the Gallium Arsenide Schottky-barrier diode [1, 16] proved very significant in terms of high efficiency and power handling capacity. The combination of this device with a harmonic filter to attenuate radiation of harmonics and to store energy for the rectification process led to the configuration shown in Figure 9-4. This was used in construction of a 4 foot diameter rectenna for Marshall Space Flight Center, and in the recently completed 25m^2 rectenna built for the Jet Propulsion Laboratory [21] that demonstrated 82% efficiency at an output power level of 32 kW.

Verification of rectenna element efficiency during this same program established a reference point on the curve of Figure 9-5. The variation of efficiency with frequency is estimated from the equivalent circuit, and is of value for system studies to establish a desirable MPTS operating frequency.

1958	First interest in microwave power transmission.
1958	No rectifiers available - turbine proposed and studied.
1959 - 1962	Some government support of rectifier technology a. Semiconductors at Purdue b. Magnetron analogue at Raytheon
1962	Semiconductor and close-spaced thermionic diode rectifiers made available.
1963	First power transmission using pyramidal horn and close-spaced thermionic diode rectifiers - 39% capture and rectification efficiency not practical for aerospace application.
1964	RADC microwave powered helicopter application demanded non-directive reception, light weight, high reliability.
1964	Rectenna concept developed to utilize many semiconductor rectifiers of small power handling capability to terminate many small apertures to provide non-directive reception and high reliability.
1968 - 1975	Continued development of rectenna concept to format with high power handling capability, much higher capture and rectification efficiency, and potentially low production cost.
1975	Development of rectenna for transmission of kilowatts of rf power over 1.54 km with reception and conversion of incident rf power to dc at high rf to dc efficiency (JPL RXCV Program).
1975	Initiation of contracted effort for improvement of rf to dc collector/converter technology (LeRc-NAS3-19722).

Figure 9-2. Chronology of Collection and Rectification of Microwave Power

Rectenna Sequence Number	Date	Sponsor	Developers	Motivation	Style	Major Contribution	Lit. Ref.
1	1964	Raytheon	George Brown Heenan	For Microwave-Powered Helicopter	Half-Wave Antennae Full-Wave Bridge	Established General Characteristics of Rectenna	7
2	1964	Raytheon/ Air Force	Brown	For Microwave-Powered Helicopter	String Type Array	High Power Density Receiver First Successful Application - Microwave Powered Helicopter	11, 12, 13
3	1968	Brown	Brown	Improve Rectenna Lower Specific Weight	Half-Wave Antennae Full-Wave Bridge Rectifier	Specific Weight - 1 Gram Per Watt	2, 7
4	1970	MSFC NASA	Brown	Improve Efficiency	Half-Wave Antennae Full-Wave Bridge Rectifier	51% Capture and Rectification Efficiency	6, 7, 8, 9
5	1971	MSFC NASA	Brown	Improve Efficiency	Half-Wave Antennae Full-Wave Bridge Rectifier	64% Capture and Rectification Efficiency	8, 10, 11
6	1974	MSFC NASA	Brown	Improve Efficiency Increase Power Output Increase Power Density	Half-Wave Antennae Half-Wave Rectifier Low Pass Filters	78-80% Capture and Rectification Efficiency 140 Watt/Sq. Ft. Power Density	
7	1971	MSFC NASA	Brown	Lightweight, Space-born, Roll-up Rectenna	Half-Wave Antennae Full-Wave Bridge	Explanatory Only	2, 7
8	1975	JPL NASA	Brown	For High Power Transmission Field Demonstration	Half-Wave Antennae Half-Wave Rectifier Low Pass Filters PHS Diode	82% Capture and Rectification Efficiency for >30 kW dc Power Output	21, 23
9	1975	LeRC NASA	Brown	High Efficiency at Low Incident RF Power Density	TBD	TBD	

Figure 9-3. Major Rectenna Development Programs

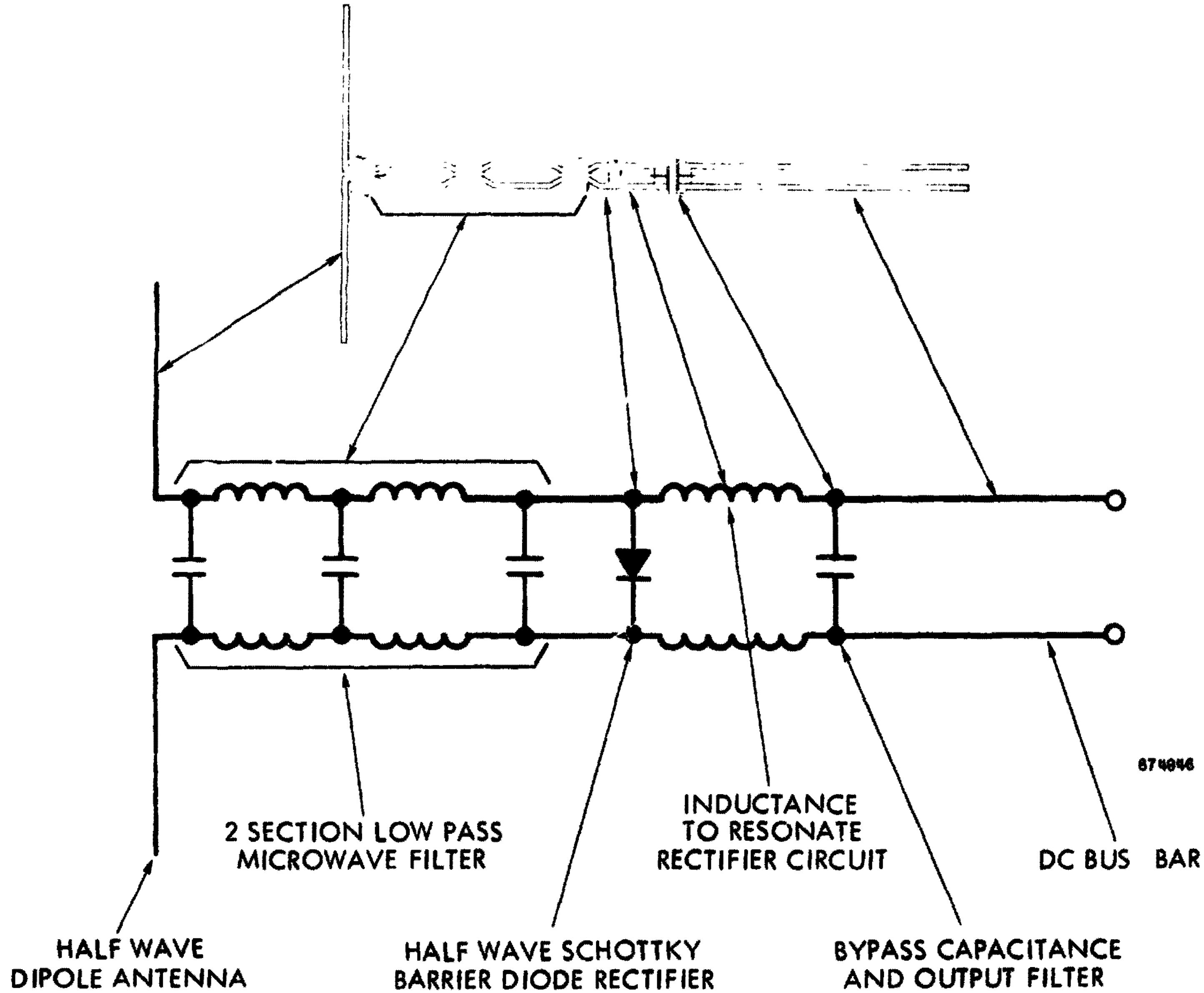


Figure 9-4. Simplified Electrical Schematic for the Rectenna Element

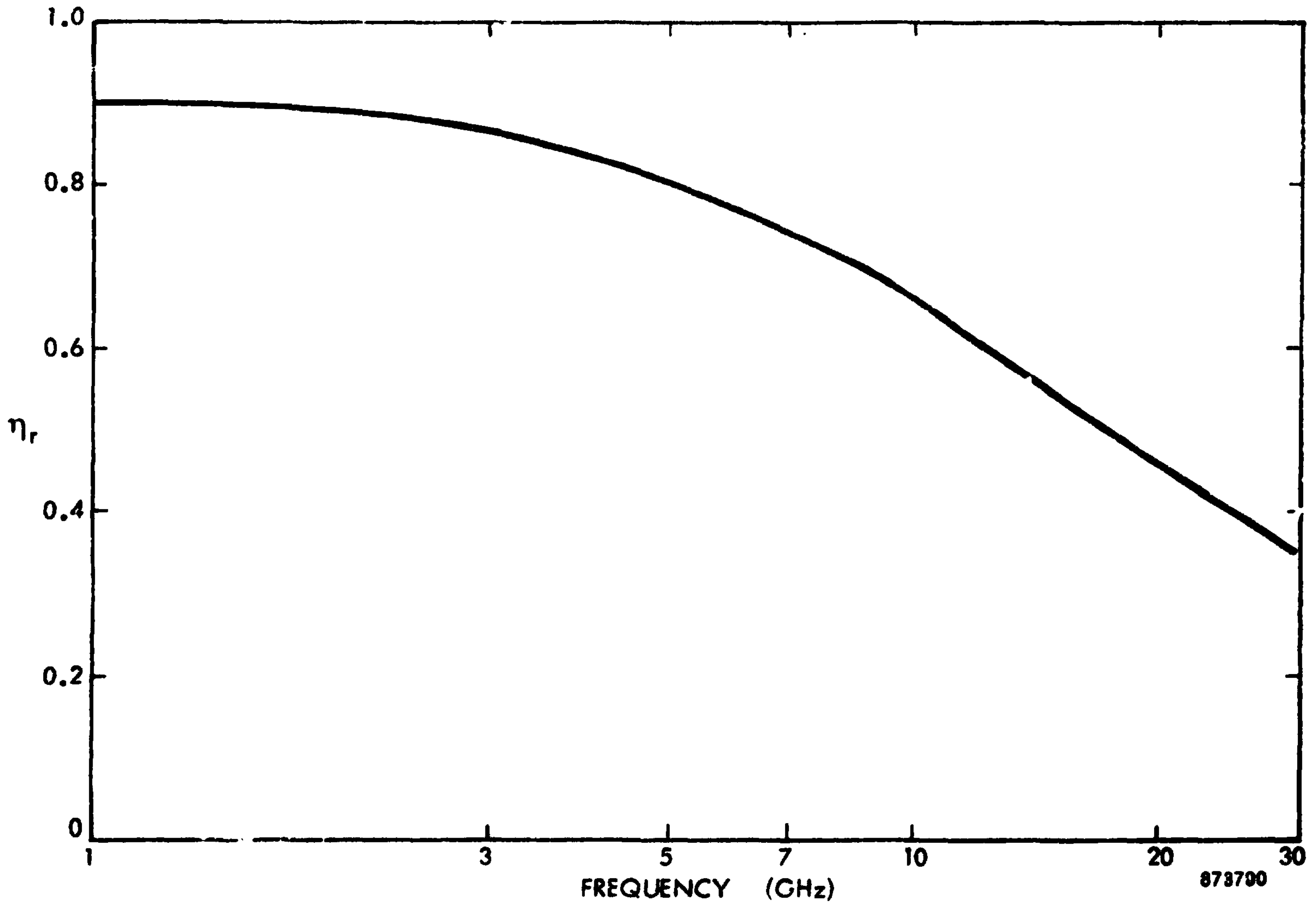


Figure 9-5. Rectenna Element Efficiency Vs Frequency

9.2 ANTENNA APPROACHES

The requirements for reception and rectification of microwave power from a transmitter in synchronous orbit are listed below.

a. Non-directive aperture
b. High absorption efficiency
c. High rectification efficiency
d. Very large power handling capability
e. Passive radiation of waste heat
f. High reliability
g. Long life
h. Low radio frequency interference (RFI)
i. Capable of being constructed in large aperture size
j. Easy mechanical tolerance requirements
k. Low cost

These requirements must be matched up with the capabilities of various approaches to performing this function. Each candidate approach must consist of a means of collecting the microwave power and then converting it into dc power. While there are a number of existing technologies that can be used to collect the power, there is only one existing rectifier technology that is at all practical and that is the semiconductor Schottky barrier diode. The diode may be used singly or grou in large numbers to provide the load for any collection approach, although obvious that auxiliary cooling will be necessary if large numbers are grouped together.

The number of ways in which the power may be collected is limited. It may be collected by an array of contiguous horns with independent microwave load, an array of contiguous reflectors and feed horns with independent microwave load, a phased array of small-aperture elements with a common microwave load, or an array of small aperture elements with independent microwave load (rectenna).

There is a basic objection to horn or reflector-horn collectors because of their inability to collect close to 100% of the power that impinges upon them. The near uniform power density of the microwave power impinging upon them will result in uniform illumination of the aperture and this will not match the natural aperture power density distribution of the horn or reflector and horn aperture. A number of steps may be taken to improve this efficiency but they will increase the cost of the collector and in any event will not make it possible to approach closely to 100% capture efficiency.

The phased array with common microwave load can improve upon this situation since the matching of its individual elements can be tailored to a uniform incident illumination. However, the common microwave load makes the phased array highly directive and would involve auxiliary cooling for the common microwave load.

A comparison of the various approaches with the requirements for reception and rectification of space-to-earth power transmission is given in Figure 9-6. It will be noted that all of the approaches with the exception of the rectenna approach fail in four or more ways to meet the criteria for ground collection and rectification. The rectenna approach meets them all.

There is one condition, however, in which the rectenna approach may be unfavorable. That condition is where the density of the illumination is so low that a single dipole cannot collect enough power to operate efficiently. Under these conditions it may be necessary to use one of the other collection schemes such as an array of dipoles which would feed enough power into a single diode to make it operate efficiently. Under these conditions the increased directivity may be acceptable.

The variation of power from the center of the receiving antenna to the edge for various system power levels is given in Figure 9-7, and the variation in efficiency with input power of a rectenna element using presently designed diodes is given in Figure 9-8. It may be seen that for a 10 km, 5 GW case that only the elements at the very center provide high efficiency. Under these circumstances it is appropriate to undertake development of a rectenna element with higher efficiency at lower power levels. Several design parameters are involved in this development. These include an increase in the circuit impedance of the rectenna element to increase the dc voltage at a given power output, a reduced junction area in the diode to optimize efficiency at the lower power levels, and finally a change in the junction materials from GaAs-Pt to GaAs-W which will produce less

REQUIREMENT FOR RECEPTION & RECTIFICATION OF SPACE-TO-EARTH POWER TRANSMISSION	ANTENNA APPROACH			
	ARRAY OF CONTIGUOUS HORNS	ARRAY OF CONTIGUOUS REFLECTORS & FEED HORNS	PHASED ARRAY OF SMALL-APERTURE ELEMENTS WITH COMMON MICROWAVE LOAD	ARRAY OF SMALL-APERTURE ELEMENTS WITH INDEPENDENT MICROWAVE LOAD (RECTENNA)
NON-DIRECTIVE APERTURE	NO	NO	NO	YES
HIGH ABSORPTION EFFICIENCY	< 70%	< 70%	∽100%	∽100%
HIGH RECTIFICATION EFFICIENCY	YES	YES	YES	YES
VERY LARGE POWER HANDLING CAPABILITY	YES	YES	YES	YES
PASSIVE RADIATION OF WASTE HEAT	NO	NO	NO	YES
HIGH RELIABILITY	YES	YES	YES	YES
LONG LIFE	YES	YES	YES	YES
LOW RADIO FREQUENCY INTERFERENCE (RFI)	YES	YES	YES	YES
CAPABLE OF BEING CONSTRUCTED IN LARGE APERTURE SIZE	YES	YES	YES	YES
EASY MECHANICAL TOLERANCE REQUIREMENTS	NO	NO	NO	YES
LOW COST	NO	NO	NO	YES

Figure 9-6. Comparison of Antenna Approaches in Meeting Requirements for Reception and Rectification in Space-to-Earth Power Transmission

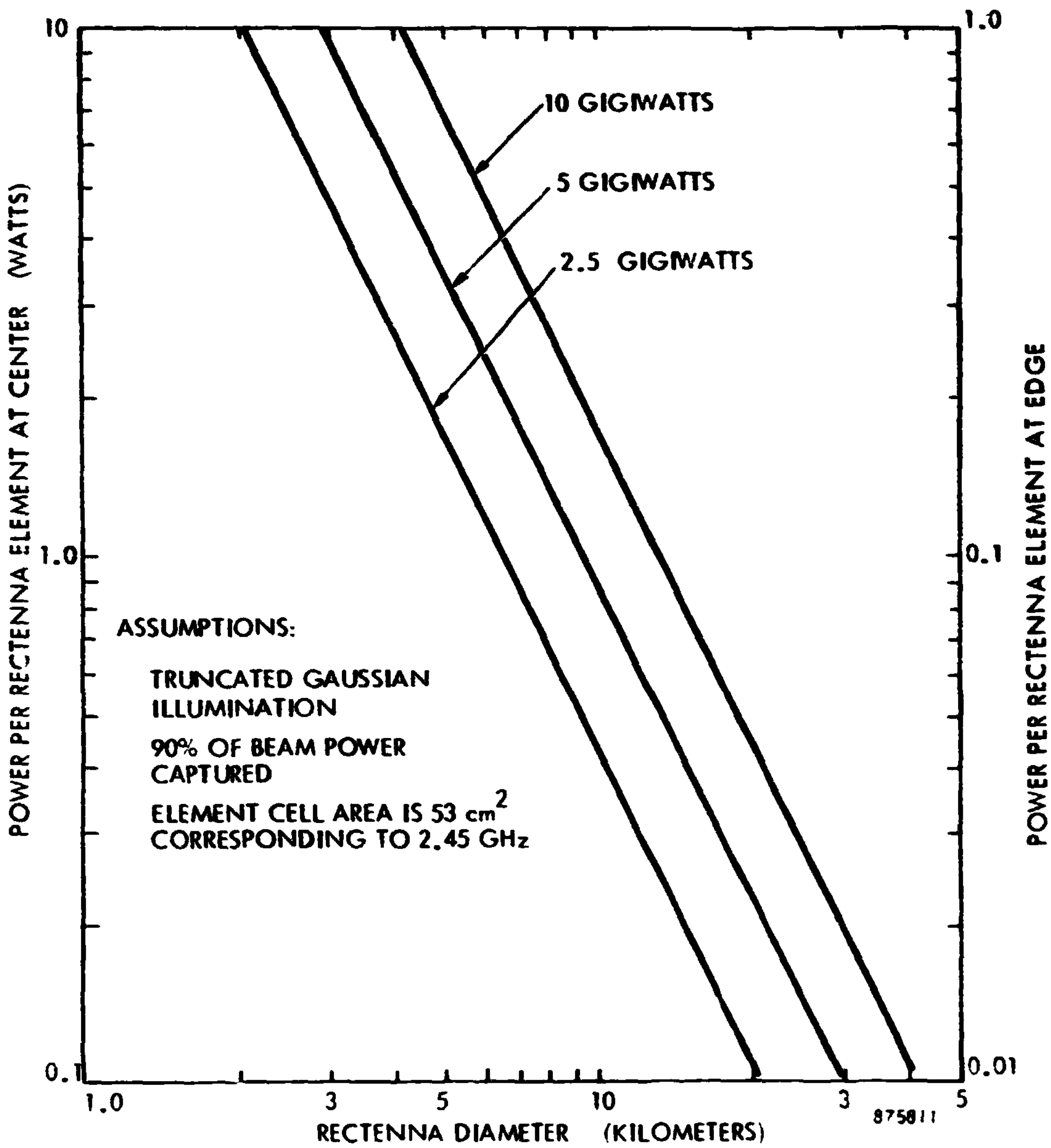


Figure 9-7. Dc Power from Center and Edge Rectenna Elements as Function of Rectenna Dia and Total dc Power Received

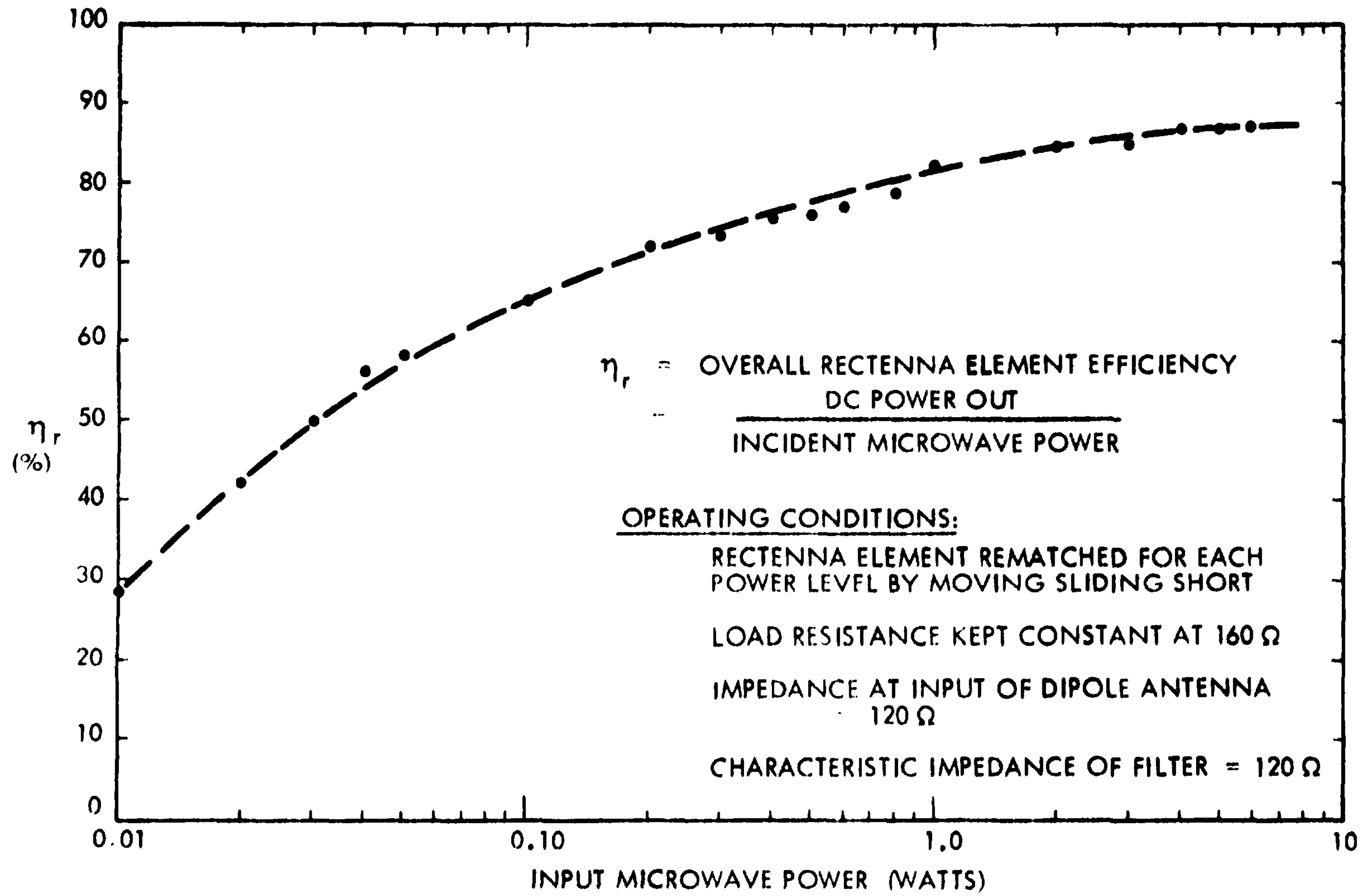


Figure 9-8. Rectenna Element Efficiency as Function of Microwave Power Input

power loss in the junction area. These are currently subjects of investigation at Raytheon under cortract NAS3-19722 to Lewis Research Center. The results of a preliminary study of the impact of these variables upon the losses in the diode are summarized in Figures 9-9 and 9-10.

9.3 TOPOLOGY OF RECTENNA CIRCUITS

Both the efficiency and low radio frequency interference requirements make it necessary to incorporate a low-pass filter into the rectenna element. A further requirement is a design configuration which can eventually be directly incorporated into a printed circuit, stripline, or similar configuration. Such a configuration has long been the ultimate objective of rectenna development programs because of its light weight and low cost. A rectenna must be a two-level structure to achieve high efficiency. However, the second level is merely a reflecting surface which need not be physically coupled to the front surface. The front surface plane can then be used to:

a. Absorb microwave power

b. Rectify it

c. Collect rectified power in dc collecting busses which carry the dc power to the edges of the rectenna section for collection into larger busses

d. Prevent radiation of power at harmonic frequencies

The use of the front plane for the first three of these functions was characteristic of several early experimental rectennas. However, these rectennas did not have filters which would prevent the reradiation of all power at harmonic frequencies. To prevent harmonic radiation it is necessary to insert a low-pass filter between the antenna element, which absorbs the power from space, and the rectifying element. This is shown schematically in Figure 9-11. In Figure 9-11, the large capacitance to the left of the dipole is placed a quarter wavelength from the dipole and therefore an infinite impedance is seen by the dipole terminals to its left.

A low pass filter must be constructed with inductance and capacitance if the losses are to be minimized, and the resulting configuration is shown in Figure 9-4 for a single section. It also shows how a single diode could be incorporated

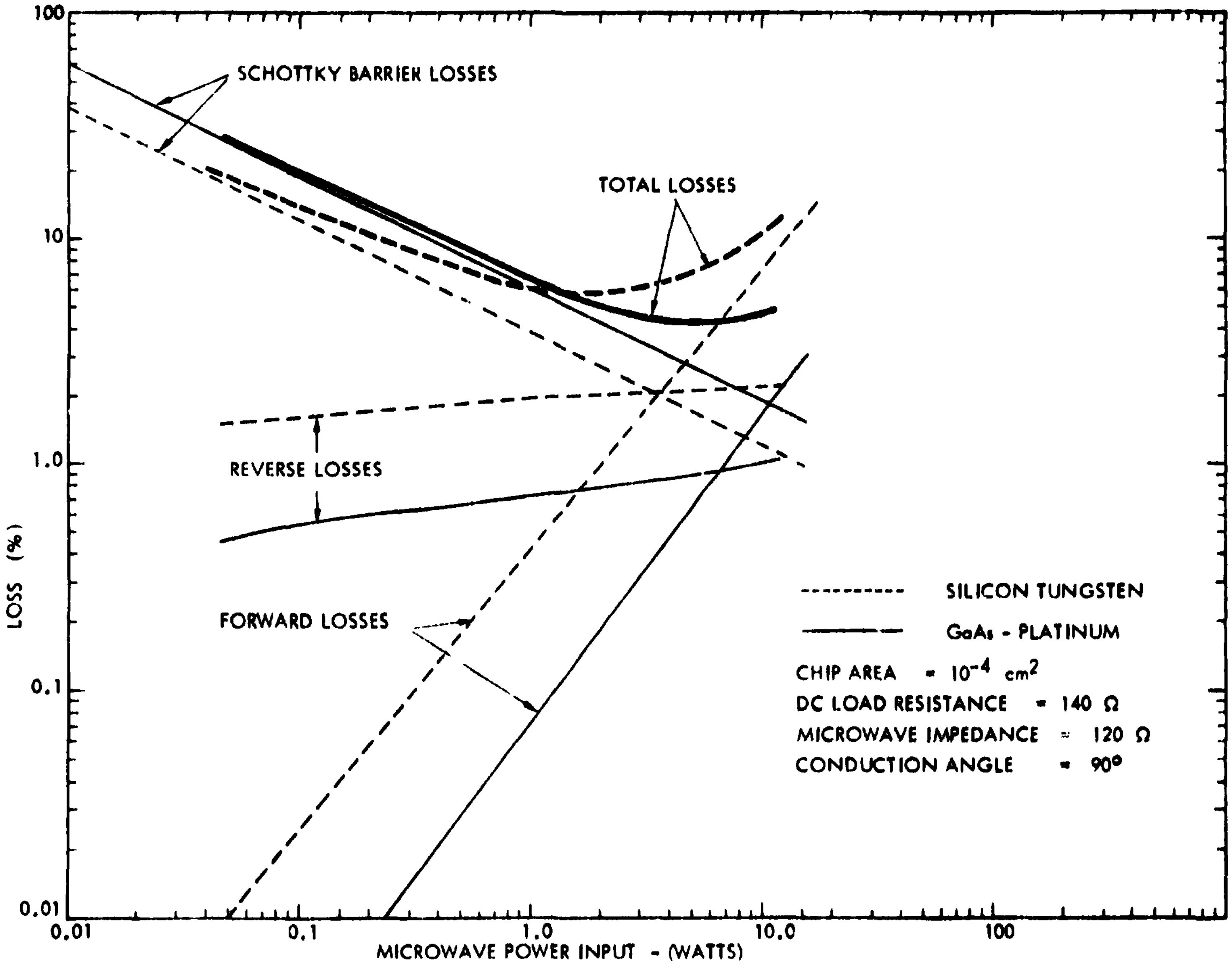
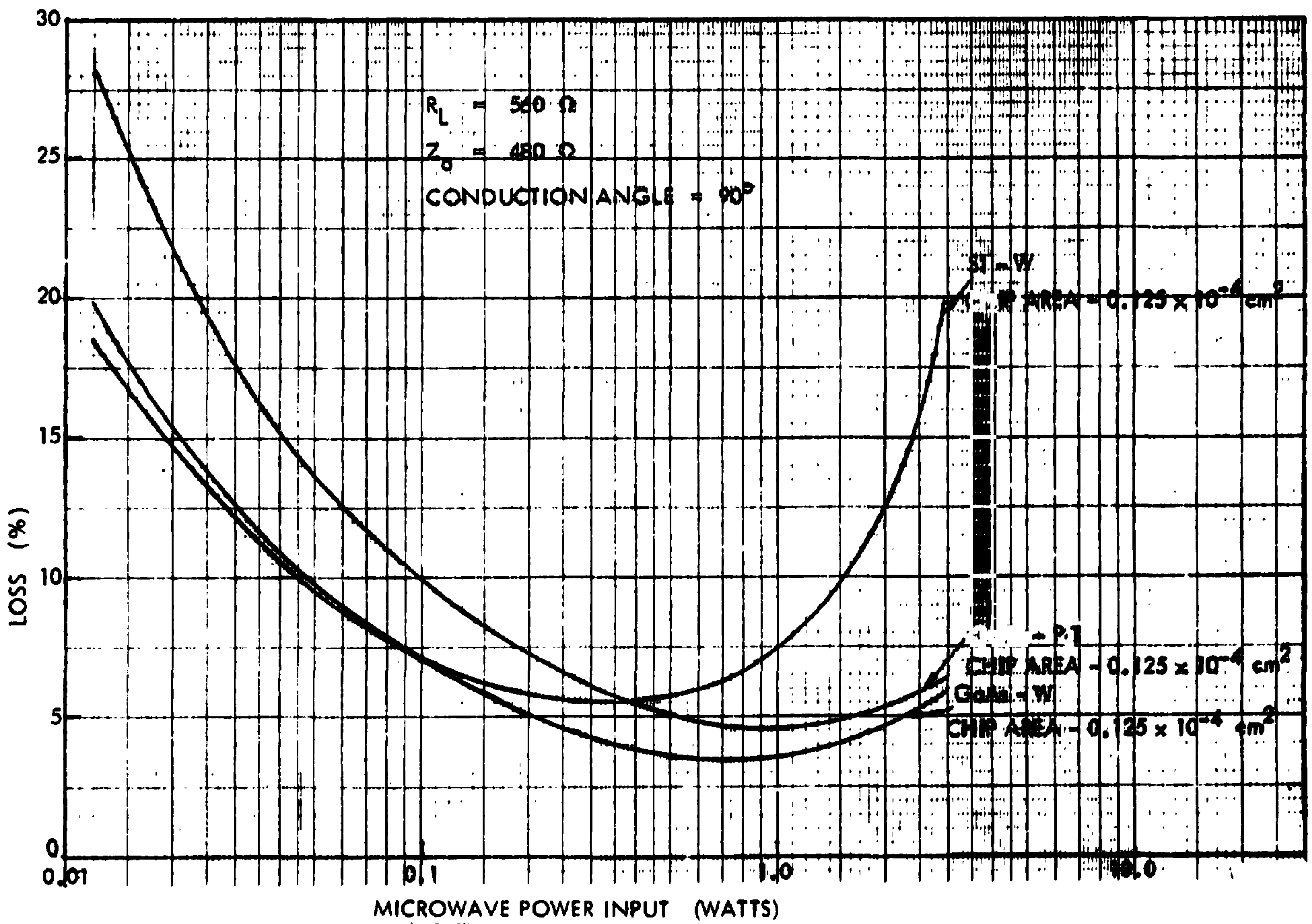


Figure 9-9. Microwave Losses in an Optimally Designed Diode as a Function of Input Power Level for a Microwave Impedance Level of 120 Ohms



NOTE: (1) Operating at High Impedance Level, (2) Small Chip Area, (3) Use of Schottky Barrier Junctions Having Lower Barrier Voltage

Figure 9-10. Losses at Low Values of Microwave Power Input

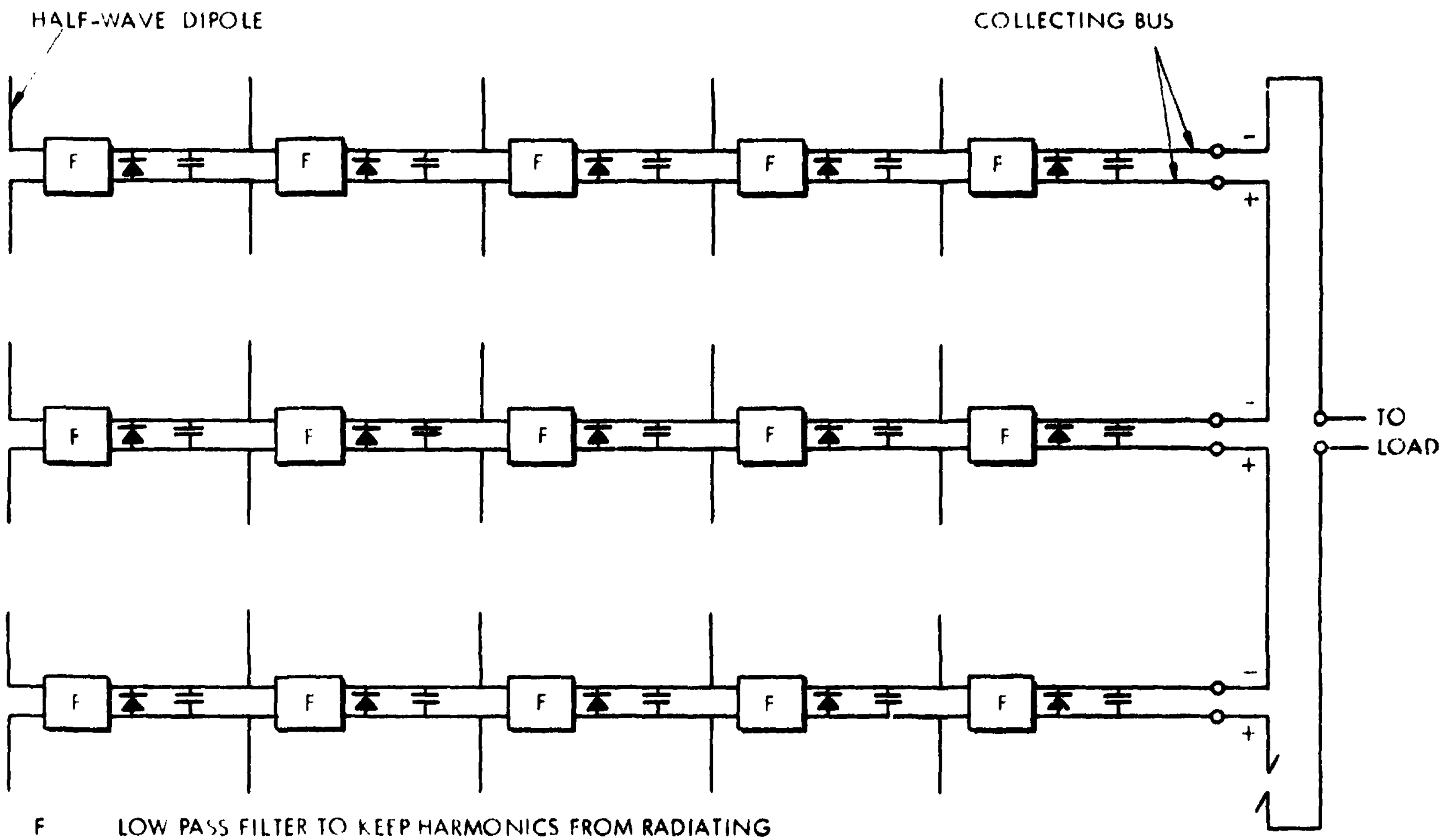


Figure 9-11. Schematic Arrangement of Rectenna

as a rectifier, but there are other arrangements which could incorporate several diodes in a function other than pure parallel operation. For the present discussion, however, attention will be focused on the filter.

It will be noted first that the low-pass filter, shown in Figures 9-4 and 9-11, allows the top and bottom of the network to be at different dc potentials. It therefore follows that the conductors which form the top and bottom of the filter can be used as dc busses to transport the rectified power to the edges of the array. A second aspect of the filter that must be taken into consideration is that a physical space is required for the construction of the filter. The space required is roughly proportional to the number of filter sections required, and there are likely to be at least two. A convenient place to put these filters is in the space between two of the half-wave dipole antennas as shown.

A second consideration is the other possible rectifier configurations that could be employed. If a full-wave rectifier is employed as in Figure 9-12, an additional bus will be required, and if it is kept in the same plane as the other conductors without intersecting them, it must pass through the center line of the capacitances. This is probably not practical. If a full-wave bridge-type rectifier is used as in Figure 9-13, the problem becomes even more acute, since two additional terminals are created. If the terminals of successive rectifiers are connected in parallel, two additional busses will be required. The early rectennas built internally at MSFC and at Raytheon used bridge-type rectifiers and the power was collected by a single dc bus, connecting the elements in series. But these rectennas contained no filters between the rectifiers and the dipole antennas. If filters were inserted, the schematic would then have to look like that of Figure 9-14 and there is no single-plane topological solution since the filter is a two-terminal pair device. There is also the problem of a strong second harmonic content at terminals B-B' and the suppression of its radiation from the series bus. It would therefore appear that if a full-wave rectifier were to be used an additional plane would be required for bussing the power. This does not necessarily rule out these configurations but there is no doubt that it places them at a disadvantage with the half-wave rectifier configuration shown in Figure 9-11.

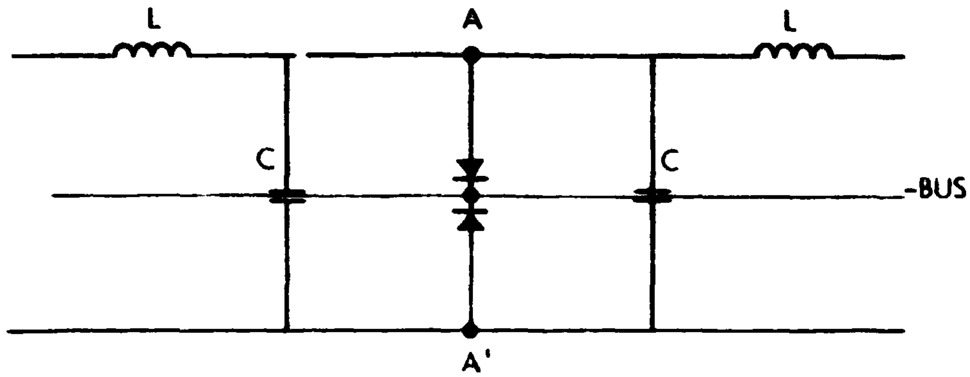


Figure 9-12. Full-Wave Configuration

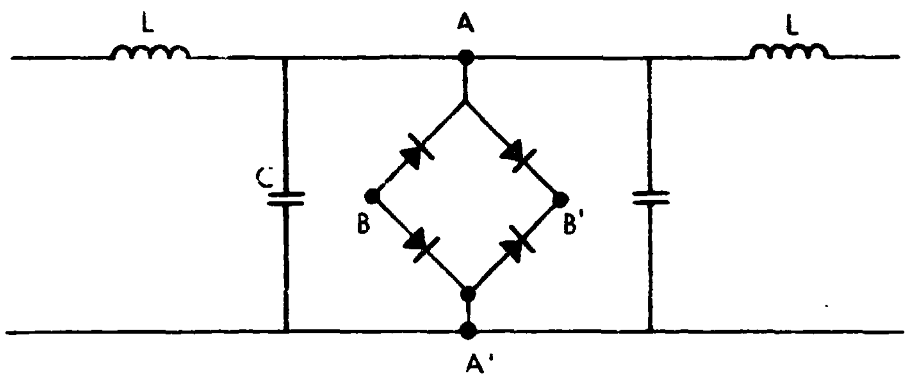


Figure 9-13. Bridge-Rectifier Configuration

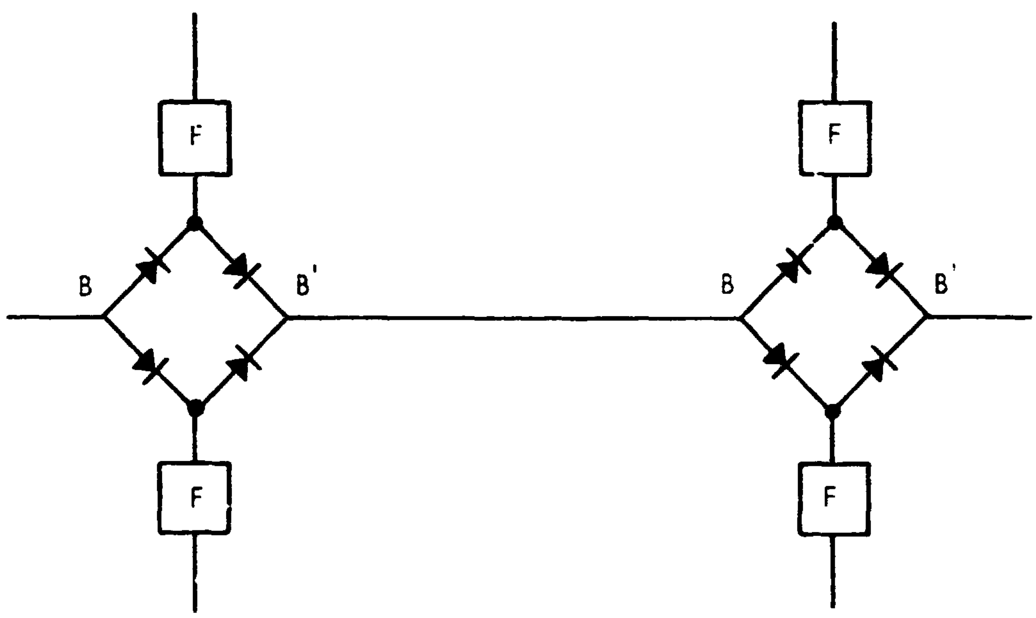


Figure 9-14. Full-Wave and Bridge-Rectifier Configurations in Relationship to Wave Filter Terminals

Before ending the discussion of rectifier configurations, attention is called to a pseudo full-wave rectifier using only two conductors. Figure 9-15 shows a two-terminal pair structure that is a low-pass filter element made up of the capacitance of the diodes themselves with an intervening inductance whose value is such that the filter operates at or near the upper cutoff frequency. This filter section then behaves as a full-wave rectifier in the sense that current flows into the dc busses on both halves of the rf cycle.* Such an element could have a considerable amount of energy storage, i.e., a significant Q. If the device were fed from one side only, the symmetry of the rectification process would be affected, being less affected with the higher Q values. The symmetry could be restored, regardless of the Q value, by feeding the network from adjacent half-wave dipoles assumed to be excited in the same phase.

In most of the experimental work to date, only a single dipole has been involved with the rectifier. This permits designing and testing a single element of the rectenna according to the procedure that has been used successfully. This procedure makes use of a section of expanded waveguide into which the complete element is matched. Accurate measurements of efficiency can be made, and the cross-section of the expanded waveguide has been correlated with the area taken up by the element in the finished rectenna.

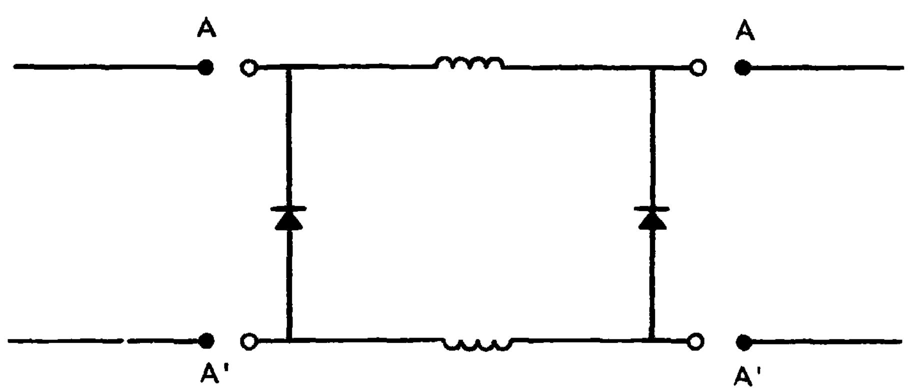


Figure 9-15. Pseudo Full-Wave Two-Conductor Rectifier

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*This same circuit was used successfully in the close-spaced thermionic diode rectifier. The circuit is briefly described in Okress, E. C. Microwave Power Engineering, Vol. I, pp. 295-298, and more fully in an unpublished Raytheon memo.

9.4 ASSEMBLY AND CONSTRUCTION

The construction approach suggested for the rectenna is illustrated in Figure 9-16 where wire mesh is supported by a simple framework to be normal to the incoming power beam phase front. The angle is not critical due to the wide beam pattern of the dipole antenna elements. The open mesh reduces wind loads and the amount of material needed, and the relatively simple support arrangement keeps the foundation and site preparation costs as low as possible.

A detail of the suggested mounting for the rectenna elements is given in Figure 9-17. Dc power is collected by the elements in parallel and then summed in series as was indicated in Figure 9-11. The voltage level for summation involves a tradeoff of I^2R losses at low voltage and high current, versus the insulation penalties at higher voltages and lower currents. A level of 1 kV was somewhat arbitrarily selected as that level for power inversion up to 66 kV for distribution to a power grid. (An integrated rectenna industrial complex would perhaps eliminate the associated extra cost and efficiency loss.)

Environmental protection for the extremely large area of rectenna poses a unique problem in that many effective techniques are too costly to consider. The conditions to be considered are rain, wind, snow and ice, temperature extremes, hail, blown sand, salt spray, and ultraviolet solar radiation. The approaches considered were: radome over the whole assembly, exposed assembly with conformal coating, and exposed assembly with a dielectric tubing shield as shown in Figure 9-18 (top and bottom halves would be heat sealed).

The radome would be too expensive; the conformal coating may pose difficulties with power loss; and the tubing may be too expensive and have cooling problems. However, the latter two concepts are proposed for further study. The main threat to damage with these methods would be the impact of large hailstones. This should be a consideration in site selection.

9.5 ROM COST ESTIMATES

Costs were generated on the basis of cost per square meter except for power distribution. It is assumed that diodes are developed to handle the full range of power densities involved and/or that power from several dipoles can be collected for a single diode at the same cost or less than for the single diode-dipole combination.

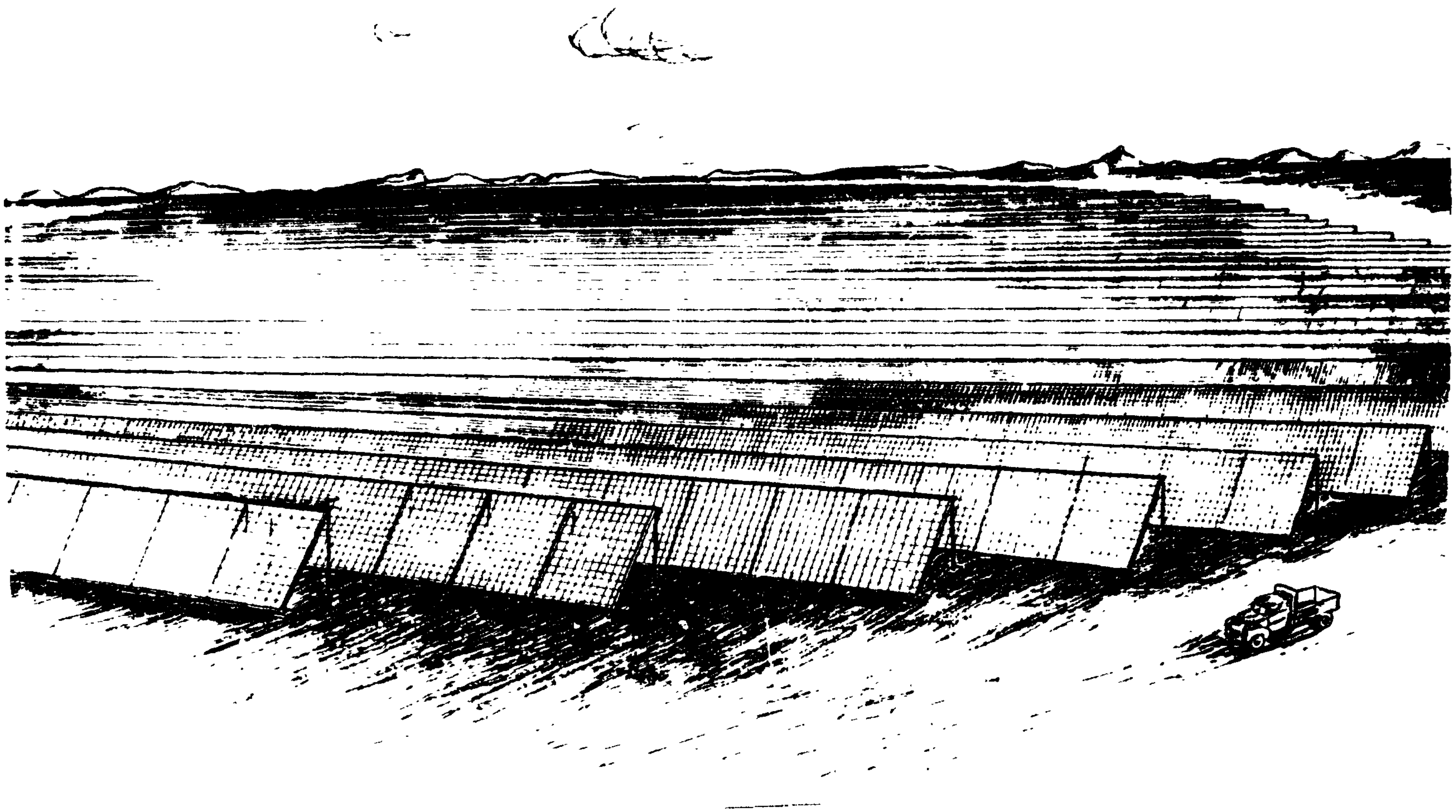

Figure 9-16. Rectenna Construction

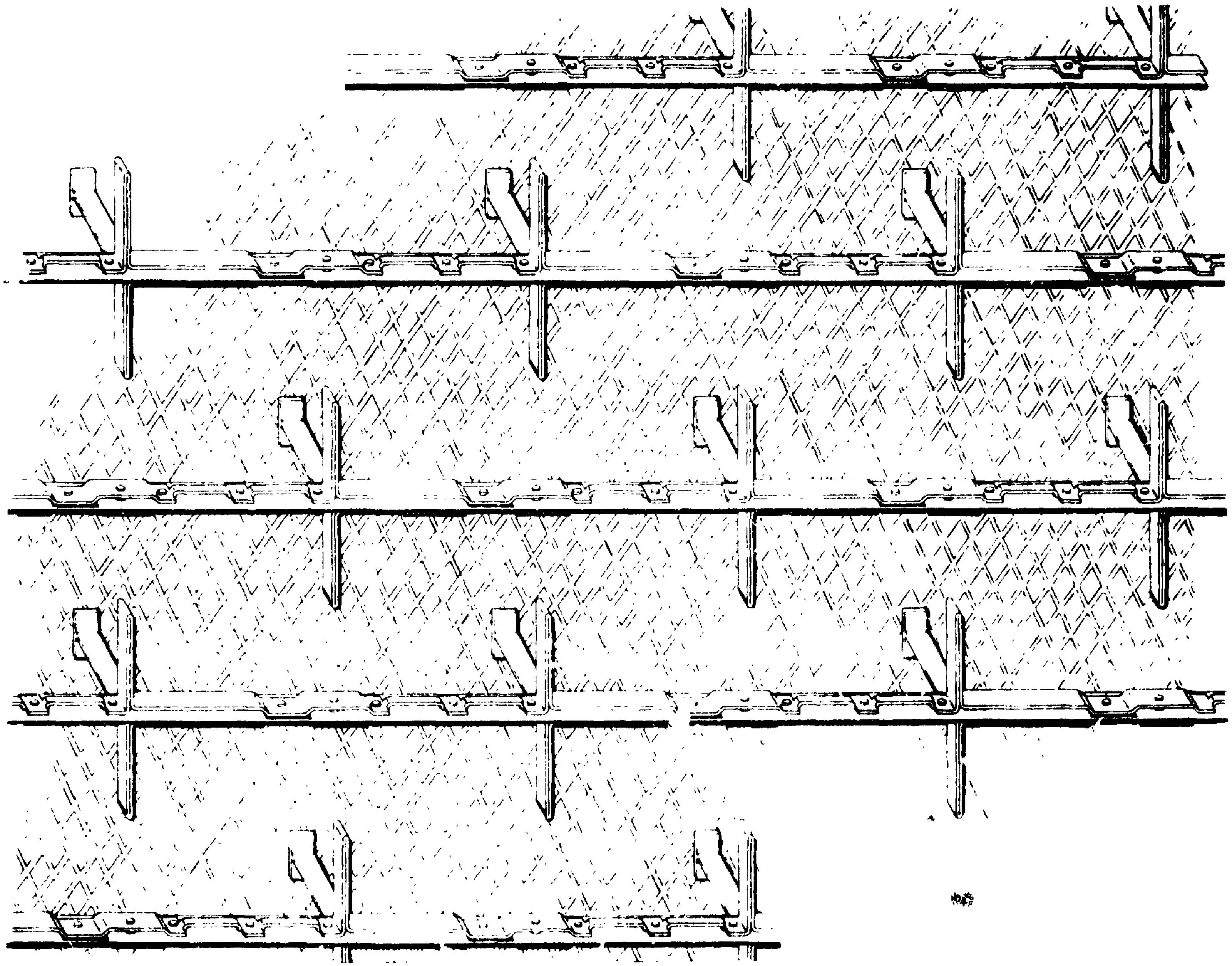

Figure 9-17. Rectenna Elements

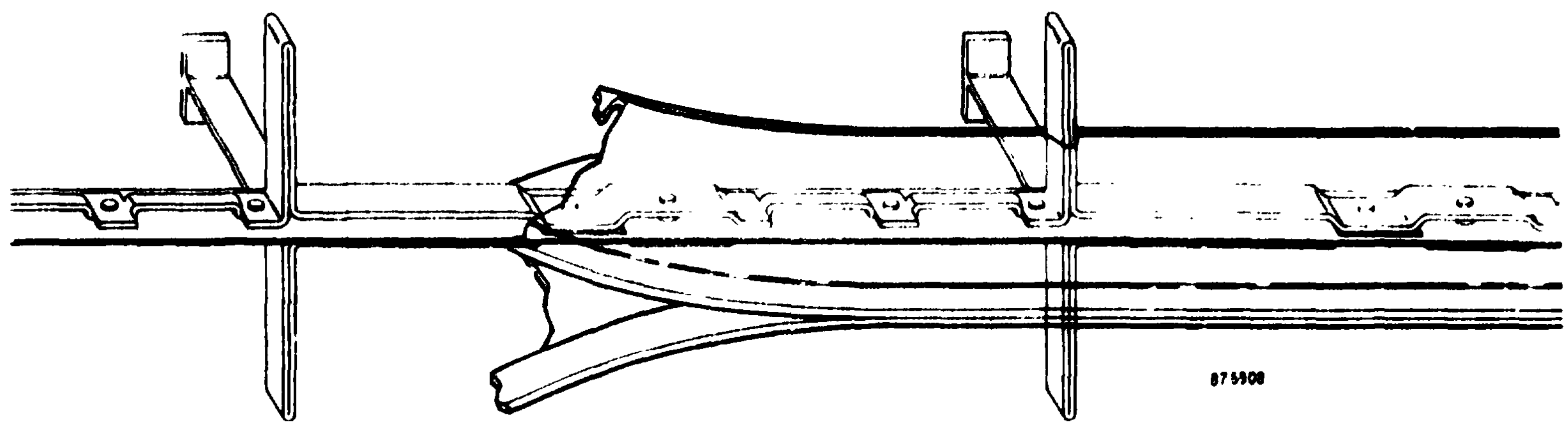

Figure 9-18. Approach to Environmental Protection of Rectenna Elements

Nominal costs are:

Real Estate	0.25 $/m^2$
Site Preparation	0.40 $/m^2$
Support Structure	6.00 $/m^2$
RF-DC Subarrays	4.00 $/m^2$
Power Distribution and Control (See Section 9.6)	45.00 $/kW (2.50 $/m^2$ for 5 GW)

The RF-dc subarray cost is made up of:

Schottky Barrier Diode	2.84 $/m^2$
Rectenna Circuit and Diode Assembly	3.16 $/m^2$

We see that the support structure is the highest cost item. The diodes are the single most costly component and must be produced at about 1 cent each in quantities of billions to meet the target. The learning curve behavior for diodes shown in Figure 9-19 lends support to this estimate.

The rectenna element assembly must also be produced in a high speed, low cost process. The scheme illustrated as an example in Figure 9-20 starts out with two spools of rectangular aluminum wire and one spool of dielectric ribbon material. Three forming machines produce the three pieces which flow together in a continuous process.

9.6 POWER INTERFACE ESTIMATES

Figure 9-21 is a simplified plane view of the general configuration analyzed. The total rectenna area has been subdivided into 5 main feeders, with each feeder handling 1000 MW, for a total rectenna output power of 5000 MW. Each main feeder receives power from 1000 - 1 kW inverters. These inverters serve the multiple functions of dc to ac inversion, phase synchronization and switchgear. The analysis assumes that a three phase ring inverter (see Figure 9-22) is suitable for the intended application. Input power to the inverter will be 1000 volts dc and the output voltage of the inverter will be 66 kV rms, three phase 60 Hz. Further conversion of the voltage can be performed at the interface with the transmission system if required.

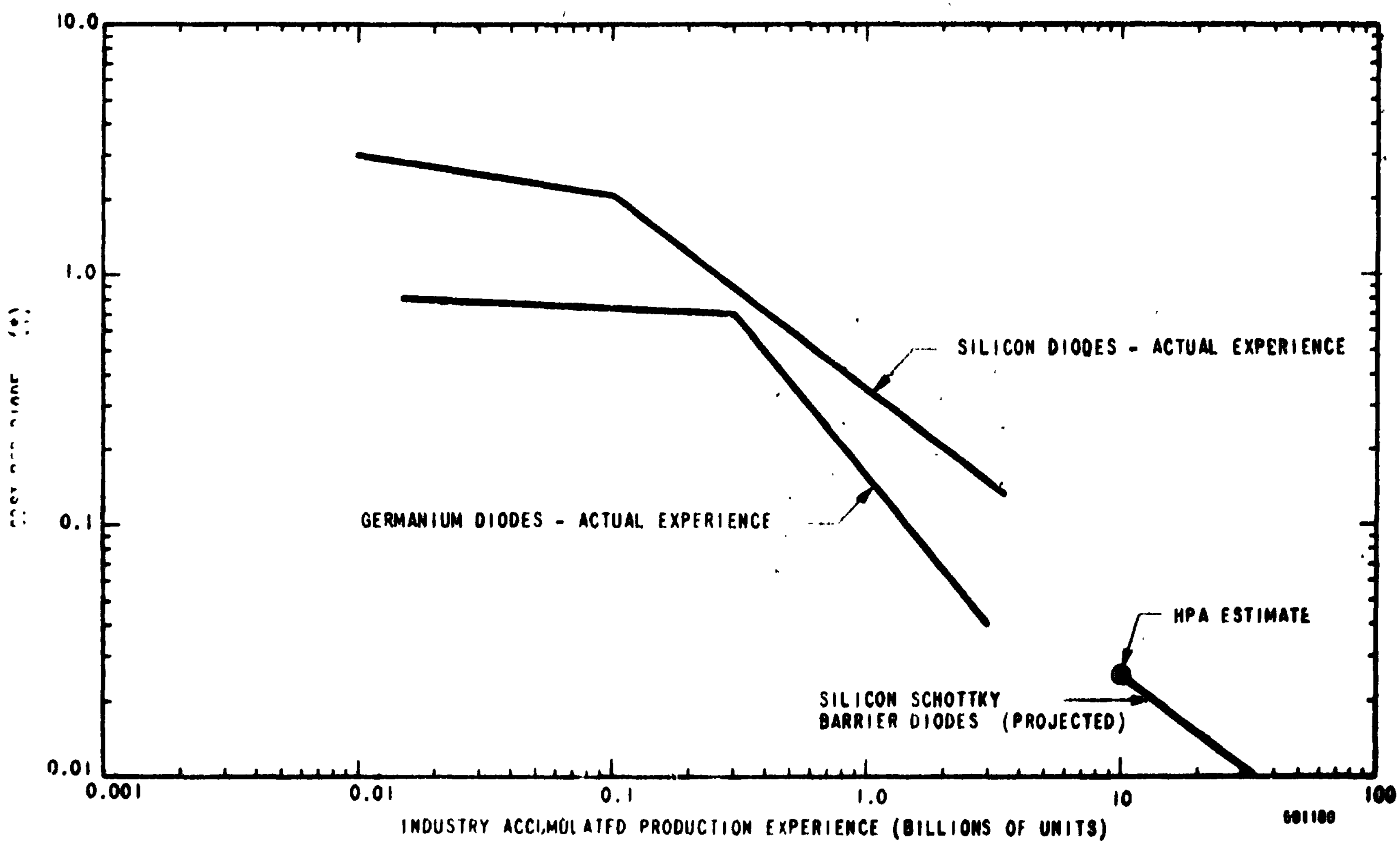

Figure 9-19. Industry Accumulated Production Experience (Billions of Units)

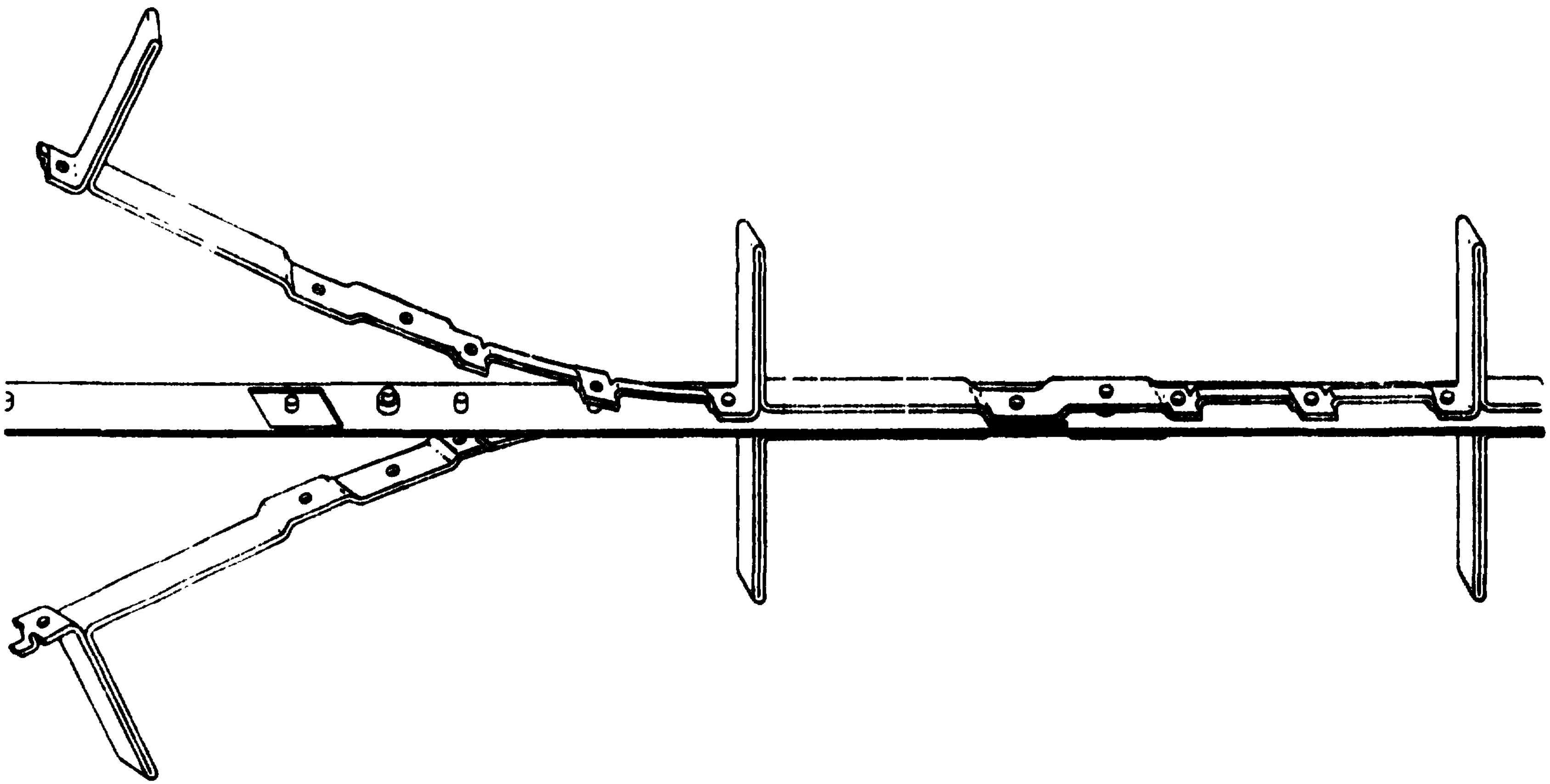

Figure 9-20. High Speed Rectenna Production

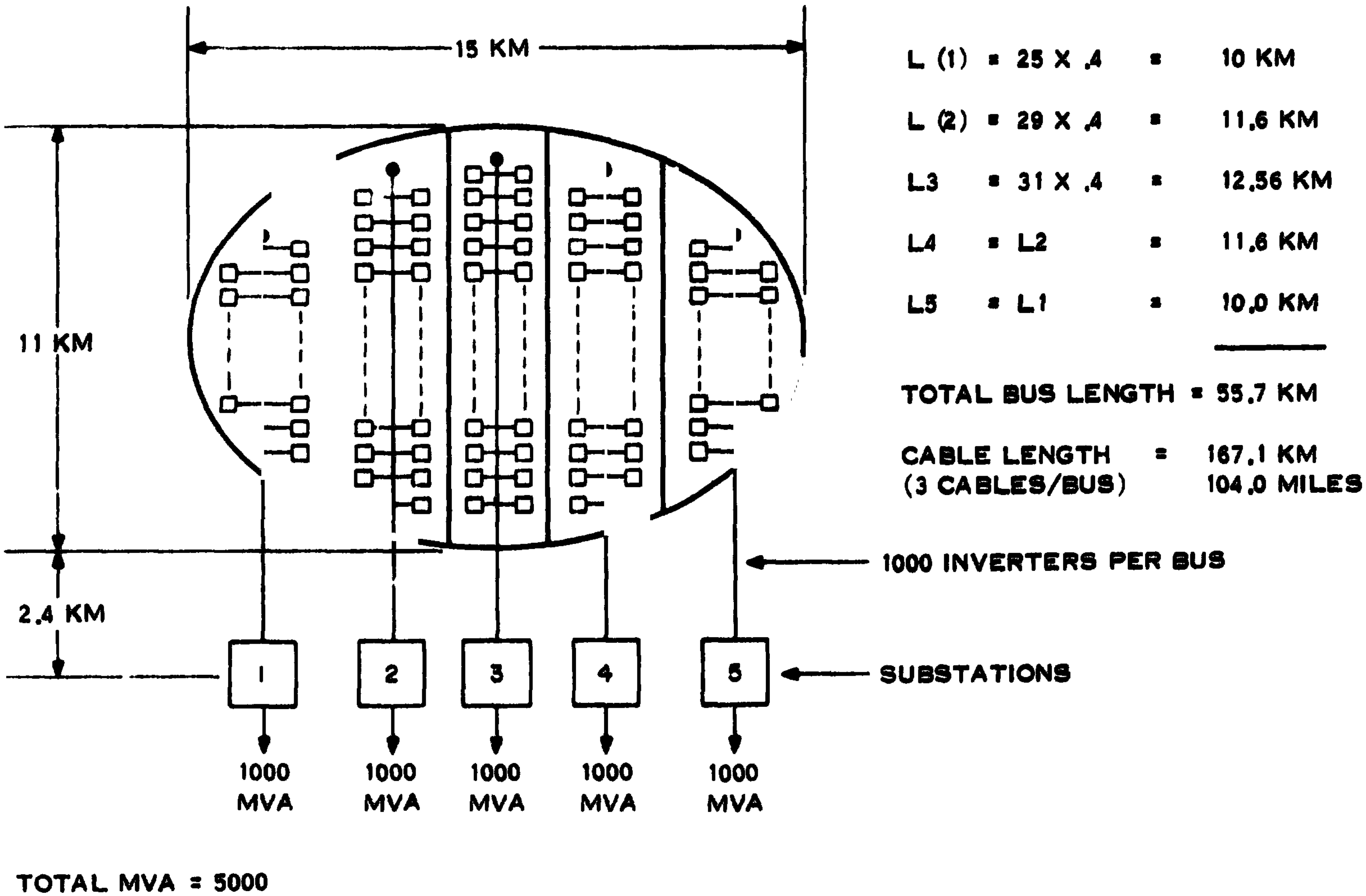

Figure 9-21. Basic Rectenna Distribution Layout

In the analysis that follows, it is assumed that dc bus losses from the rectenna to the inverters are a part of the rectenna system. In addition, the substations located at points 1 through 5 in Figure 9-21 will be defined largely by individual site and specific transmission systems. Accordingly, these costs are not included.

The overall efficiency of an inverter for the proposed application is difficult to estimate at this time. Figure 9-22 tabulates the probable losses, using what can be considered the lowest achievable values for each identified loss. Achieving these in an actual system will require a significant development program.

SCR Losses	-	2%
Transformer	-	2%
Harmonic Losses	-	3%
I^2R and Miscellaneous	-	1%
Total Losses	-	8%
Net Efficiency	-	92%

Figu '-22. Estimated dc-ac Interface Losses

ROM costs for the dc-ac interface equipment has been developed in three steps. First, the basis cost of 1 kW inverter is estimated and then a learning curve applied for the total system cost. Secondly, the power distribution system, consisting principally of the 5 MW feeders have been estimated, and thirdly, the results of steps 1 and 2 have been combined for the total system cost.

9.6.1 INVERTER SYSTEM

The unit costs are derived as shown in Figure 9-23.

Item	Quantity	Cost Per Item	Total Cost Per Unit
SCR	12	$ 200.00	$ 2400.00
Transformer	1	150,000.00	150,000.00
Diodes	12	100.00	1200.00
Magnetics	1 Set	1000.00	1000.00
Control Circuits	1 Set	1000.00	1000.00
Miscellaneous	1 Set	3000.00	3000.00
		Material Cost	$158,600.00
Material Cost			158,600.00
Factory Labor			35,000.00
Total Per Unit Cost			$193,600.00 (Qty. of one)

Applying an 85% learning curve for a quantity of 5000 we have a production unit cost of:

$$\text{Production Unit Cost} = (193,600)(.85)^{12.29} = \$26,270.00$$

Figure 9-23. Inverter Unit Cost Derivation

9.6.2 POWER DISTRIBUTION COSTS

For preliminary ROM estimating purposes the five main feeder cables have been considered to consist of five 1,000,000 circular mil single conductor oil filled paper insulated cables per phase. Each cable diameter is approximately 2.192 inches and cable weight is 8,630 pounds per 1000 feet. For the 5 main feeders a total cable length of 104 miles is required. Power distribution ROM system costs are summarized in Figure 9-24.

Item	Quantity	Unit Cost	Total Cost
Feeder Cable	104 Miles		$\$18.8 \times 10^6$
Other Cable	-	-	7.0×10^6
Total Cost (including factory labor)			$\$25.8 \times 10^6$

Figure 9-24. Power Distribution ROM System Cost

9.6.3 SYSTEM COST

Figure 9-25 summarizes the total system costs including installation labor. A rough estimate is also included of related site costs. These costs include handling and test equipment, footings and support structures, cable laying equipment, etc.

Item	Unit Cost	Quantity	Total Cost
Inverter	$26,270.00	5000	$\$131.5 \times 10^6$
Power Distribution			25.8×10^6
Installation and Test Labor			30.0×10^6
Related Site Costs			43.0×10^6
		Total Cost	$\$230.3 \times 10^6$

For a total output power of 5000 MW, the normalized cost is $45/kW

Figure 9-25. Total Power Interface ROM Cost

9.7 CONCLUSIONS AND RECOMMENDATIONS

For the receiving antenna:

a. An array of small independent elements able to collect and rectify incident microwave power is required for low cost and high efficiency.

b. A linearly polarized dipole with GaAs Schottky barrier diode is recommended.

c. Development of rectifying antenna elements including diodes for low power density is needed.

d. Rectenna collection and conversion efficiency is 84 percent and a realistic development goal is 90 percent.

e. Support structure is major cost item requiring further in-depth study as types of terrain, soils, mechanics and environments are established.

f. Power interface to the user network needs development to reach 92 percent and greater efficiency.

REFERENCES (SECTION 9)

1. W.C. Brown, 'Free-Space Microwave Power Transmission Study, Phase 2", Raytheon Report No. PT-3539 covering period from April 1, 1971 - August, 1972. NASA Contract No. NAS-8-25374.

2. E.M. Sabbagh, Microwave Energy Conversion, Rept. WADD-61-48, Pt. III. Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, May 1962.

3. R.H. George and E.M. Sabbagh, "An efficient means of converting microwave energy to dc using semiconductor diodes", IEEE Intern. Conv. Record, Electron Devices, Microwave Theory Tech., vol. 11, Pt. 3, pp. 132-141, March 1963.

4. J. Thomas, High Power Microwave Converter, Tech. Rept. No. ASDTR61-476, Pt. II, February 1963, ASTIA, Document No. AD-402975.

5. Okress, F.C., Microwave Power Engineering, vol. 1 and 2, New York: Academic, 1968.

6. W.C. Brown, "Thermionic Diode Rectifier", in Okress, Microwave Power Engineering, pp. 295-297.

7. W.C. Brown and R.H. George, "Rectification of microwave power", IEEE Spectrum, vol. 1, pp. 92-97, October 1964.

8. W.C. Brown,"A Survey of the Elements of Power Transmission by Microwave Beam", 1961 IRE International Convention Record, Vol. 9, Part 3, pp. 93-105.

9. J.F. Skowron, G.H. MacMaster and W.C. Brown, "The Super Power CW Amplitron", Microwave Journal, October, 1964.

10. W.C. Brown, "Experiments in the Transportation of Energy by Microwave Beam", 1964 IEEE International Convention Record, Vol. 12, Part 2, pp. 8-17.

11. W.C. Brown, "Experiments Involving a Microwave Beam to Power and Position a Helicopter", IEEE Trans. on Aerospace and Electronic Systems, Vol. AES-5, No. 5, pp. 692-702, Sept., 1969.

12. W.C. Brown, "Experimental Airborne Microwave Supported Platform", Technical Report No. RADC-TR-65-188, Dec., 1965. Contract AF30 (602) 3481.

13. W.C. Brown, Experimental System for Automatically Positioning a Microwave Supported Platform", Technical Report No. RADC-TR-68-273, Oct., 1968. Contract AF 30 (602) 4310.

14. R.H. George, Solid State Microwave Power Rectifiers, Rept. RADC-TR-65-224, Rome Air Develop. Center, Griffiss Air Force Base, New York, August 1965.

15. W.C. Brown, "Progress in the Efficiency of Free-Space Microwave Power Transmission", Journal of Microwave Power, Vol. 7, No. 3, pp. 223-230.

16. W.C. Brown, "Free-Space Microwave Power Transmission Study", Raytheon Report No. PT-2931 covering period of Dec., 1969 to Dec., 1970. NASA contract no. NAS-8-25374.

17. W.C. Brown, "Progress in the Design of Rectennas", Journal of Microwave Power, Vol. 4, No. 3, pp. 168-175, 1969.

18. W.C. Brown, "The Receiving Antenna and Microwave Power Rectification", Journal of Microwave Power, Vol. 5, No. 4, pp. 279-292, 1970.

19. Robinson, W.J., "Wireless power transmission in a space environment," J. Microwave Power. vol. 5, Dec. 1970.

20. Glaser, P.E., "Power from the sun: its future", Science, vol. 162, pp. 857-861, Nov. 22, 1968.

21. "Reception Conversion System for (RXCV) for Microwave Power Transmission System, Final Report", JPL Contract No. 953968, Raytheon Company, Sudbury, Mass., September 1975.

22. R.E. Bettand and V.D. Nene, "Analysis and Performance of a Three-Phase Ring Inverter", IEE Transactions on Industry and General Applications, Vol IGA-6, pp. 488-496, September/October 1970.

23. Dickinson, R.M., "Evaluation of a Microwave High-Power Reception-Conversion Array for Wireless Power Transmission", JPL Technical Memorandum 33-741, September 1, 1975.

SECTION 10

FREQUENCY INTERFERENCE AND ALLOCATION

The frequency interference and allocation aspects of an MPTS are of great importance because of the potential impact on the design and the cost benefit of an SPS. As a general rule the lower the frequency, the greater the effect on established users of the spectrum. It has been shown that the higher the frequency (above 3 GHz) the greater the risk of brownout in heavy rain. The system analysis and evaluation in a following section indicates the region in the vicinity of 2 GHz will provide a comparatively cost effective solution.

Figure 10-1 provides an overview of the spectrum utilization in the areas of interest, the details of which are given in Reference 10-1. Of special interest are the radio astronomy bands, and the USA industrial band from 2.4 GHz to 2.5 GHz centered at 2.45 GHz. The radio astronomy bands imply tighter specs on noise interference due to the high gain receiving systems, and also pose difficulties in allocation if the band is associated with naturally occurring phenomena in space. The latter is the case for the 1.4 GHz and 1.7 GHz bands which correspond with hydrogen and hydroxyl resonance lines. The 2.7 GHz and 5.0 GHz bands are simply "windows" established for the convenience of the astronomy community in making observations in that general frequency region. The astronomers actually carry out observations throughout the RF spectrum with particular sites covering certain bands more frequently than others.

The industrial band at 2.45 GHz is the recommended location for the MPTS. It is near optimum from component and system points of view and follows a precedent for this type of usage. The following paragraphs cover the impact of this choice on users outside of this band for one satellite power source delivering 5 GW to the ground. For additional systems, e.g., 100, the noise and harmonics generated would increase by 20 dB. Impact of this on the equipment and other users requires further in-depth investigation.

GHz	-	UTILIZATION
0.470 - 0.806	-	TV- USA
0.806 - 0.902	-	Land Mobile
0.902 - 0.928	-	Radio Location
0.928 - 0.947	-	Land Mobile
0.947 - 0.960	-	Point - Point Communication
0.960 - 1.215	-	Aero Nav (Tacan)
1.215 - 1.350	-	ATC Radar
1.350 - 1.400	-	Defense Radar
1.400 - 1.427	-	Radio Astronomy
1.427 - 1.429	-	Telecommand
1.429 - 1.535	-	Aeronautical Telemetry
1.535 - 1.660	-	Aeronautical and Maritime Satellites
1.660 - 1.670	-	Radio Astronomy
1.670 - 1.700	-	Met Sats and Aids
1.700 - 1.850	-	Space Research and Line of Site Communication
1.850 - 2.025	-	Fixed and Mobile Operations
2.025 - 2.200	-	Unified S-Band Up-Link (NASA)
2.200 - 2.300	-	Unified S-Band Down-Link (NASA)
2.300 - 2.400	-	Def .se Systems Radio Location
2.400 - 2.500	-	Fixed and Mobile, Industrial Microwave (USA)
2.500 - 2.690	-	Communication Satellites
2.690 - 2.700	-	Radio Astronomy
2.700 - 2.900	-	ATC Surveillance Radar
2.900 - 3.100	-	Ship-borne Radar
3.100 - 3.700	-	Defense Radar and Police Radio Traps
2.700 - 4.200	-	Communication Satellites and Fixed Microwave
4.200 - 4.400	-	Altimeters
4.400 - 4.990	-	Fixed, Mobile and Troposcatter Communication
4.990 - 5.000	-	Radio Astronomy

Figure 10-1. RF Spectrum Utilization

10.1 NOISE CONSIDERATIONS

10.1.1 AMPLITRON

Discussing the amplitron first and utilizing the information in Section 4, Figure 4-45, we see that a ten tube amplifier chain has a noise power which is 70.1 dB/MHz below the power at the fundamental transmitted frequency (f_o). This translates to -130.1 dB/Hz. The noise spectrum has been described as essentially flat over a bandwidth of approximately 500 MHz above the center frequency, and noise shaping is shown in Figure 4-53.

The noise power is going to have an effective gain from the transmitting antenna which depends on the area over which the noise is coherent. If we consider 10 converters in series the noise will be essentially determined by the first tube. Therefore a high coherency factor will be maintained over the area taken up by that set of 10. The total power per set is then 5 kW x 10 or 50 kW. Since a total of about 7 GW will be generated at f_o (for 5 GW ground output power), there will be 1.4×10^5 such sets. The transmitting antenna has a radius of about 500 meters and therefore has an area of

$$A = \pi R^2 = 7.85 \times 10^5 \ m^2$$

On the average, each set of 10 tubes will then take up an area of about

$$A/_{set} = \frac{7.86 \times 10^5}{1.4 \times 10^5} = 5.62 \ m^2$$

The noise gain is then

$$G_n = \frac{4\pi A}{\lambda^2} \times .5$$

$$= 2350 = 33.7 \text{ dB}$$

The factor of 0.5 is inserted as an approximation to the coherency factor.

The average distance from the satellite to the earth's surface is taken as 3.71×10^7 meters. The distance attenuation is therefore

$$\frac{1}{4\pi D^2} = \frac{1}{4\pi x(3.71)^2 x10^{14}} = 5.78 \times 10^{-17}$$

$$= -162 \text{ dB}$$

For the amplitron at f_o the noise power per Hz is -130 dB down from this, or

$$\text{Noise power} = 98.5 - 130 = -31.5 \text{ dBw/Hz}$$

The absolute noise power density at the earth's surface at f_o is

$$-31.5 + 33.7 - 162 = 160 \text{ dBw/m}^2\text{/Hz}$$

Combining this with the shpaed noise spectrum, we obtain the noise power density at the earth's surface as a function of frequency away from f_o shown in Figure 10-2.

10.1.2 KLYSTRON

Again drawing upon the information in Section 4, Figure 4-45, we see that the noise power of a parallel driven klystron is 90.8 dB per MHz below the carrier. Following the format laid down for the amplitron the 90.8 dB translates to -150.8 dB/Hz. The klystron noise shaping is given in Figure 4-52.

Each 18m x 18m subarray is driven by a single source, so that the area for coherent noise will be

$$A = 18 \times 18 = 324 \text{ m}^2$$

The effective noise gain of the klystron is then

$$G_n = \frac{4\pi A}{2} = 271000 = 54.3 \text{ dB}$$

The distance attenuation is the same as for the amplitron case (-162 dB).

The total power transmitted at f_o is $7 \times 10^{?}$ watts

$$= 98.5 \text{ dBw}$$

The noise power per Hz is 150.8 dB down from this figure or

$$\text{Noise power} = 98.5 - 150.8$$

$$= -52.3 \text{ dBw/Hz}$$

The absolute noise power density at the earth's surface at f_o is

$$-52.3 + 54.3 - 162 = -160 \text{ dBw/m}^2\text{/Hz}$$

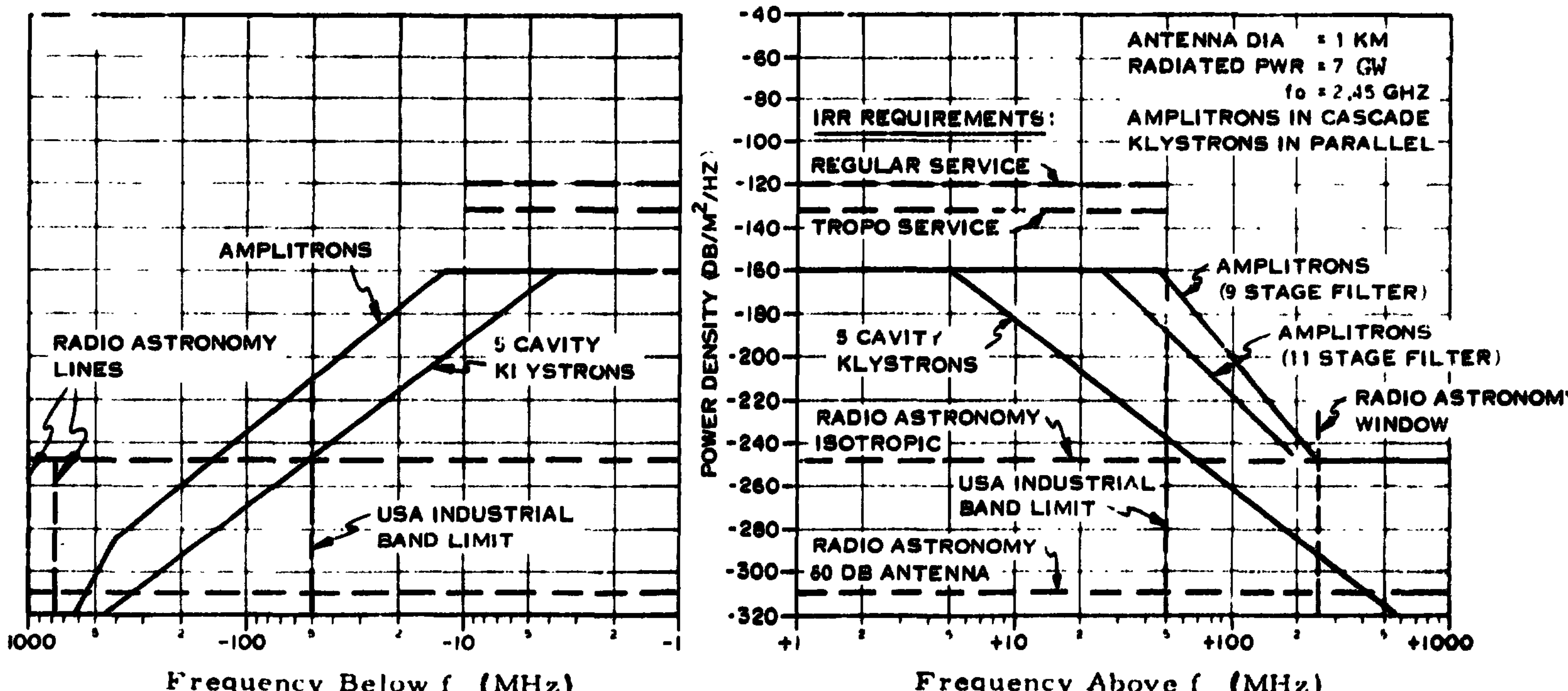

Figure 10-2. Estimated Noise Power Density at Earth

This is the same as for the amplitron. Combining this with the filter curve of Figure 4-52 we obtain the noise power density at the earth's surface as a function of f away from f_o shown in Figure 10-2.

10.1.3 INTERFERENCE LIMITS AND EVALUATION

The interference limits as prescribed in Reference 10-1 are:

Radio Astronomy	A.	Isotropic Level $-249\ dBw/m^2/Hz$
	B.	60 dB gain antenna $-309\ dBw/m^2/Hz$
Tropo Service	C.	$-132\ dBw/m^2/Hz$
Regular Service	D.	-118 dBw/Hz

These are plotted on Figure 10-2, where we see that the klystron is estimated to have a narrower band for potential interference than the amplitron. We see also that no problem exists with regular and tropcscatter commercial regulations. A selection of 2.45 GHz is demonstrated to be reasonably good. The klystron noise is essentially below the isotropic requirement outside of the 2.4-2.5 GHz band, and noise for both klystron and amplitron is below the natural lines at 1.4 GHz and 1.7 GHz for the 60 dB antenna requirement. The amplitron extends beyond the industrial band (+250 MHz, -150 MHz) for isotropic requirements and does not meet the 60 dB requirement above the high end of the industrial band. The reason for this is that the added filter attenuation extends only to the vicinity of -80 dB to -100 dB before leveling out.

The natural lines could be further protected by bringing waveguide cutoff into play above 1.7 GHz. The design represented in this study is 12 cm wide, which cuts off at 1.25 GHz, so that the width would have to be decreased to about 8 cm (integral factor of radiator diameter of 48 cm) for a cutoff at 1.875 GHz. This produces additional center frequency attenuation and adds weight to the antenna (more walls) so that it may be better to build only the amplitron-to-array waveguide feeds with the necessary cutoff characteristics. This area should be examined in a follow-on study.

10.2 HARMONIC CONSIDERATIONS

The interference on the earth's surface caused by MPTS harmonic generation is a function of the following parameters:

a. The inherent level of the harmonics in an amplitron or klystron.

b. The effect of a harmonic filter.

c. The residual effect of the bandpass filter which reduces the noise generation in the vicinity of f_o (2450 MHz).

d. The absolute phases of the harmonics generated by the amplitrons and klystrons differ from tube to tube even when the fundamental frequencies are locked. The net effect is that the antenna pattern is determined by the effective area that each tube has in the transmitting antenna. This is especially true when considering a very large number of sources.

e. The effective gain of the transmitting antenna at the harmonic frequencies.

In discussing the above parameters the following constants are applicable as noted also in the above section:

a. The distance attenuation is $1/4\pi D^2$ where D is the path length from the transmitting antenna to the earth's surface.

$$\frac{1}{4\pi D^2} = \frac{1}{4\pi \times (3.71)^2 \times 10^{14}} = -162 \text{ dB}$$

b. The total power transmitted at the fundamental is 7×10^9 watts.

c. The transmitting antenna has a radius of 500 meters and therefore has an area of:

$$A = \pi R^2 = 3.14 \times (500)^2 = 7.85 \times 10^5 \text{ m}^2$$

d. The effective antenna area for each tube is:

$\frac{\text{Antenna Area}}{\text{Total Power}}$ x Power Per Tube		Converter
1. Amplitron	$= \frac{7.85 \times 10^5}{7 \times 10^9} \times 5 \times 10^3 = 0.560 \text{ m}^2$	A
2. Klystron (6 kW)	$= 0.672 \text{ m}^2$	B
3. Klystron (48 kW)	$= 5.39 \text{ m}^2$	C

f. The wavelengths for the harmonics are:

f_o = 2450 MHz = .1224 meters

$2\ f_o$ = Second Harmonic = 4900 MHz = .0612 meters

$3\ f_o$ = Third Harmonic = 7350 MHz = .0408 meters

$4\ f_o$ = Fourth Harmonic = 9800 MHz = .0306 meters

g. The gain to be expected for the different tubes at the various harmonics is given by

$$G_e = \frac{4\pi A_e}{\lambda^2} K$$

where

G_e is the effective gain

A_e is the effective area

λ is the wavelength of the harmonic

K will vary with the particular harmonic as explained below.

The value of K will vary with the particular harmonic. Considering that the slots are about 0.075 meters apart,

$0.075/\lambda$ = normalized distance between slots (wavelengths)

Frequency	$0.075/\lambda$
f_o	0.61
$2f_o$	1.23
$3f_o$	1.83
$4f_o$	2.46

This table indicates two things: (1) the slots are more than one wavelength apart for the harmonics which essentially means multiple lobe patterns for the harmonics that would significantly reduce the gain; (2) it would be fortuitous if the phasing turned out to be such that one of these lobes had a maximum in the direction of the earth. We also have the condition arising where the slot length will be longer than a wavelength which would compound the above pattern affect and also modify the impedance parameters. An estimate for the K factor as a function of the harmonic is:

Frequency	K
$2f_o$	0.15
$3f_o$	0.04
$4f_o$	0.01

A table of G_e versus converters A, B, and C and harmonics $2f_o$, $3f_o$, and $4f_o$ is given below.

Antenna Harmonic Gain, dB

	Converter		
Frequency	A	B	C
$2f_o$	24.5	25.3	34.4
$3f_o$	21.9	22.7	31.8
$4f_o$	18.7	19.5	28.6

A table listing the inherent level of the harmonics and effects of the filtering using the converter characteristics described above is given below:

Inherent Harmonic Level, dB

		Converter		
Frequency	Contributor	A	B	C
$2f_o$	I	-50	-40	-40
	II	-25	-25	-25
	III	-30	0	0
$3f_o$	I	-40	-65	-65
	II	-35	-35	-35
	III	-30	0	0
$4f_o$	I	-65	-85	-85
	II	-45	-45	-45
	III	-30	0	0

Adding the power budgets for the various tubes:

Total Power + Effective Antenna Gain - Path Loss - Inherent Level of Harmonic (I) - Effect of Harmonic Filter (II) - Residual Effect (III).

This gives us the dBw/m^2 on the earth's surface for the harmonics:

A - 5 kW Amplitron

for $2f_o$, $98 + 25 - 162 - 50 - 25 - 30 = -144\ dBw/m^2$

for $3f_o$, $98 + 22 - 162 - 40 - 35 - 30 = -147\ dBw/m^2$

for $4f_o$, $98 + 19 - 162 - 65 - 45 - 30 = -185\ dBw/m^2$

B - 5 kW Klystron

for $2f_o$, $98 + 25 - 162 - 40 - 25 = -104\ dBw/m^2$

for $3f_o$, $98 + 23 - 162 - 65 - 35 = -141\ dBw/m^2$

for $4f_o$, $98 + 20 - 162 - 85 - 45 = -174\ dBw/m^2$

C - 48 kW Klystron

for $2f_o$, $98 + 34 - 162 - 40 - 35 = - 95\ dBw/m^2$

for $3f_o$, $98 + 32 - 162 - 65 - 35 = -132\ dBw/m^2$

for $4f_o$, $98 + 29 - 162 - 85 - 45 = -165\ dBw/m^2$

Figure 10-3 shows the harmonic power densities in relation to the allowable no-interference condition for commercial installations and radio astronomy obtained from Reference 10-1, pages RR-722, 23, for commercial service and REP 224-2, page 437 for radio astronomy. The results can be summarized as follows:

a. The second harmonic emission of the two klystrons will interfere with commercial installations unless an additional -22 dB harmonic filter is added.

b. The second harmonic of the amplitron will interfere with radio astronomy (Class A) but not with commercial.

c. The third harmonic of all three tubes will interfere with radio astronomy (Class A) but not with commercial.

d. The fourth harmonic of all three tubes is below the level of radio astronomy (Class A).

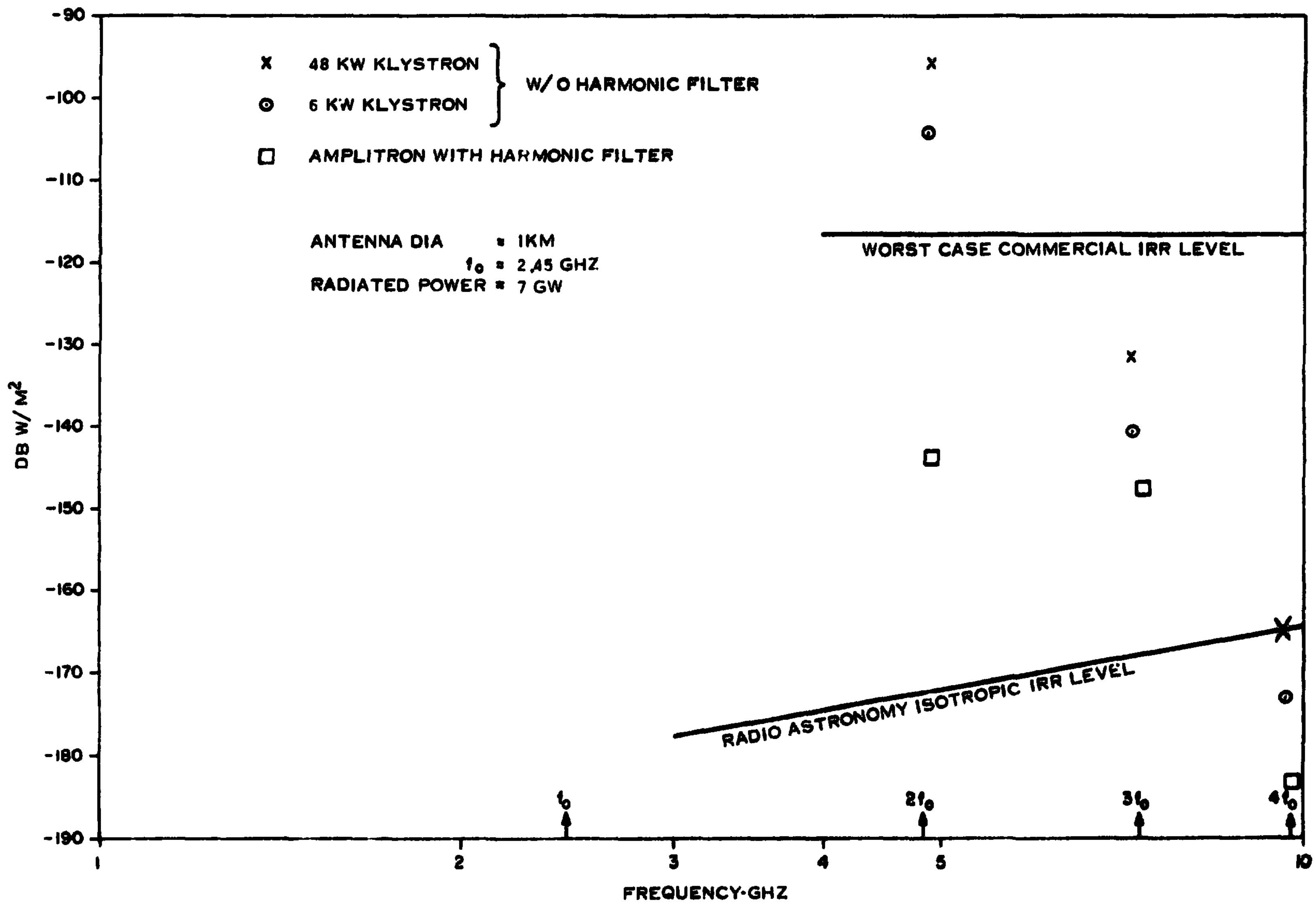

Figure 10-3. MPTS Ground Power Densities for Harmonics

It is possible to alleviate the problems by using narrow band notch filters in the radio astronomy receivers. It should be remembered that, unlike the noise which covers the whole spectrum, the harmonics have a very narrow band. It is therefore possible to design a filter which specifically inhibits the harmonics.

10.3 CONCLUSIONS AND RECOMMENDATIONS

For both amplitron and klystrons

a. Selection of 2.45 GHz is recommended as the operating frequency.

b. Harmonic filters at the rf generators are needed to meet commercial service regulations.

c. Radio astronomy and similar sensitive receiving systems will need notch filters to protect against MPTS harmonics.

d. Multiple SPS installations require further in-depth investigation.

For the amplitron:

a. A bandpass filter is needed to improve performance relative to radio astronomy noise regulations.

b. Noise level with filter added is estimated to exceed radio astronomy isotropic regulations between 2.3 GHz and 2.7 GHz, and to exceed radio astronomy 60 dB antenna regulations above 1.9 GHz. Early development of the amplitron and filters is required to establish noise characteristics.

For the klystron:

a. Noise level exceeds radio astronomy isotropic regulations only in USA industrial band of 2.4 GHz to 2.5 GHz.

b. Noise level exceeds radio astronomy 60 dB antenna regulations between 2.1 GHz and 2.85 GHz.

SECTION 11

RISK ASSESSMENT

11.1 TECHNOLOGY RISK RATING AND RANKING

The technology status and risk for the MPTS was assessed to guide future development activities. The approach is described in Figure 11-1. A work breakdown structure (WBS) was developed for the complete SPS to place the MPTS portions in the proper perspective. This is shown in Figure 11-2 with the appropriate risk ratings entered.

		RISK RATING				
		1	2	3	4	5
		IN USE	IN DEVELOPMENT	ON THE TECHNOLOGY FRONTIER	CONCEPTUAL	INVENTION
STATUS ANTICIPATED WITH a) SPECIFIC MPTS-FUNDED PROGRAM b) OTH[illegible] KN[illegible] PROGRAMS	TECHNOLOGY	FULLY DEVELOPED	PARTLY DEVELOPED	KNOWN BUT NOT DEVELOPED	NOT KNOWN, CHANCE OF IT BECOMING KNOWN IN TIME FOR MPTS IS GOOD	NOT KNOWN, CHANCE OF IT BECOMING KNOWN IN TIME FOR MPTS IS POOR
	HARDWARE	OFF-THE-SHELF ITEM OR PROTOTYPE AVAILABLE HAVING REQUIRED FUNCTION, PERFORMANCE & PACKAGING	FUNCTIONALLY EQUIVALENT HARDWARE IN USE (OPERATIONAL)	FUNCTIONALLY EQUIVALENT HARDWARE IN DEVELOPMENT	NO HARDWARE IN USE OR DEVELOPMENT BUT DEVELOPMENT IS PROBABLE	HARDWARE WILL NOT BE AVAILABLE UNLESS A BREAKTHROUGH OR INVENTION IS DEVELOPED
PROBABILITY OF DEVELOPMENT COMPLETION WITHIN SCHEDULE AND COST		CERTAIN (ALREADY EXIST)	VERY HIGH	HIGH	LOW	VERY LOW

Figure 11-1. Technology and Hardware Development Risk Rating Definition

A risk rating, 1 through 4, was established for each of the items, as currently conceived, in the late 70's to early 80's, and mid 80's assuming the recommended technology development programs would be implemented. These ratings are displayed in Figure 11-2 under the appropriate items at the level where the assessment was made and the most critical set was carried forward to the higher levels of assembly. For the items inside the purview of Microwave Power Transmission (MPTS) the assessment was made through discussions with the

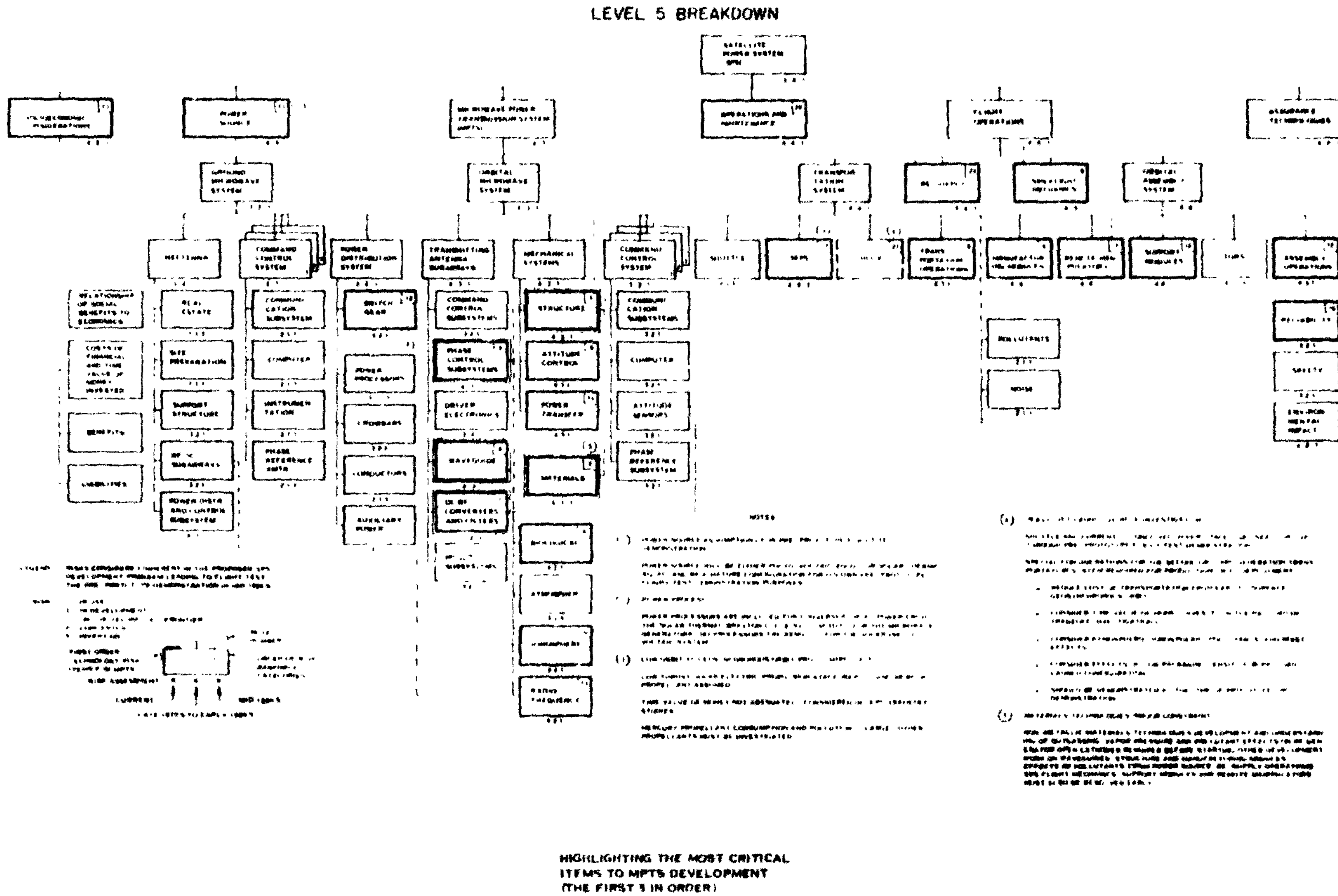

Figure 11-2. Satellite Power System Technology Risk Assessment

appropriate Raytheon task managers. For items outside the the purview of MPTS the assessment was made. primarily for the impact on the MPTS, through discussions with the Grumman task manager and limited discussions with NASA personnel having responsibilities in the appropriate field. From the results of these discussions, a ranking of the most critical items was established and displayed in the upper right corner for the item. It may be that a more in-depth investigation of the power source, flight operations, operations and maintenance, and particularly socio-economic considerations would result in a change of ranking. However, until the technology for the more critically ranked items is pursued and favorable results are forthcoming, emphasis should be applied according to the ranking shown. Further in-depth studies and technology developments should be conducted and periodic re-ranking should be done as a function of study findings and technology development results both favorable and unfavorable.

The method used in obtaining this assessment was to:

a. Ask a broad set of questions of the task managers for the MPTS study.

b. Ask the task managers to rate the several areas of technology against the criteria and discuss or show by the use of schematics and block diagrams the features wherein the areas of technological concern are greatest.

c. Review the responses, clarify assumptions and modify ratings as appropriate.

d. Prepare a uniform set of discussion narratives for each of the less mature items and, based on these narratives, rank them in descending order of program risk.

It was concluded from a list of 24 critical items that the areas which should receive attention with most urgency in the MPTS technology program are:

a. dc to rf converters and filters

b. Materials

c. Phase control subsystems

d. Waveguide

e. Structure

Both the waveguide and structure may well employ manufacturing modules (Ranked 6), however, until the materials, waveguides and structure are better understood and until it is assured that the approaches used do not adversely effect the open cathodes on the rf generators, applicable technology development should be limited.

It should be pointed out that Power Source and Flight Operations technologies are not addressed, rated nor ranked as they should be upon completion of more in-depth investigations in those areas. Furthermore, a current risk rating of four does not mean that the program would be adequately supported if those having risk rating of three or less were significantly delayed.

The area which should receive attention with most urgency in integrated ground testing has to do with the total phase front establishment, command and control. Objectives for the test and the associated technology center around the following:

a. Phase Control Subsystems

b. Command Control Subsystems (ground and orbital microwave systems)

c. Driver Electronics

d. dc-rf converters

e. Waveguide

f. Structure

Other areas such as Rectenna, Power Distribution, Power Subsystems and Attitude Control will also be represented or simulated to some extent; however, they would be in a "support" category for this activity.

Details of the ratings and assessments are given in the following charts.

ITEM	TECHNOLOGY RISK ASSESSMENT		DISCUSSION
	RATING	RANKING	
DC-RF CONVERTERS & FILTERS	4+++	1	Pre-amplifier, amplifier & filters convert the high voltage DC power to RF power having low noise and harmonic content. There are 0.1 to 1.5 million identical devices in one system. This is the highest single contributor to dissipation loss (15 to 19%) with the amplifier contributing 90% of that dissipation. The simplest design concept still results in the most complex mechanical, electrical & thermal set of technology development problems in the system. This combines with requirements for the development of a high production rate at low cost, resulting in reliable operation over a long life. What the noise & harmonic characteristics for the converters are and how they will act in cascade are not known. Filter requirements are to be determined. Ability to develop all the parts, interface them with each other and with the slotted array and operate them with full control and stability constitutes a high development risk and requires the longest lead time in an ambitious development program. Risk rating should then be a very strong 4+++.
MATERIALS	4++	2	Most critical and unusual requirements for materials in this application relate to the presence of the exposed cathodes of the rf generators. In addition, it is desirable that structural thermal strain be small so that distortions over the large dimensions are manageable. The waveguide distortions must be small to permit efficient phase front formation. The waveguide deployed configuration results in l[illegible]v packaging density so that it is desirable to form the low [illegible]sity configuration on orbit out of material packaged for high density launch. Before meaningful technology development can begin relating to fabrication, manufacture & assembly, it is necessary to determine the applicability of the non-metallic materials in particular as they relate to potential contamination of the open cathodes of the rf generators. Due to the critical interaction of materials with structures, waveguides and rf generators, the materials devel[illegible]nt risk rating should be a strong 4++.

ITEM	TECHNOLOGY RISK ASSESSMENT		DISCUSSION
	RATING	RANKING	
PHASE CONTROL SUBSYSTEMS	4++	3	Phase front control subsystems projected scatter losses (2 to 6%) are second only to the microwave array losses (19 to 25%) in the microwave power transmission efficiency chain. The uncertainity associated with limiting losses to this value is significant. Phase control, being essential to beam pointing as well as focusing, must be shown to be reliable for power user and safety purposes. Risk rating should then be a strong 4++.
WAVEGUIDE	4+	4	Slotted waveguides interface with the RF generators in a high temperature environment. They must distribute the power and emit it uniformly with low losses. They represent a large % of the weight and are conceived to be of .020" wall thickness in aluminum or possibly non-metallic composite layups with metallic coating. The ability to manufacture, fabricate & assemble such waveguides is not certain. To provide proper interfacing with RF generators, to limit distortion so as to operate satisfactorily as a subarray of slotted waveguides, and to do so within estimated cost & schedule constitutes high development risk. Risk rating should therefore be a strong 4+; however, significant materials technology development and selection must precede in depth technology investigations.

ITEM	TECHNOLOGY RISK ASSESSMENT		DISCUSSION
	RATING	RANKING	
STRUCTURE	4	5	Structure is characterized as being thin wall, low deployed density, high surface-to-mass ratio, metallic or possibly composite elements assembled into open space frame structural elements which in turn are assembled into yet larger space frames forming very large (approx. 1 km) antenna and even larger solar arrays. After materials technology development & selection, the new problems associated with low thermal inertia large dimension structures traversing the sunlight/shadow terminator at orbital velocities must be resolved. The resulting basic design, recognizing high launch packaging density limitations, must be fabricated on orbit to achieve the final low density deployed configuration. How this should be done is not known and development risk rating should be considered as a firm 4.
MANUFACTURING MODULES	4	6	The specific technology for manufacturing modules is not known at this time, but should be relatively straightforward to develop once the basic design & materials have been established for the items to be manufactured in space. The major items are structural elements (open space frame structures) and slotted waveguides for the subarrays. Materials technology must be understood first and then engineering effort for relatively automated manufacture must begin. Several iterations are probably required so the development must be paced to assure a reliable economic process. Development risk rating should be a firm 4.
REMOTE MANIPULATORS	4	7	The specific technology for remote manipulation modules is not known at this time. However, some investigations have been conducted in associated control systems. The development of these particular remote manipulators should begin after the hardware to be maneuvered and joined has been defined. The control links will probably be through TDRS so capabilities and limitations may begin earlier. Development risk rating should be a firm 4.

ITEM	TECHNOLOGY RISK ASSESSMENT		DISCUSSION
	RATING	RANKING	
BIOLOGICAL	4	8	The CW microwave frequency and power densities to be investigated are rather well established. Effects to be anticipated in the sites yet to be selected are functions of ambient condition and the life forms peculiar to the region and those that are in transit. Most certainly areas like the desert southwest of the U.S. would be leading contenders so that effects on plants and animals should be investigated. Detailed investigations building on those conducted for more general purposes must be conducted to assure complete understanding of long term and transient effects and to provide the basis for securing national and international agreement on frequency allocations, intensities, and exposure limits. Development risk rating should be 4.
ATTITUDE CONTROL	4	9	Control of antenna pointing conceived to be accomplished by mechanical action between the antenna and main mast as well as between the ends of the main mast and the solar array primary structure in the vicinity of the slip rings. These are very large members, of light weight construction, having to transmit unprecedented power across the relative motion interfaces, to operate in the space environment, with high reliability & safety, at low cost, packaged for high density earth launch, deployed or assembled in space, for a very long time with limited operations & maintenance attention. The actuators to establish the motion, the moving joints and the moving or flexing conductors are the largest and most complex machinery employed in the photovoltaic powered station and will be the subject of most critical operations & maintenance analyses in order to design the machinery to be essentially maintenance-free. Nevertheless it must be designed to permit maintenance under most adverse conditions of damage and environment. Development risk rating should be 4.

ITEM	TECHNOLOGY RISK ASSESSMENT		DISCUSSION
	RATING	RANKING	
IONOSPHERE	4	10	Effects of the ionosphere on the phase control link are not known definitively, however existing data & analysis indicate that they are probably insignificantly small at the frequencies and power densities being considered. The effects on the ionosphere induced by the microwave power beam are believed to be small. However, from the point of view of other users of the ionosphere and its participation in natural processes there may yet be limits imposed on the power density. The theoretical approaches to doing this are known but the limits that may yet be imposed are unknown. Development risk rating should be 4.
POWER TRANSFER	4	11	The electrical power transfer function, at this large size and power level across flexing and rotating joints, can not be separated from the mechanical and attitude control functions entirely. Although the technology for performing the functions is basically known, the large scale will present significant new problems. Development risk rating should be 4.
SWITCH GEAR	4-	12	Switch gear had been conceived assuming multiple brushes from high voltage DC source transferred power to a single slip ring. Extraordinarily high currents in the switch gear resulted and would be the subject of a high risk (4+) technology development program. Decision has now been made to make the multiple brushes feed multiple slip rings, bringing the individual switch gear currents close to the region where the basic technology is known and the major advances would be in packaging for space operations. Risk rating should then be 4-. Some aspects of the packaging technology having to do largely with size are not known, which leads to a risk rating of 4-.

ITEM	TECHNOLOGY RISK ASSESSMENT RATING	TECHNOLOGY RISK ASSESSMENT RANKING	DISCUSSION
RADIO FREQUENCY	4-	13	Radio frequency and bandwidth allocation is normally a long process involving national & international technology and socio-economic considerations. It will take 2 to 4 years of DC-RF converters' and filters' technology development to mature the concept and make available meaningful data. Convincing the national & international community involved that gigawatts of power beamed from space at an allocated frequency with a specified narrow bandwidth will not in fact result in significant interference requires a positive approach that is yet to be defined. When it is shown convincingly that power from space would (a) be a significant answer to the national and international future power needs, and (b) permit frequency allocation and bandwidth to be defined without significant interference outside the band; then securing high priority for frequency allocation will be a normal process. The appropriate risk rating is 4-.
SUPPORT MODULES	4-	14	Support modules for orbital assembly have been defined as life support modules from which required on-orbit manned operations would be conducted. The general strategy for orbital assembly derives in large part from the strategy for maintenance & operations which are monitoring, adjusting, disassembling and assembling types of activities. Operations & maintenance is also by definition in geosynchronous orbit and will be planned as a set of remotely controlled operations. The maintenance equipment itself, such as remote manipulators, jigs, rigs & tools, will be more complex & prone to malfunction than the primary operational equipment. Support modules then might be (a) living quarters, (b) monitoring command & control station, and (c) maintenance repair & storage hangar. In the commercial operational time period the on orbit manned participation should be planned to be minimal. However, full hardware & transportation provisions should be maintained available to support on orbit manned participation as contingencies arise. Support modules for orbital assembly will be used primarily in low orbit

	TECHNOLOGY RISK ASSESSMENT		
ITEM	RATING	RANKING	DISCUSSION
SUPPORT MODULES (Continued)	4		permitting daily manned access from earth. However duty periods of several weeks would normally be planned, limited by crew well-being limits without artificial gravity. Considerable knowledge & technology is known for such activities. However, the approaches for the specific functions are not known, therefore the appropriate risk rating is 4-. It would continue to be 4 in some respects on into the late 70's to early 80's, but it would be highly desirable if not mandatory to have the development proceed so that it is in use, risk rating 1, in the mid 80's.
ORBITAL ASSEMBLY OPERATIONS	4-	15	Detail orbital assembly operations definition will proceed in parallel, but somewhat lag, operational system design and technology development. It will precede maintenance operations definition, however, in that maintenance operations will be in large part disassembly and assembly activities as discussed under "Support Modules". The definition and technology developments of both assembly and maintenance operations will be highly interactive. Development risk rating should be 4-.
RELIABILITY	4	16	Standard considerations for reliability having to do with functional performance, safety and fail-safe operation apply to each of the equipments. The technologies for reliable operation for 30 years or more of the millions of DC to RF generators on orbit and the billions of diodes on the ground, as examples, are not known even though design approaches may be put forth which appear to have no known failure mechanisms and the guideline for design would be to have no known life limit. The effects associated with the coupling of Reliability and Maintainability requirements for such large numbers of components in the operational environment and location to achieve required safety and good economy are not known. The impact of reliability to the concept as well as detail for Operations & Maintenance is not known and should become known early in the program to guide development of technology as well as design and development of functional equipment, manufacturing modules, remote manipulators and support modules. A risk rating of 4 should apply at this time.

ITEM	TECHNOLOGY RISK ASSESSMENT		DISCUSSION
	RATING	RANKING	
SOLAR ELECTRIC PROPULSION STAGE (SEPS)	4	17	The concept of a low thrust solar electric propulsion stage using mercury propellant was employed, as directed, in the transportation related investigations. In recognition of the importance of the time value of money invested in the payload it is important to consider this factor in future transportation system tradeoff investigations. Mercury pollution to the extent indicated for the operational system would not be acceptable and further transportation system investigations must include other propellants. A risk factor of 4 should apply not only currently but on into the late 70's to early 80's due to a probable delay in the decision process, whereby high performance, low cost, low to geosynchronous orbit transportation would be justified only by a firm commitment to the power from space program. It is anticipated that SEPS would not be in use, rather be in development, in the mid 80's so that large scale pre-prototype flight test demonstrations in that time period would be confined to low earth orbit which is probably acceptable. It would be desirable to have the fully operational SEPS for the early phases of prototype transportation to geosynchronous orbit and mandatory to have it for the completion of the prototype to a complete operational system.
TRANSPORTATION OPERATIONS	4	18	Transportation operations which are functions of shuttle are in development and may be adequate for conducting program development up through pre-prototype flight test demonstration. Whether or not satellite power system development or operational payloads should impact the shuttle concepts must be the subject of payload investigations. How the tranportation operations as well as the vehicles (SEPS & HLLV) themselves may effect the orbital microwave system technologies and vice versa will become known only as in depth investigations of payload and transportation are conducted in parallel. A risk rating of 4 should apply.

ITEM	TECHNOLOGY RISK ASSESSMENT		DISCUSSION
	RATING	RANKING	
SPS FLIGHT MECHANICS	4	19	The maneuvering, station keeping, natural forces, attitude stabilization and control functions will involve reaction engines in various locations around the station. The propellants from these engines may form an atmosphere and particulates that would be deleterious to the open cathode of the DC to RF converters. Understanding the associated flight mechanics for this application in particular is a new area of technology. A risk rating of 4 should apply.
OPERATIONS & MAINTENANCE	4	20	The concept is to design and develop the operational equipment and maintenance equipment so that after deployment, whether on orbit or on the ground, the maintenance function would be one of monitoring, controlling, adjusting, de-installing a module and installing a replacement. These would be done remotely for on orbit equipment and for ground equipment where they were repetitious functions insofar as this approach would lead to better economy, low risk and be generally beneficial. Provisions would also be developed and deployed to permit more close participation by man. When equipment is known in some detail, the operations & maintenance functional considerations will be developed in parallel. This is an area of considerable unknowns at this time and should be in the risk rating 4 category.
POWER SOURCE	4	21	Outgassing and particulate matter from the power source may interact adversely with the open cathodes of the DC to RF converters. It may also be that the fields between and around high voltage conductors will introduce phenomena that affect the operation, life, reliability & safety. Leakage of fluids that may be internal to the equipment and outgassing or vapor pressur associated with non-metallics in particular must be investigated critically for this application. As a part of the power sources set of technology issues the above indicate unknown technology areas that would interact with the orbital microwave system. A risk rating of 4 should apply.

ITEM	TECHNOLOGY RISK ASSESSMENT		DISCUSSION
	RATING	RANKING	
HEAVY LIFT LAUNCH VEHICLE (HLLV)	4	22	The existing shuttle and conceived upper stages are assumed to provide satisfactory transportation for the development program up to and including the pre-prototype flight test demonstration. Second or third generation transportation systems which significantly reduce the cost of transportation to geosynchronous orbit are required for deployment of the production units and should be demonstrated in the demonstration of the prototype. It is assumed that such a deployment system will be defined in the current and future HLLV Upper Stages and Operations investigations. Basic transportation and associated operations costs, time value of money invested in the payloads, atmospheric and ionospheric effects, pollutants, noise and launch packaging density should be major considerations in transportation system tradeoff studies. What technology would be used is not known at this time; however, it is understood that technology that is in development at least would be preferred. The nature of such programs however tends to use the technology that is on the frontier. Even if some unknown technologies are not to be developed, it may well be prudent to recognize that a risk ratin of 4 should apply due to the integrated problem at least. This is not considered to be required for pre-prototype flight test demonstration of the satellite power station itself, but would be highly desirable for the early phases of prototype flight test and mandatory for the latter phases.

ITEM	TECHNOLOGY RISK ASSESSMENT		DISCUSSION
	RATING	RANKING	
SOCIO-ECONOMIC CONSIDERATIONS	4	23	How to treat certain of the social considerations, both positive and negative, along with the technical ones in comparative terms is not known totally. How much advancement is required in technology in order to develop a viable system is also not known totally. Establishing the energy payback flow for the total system in a complete way may be revealing to the total program as well as to identify and develop technological approaches to enhance the flow. The conduct of non-direct socio-economic investigations in concert with the more direct socio-economic and technical investigations results in a risk rating of 4 being most appropriate.
RE-SUPPLY	4	24	Re-supply of the satellite's consumables and replacement of malfunctioned modules should be planned as both manned and unmanned remotely controlled operations, with the satellite operating as well as not operating. The propulsion and fluid transfer features of re-supply operations will no doubt result in release of material that may be deleterious to the open cathodes of the RF generators. The extent to which this may alter the design of the re-supply vehicles and/or the design of the waveguides and RF generators is not known. This leads to a risk rating of 4 being appropriate.

11.2 TECHNOLOGY ASSESSMENT CONCLUSIONS AND RECOMMENDATIONS

The following are recommended as considerations for risk assessment in developing the system concept, technology development, ground test and flight test.

a. The microwave power transmission system can be configured in such a manner as to not require invention or technology breakthrough, however, continuing efforts should be made to take advantage of applicable breakthroughs as they might be developed over the years.

b. There are 24 items having significant technology risk for the MPTS which require agressive development programs before high confidence can be established in their implementation.

c. The first five most critical items needing technology development in order of priority are: dc-rf Converters and Filters, Materials, Phase Control Subsystems, Waveguides, and Structures.

d. Although Manufacturing Modules and Remote Manipulators are in the critical technology category, significant advancement cannot be undertaken until certain characteristics associated with the technology of the first five items are established.

e. General existing developments leading to the understanding of biological effects of low and high microwave power densities are important. In addition, specific investigations must be undertaken which are site dependent to a large extent. These should be undertaken as the development and operational sites are identified.

f. Attitude control technologies for the operational system interact with beam efficiency, safety and depending on the approach they may result in dynamic loads and materials that will impact the microwave system and components. For flight test systems operating at low orbital altitudes, high angular rates and accelerations lead to significantly more complex implementation than is required for the operational system. These require further in-depth investigation as flight test objectives and their implementation are progressively and more firmly established.

g. Ionospheric effects on the microwave power transmitting system will probably be small. Effects of the system on the ionosphere and on its other users may be significant. The flight test system, in particular the size of the system, may be established by ionospheric effects demonstration test requirements. Further in-depth analysis and tests are required before establishing the requirements firmly.

h. Power transfer at high power levels across flexing and rotary joints constitute a large scale technology development problem.

i. Switchgear including protective elements must be developed for the high power spaceborne application.

j. When it has been established that power from space can be a significant part of the solution to national and international power needs, detailed radio frequency interference investigations must be undertaken and frequency allocations must be established. Radio astronomy users must be major participants in this activity.

k. Support modules and orbital assembly techniques for space flight operations must be developed as the requirements are established in detail.

l. Reliability as well as operations and maintenance considerations to assure long life in space and on the ground will be critical to the operational acceptability of the system. Both mechanically passive and active elements are involved. The maintenance equipment may well be more complex than the functional equipment and a thorough tradeoff of competitive approaches is required.

m. Solar electric propulsion stages, transportation operations, heavy lift launch vehicles, SPS flight mechanics and the power source will have characteristics that impact the design of the microwave power transmission system and its equipments. Thorough understanding of these characteristics and perhaps associated constraints must be established as technology development and concept formulation progresses.

n. Socio-economic considerations will become most important as the total concept formulation is established. How the considerations of environmental impact, favorable and unfavorable, interact with design, operations and economics are yet to be established in the required detail.

o. Re-supply of the space station, particularly of gases and fluids, will impact the system and equipment design. Operations must be established to assure an acceptable level of contamination of sensitive components such as the open elements of the many rf generators.

p. Progressive technology risk assessments and rankings must be established as the technology developments mature and the system concept is established. This will play in important part in technology development, ground test and flight test program definition and re-definition as well as in the details of the overall concept.

SECTION 12

SYSTEM ANALYSIS AND EVALUATION

The important factors in MPTS analysis are operating frequency, power level, cost, ground power density and efficiency. The efficiency can be evaluated in terms of its impact on SPS power source cost. Orbital transportation and assembly costs for both MPTS and SPS must be considered as well. Two cost measurements are used: capital cost per kilowatt which ignores interest, maintenance and return on investment charges; and energy cost in mills per kW hour which includes these costs for the projected lifetime of the station and for a utilization factor less than 100 percent.

12.1 SYSTEM GEOMETRY

Figure 12-1 shows the geometry. The geosynchronous power station is located in an equatorial orbit at a height of $h = 3.63 \times 10^7$ meters. The earth is assumed to be spherical with a radius $r_e = 6.37 \times 10^6$ meters. The rectenna farm is located at a latitude of ϕ_1 and a longitude of ϕ_2 relative to the satellite. The distance from the rectenna to the satellite is given by

$$D = \sqrt{(h + r_e)^2 + r_e^2 - 2(h + r_e)\, r_e \cos \phi_1 \cos \phi_2}$$

The nadir angle at the rectenna is given by

$$\theta_N = \cos^{-1} \left[\frac{(h + r_e) \cos \phi_1 \cos \phi_2 - r_e}{D} \right]$$

The elevation angle more commonly used is

$$\theta_E = \pi/2 - \theta_N$$

The satellite location was chosen as 123°W, which is the stable node nearest the continental USA. Two examples of rectenna locations were taken as 41° 30'N, 78°30'W in the Southwest and 33°00'N, 113°30'W in the Northeast. These represent the range of elevation angles of interest for sites suggested in Reference 6 of Section 1 and therefore extremes in rectenna area, range, and atmospheric attenuation, n_a. Values for parameters were:

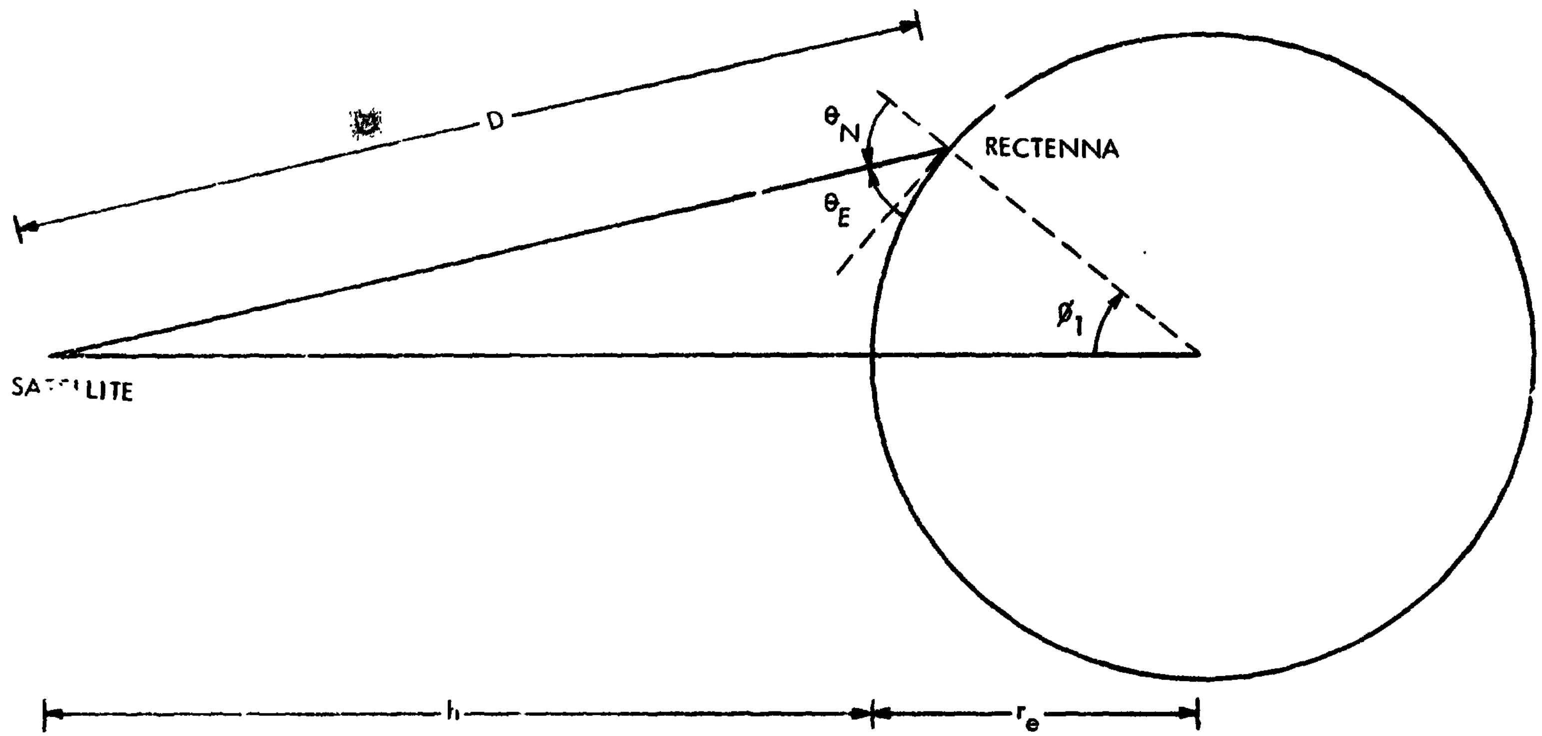

Figure 12-1. MPTS Geometry

Southwest Location	Northeast Location
$\theta_E = 50^o$	$\theta_E = 20^o$
D = 37,092 km	D = 39,569 km
$n_a = 1.99 - e^{0.001f}$	$n_a = 1.98 - e^{0.002f}$

where f is frequency in GHz. Preliminary results showed about 5 percent difference between these locations as regards overall costs. The NE location, which gives the greatest loss, was dropped and the SW location retained for further studies in the interest of simplification.

12.2 PARAMETRIC STUDIES

12.2.1 SYSTEM RELATIONSHIPS

The chain of efficiencies for the MPTS giving the overall efficiency, n, with reference to the functional diagram of Figure 12-2 is:

$$n = n_t n_b n_a n_s n_r$$

where

- n_t = input power distribution, dc-rf conversion, rf distribution at the transmitting antenna
- n_b = beam formation by the transmitting antenna
- n_a = propagation through the atmosphere and ionosphere
- n_s = beam interception at the receiving antenna
- n_r = rf-dc conversion including losses associated with reflected power and interface to power grid

The total cost, C, of an SPS can be represented by:

$$C = \underbrace{(C_1 + KC_2)\frac{P_G}{n}}_{\text{Power Source} = C_{PS}} + \underbrace{(C_3 + C_4K)\left(\frac{P_G}{n}\right)^{1/2}}_{\text{Power Distribution} = C_{PD}} + \underbrace{(C_5 + C_6K)\left(\frac{P_G}{n_b n_a n_s n_r}\right)}_{\text{Converters} = C_C}$$

$$+ \underbrace{(C_7 + C_8K)A_T}_{\text{Transmitting Antenna} = C_{TA}} \quad \underbrace{C_9A_R + C_{10}(P_G)^{1/2}}_{\text{Receiving Antenna} = C_{RA}}$$

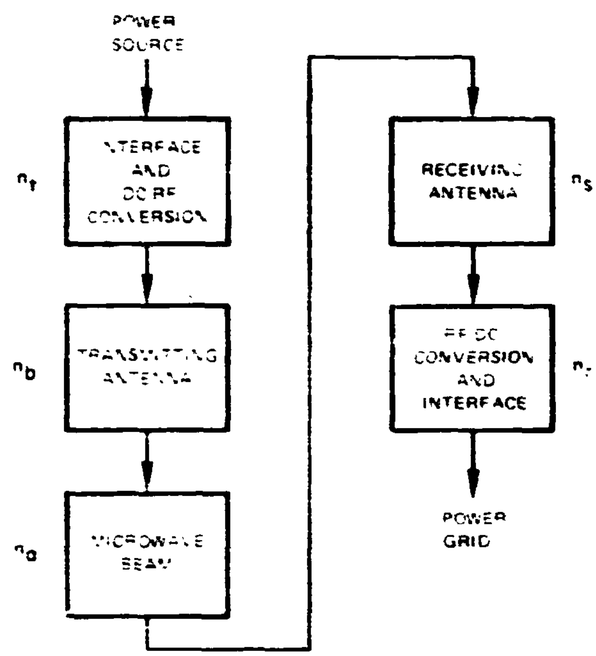

Figure 12-2. MPTS Functional Diagram

where:

K = orbital transportation-assembly specific cost

P_G = ground output power

A_R = receiving antenna area

A_T = transmitting antenna area

$C = C_{PS} + C_{PD} + C_C + C_{TA} + C_{RA}$

where:

$C_1, C_3, C_5, C_7, C_9, C_{10}$ = manufacturing specific costs

C_2, C_4, C_6, C_8 = specific weights

$$C_1 = \$/kW = \frac{\text{Cost of the Power Source}}{\text{Power Output at the Power Source}}$$

$$C_3 = \$/\sqrt{W} = \frac{\text{Cost of the Orbital Power Distribution}}{\sqrt{\text{Power Output at the Power Source}}}$$

$$C_5 = \$/kW = \frac{\text{Cost of the DC to RF Converters}}{\text{Power Output at the Radiating Slots}}$$

$$C_7 = \$/m^2 = \frac{\text{Cost of the Transmitting Antenna}}{\text{Area of the Transmitting Antenna}}$$

$$C_9 = \$/m^2 = \frac{\text{Cost of Receiving Antenna}}{\text{Area of Receiving Antenna}}$$

$$C_2 = \frac{KG}{KW} = \frac{\text{Weight of the Power Source}}{\text{Power Output at the Power Source}}$$

$$C_4 = \frac{KG}{\sqrt{W}} = \frac{\text{Weight of Orbital Antenna Power Dist. System}}{\sqrt{\text{Power Output at the Power Source}}}$$

$$C_6 = \frac{Kg}{KW} = \frac{\text{Weight of Converters}}{\text{Power Output at the Converter}}$$

$$C_8 = \frac{Kg}{m^2} = \frac{\text{Weight of Transmitting Antenna}}{\text{Area of Transmitting Antenna}}$$

$$C_{10} = \$/\sqrt{W} = \frac{\text{Cost of Receiving Antenna}}{\sqrt{\text{Power Output to the Power Grid}}}$$

Since $\sqrt{A_T A_R}/\lambda D = \gamma$ for a given n_s and beam taper as shown in Figure 12-3.

$$A_R = \frac{(\lambda D \gamma)^2}{A_T}$$

and substituting, the specific cost, C/P_G, is

$$\frac{C}{P_G} = \frac{(C_1 + KC_2)}{n} + \frac{C_3 + C_4 K}{n^{1/2} P_G^{1/2}} + \frac{(C_5 + C_6 K)}{n_b n_a n_s n_r}$$

$$+ \frac{(C_7 + C_3 K) A_T}{P_G} + \frac{C_9 (\lambda D \gamma)^2}{A_T P_G} + \frac{C_{10}}{P_G^{1/2}}$$

We see that specific cost decreases for increased power output and increased frequency. It will approach a level value dependent upon the power source, converter, transportation (C_1, C_2, C_5, C_6, K) and efficiencies as power level becomes very high. High efficiencies reduce specific cost for a given A_T. To examine the effect of variation in A_T for fixed efficiencies, beam taper and power output, note that

$$C/P_G = \text{constant} + \frac{(C_7 + C_8 K) A_T}{P_G} + \frac{C_9 (\lambda D \gamma)^2}{A_T P_G}$$

so the lowest cost system will have

$$A_T = \left[\frac{C_9 (\lambda D \gamma)^2}{C_7 + C_8 K} \right]^{1/2} = \lambda D \gamma \left[\frac{C_9}{C_7 + C_3 K} \right]^{1/2}$$

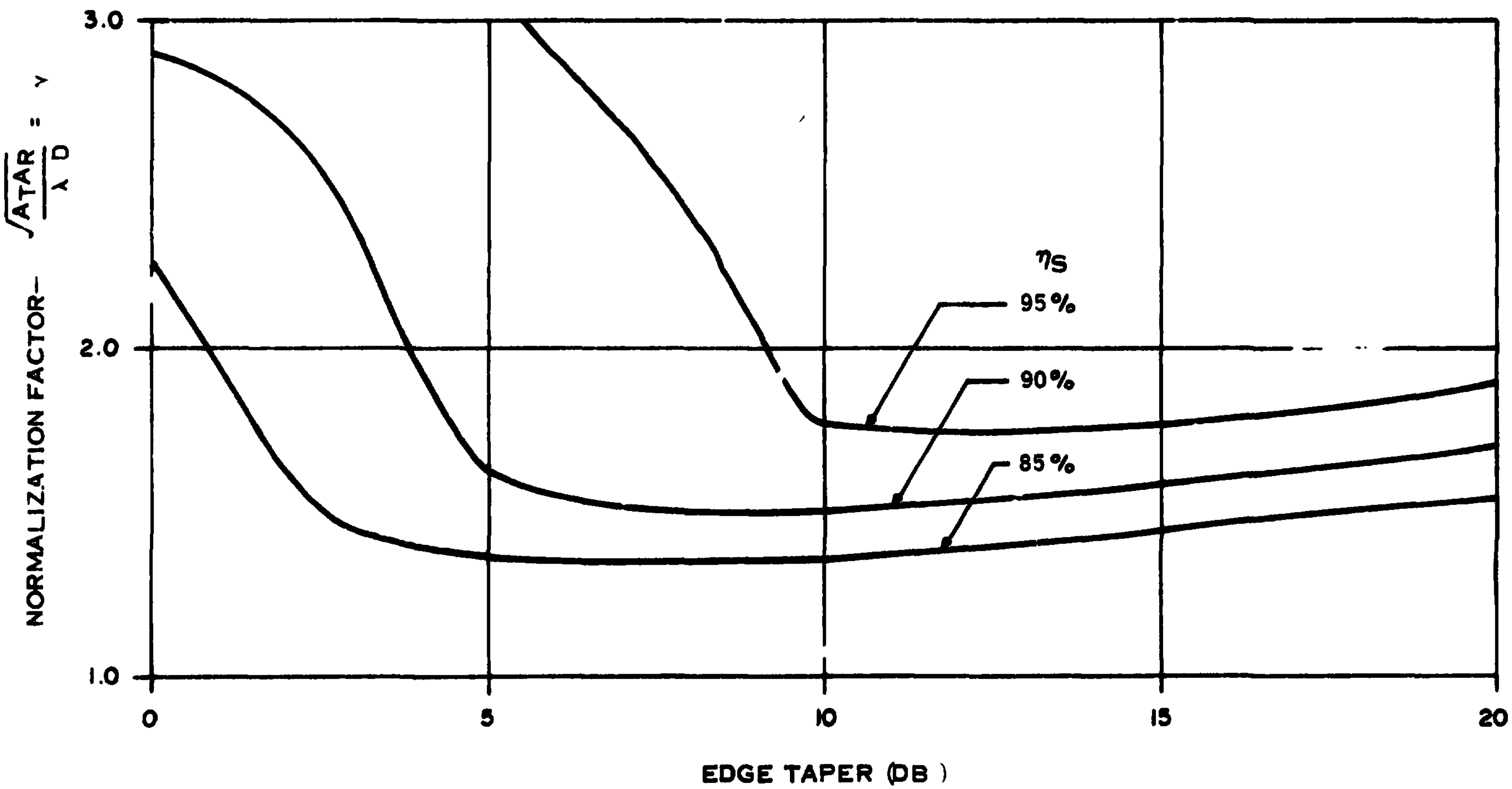

Figure 12-3. Beam Efficiencies (η_s) for Truncated Gaussian Tapers

The transmitting antenna therefore will tend to be smaller as its manufacturing and orbital transportation-assembly costs, $C_7 + C_8K$, increase and as the receiving antenna costs, C_9, decrease.

To examine the specific cost relationships for a given value of A_T as η_s and γ are varied, we that see that

$$\frac{C}{P_G} = \frac{1}{\eta_s}\left\{\frac{C_1 + KC_2}{\eta_t \eta_b \eta_a \eta_r} + \frac{\eta_s (C_3 + C_4K)}{\eta^{1/2} P_G^{1/2}} + \frac{C_5 + C_6K}{\eta_b \eta_a \eta_r}\right\} + \frac{(C_7 + C_8K)A_T}{P_G} + \frac{C_9 (\lambda D \gamma)^2}{P_G A_T}$$

Since for any taper, γ increases with η_s (Figure 12-3), the lowest cost SPS will be found by a tradeoff between orbital specific costs, C_1 through C_6, and the ground antenna specific cost, C_9.

12.2.2 EFFICIENCY, WEIGHT AND COST

The efficiency, weight and cost values for the MPTS used in the parametric study were later revised in some cases, as noted in paragraph 12.3.1 but the trends remain valid as bases for selection of power levels and operating frequency.

The efficiencies used at a frequency of 2.45 GHz were:

η_t = 82.0% (81.4% for klystron)

η_b = [illegible].0%

η_a = 98.8%

η_s = variable

η_r = 81.4%

η = 58.0% for η_s = 90%

Discussion of efficiency variation with frequency has been presented in earlier sections. The graphic data were approximated by analytical expressions as follows, where f has the units GHz:

$$n_t = 1.845 - e^{0.01f} \text{ for the amplitron configuration}$$

$$= 1.814 - e^{0.003f} \text{ for the klystron configuration}$$

$$n_r = 1.896 - e^{0.022f} \text{ for rf-dc conversion and interface}$$

Overall efficiency, n, is shown in Figure 12-4 for the amplitron configuration. These approximations emphasize the frequency region 1 GHz to 5 GHz. Although preliminary studies examined performance to higher frequencies, the rain attenuation data showed that the region of interest should not extend much above 3 GHz. Also, in this range the atmospheric attenuation presented above is the dominant propagation factor; lower frequencies would have to consider the effect of Faraday rotation ($1/f^2$ dependence) on the efficiency of the rectenna which is designed to a linear polarization, or the rectenna would have to be designed for dual polarization at added expense.

Cost factors for all system elements are dependent on weight, area or power level, and extrapolations were made from nominal designs at either 5 GW or 10 GW ground output power. A summary of these is given in Figure 12-5, where a range of values is given for the power source and orbital operations costs and for microwave orbital and ground systems. Frequency is taken as 2.45 GHz. It is assumed that peripheral land out to a level of 0.1 mW/cm^2 power density is purchased for safety reasons.

The power source characteristics enter the search for a desirable MPTS design because its weight and cost reflect the impact of MPTS efficiency, or lack of it, as noted above. The key parameters are specific cost in dollars per kilowatt and specific weight in kilograms per kilowatt (or grams per watt), where the reference power is that delivered in orbit to MPTS. The use of ground delivered power often is used as a normalization factor but that approach mixes the power source and MPTS parameters, and leads to confusion in the optimization process. Also, the recommended approach permits a direct comparison of SPS power source characteristics with those for ground based systems.

The candidate technologies for the power source - solar photovoltaic, solar thermal, and nuclear - have been studied in decreasing detail for space application in the order given[10, 11]. The suggested group of parameters evolved over the course of the study as a composite set representing the widest range

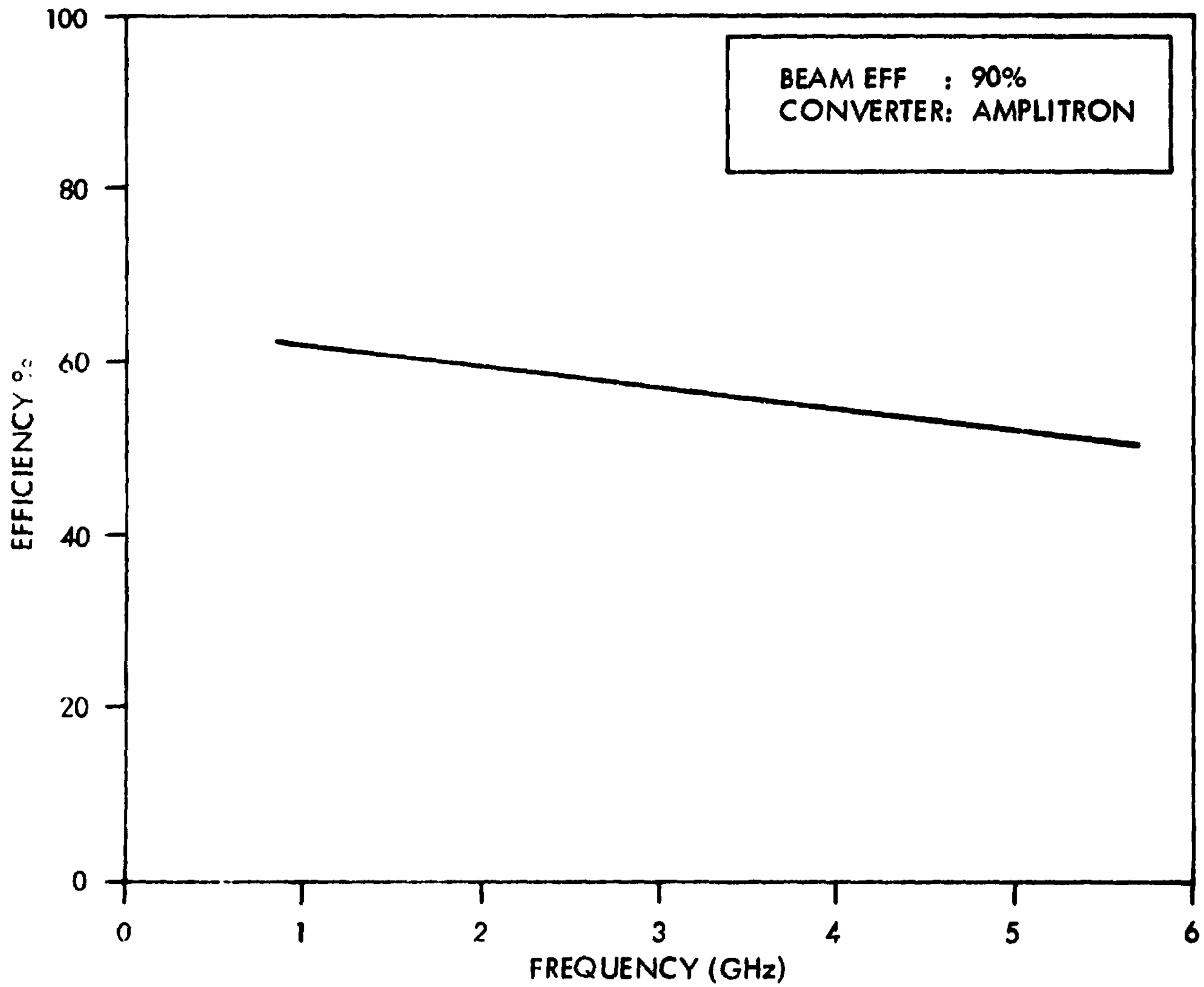

Figure 12-4. MPTS Efficiency (η) vs Frequency for Parametric Studies

TRANSPORTATION AND POWER SOURCE			
	Low (L)	Medium (M)	High (H)
Transportation (K)	\$100/kg	\$300/kg	\$600/kg
Power Source (C_1)	\$200/kW	\$500/kW	\$1000/kW
Power Source (C_2)	0.75 kg/kW	1.5 kg/kW	2.5 kg/kW
ORBITAL MICROWAVE (TRANSMITTING ANTENNA)			
	Low (L)	Medium (M)	High (H)
Power Distribution (at 6.75 GW)	\$4.73 x 10^6	\$79.4 x 10^6	\$114.9 x 10^6
	-	0.512 x 10^6 kg	-
Electronics	0.0877 kg/m^2	0.195 kg/m^2	0.414 kg/m^2
Waveguide - Aluminum	-	3.5 kg/m^2	-
	-	134 \$/kg	-
Waveguide - Graphite	-	2.1 kg/m^2	-
	-	335 \$/kg	-
DC-RF Converter - Amplitron	0.21 kg/kW	0.33 kg/kW	0.47 kg/kW
	15.49 \$/kW	24.62 \$/kW	34.8 \$/kW
DC-RF Converter - Klystron	-	1.04 kg/kW	-
	-	42.90 \$/kW	-
Structure - Aluminum	-	1.375 kg/m^2	-
	-	134 \$/kg	-
Structure - Graphite Comp.	-	0.825 kg/m^2	-
	-	335 \$/kg	-
GROUND MICROWAVE (RECEIVING ANTENNA)			
	Low (L)	Medium (M)	High (H)
Rectenna (at 2.45 GHz)	7.2 \$/m^2	10.65 \$/m^2	15.4 \$/m^2
Command Control	\$12.85 x 10^6	\$24.7 x 10^6	\$49.4 x 10^6
Peripheral Land (to 0.1 mW/cm^2)	-	0.25 \$/m^2	-

Figure 12-5. Parametric Study Specific Costs and Weights

that reasonably could be expected over a development-deployment time period extending into the next century. At the low end, the technology is pushed; at the high end the costs become marginally competitive with other sources, as will be seen subsequently. For the solar photovoltaic system Grumman Aerospace Corp. derived a 1.46 kg/kW specific weight for a 14 percent cell efficiency during this study.

The transportation-assembly costs range from a low cost Heavy Lift Launch Vehicle (HLLV) figure of 100 \$/kg to a Shuttle based figure of 600 \$/kg described in Section 8. Preliminary studies examined costs extending up to [illegible]000 \$/kg, but these were discarded as the Shuttle costs were derived and served as an upper bound.

Relations for DC-RF converter medium weight and cost parameters as functions of frequency were:

Amplitron:	Cost (\$/kW)	=	$11.75 + 5.25\,f$
	Weight (kg/kW)	=	$0.377 - 0.026\,f,\ f \leq 2$ GHz
		=	$0.306 + 0.01\,f,\ f \geq 2$ GHz
Klystron:	Cost (\$/kW)	=	$34.231 + 3.333\,f,\ f \leq 2.2$ GHz
		=	$29.77 + 5.357\,f,\ 2.2 \leq f \leq 5$ GHz
	Weight (kg/kW)	=	$1.245 - 0.094\,f,\ f < 2.2$ GHz
		=	$1.039,\ 2.2 \leq f \leq 5$ GHz

The rectenna portion of the receiving antenna (excluding power interface) expense depends upon frequency because shorter wavelength means more diode-dipole elements per unit area. For the medium value:

$$\text{Rectenna Cost } (\$/m^2) = 6.65 + 4\,(f/2.45)^2$$

where f is given in GHz.

12.2.3 CONVERTER PACKING

The converter thermal radiator diameter limits the tube packing and radiated power density at the center of the transmitting antenna, and therefore sets a minimum antenna diameter for a given value of total radiated power and beam taper. The thermal radiator diameter depends upon converter efficiency which is a function of frequency.

The total radiated power, P_T, is

$$P_T = P_0 A_T \left[\frac{1 - 10^{-dB/10}}{0.23\ dB}\right]$$

where

P_0 = peak power density at the center of the antenna

dB = beam taper at the transmitter aperture.

The maximum value for P_0 is given by the following:

Amplitron: $$P_{0_{max}} = 21.7 \times 10^3 \left[\frac{1 - n_t'}{1 - n_t}\right] w/m^2$$

Klystron: (43 kW) $$P_{0_{max}} = 1.44 \times 10^3 \left[\frac{1 - n_t'}{1 - n_t}\right] w/m^2$$

where n_t' = efficiency at f = 2.45 GHz.

These values correpond with thermal radiator diameters of 48 cm for the amplitron and 174 cm for the klystron at 2.45 GHz.

12.2.4 CAPITAL COST VS POWER AND FREQUENCY RESULTS

A beam taper of 5 dB and a beam collection efficiency, n_s, of 90 percent were selected to exhibit trends of capital cost as frequency and power are varied. The results in capital cost per unit output power are given in Figures 12-6 and 12-7 for the low and medium cost combinations of power source and orbital operations, with microwave costs at the medium level. All costs are expressed in 1975 dollars. The factors entering into the overall cost are shown in Figures 12-8 through 12-11.

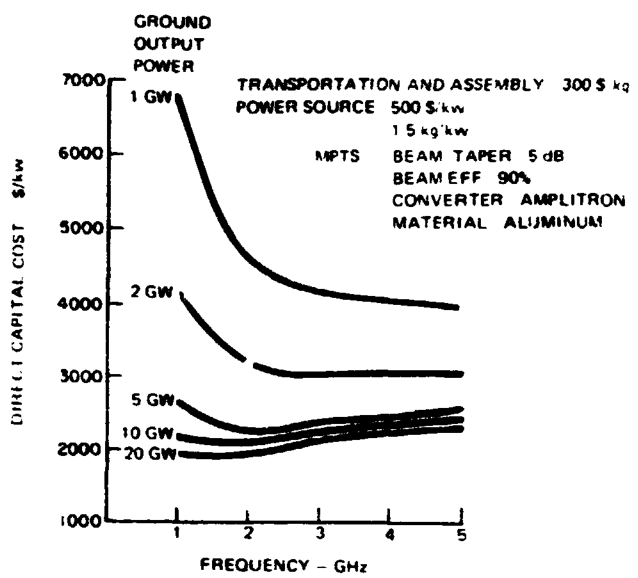

Figure 12-6. SPS Capital Cost vs Frequency - 300 $/kg

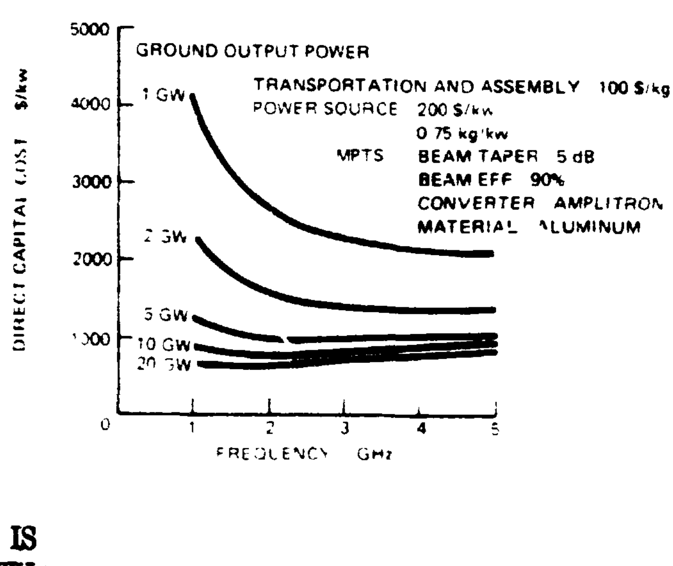

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Figure 12-7. SPS Capital Cost vs Frequency - 100 $/kg

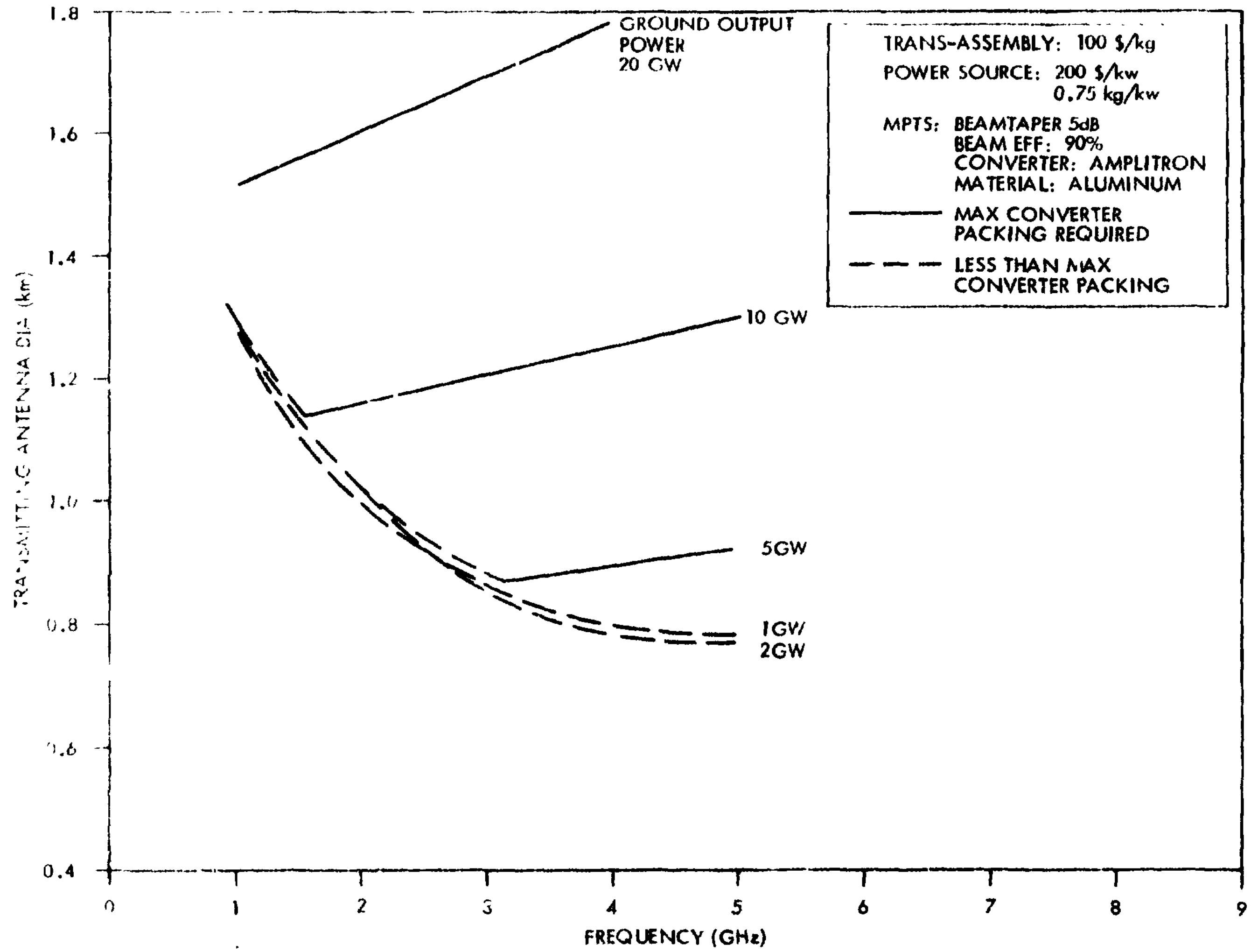

Figure 12-8. Transmitting Antenna Diameter for Lowest Cost SPS

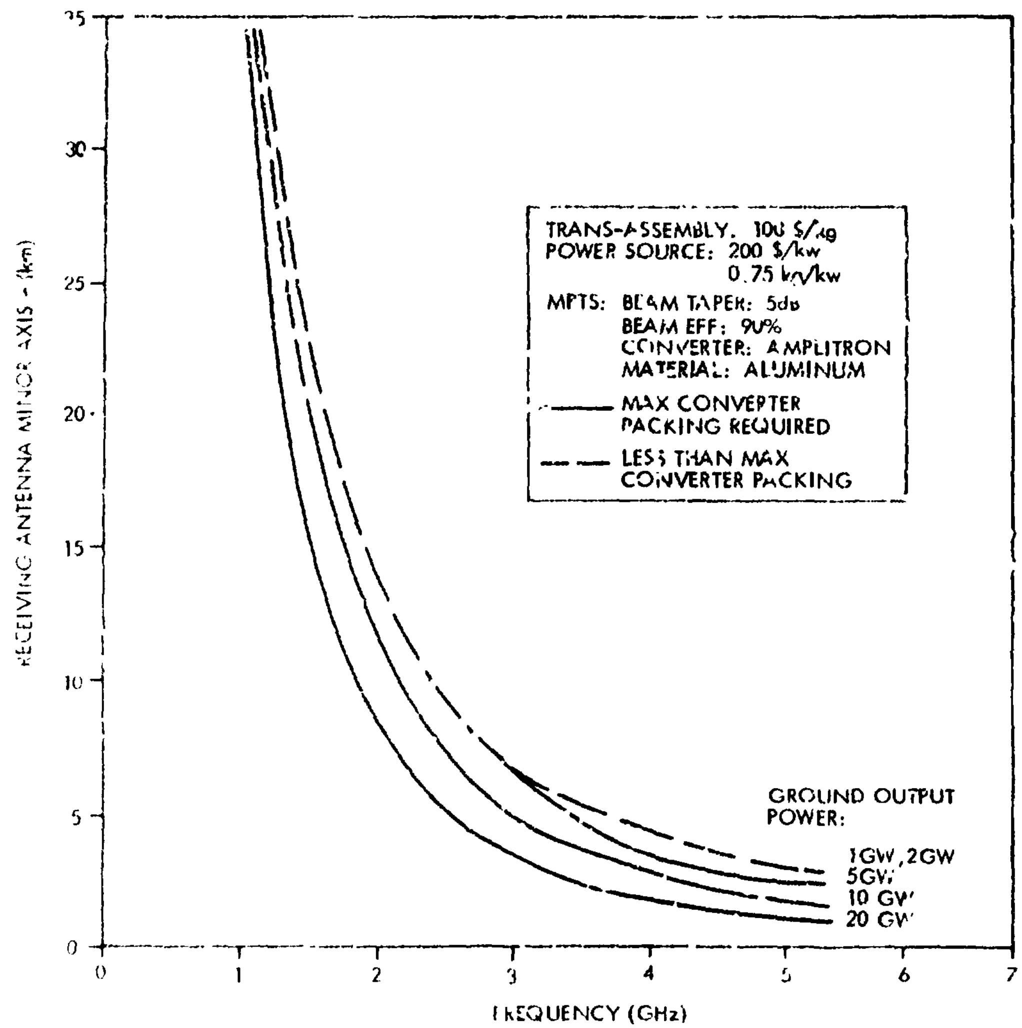

Figure 12-9. Receiving Antenna Minor Axis for Lowest Cost SPS

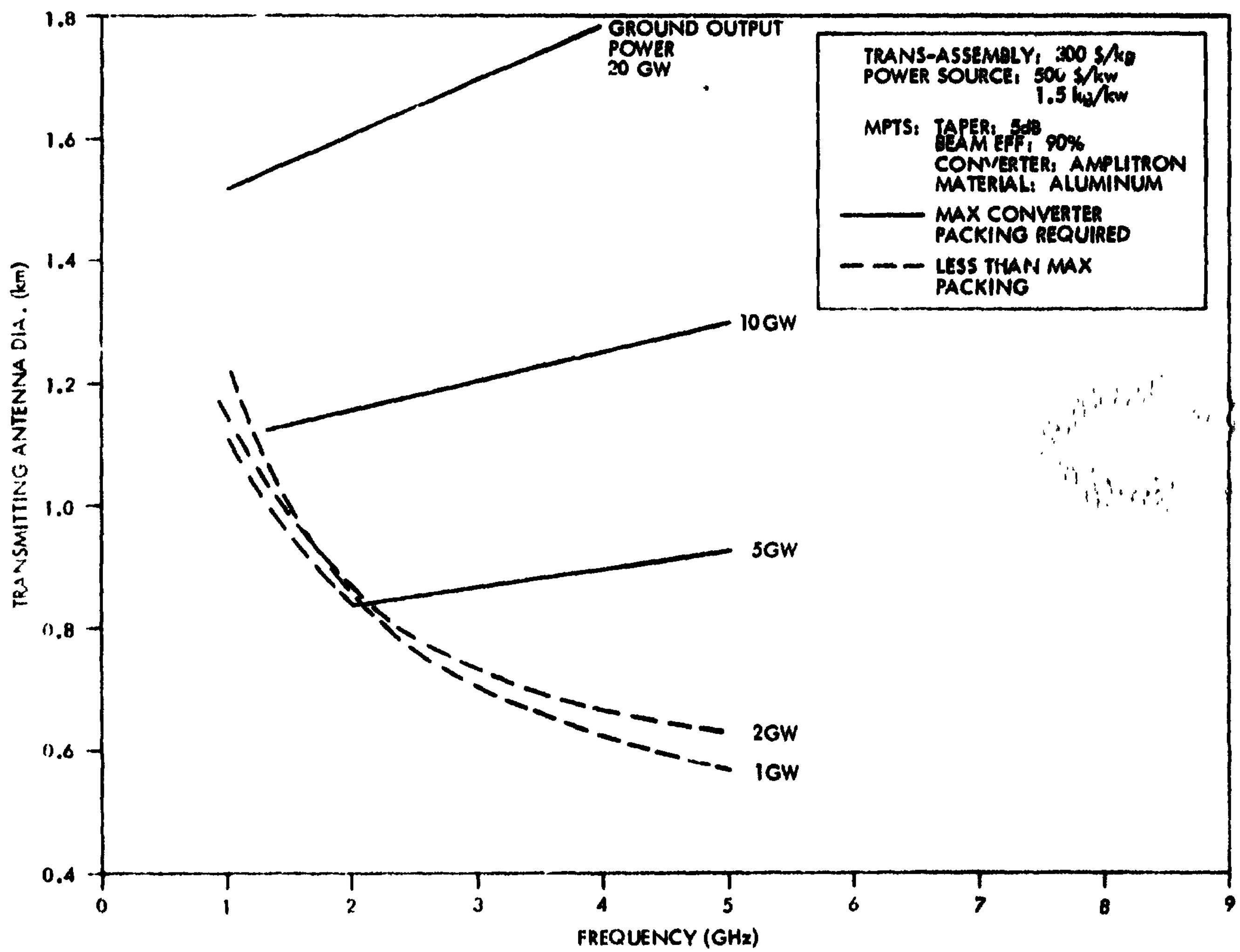

Figure 12-10. Transmitting Antenna Diameter for Lowest Cost SPS (300 $/kg, 500 $/kW)

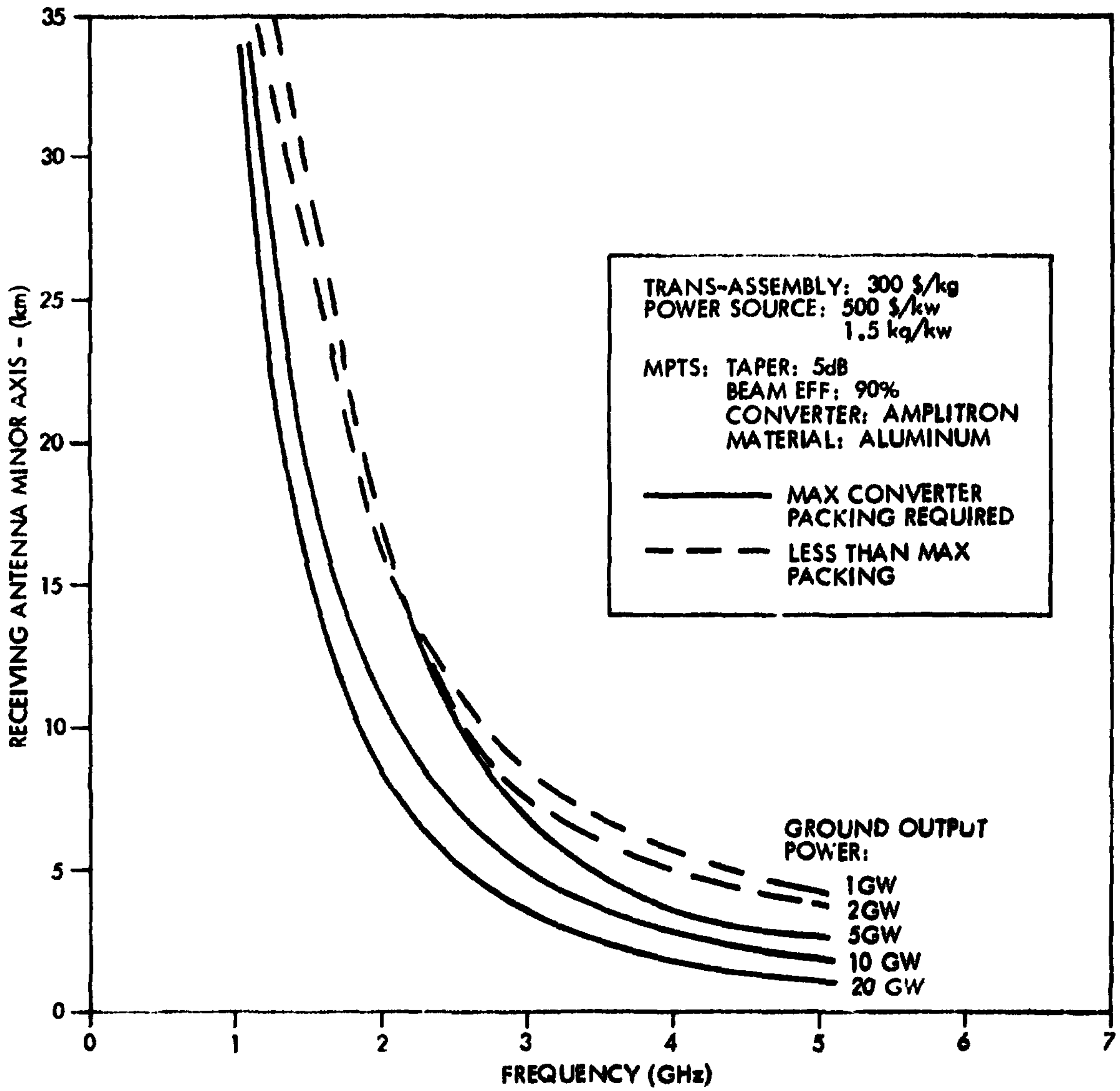

Figure 12-11. Receiving Antenna Minor Axis for Lowest Cost SPS (300 $/kg, 500 $/kW)

We see that trends expected from the relations previously described are present, including the effects of converter packing limitations. The latter produces discontinuities in the higher power transmitting antenna diameter trends and as a result there are gradual increases in the capital cost near 2 GHz for the higher powers. Decreasing efficiencies also contribute to a leveling off of costs for the lower power cases.

The trends for klystron configurations of both aluminum and graphite composite materials shown in Figure 12-12 follow the same pattern as for the amplitron-aluminum cases of Figures 12-7 and 12-8. There is a slight shift to minima at higher frequencies for the klystron.

12.2.5 GROUND POWER DENSITY AND POWER LEVEL SELECTION

The microwave power density at the ground has implications for both environmental and biological effects and so is a key parameter in describing the MPTS. The peak level at the center of the beam is of primary interest and its magnitude, P_D, is given by:

$$P_D = \frac{P_0 A_T^2}{\lambda^2 D^2} \left[\frac{1 - 10^{-dB/20}}{0.115\ dB} \right] n_a n_b$$

The peak levels are plotted in Figure 12-13 for the ranges of power levels and operating frequencies of interest. Maximum converter (amplitron) packing at the transmitting antenna is assumed which results in the minimum ground power density, i.e., the smallest antenna gives the lowest peak ground power density for a given overall power level and beam taper. Also plotted are the approximate level for ground solar radiation (100 mW/cm^2), the threshold estimated for onset of self-induced irregularities in the ionosphere, and the USA standard for continuous exposure (10 mW/cm^2).

We see that power levels above 5 GW increase the potential for environmental distrubance in the ionosphere and for potential difficulties in adequately safeguarding the air space above the receiving antenna. It is quite probable that ionospheric effects will be so localized that other users will not be disturbed, and that aircraft and bird fly-throughs will be too rapid to cause damage, but it

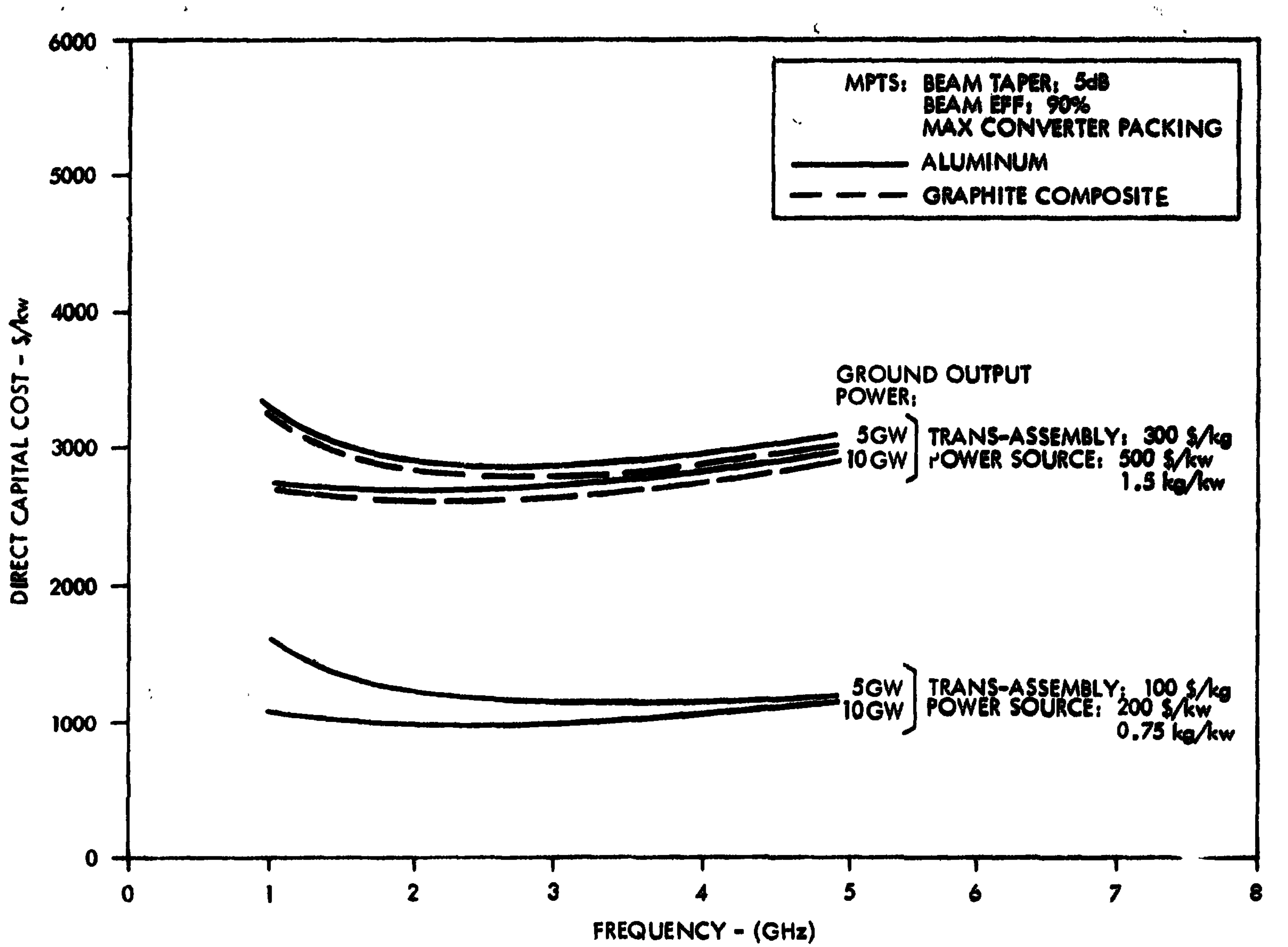

Figure 12-12. SPS Capital Cost for Klystron Configurations

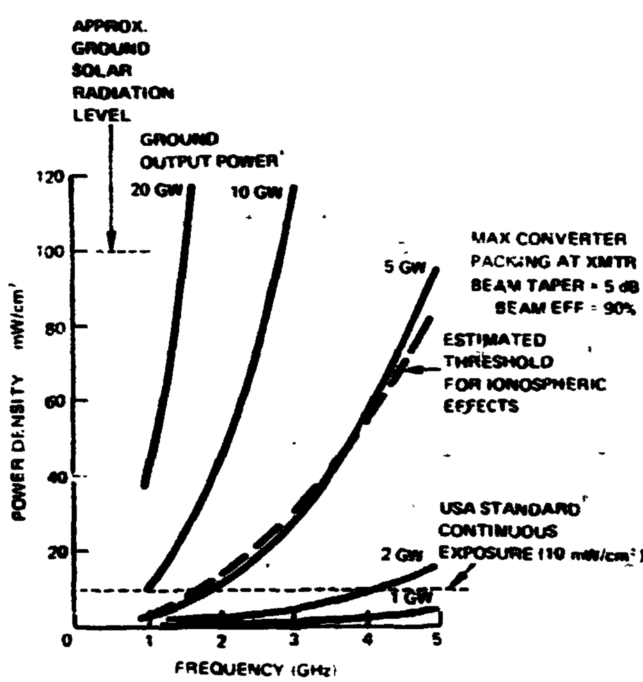

Figure 12-13. Peak Ground Power Density vs Frequency

would be prudent to limit levels to 5 GW, or 10 GW at most. The penalty is not large since the economy of scale is achieved at the 5 GW level.

12.2.6 FREQUENCY SELECTION

Frequency selection perhaps is the most important output of this study since device development is intimately related to the choice, and system development can be severely impacted by difficulties in radio frequency interference and allocation. The DC-RF converter characteristics and the system efficiency and cost factors have been shown to be favorable in a broad range near 2 GHz so that a choice of the USA industrial band of 2.4-2.5 GHz centered at 2.45 GHz appears to be straightforward. The effect on other users of the spectrum can be significant for any choice, but the 2.45 GHz selection appears to have minimal impact as discussed in an earlier section.

12.2.7 CHARACTERISTICS OF 5 GW AND 10 GW SYSTEMS

Attention was directed to the effects of beam taper, beam collection efficiency and cost assumptions on the characteristics of 5 GW and 10 GW systems at the selected frequency of 2.45 GHz. It was assumed in these calculations that the converters would be fully packed at the center of the transmitting antenna, which as stated earlier minimizes orbital antenna diameter and ground power density. Note that these assumptions do not necessarily give minimum cost results in all cases. They do lead to lowest cost for beam tapers of 5 dB and greater if power source and transportation-assembly estimates are medium level or higher for the assumptions in Figure 12-5.

The results in Figure 12-14 show that there will be favored combinations of taper and beam efficiency to make best utilization of the receiving antenna, as could be anticipated from Figure 12-3. Figure 12-15 shows that increasing taper increases transmitting antenna size, and Figure 12-16 shows that increasing taper causes higher ground power densities. The 5 dB taper 90 percent beam efficiency combination is attractive in that it has a relatively low power density on the ground with a reasonably small receiving antenna. These results are independent of cost assumptions.

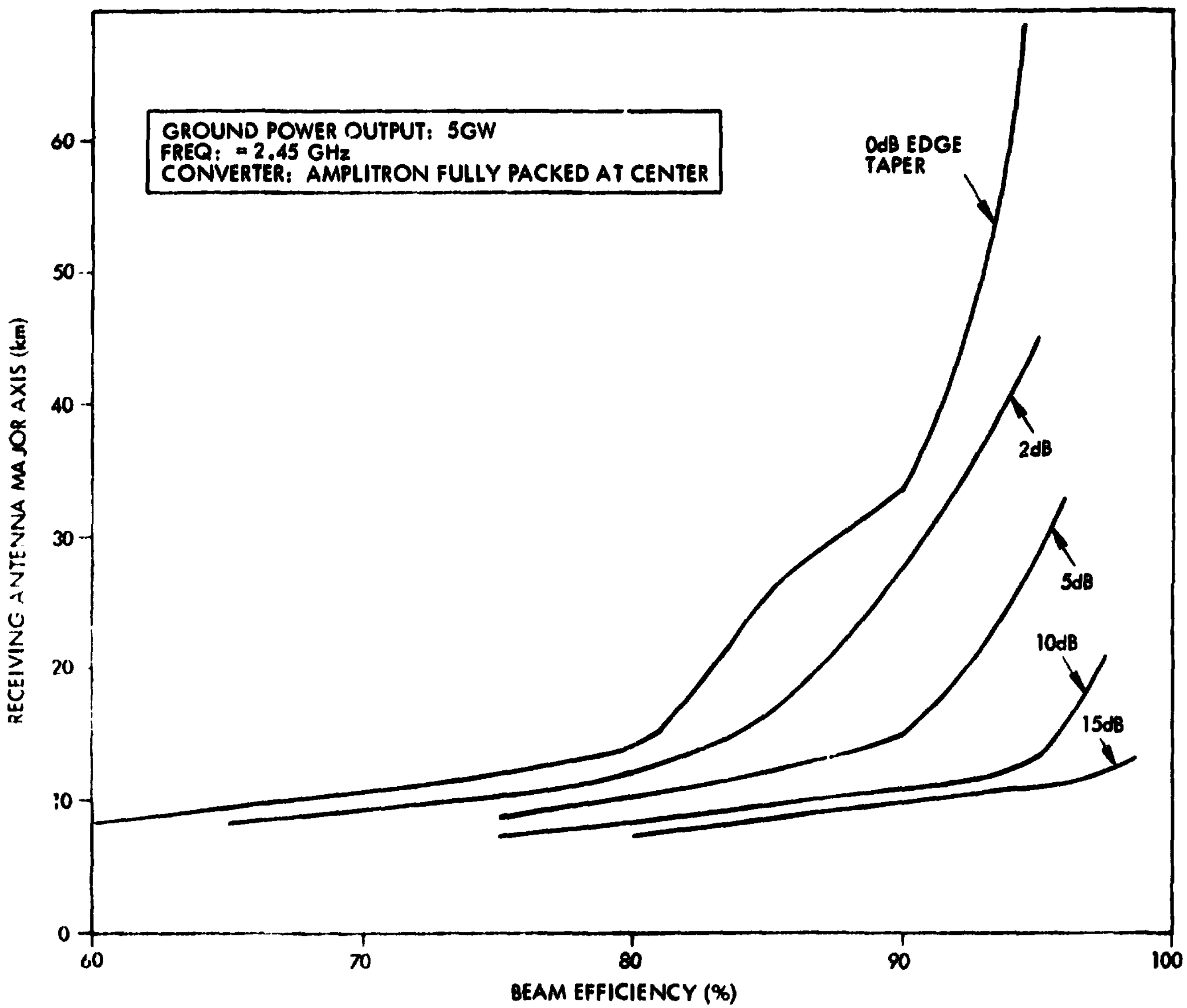

Figure 12-14. Receiving Antenna Size vs Beam Efficiency and Taper

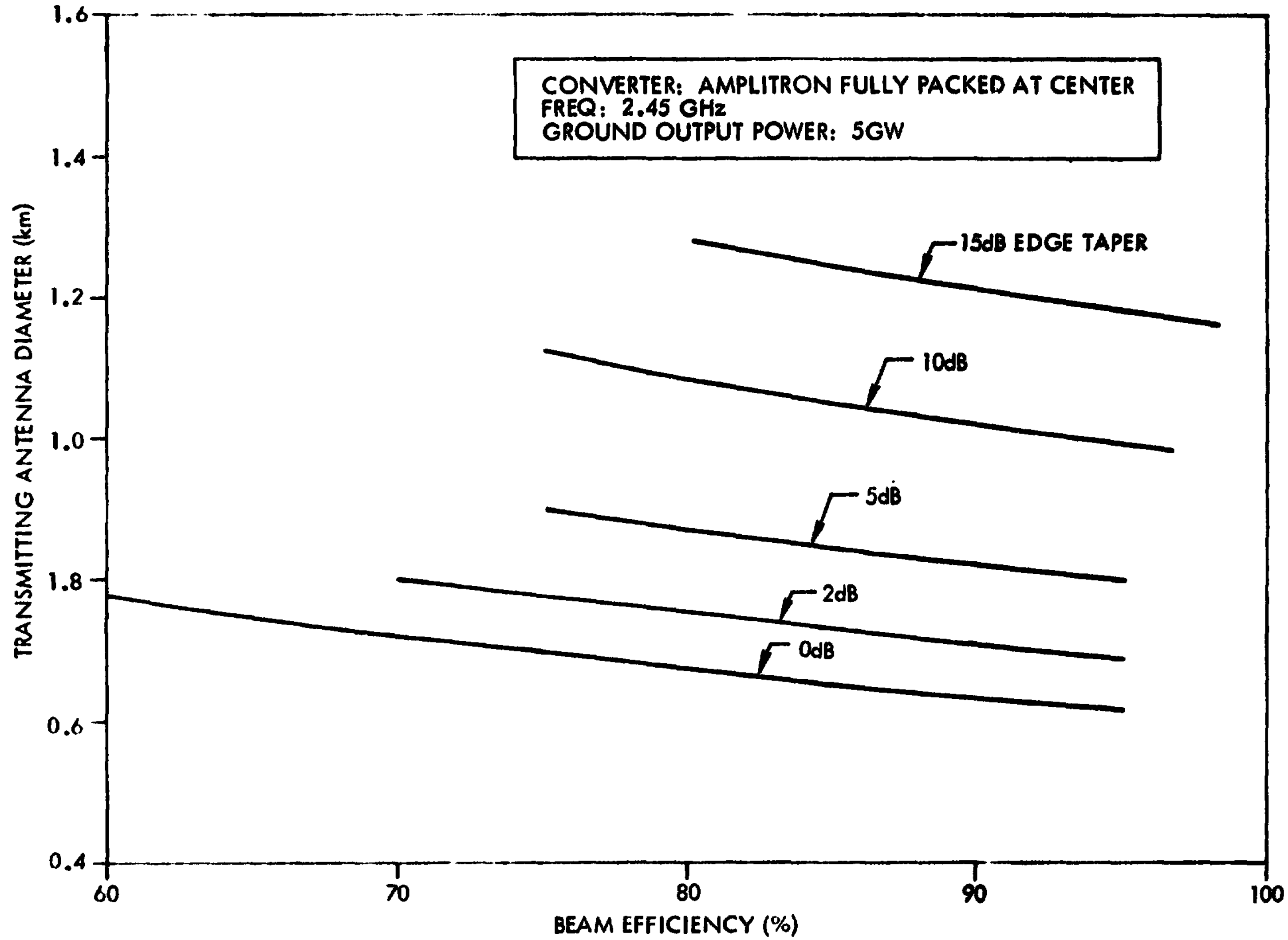

Figure 12-15. Transmitting Antenna Size Vs Beam Efficiency and Taper

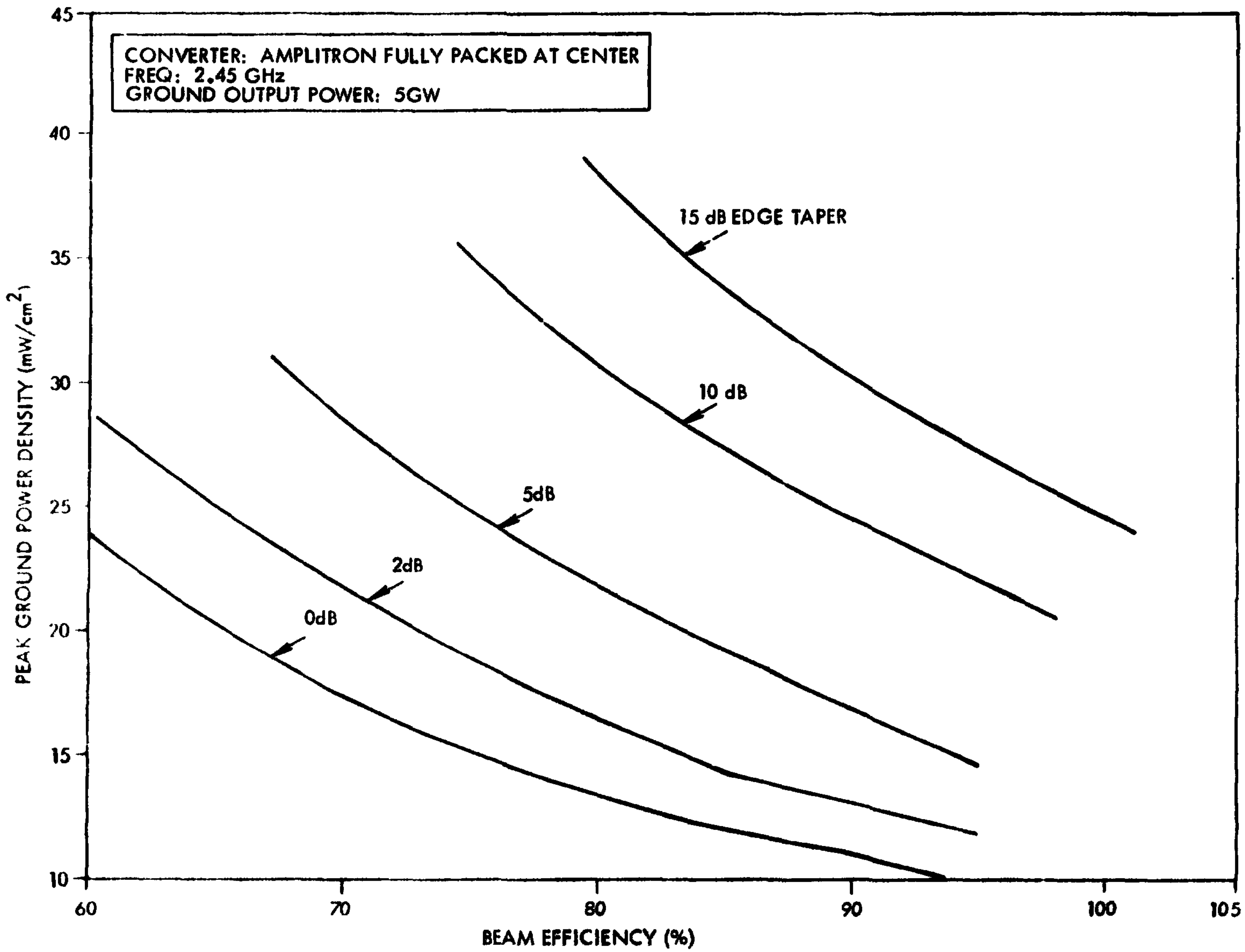

Figure 12-16. Peak Ground Power Density vs Beam Efficiency and Taper

Results of an examination of the impact of cost variations for amplitron-aluminum systems at various taper and beam efficiencies are given in Figures 12-17 through 12-20. Assumptions with respect to cost level (Low (L), Medium (M), High (H)) of the power source and transportation, orbital portion of the microwave power transmission system, and ground portion of the microwave power transmission system are noted as the "case" on the figures; e.g., in the LMM the L denotes low cost power source and transportation, the first M denotes medium cost orbital portion of the microwave power transmission system, and the last M denotes medium cost for the ground portion of the microwave power transmission system. The principal cost drivers are the power source and transportation-assembly. Near minimum cost can be achieved by several taper and efficiency combinations, so that the selection can be made for reasons related to power density and land use without excessive cost penalty. A comparable set of data depicted in Figures 12-21 through 12-24 for a power output of 10 GW shows similar results.

The sets of 5 dB, 90 percent and 10 dB, 95 percent were selected for a summary comparison of 5 GW and 10 GW systems as shown in Figure 12-25 and the klystron and graphite composite material options were compared for a 5 dB, 90 percent set in Figure 12-26. The lower ground power density and smaller transmitting antenna favor the 5 dB, 90 percent combination and the considerably lower cost for the amplitron favors its choice over the klystron. The graphite composite choice is lower weight but similar overall cost due to higher material and processing costs. The 5 GW, 5 dB, 90 percent amplitron-aluminum configuration is selected for additional evaluation in terms of bus bar cost of electrical power as described in the next section. A summary of its characteristics is as follows:

Ground Output Power	5 GW
Overall Efficiency	58 percent
Radiated Power	7 GW
Transmitting Antenna Dia.	0.83 kM
Peak Power Density at Transmitter	21.7 kW/m^2
Peak Power Density at Receiver	17.0 mW/cm^2
First Sidelobe Power Density	0.2 mW/cm^2
Rectenna Size	14.7 km x 11.3 km
Fence Size (to 0.1 mW/cm^2)	26.5 km x 20.4 km

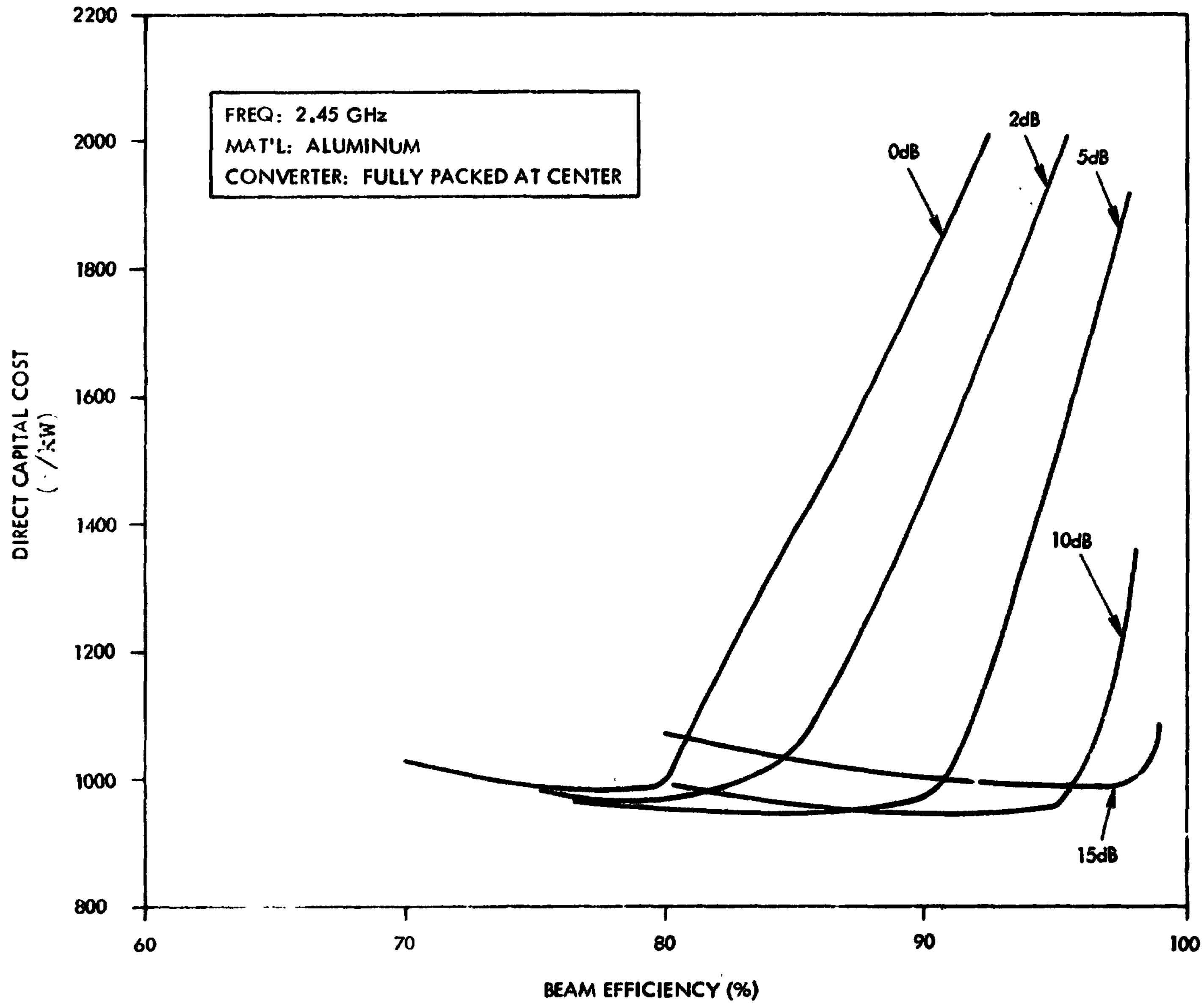

Figure 12-17. Cost Matrix - 5 GW - Case LMM

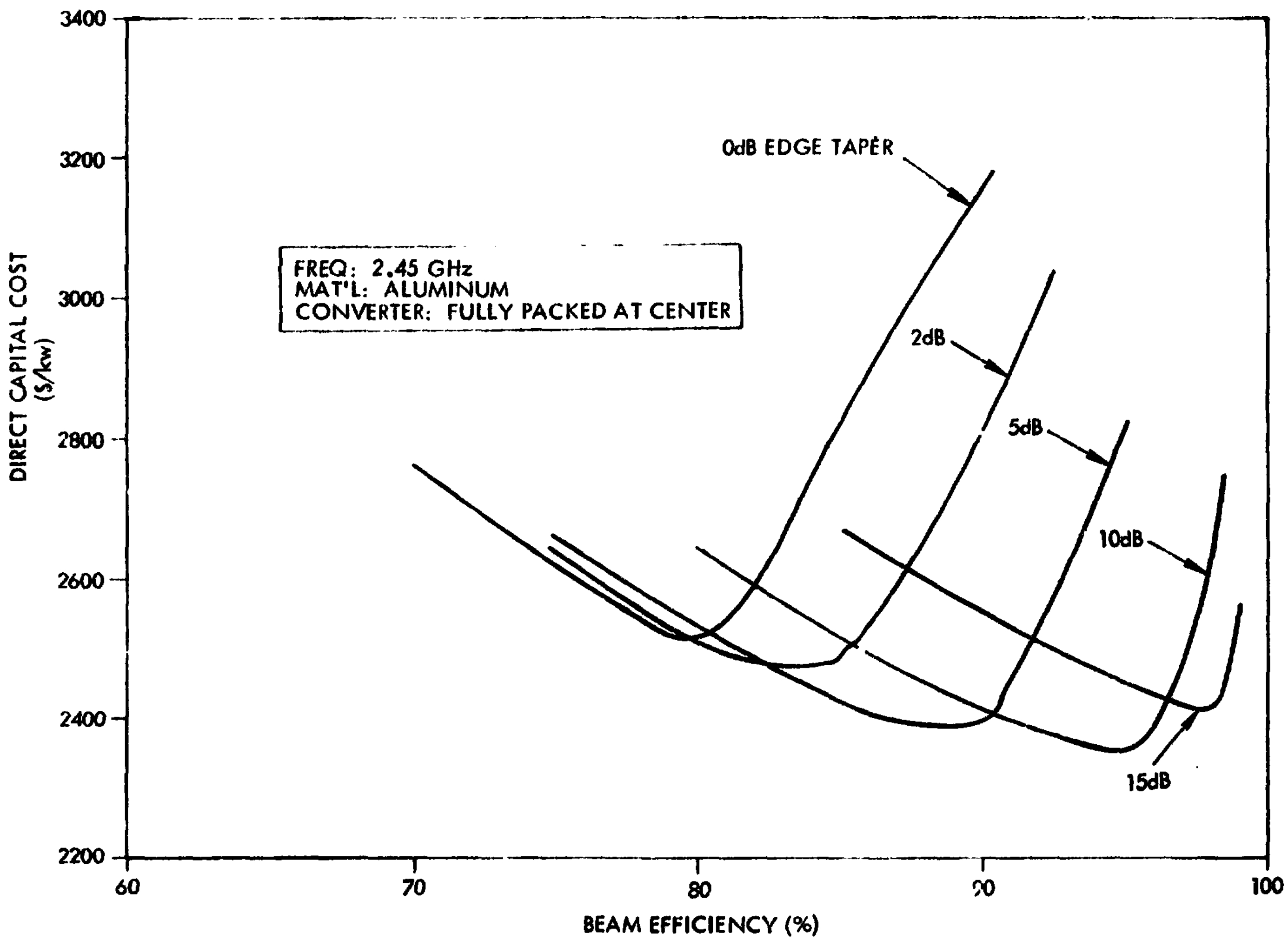

Figure 12-18. Cost Matrix - 5 GW - Case MMM

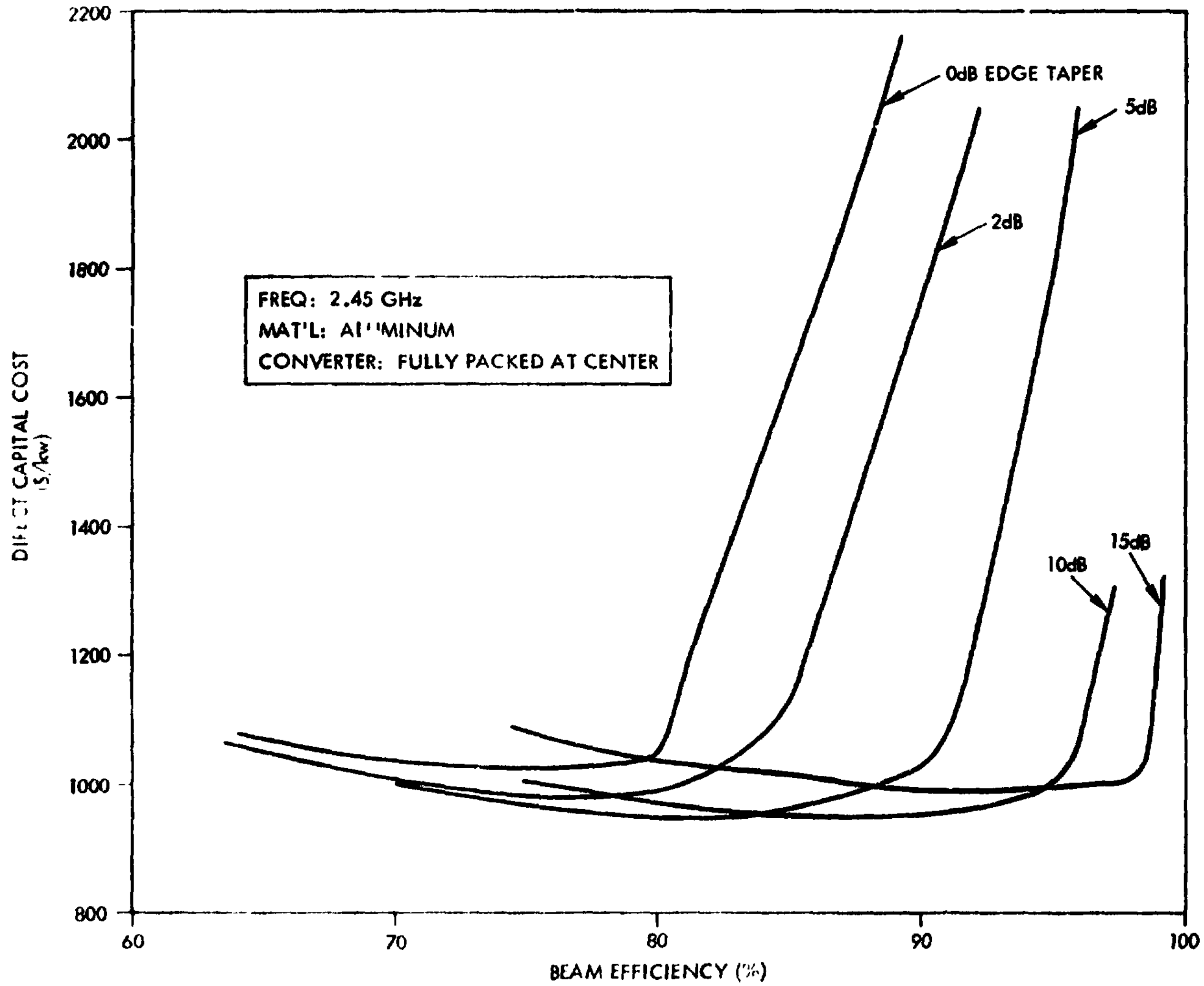

Figure 12-19. Cost Matrix - 5 GW - Case LLH

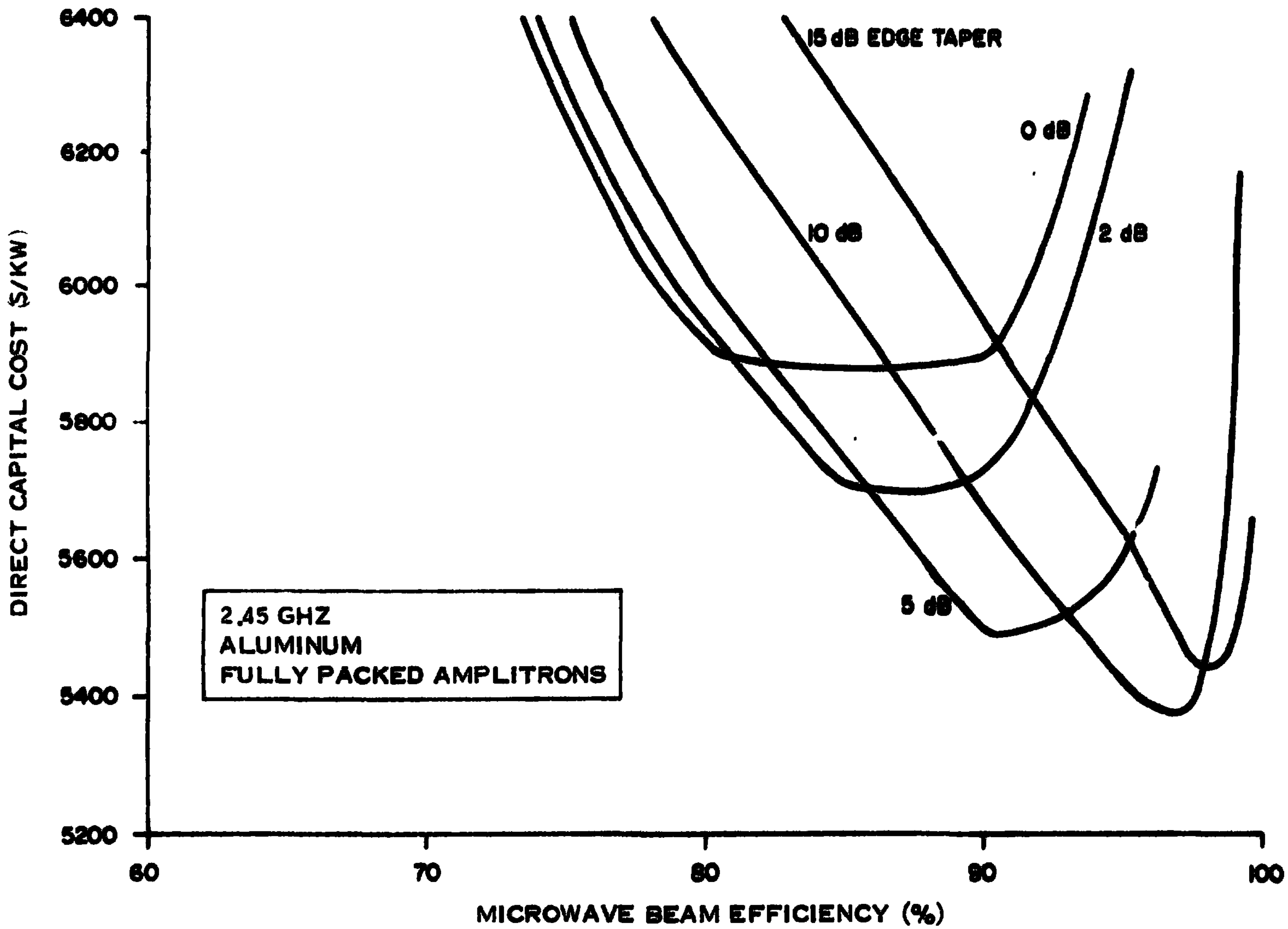

Figure 12-20. Cost Matrix - 5 GW - Case HHL

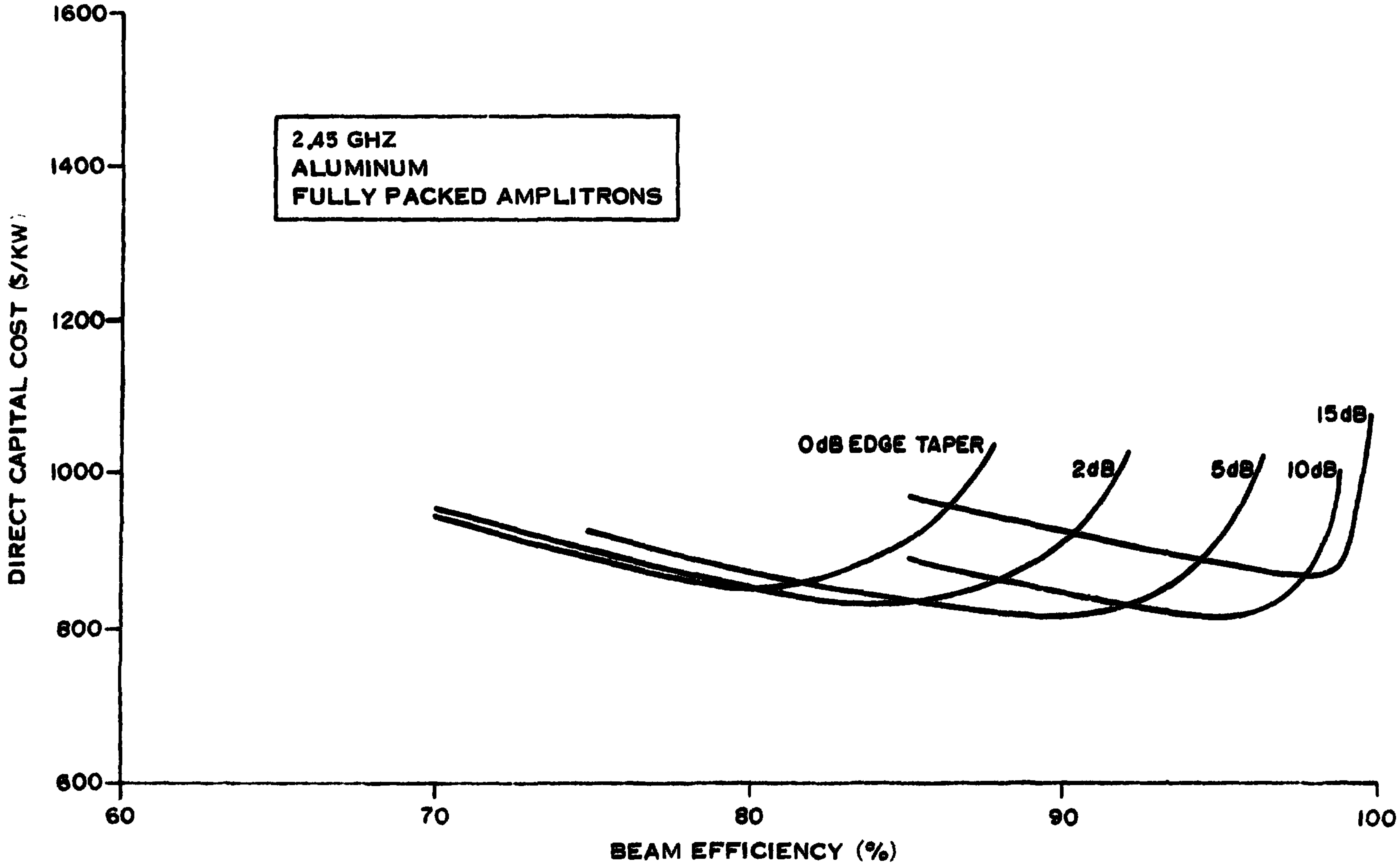

Figure 12-21. Cost Matrix - 10 GW - Case LMM

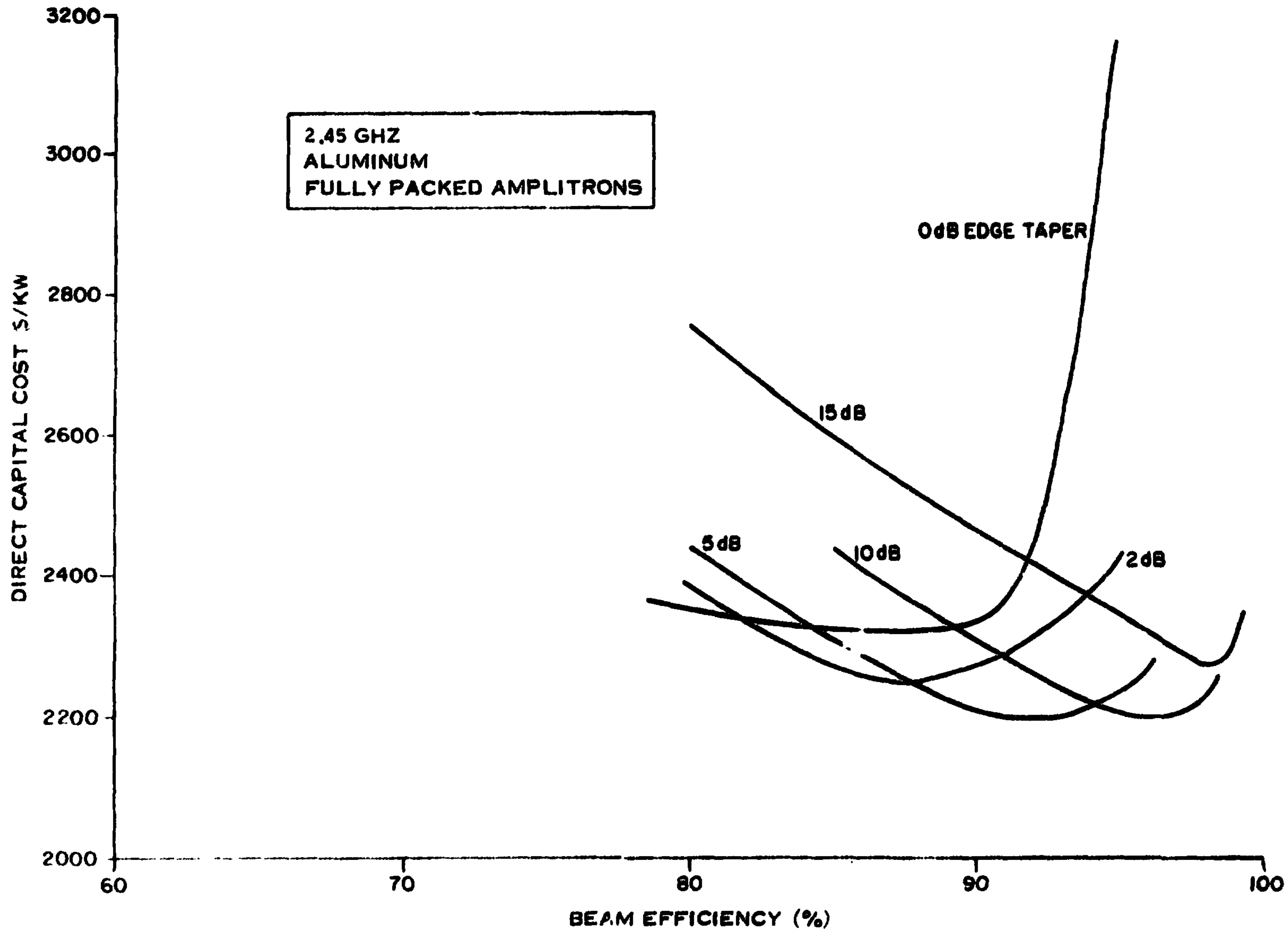

Figure 12-22. Cost Matrix - 10 GW - Case MMM

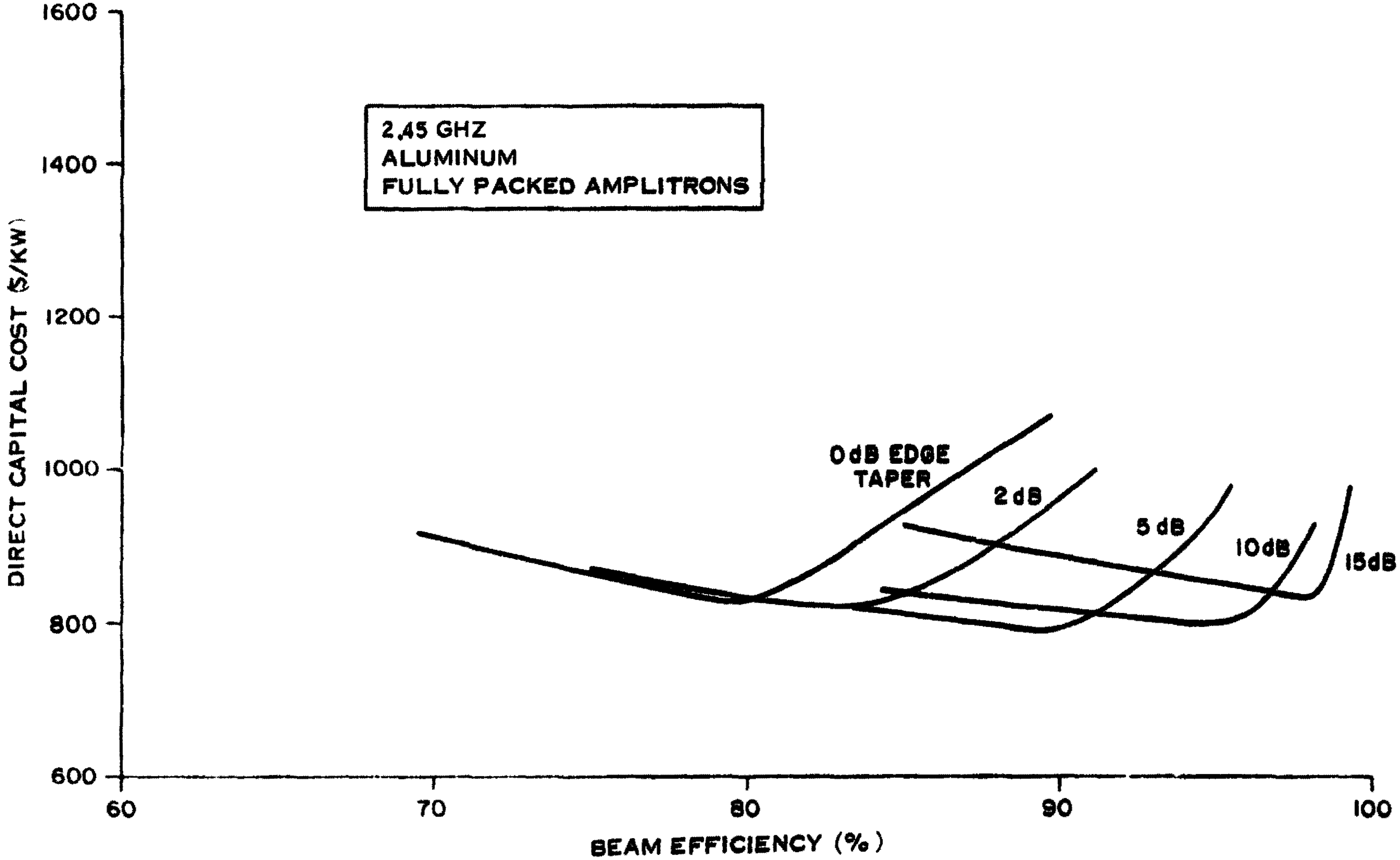

Figure 12-23. Cost Matrix - 10 GW - Case I-LH

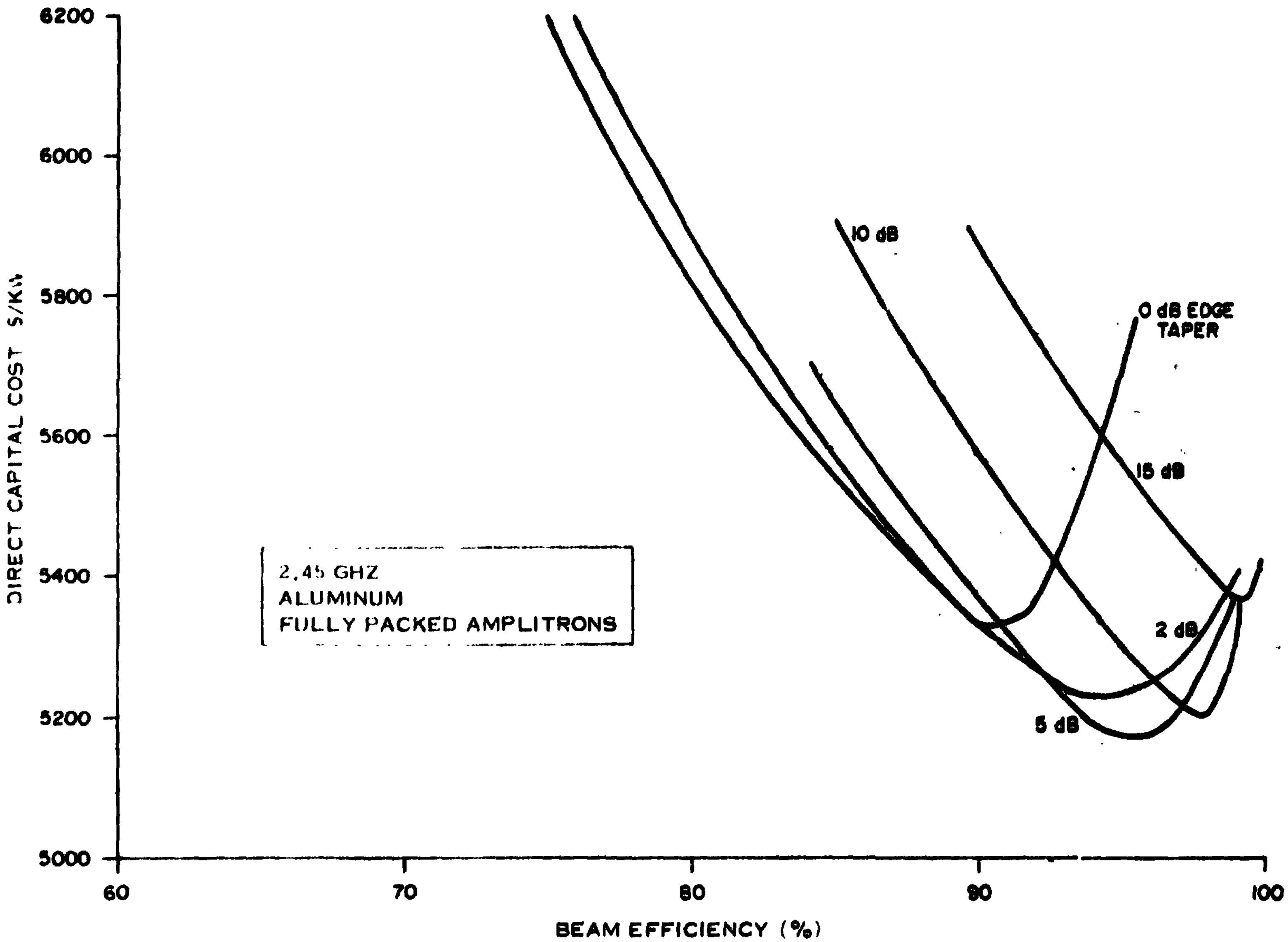

Figure 12-24. Cost Matrix - 10 GW - Case HHL

GROUND POWER GW	XMTR TAPER dB	BEAM INTERCEPTION %	TRANSMITTING ANTENNA WT – KGX10^6	TRANSMITTING ANTENNA DIA – kM	RECTENNA DIMENSIONS* kM	MAX GROUND POWER DENSITY mW/cm^2
5	5	90	6.2	0.8	11 x 15	17
	10	95	8.3	1.0	10 x 13	22
10	5	90	11.9	1.2	8 x 10	68
	10	95	14.3	1.4	7 x 9	87

*MAJOR AXIS IS FOR ELEVATION ANGLE = 50 DEG

Figure 12-25. Amplitron-Aluminum MPTS Comparison

TAPER = 5 dB
BEAM EFFICIENCY = 90%

POWER SOURCE – 1.5 kg/kw
– 500 $/kw
TRANSPORTATION ASSEMBLY – 300 $/kg

DC-RF CONVERTER	STRUCTURE & WAVEGUIDE MATERIAL	DC RF CONVERTER WT KG X 10	TRANSMITTING ANTENNA TOTAL WT KG X 10^6	MPTS $/kw	SPS $/kw
AMPLITRON	ALUMINUM	2.6	6.2	700	2300
	COMPOSITE	2.6	5.0	700	2300
KLYSTRON	ALUMINUM	7.3	12.5	1100	2800
	COMPOSITE	7.3	12.5	1100	2800

Figure 12-26. Comparison of 5 GW Systems

12.2.8 ENERGY COST

Let the total energy cost be expressed as:

$$M = \text{mills/kwhr}$$

$$= \frac{1000}{E}\left[\frac{CI}{Y} + CO\right]$$

where

E = nominal energy in kwhr/year delivered to busbar from rectenna

Y = service-life-expectancy of system in years

$\frac{CI}{Y}$ = annual amortization of the initial capital investment in dollars over the service-life of the system

CO = annual operating (operating and maintenance) cost in dollars

For capital investment

$$\frac{CI}{Y} = \left[\sum_{j=1}^{m} P_j(1+i)^{m+1-j}\right]\left[\frac{i(1+i)^Y}{(1+i)^Y - 1}\right]$$

$$= \sum_{j=1}^{m} P_j(\text{caf'-i} - (m+1-j)) (\text{crf-i} - Y))$$

where

m = number of years of construction until the system is operational

i = r + t, if the inflation factor is ignored

or i = r + t + q, if the inflation factor is considered

for:

r = the designated attractive rate-of-return or capital

t = allowance for reserve on taxes, profits, etc.

q = yearly inflation factor

and

P_j = capital investment in the j^{th} year of construction for j=1, 2, ...m (caf' - i - (m + 1 - j)) = single payment compound amount factor for an interest rate i at the j^{th} year, i.e., the m + 1 - j years until the system is operational

(crf - i - Y) = uniform series yearly capital recovery factor over the service life Y of the system

For annual operations-and-maintenance cost:

CO_k = N_k if the annual operations-and-maintenance cost are uniform and the inflation factor q is ignored. In practice the annual selling price of energy increases proportionally with the inflation factor. Therefore, the inflation factor is not a parameter to be amortized or considered as an annual cost.

CO_k = $N_k (1 + q)^{m+k-1}$ if the inflation factor q is considered.

where

CO_k = the uniformly annualized operation-and-maintenance cost in dollars for the k^{th} year the system is in operation or service

N_k = the actual annual operation-and-maintenance cost in dollars for the k^{th} year of service.

k = 1, 2, ..., Y

Following the postulated declining-cost schedule of Appendices A and B for the first six years, ignoring the inflation factor:

$CO_1 = N_1$

$CO_2 = 0.75\ N_1$

$CO_3 = 0.80\ CO_2$

$= 0.6\ N_1$

$CO_4 = 0.85\ CO_3$

$= 0.51\ N_1$

$CO_5 = 0.90\ CO_4$

$= 0.459\ N_1$

$$CO_6 = 0.95\ CO_5$$

$$= 0.43605\ N_1$$

$$CO_k = 0.43605\ N_1 \text{ for } k = 6,\ 7,\ \ldots\ldots, Y$$

If the inflation factor q is considered:

$$CO_1 = N_1(1 + q)^m$$

$$CO_2 = 0.75\ N_1\ (1 \qquad {}^{n+1}$$

$$CO_3 = 0.6\ N_1\ (1 + q)^{n+2}$$

$$CO_4 = 0.51\ N_1\ (1 + q)^{n+3}$$

$$CO_5 = 0.459\ N_1(1 + q)^{m+4}$$

$$CO_k = 0.43605\ N_1\ (1 + q)^{m + k - 1} \text{ for } k = 6,\ 7,\ \ldots Y$$

Taking the time-value of money into consideration where the incremental higher costs for the first six years are treated as negative gradients to be amortized over the expected life of the equipment, ignoring the inflation factor:

$$\Delta CO_1 = (N_1 - 0.43605N_1) \left[\frac{1}{(1 + i)^{k - 1}}\right] \left[\frac{i\ (1 + i)^Y}{(1 + i)^Y - 1}\right]$$

$$\Delta CO_1 = N_1\ (1 - 0.43605)\ (pwf' - i \quad - 0)\ (crf - i \quad - Y)$$

$$\Delta CO_2 = N_1\ (0.75 - 0.43605)\ (pwf' - i \quad - 1)\ (crf - i \quad - Y)$$

$$\Delta CO_3 = N_1\ (0.6 - 0.43605)\ (pwf' - i \quad - 2)\ (crf - i \quad - Y)$$

$$\Delta CO_4 = N\ (0.51 - 0.43605)\ (pwf' - i \quad -3)\ (crf - i \quad - Y)$$

$$\Delta CO_5 = N\ (0.459 - 0.43605)\ (pwf'\ i \quad - 4)\ (crf - i \quad - Y)$$

where

(pwf' - i% - (k-1)) = single-payment-present-worth-factor at i rate-of-return of an incremental operations-and-maintenance expenditure during the k^{th} year

(crf - i% - Y) = uniform series yearly capital-recovery-factor for an incremental operations-and-maintenace expenditure during the k^{th} year but based on a present worth.

Therefore, the uniform annual operations-and-maintenance cost for any year k, ignoring the inflation factor:

$$CO_k = 0.43605N_1 + \sum_{\ell=1}^{5} \Delta CO_\ell$$

If the inflation factor is to be considered, the first-year annual operations-and-maintenance cost N is multiplied by the factor $(1 + q)^{m+k-1}$ as noted above.

The estimated operations and maintenance cost derived in Appendices H and I of 9 $/kW and 8 $/kW are negligible compared with the capital cost of the system and its annual charges. These cost estimates are relatively low because the design and development of the operational equipment must be such as to minimize the operations and particularly the maintenance equipment. The MPTS equipment is made up of essentially thousands of identical and simple components assembled in fault tolerant configurations. The operations and maintenance equipment would probably be much more complex than the equipment it is operating on and maintaining, thereby compounding the O and M problem. The total system must be developed and matured with one of the objectives being to require as little or at least as simple maintenance as possible. It is appropriate therefore to set low operational cost goals for operations and maintenance and put significant amounts of effort into the technology development of both the MPTS equipment and the associated operations and maintenance equipment to assure that the low operational costs are achieved.

Curves relating specific energy cost to rate of return and build cycle time were developed and are shown in Appendix J, Figures J-9 and J-10 for ready reference.

The energy cost for the complete 5 GW SPS system was computed for the range of power source and transportation-assembly factors noted in Figure 12-5, for annual return percentages ranging from 12 percent to 18 percent, and for medium or 50 percent cost factor of the MPTS. It was assumed that a lump sum funding was obtained for construction of the equipment and that a second lump funding was obtained for the launch vehicles and orbital operations at time of launch.

The results, including direct capital cost, are shown in Figures 12-27 through 12-30 for the 58 percent system efficiency (initial) and for an assumed 72 percent system efficiency (goal) covering a range of values appropriate to

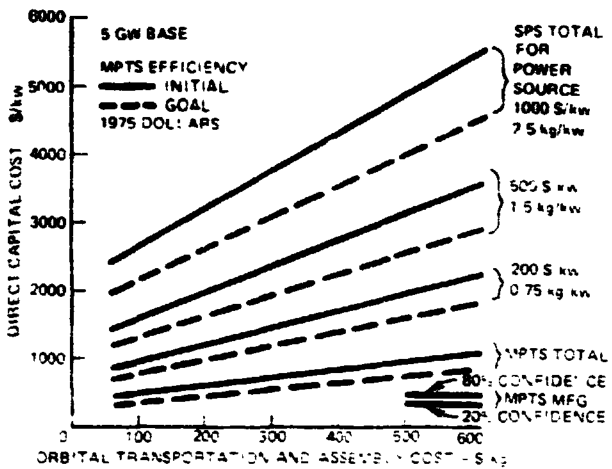

Figure 12-27. SPS Capital Cost for Various Power Source Characteristics

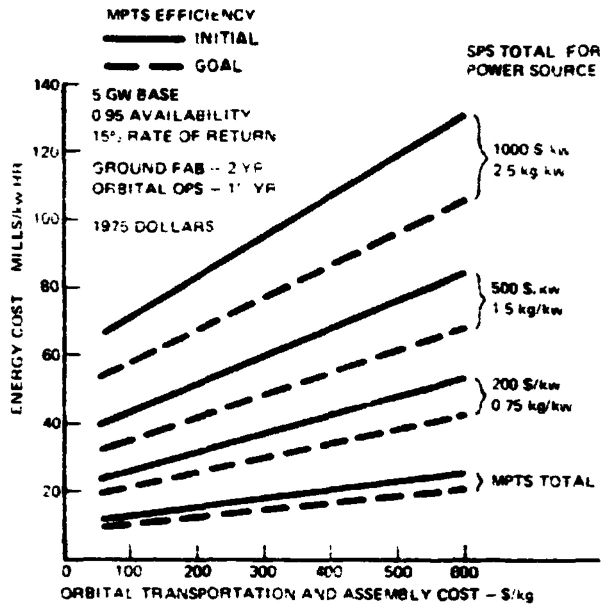

Figure 12-28. SPS Energy Cost for Various Power Source Characteristics

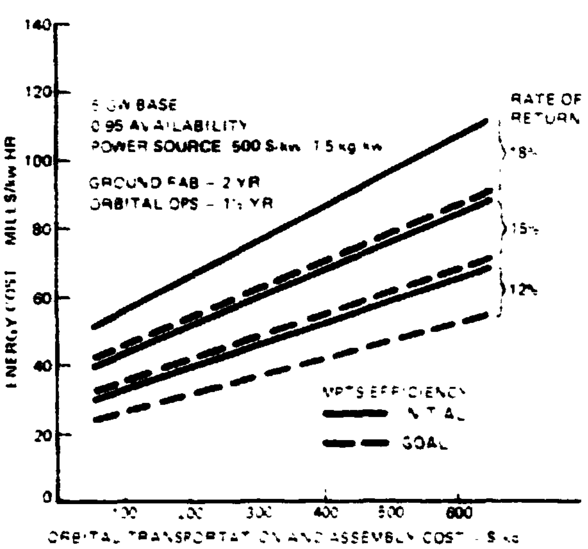

Figure 12-29. SPS Energy Cost for Various Rates of Return

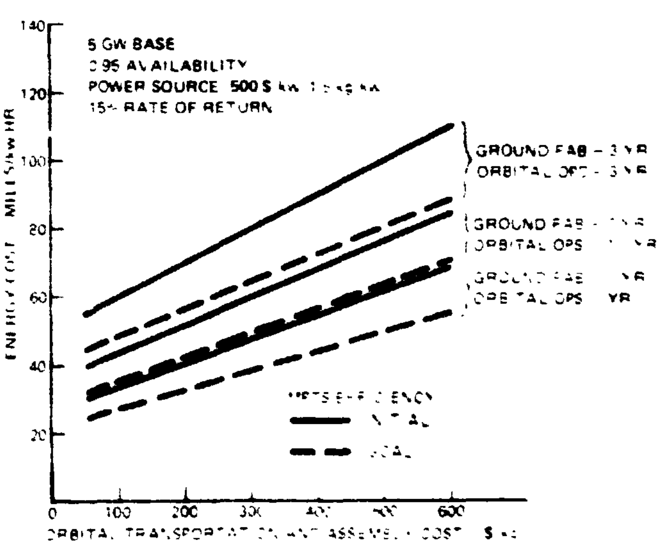

Figure 12-30. SPS Energy Cost for Various Construction Cycles

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the deployment cycle of many systems. The data are plotted versus the transportation-assembly cost. We see that the major impact on energy cost is the power source and transportation assembly with the MPTS portion having an impact perhaps less than the variations in the annual rate of return or build cycle. Since projections of future costs for the competing nuclear fueled terrestrial systems range up to 35 mills per kW hour, it is important to set the goals for the transportation-assembly at no more than 200 $/kg, and the power source no more than 350 $/kW with 1 kg/kW specific weight. These combinations, together with a nominal 60 percent MPTS efficiency, would be near the 45 mills per kW hour level for a three year ground fabrication and orbital operations (build) cycle, 80 percent utilization in recognition of less demand than the full availability of 95 percent would allow, and 15 percent rate of return.

12.3 FINAL SYSTEM ESTIMATES

12.3.1 COST AND WEIGHT

A review of all subsystem estimates was made in preparation of this report and some revisions resulted in subsystem estimates relative to the values used in the parametric studies. The data are presented in Figure 12-31 keyed to Work Breakdown Structure items. Changes were as follows:

Rectenna Power Interface (Item 1.5)

The original estimate of 12 $/kW was increased to the equivalent of 45 $/kW for a 5 GW system to reflect the later value derived in Section 9.

Transmitting Antenna Subarray Electronics (Items 4.1, 4.2, 4.3)

The specific costs of these items were normalized to a uniform 1000 $/kg to reflect experience with equipment of this complexity for the space environment. A learning curve of 85 percent was used. This represents a cost increase since a portion has been costed at a lower value.

Transmitting Antenna Subarray Waveguide (Item 4.4)

The waveguide costs were revised downward to reflect mass production and a more appropriate cost scaling technique. Raytheon cost experience in large phased array ground radars was used on a $\$/m^2$ basis together with an 85 percent learning curve for the aluminum case. A 31 $/kg value resulted. The latter had been adopted in common with the structure estimated by Grumman (see Section 8).

	WBS ITEM	TITLE	SPECIFIC COST ESTIMATES 20%	50%	80%	COST BASIS	COMPONENT OR SUB-SYSTEM TOTALS WT -KG	AREA -M²	MEDIUM COST $	SYSTEM NORMALIZATION
GROUND	1.0	RECTENNA						(x10⁶)	(x10⁶)	
	1.1	REAL ESTATE	0.10	0.25	0.35		-	428	107	FENCED AREA
	1.2	SITE PREPARATION	0.10	0.40	100	$/M²	-	131	53	PROJECTED AREA
	1.3	SUPPORT STRUCTURE	4.00	6.00	8.00		-	100	600	NORMAL AREA, A_R
	1.4	RF-DC SUBARRAYS	3.00	4.00	6.00		-	100	400	NORMAL AREA, A_R
	1.5	POWER INTERFACE	23	45	90	(5 GW Output)	-	(5 GW Output)	225	[OUTPUT PWR / 5 GW]
	2.0	COMMAND CONTROL SYSTEM (GROUND)		(x10⁶)					(x10⁶)	
	2.1	COMMUNICATION SUBSYSTEM BLDG.	11.0	21.0	42.0	PER SYSTEM	-	-	21	PER SYSTEM
	2.2	COMPUTER	1.0	2.5	3.0		-	-	2.5	
	2.3	INSTRUMENTATION	1.2	2.5	5.0		-	-	2.5	
	2.4	PHASE REF TRANS.	0.05	0.1	0.2		-	-	0.1	
ORBITAL	3.0	POWER DISTRIBUTION		(x10⁶)			(x10³)		(x10⁶)	
	3.1	SWITCHGEAR	3.0	5.7	6.1	9 GW SOURCE POWER	62.1	-	5.7	[SOURCE POWER / 9GW]$^{1/2}$
	3.2	CROWBAR	19.2	33.6	41.4		301		33.6	
	3.3	CONDUCTOR	0.2	0.2	0.3		96.8		0.2	
	3.4	AUX. POWER	32.2	52.2	78.2		88.3		52.2	
	4.0	TRANS. ANTENNA SUBARRAYS							(x10³)	
	4.1	COMMAND CONTROL	↑				35	-	35	↑
	4.2	PHASE CONTROL	500	1000	2000	$/KG	17.2	-	17	231 $/M²
	4.3	DRIVER ELECTRONICS	↓				22.7	-	23	↓ Antenna Area
	4.4	(a) WAVEGUIDE (AL)	64	132	264	$/M²	1381	324	43	132 $/M²
		(b) (GRAPHITE)	120	220	355	$/kg	830	324	182	563 " Antenna Area
	4.5	DC-RF CONVERTERS								
		(a) AMPLITRON (5KW)	57	91	141	UNIT	1.62	-	0.091	RAD. POWER / 5KW
		(b) KLYSTRON (48KW)	1310	1853	2470		50.6	-	1.853	RAD. POWER / 48KW
	5.0	MECHANICAL SYSTEMS								
	5.1	(a) STRUCTURE (AL)	4	8	14		0.262KG/M²		2.10$/M²	Antenna Area
		(b) (GRAPHITE)	100	200	335	$/KG	0.185KG/M²		37.0$/M²	
	5.2	POWER SOURCE INTERFACE	72	134	268		172x10³	-	23.1x10⁶	PER SYSTEM
	5.3	SCREWJACK ACTUATORS	250	500	1000		0.184KG/M²		92.1$/M²	Antenna Area
	6.0	TRANSMITTER COMMAND CONTROL SYSTEM	2.6	5.1 (x10⁶)	10.2	PER SYSTEM	775	-	5.1x10⁶	PER SYSTEM

Figure 12-31. MPTS Cost Matrix

The specific cost for the graphite composite option was left on a \$/kg basis due to the exceptionally high material and processing costs forecasted. However, later estimates obtained by Grumman for the structure indicated the mean value could be lowered (see below). A 10 percent differential relative to the structure cost was added to cover more extensive assembly and processing requirements.

<u>Transmitting Antenna Subarrays - DC-RF Converters (Item 4.5)</u>

Cost and weight in the amplitrons was reduced to represent the movable pole piece design instead of the impulse magnet design. There is greater confidence in parameters for the former.

Cost on the klystrons was adjusted only slightly downward to reflect a later estimate.

<u>Mechanical Systems (Items 5.1, 5.3)</u>

Overall weight was reduced by about 30 percent to correct an error in the original estimate. Cost for the structure in aluminum was reduced from 134 \$/kg to 8 \$/kg, which represents quoted cost for large quantities of stock aluminum suitably anodized. The higher estimate was for a low quantity of relatively complex pieces. The graphite cost was reduced by about 50 percent to reflect large quantity manufacture.

The screwjack actuator estimate was substantially increased to better reflect the electromechanical complexity of this key item.

12.3.2 EFFICIENCY BUDGET

The final efficiency budget for MPTS is given in Figure 12-32 for initial implementation and for what are believed to be goals that could be realized as the technology matures into the next century. A competitive program must strive to achieve these goals.

We see that an overall 58 percent efficiency used in the parametric study at a beam efficiency of 90 percent falls midway between the initial and goal totals for the amplitron, and so is representative of a nominal performance. The klystron efficiency falls at the goal level and so the parametric study depicted a relatively optimistic picture.

Symbol	Contributor	Amplitron - 5 kW	Klystron - 48 kW
	Power Distribution	97.8 (98)	95.8 (96)
	Preamplifiers	98.7 (99)	99.8
	Converters	85.0 (90)	79.2 (80)
	Waveguide	99.6	99.0* (99.6)
n_t	Subtotal $\frac{\text{Radiated Power}}{\text{Input Power}}$	81.7 (87.)	75.0 (76.3)
	Adaptive Phase Control	98.0 (99)	98.0 (99)
	Waveguide Distortion	98.0 (99)	98.0 (99)
	Structural Deflection	99.5	99.5
	Attitude Control	99.4	99.4
n_b	Subtotal $\frac{\text{Directed Power}}{\text{Radiated Power}}$	95.0 (96.9)	95.0 (96.9)
n_a	Atmosphere	98.8	98.8
n_s	Beam Interception	90-95	90-95
	Rectenna	84.1 (90)	84.1 (90)
	Power Grid Interface	92.0 (94)	92.0 (94)
n_r	Subtotal $\frac{\text{Output Power}}{\text{Intercepter Power}}$	77.4 (84.6)	77.4 (84.6)
n	Total $\frac{\text{Output Power}}{\text{Input Power}}$	53.4 - 56.4 (63.4 - 66.9)	49.0 - 51.7 (55.6 - 58.7)

*For 6/1 Power Divider

Frequency = 2.45 GHz, Initial and Goal ( ) Values

Figure 12-32. MPTS Efficiency Budget

12.3.3 CAPITAL COST AND SIZING ANALYSES

Three sets of calculations have been prepared in Appendix J giving sources of information and the rationale for assumptions. These should serve as a "road map" to do similar calculations making similar assumptions as the needs or considerations in the program change.

The transmitting antenna has been sized at a value of 64.7×10^4 m^2 (910. m diameter) as the near optimum value with respect to minimum cost for the final operational systems, assuming about 100 total.

The initially deployed operational systems are assumed to operate at low overall efficiency of n = 0.536 and to tend toward the high costs noted by (H).

The final operational systems are assumed to operate at high overall efficiency of n = 0.6345 and to tend toward the low costs noted by (L).

Figure 12-33 summarizes the major results of the analyses.

12.4 CONCLUSIONS AND RECOMMENDATIONS

a. Capital specific cost decreases as ground power output increases.

b. At higher power levels, cost is lowest near 2 GHz.

c. Frequency of 2.45 GHz in the industrial band is the recommended choice.

d. System configurations having ground bus power levels above 5 GW exceed 20 mW/cm^2 peak ground power density which is beginning to affect the ionosphere and so 5 GW is currently recommended as the maximum for planning purposes. Further in-depth analysis and testing is required to understand these effects more thoroughly and perhaps relax the constraint.

e. Overall MPTS efficiency is expected to be about 54%-56% initially with improvement potential to about 63%-67% for amplitron configurations: klystron configurations would be 49%-52% to 56%-59%.

f. Amplitrons result in lower cost systems than do klystrons.

g. Aluminum results in potentially lower cost but more complex systems than do graphite composites.

	Initial Operational System	Final Operational System
Power Source		
Cost of Power on Orbit	350 $/kW	350 $/kW
Power on Orbit	7.9 GW	7.9 GW
Specific Weight	1.5 kg/kW	1.5 kg/kW
Weight on Orbit	11.8×10^6 kg	11.8×10^6 kg
Microwave Power Transmission System		
Diameter on Orbit	910M	910M
Area on Orbit	64.7×10^4 M^2	64.7×10^4 M^2
Weight on Orbit	6.02×10^6 kg	6.02×10^6 kg
Efficiency (Overall)	54%	63%
Rectenna		
Minor Axis	10.3 km	10.3 km
Major Axis	13.4 km	13.4 km
Power Density (Peak) at Ground Main Beam	23 mW/cm^2	27 mW/cm^2
Power Density (Peak)		
At First Sidelobe	0.19 mW/cm^2	0.22 mW/cm^2
At Second Sidelobe	0.05 mW/cm^2	0.05 mW/cm^2
Transportation and Assembly		
Specific Cost	200 $/kg	200 $/kg
Weight to be Transported & Assembled		
Power Source	11.8×10^6 kg	11.8×10^6 kg
Antenna	6.02×10^6 kg	6.02×10^6 kg
Total	17.8×10^6 kg	17.8×10^6 kg
Cost of Transportation & Assembly with Respect to Power Delivered on Ground		
Power Source	559 $/kW	472 $/kW
Antenna	286 $/kW	241 $/kW
Total	845 $/kW	713 $/kW
(% of Total)	(65 %)	(47%)
Total System		
Weight	17.8×10^6 kg	17.8×10^6 kg
Ground Power Output	4.22 GW	5.0 GW
Cost Including Transportation and Assembly		
Power Source	1215 $/kW	1023 $/kW
Microwave Power Transmission	1175 $/kW	[illegible]
Total	[illegible]	1532 $/kW

Figure 12-33. Summary of Initial and Final Operational System Characteristics

h. Dominant cost factors for SPS are the power source and transportation.

i. As a guide, the power source parameters should not exceed the combination of 350 \$/kW with 1.0 kg/kW or possibly 250 \$/kW with 1.5 kg/kW where the power is as delivered to the transmitting antenna.

j. As a guide, transportation and orbital assembly should not exceed 200 \$/kg.

k. As a guide, build and deploy cycle for SPS should not exceed three years to limit interest charges.

l. For the aluminum-amplitron configuration, near optimum transmitting antenna and receiving antenna sizes are 0.9 km and 10 km, respectively, and transmitting antenna weight is about 6×10^6 kg.

REFERENCES

12-1. Crane, IEEE Proceedings, Vol. 59, page 173, February, 1971.

SECTION 13

CRITICAL TECHNOLOGY AND GROUND TEST PROGRAM

The purpose of a critical technology and ground test program is to provide design confidence for orbital tests (described in the next section). The objectives are of course constrained by an atmospheric environment for the transmitting array.

13.1 GENERAL OBJECTIVES

Primary objectives for the Ground Test Program are designed to provide substantive data relating to three fundamental issues for MPTS: technical feasibility, safety, and radio frequency interference. Primary and secondary objectives are:

Primary

a. Adaptive and commanded phase front control accuracy (Feasibility Issue)

b. System control performance for start up, shut down, transients, failure mode protection and recovery (Safety Issue)

c. Amplitude and spectra of random noise and harmonic output of transmitting array and rectenna (RFI Issue)

Secondary

a. Transmitting array integration

b. Power source interface

c. Rectenna array integration

d. Power load interface

e. Rectenna environmental protection

f. Component producibility

g. Large sample subsystem and component efficiency and performance data

h. Cost learning curve data for components

i. Efficient dc-dc high power transmission

j. Efficient dc-dc long range power transmission

The general objective of the Critical Technology Development Program is to provide the component, subsystem and system technology base required to properly implement the ground test program.

13.2 DETAILED GROUND TEST OBJECTIVES

The ground demonstration is conceived as being implemented in three phases with objectives as stated in paragraph 13.1. Detailed primary objectives are to demonstrate:

Phase I - Primary

a. Phase control steady state accuracy on a single axis basis subjected to combined effects of errors in control circuits, driver amplifiers, waveguide, phase reference circuits, instrumentation, and of algorithm approximations, atmospheric turbulence and rain.

b. System transient responses in a single axis combining electronic and mechanical beam steering during start up, shut down, failure mode detection and recovery, and disturbances due to weather fronts and rain squalls.

Phase II - Primary

a. Phase control steady state accuracy in a single axis subject to error contributions of many dc-rf converters and of control circuits operating in a high power radio frequency environment.

b. System transient responses in a single axis due to start up, shut down, and failure mode detection and recovery, including arcing, with many converters.

c. Amplitude and spectra of transmitting array random noise and harmonic output with converters and associated filters.

Phase III - Primary

a. Phase control steady state accuracy with two axis implementation, with converters, a high power environment and long range.

b. System transient responses with two axis implementation, with converters and at long range.

c. Radio frequency interference outputs of a large transmitting array and a large rectenna installation.

13.3 IMPLEMENTATION - GROUND TEST

13.3.1 SUMMARY

The site examined in some detail for the ground test was the JPL Venus Station where an RXCV (rectenna) demonstration and test facility has been installed. This has potential advantages in making possible the use of existing facilities, such as the Venus tracking antenna pedestal, collimation facility, power source and data instrumentation. However, as will be seen, the lines of sight to potential receiving antenna locations at larger ranges have lower elevation angles than would be desired. There also may be objections to creating a potential RFI problem for the other facilities at Goldstone or to sharing the Venus station with its deep space tracking mission; so this site should be treated as an example only. A more extensive site survey than possible in this study should be taken in the future.

In addition, the amplitron is taken as the dc-rf converter for the purpose of illustration. The objective could be met for the klystron as well, and in fact one version uses low power klystrons as driver stages for the amplitron.

The functional block diagram for the test is shown in Figure 13-1. The mechanical steering function is shown as well as the basic electronic beam control for the transmitter array. Mechanical steering is a desirable feature to demonstrate the control algorithms that must meld mechanical and electronic steering in an operational system. It could be eliminated, saving cost, if an existing antenna mount were used.

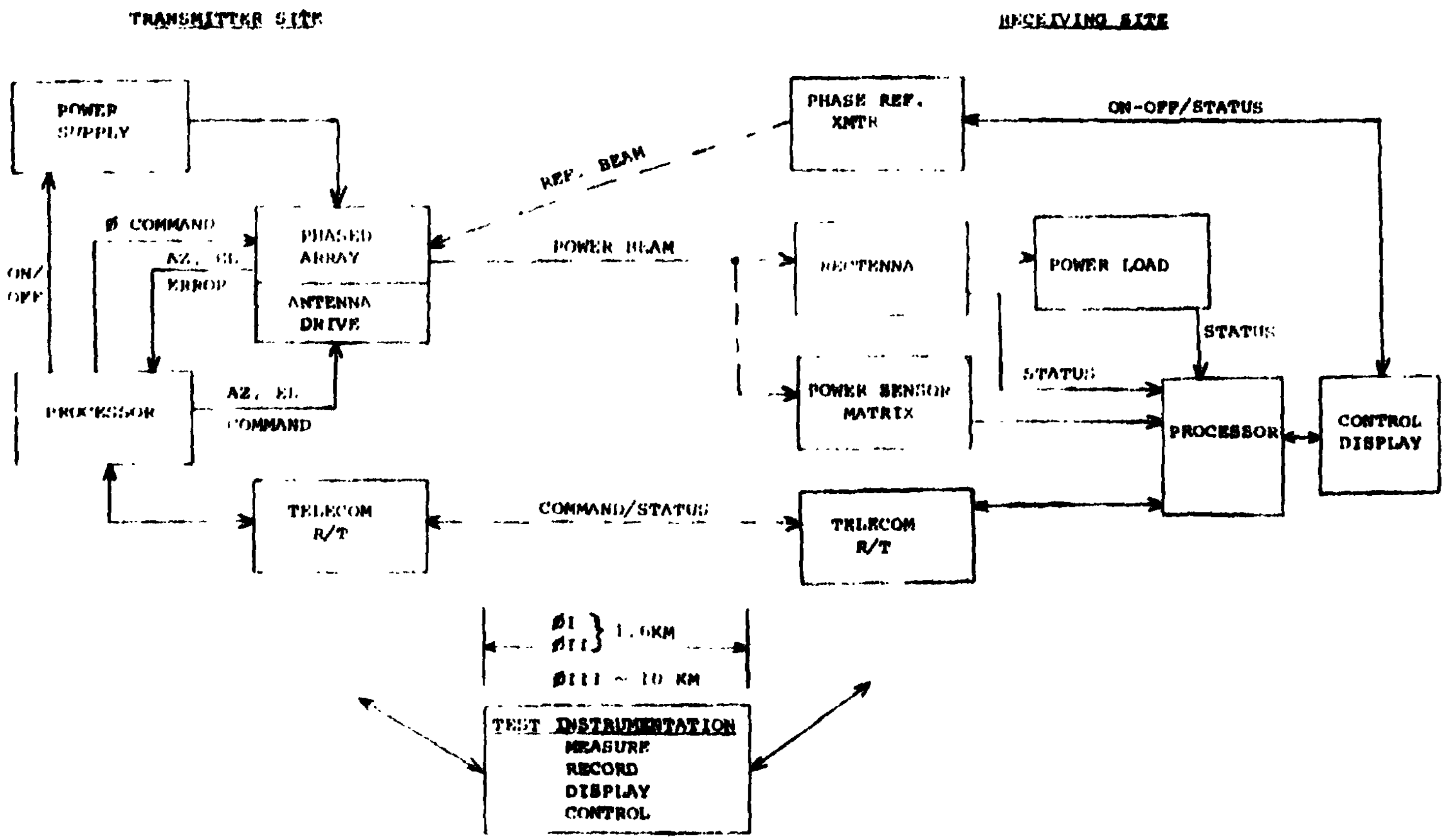


Figure 13-1. MPTS Ground Test Functional Block Diagram

The processor at each site can be combined with the processor for the test instrumentation at a single location, and this is proposed as detailed in Figure 13-2. The ranges noted relate to the Venus Site collimation tower (1.6 km) for Phases I and II and to a new receiving site (~10 km) for Phase III.

13.3.2 PHASE I

A single axis array, 2M x 18M, is used in Phase I with nine subarrays, 2M x 2M, to provide electronic beam steering in azimuth as shown in Figure 13-3. Phase control is accomplished with all control circuits and driver klystrons, but without the output amplitrons. Phase reference beam and power distribution sensors are located at the Collimation Tower for demonstration of adaptive and command modes of beam steering.

The transmitting Array may be located either on top of the Venus Power Amplifier Enclosure at the rear of the dish or on the quadrapod at the front of the dish. The former location avoids time and cost to reconfigure the facility for space science and tracking missions.

13.3.3 PHASE II

The single axis array has 5 kW amplitrons added in Phase II: eight per subarray for a total power output of 360 kW as shown in Figure 13-3. Each subarray would be as shown in Figure 13-4. Amplitrons are air cooled. Eight cascaded amplitrons should be adequate to demonstrate phase performance in each subarray, and all 72 amplitrons can be driven in cascade to demonstrate both phase control (with mechanical beam steering) and RFI characteristics. Subarrays can be mechanically adjusted to simulate thermal distortion effects, and various illumination tapers can be examined. A number of rectenna subarrays are tested in preparation for Phase III and to demonstrate dc-dc efficiency. The transmitting array mounting is the same as Phase I, and the receiving system remains at the collimation tower, where the beam pattern will be shown in Figure 13-5. The horizontal plane pattern is used for the control demonstration.

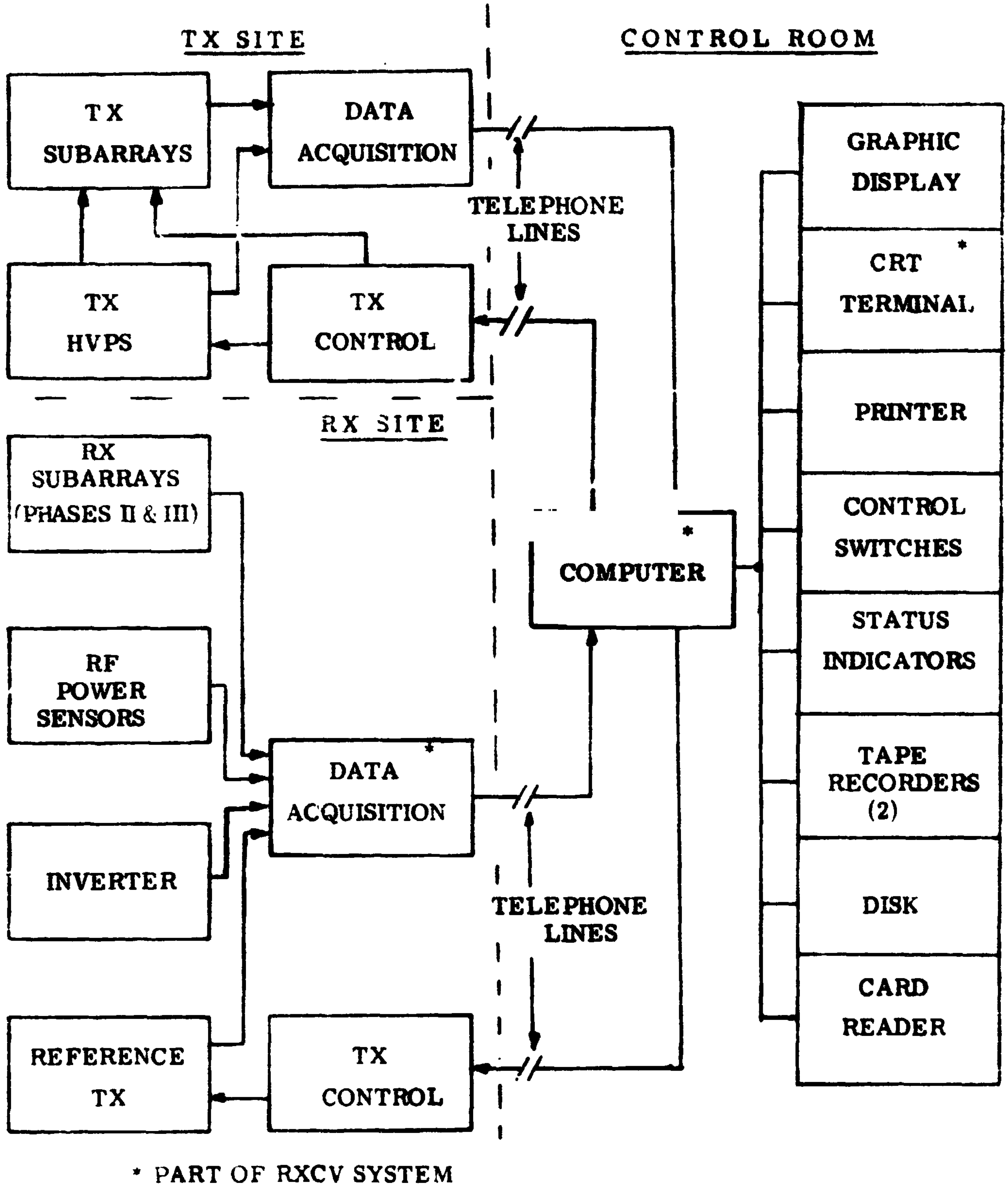


Figure 13-2. Instrumentation System Block Diagram

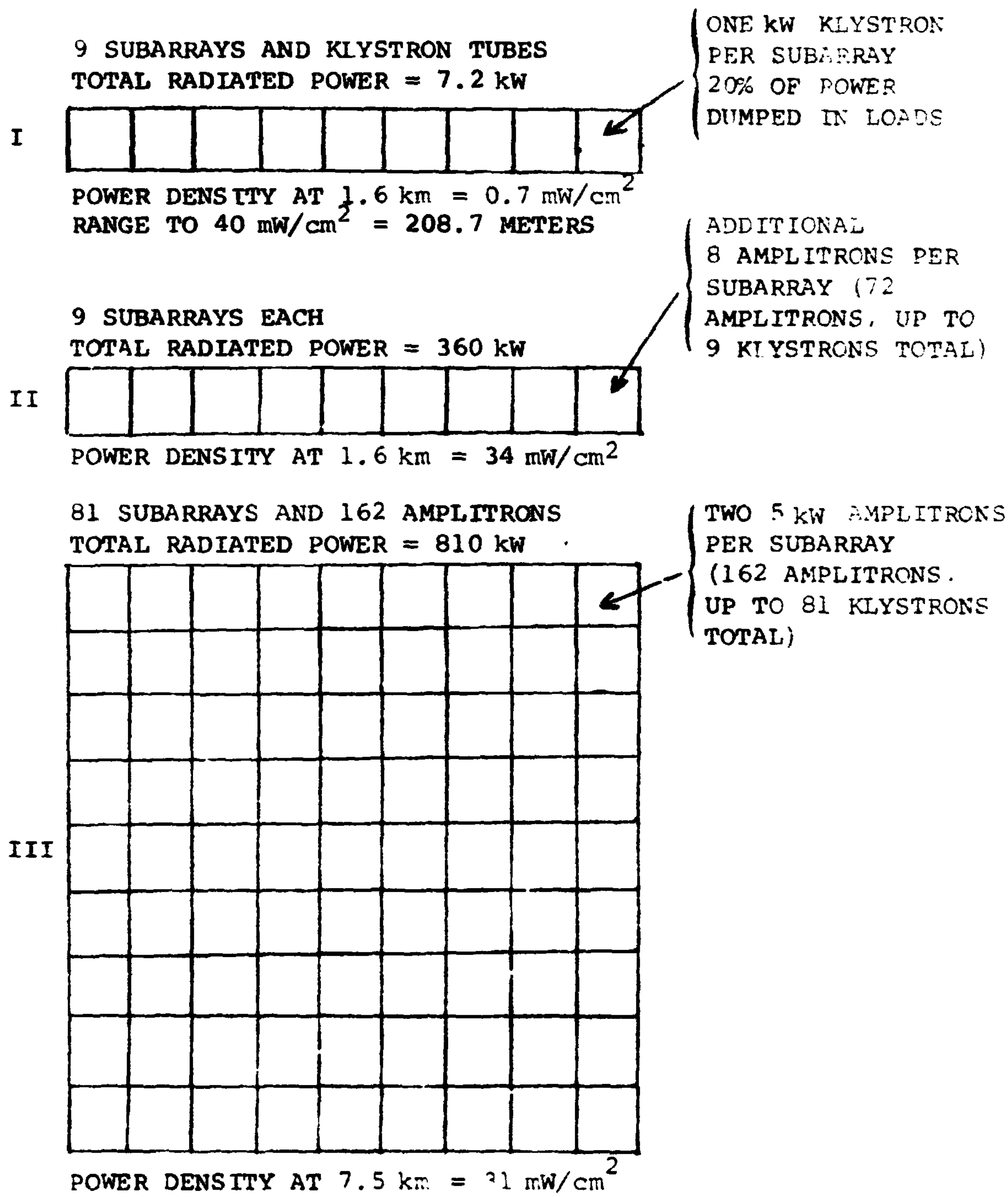


Figure 13-3. Ground Test Program Array Characteristics

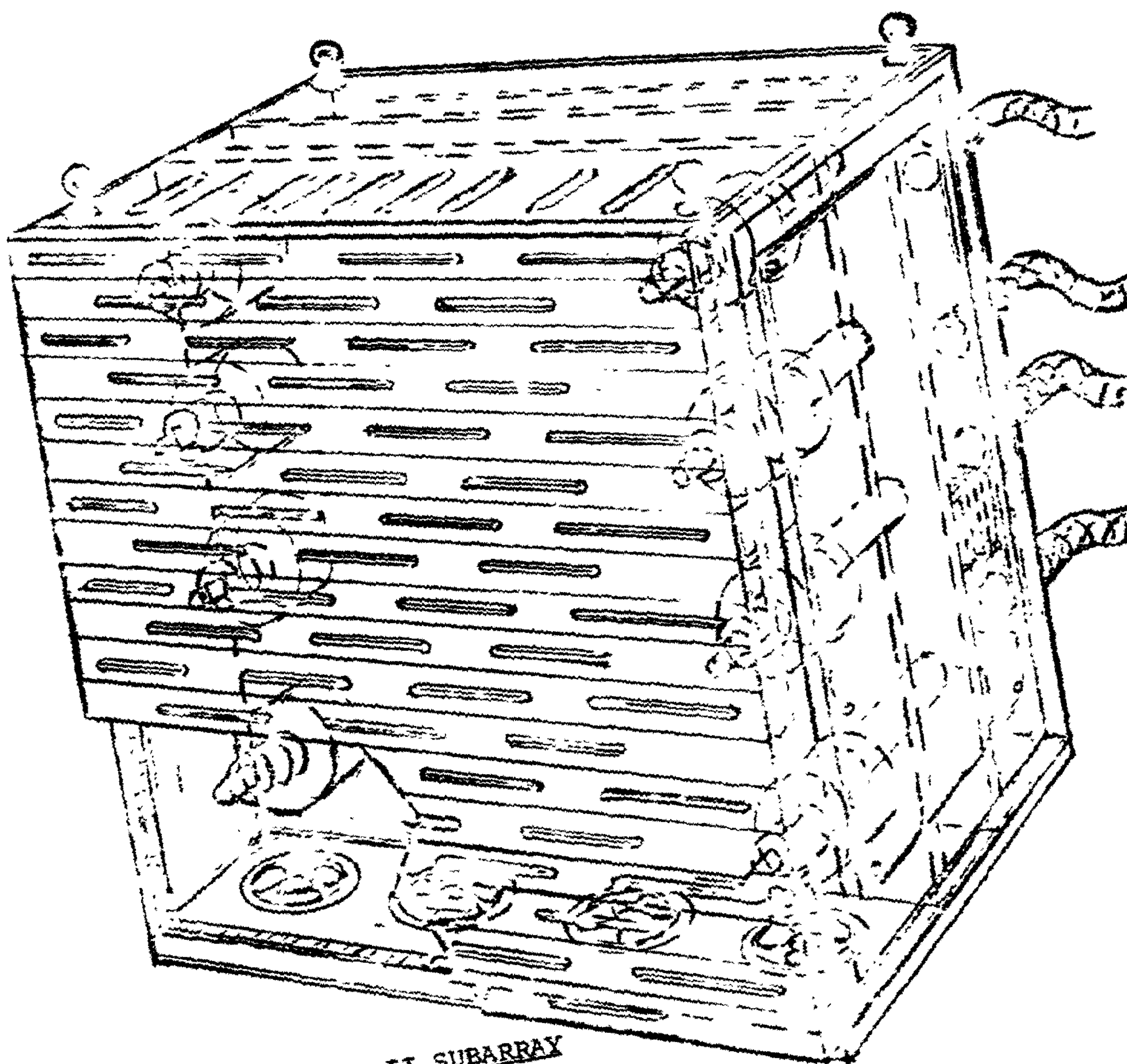


Figure 13-4. Phase II Subarray - 2 x 2M - 40 kW

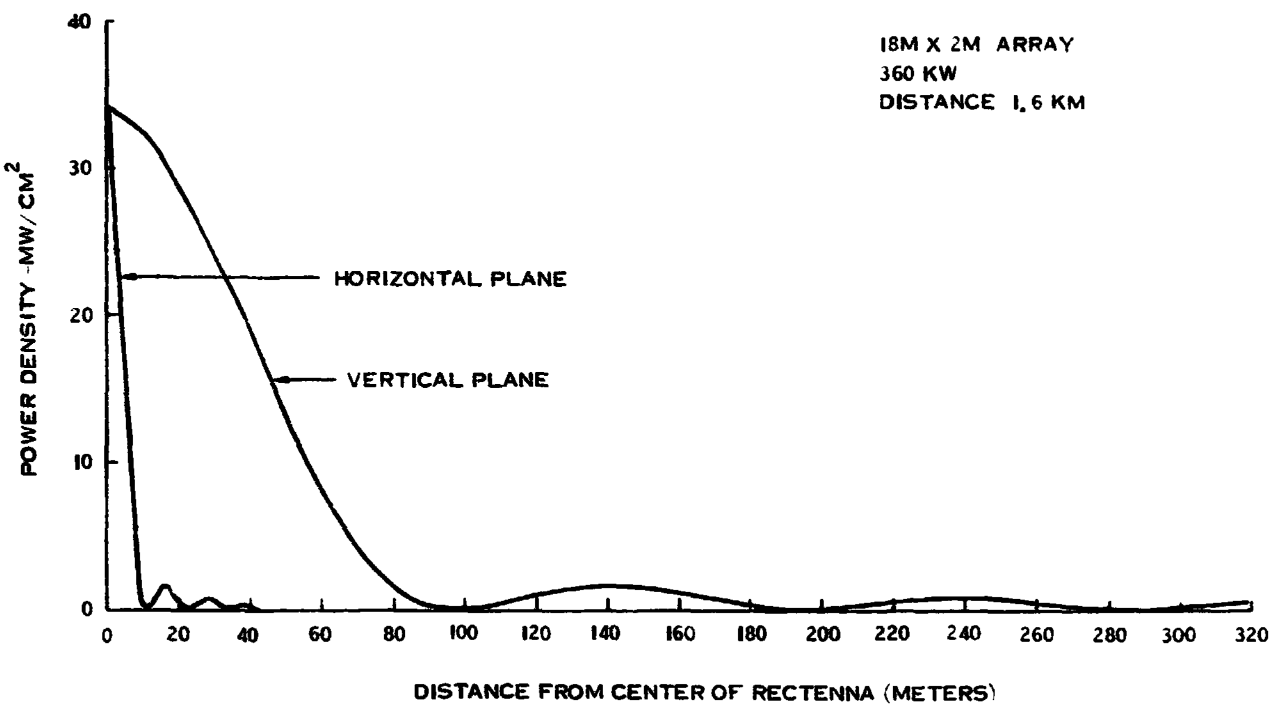


Figure 13-5. Received Power Density

13.3.4 PHASE III

A full two axis implementation is achieved in Phase III (Figure 13-3) with expansion of the Transmitting Array to 18M by 18M. The subarray dimensions planned for the operational system are 18 M x 18M; an average of two amplitrons per 2M x 2M subarray is planned for a total output of 2 x 81 subarrays x 5 kW/ subarrays = 810 kW. Amplitrons can be arranged so that illumination taper could be varied and efficiency and quantization effects examined. Maximum density would be eight tubes per subarray as in Phase II.

The Transmitting Array would be mounted on the quadrapod at the front of the dish, and the Receiving System, including a Rectenna Array of significant dimensions, would be located at a larger distance than in earlier phases. A potential site 7 km to 8 km distant is shown on the topographic map of Figure 13-6. The rectenna array shown in Figure 13-7 is sized to exhibit properties of height and spacing, and of integration to a voltage (~ 1 kV) sufficient for a proper interface with a power load and for demonstration of RFI properties.

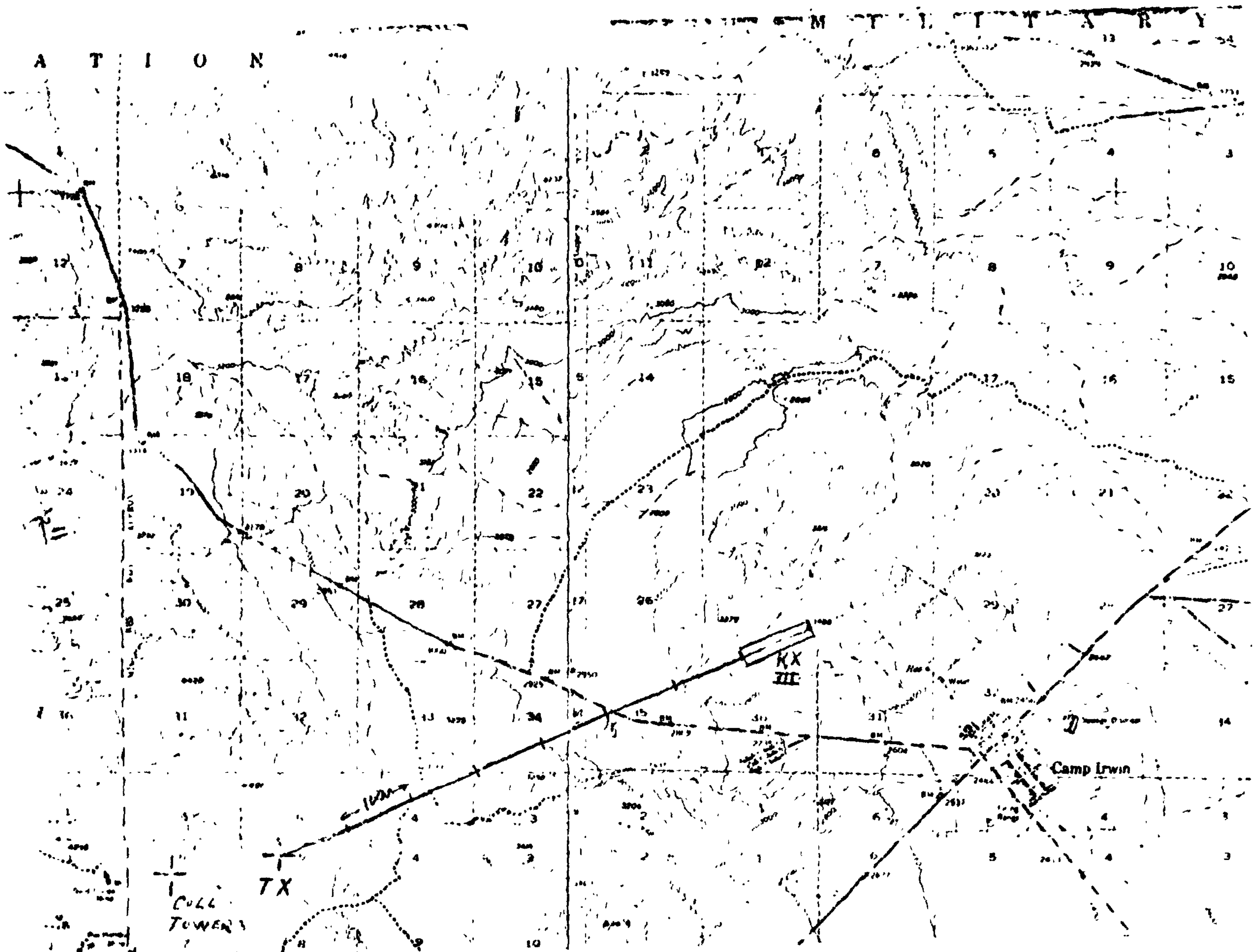


Figure 13-6. Candidate Location for Phase III Demonstration

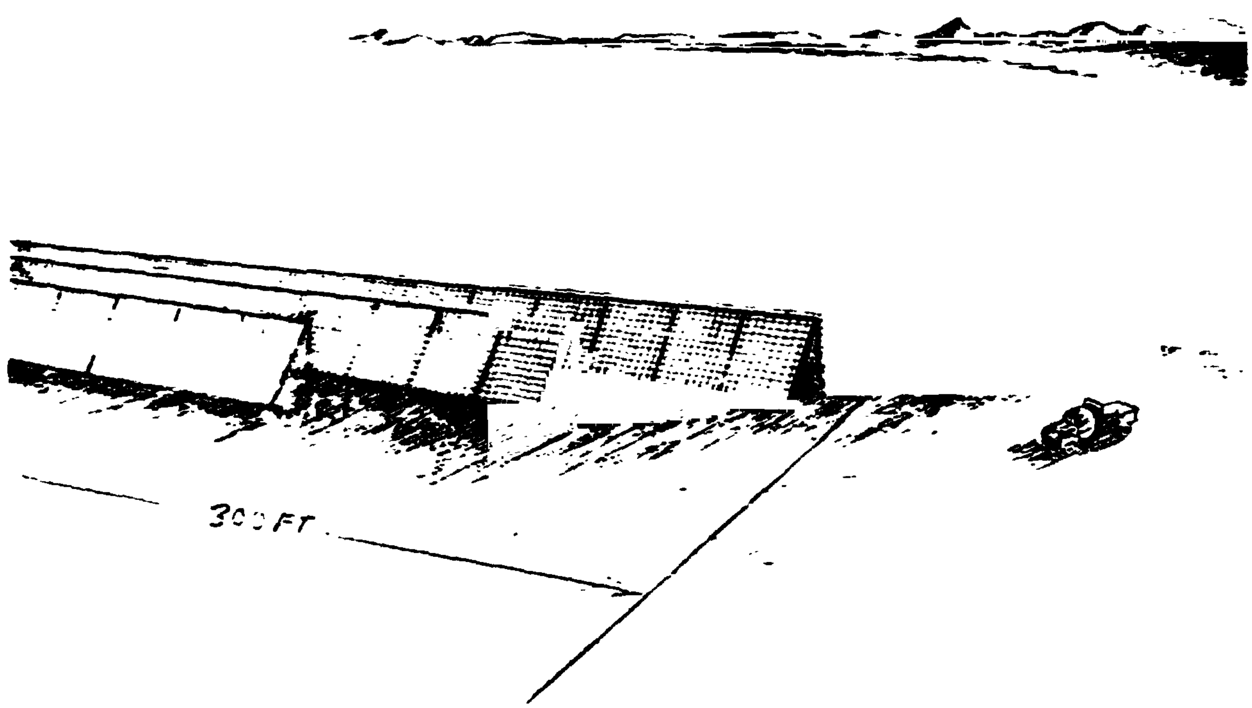


Figure 13-7. Phase III Rectenna

A dc-ac Inverter is recommended so that transmission demonstrations can use loads within the local power grid. The greater range than in Phases I and II better models the equivalent distance for atmospheric turbulence effects found in an operational configuration, and it also provides realistic power density conditions at the rectenna.

The received power density and related efficiency are shown in Figure 13-8 and the siting profile for the line-of-sight given in Figure 13-6 is shown in Figure 13-9. We see that the transmitter actually is looking down toward the rectenna and that clearance angles are quite small, although not so small as to block the main beam. Radiation over the intermediate roads probably would require that traffic be halted during demonstrations for safety.

13.3.5 ALTERNATE PHASE I CONVERTER IMPLEMENTATION

The Phase I test could not incorporate the amplitron as proposed in the MPTS because, as will be seen shortly, the amplitron is a critical technology item requiring two to three years to produce a model for field use. Phase I,

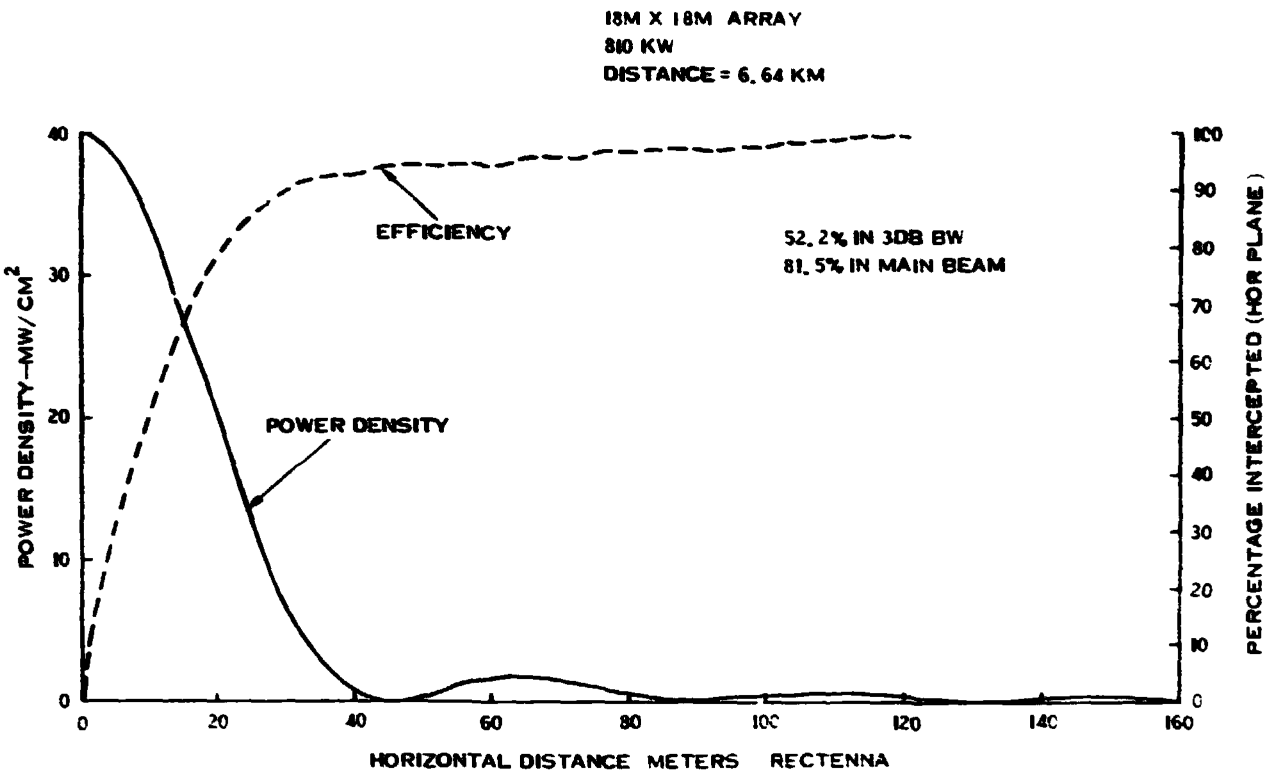


Figure 13-8. Phase III Received Power

therefore, was devised to prove phase control concepts using 1 kW driver klystrons that later would be incorporated as a driver in an amplitron configuration for Phases II and III.

An alternative approach suggested is to use available oven magnetrons (~1 kW) that would be configured with external rf equipment such as a circulator to simulate the amplitron's behavior. This may be a reasonably economical approach and at the same time may provide an early demonstration of phase control behavior with many converters in cascade as proposed for the MPTS. The magnetron is much more phase sensitive to input and environmental changes than the proposed amplitron will be, but perhaps this might be turned to advantage in showing how individual converter phase can be controlled, a feature that the MPTS may need for the final amplitron design.

It is recommended that this alternative be explored further in preparation for any ground test procurement that is in advance of amplitron availability.

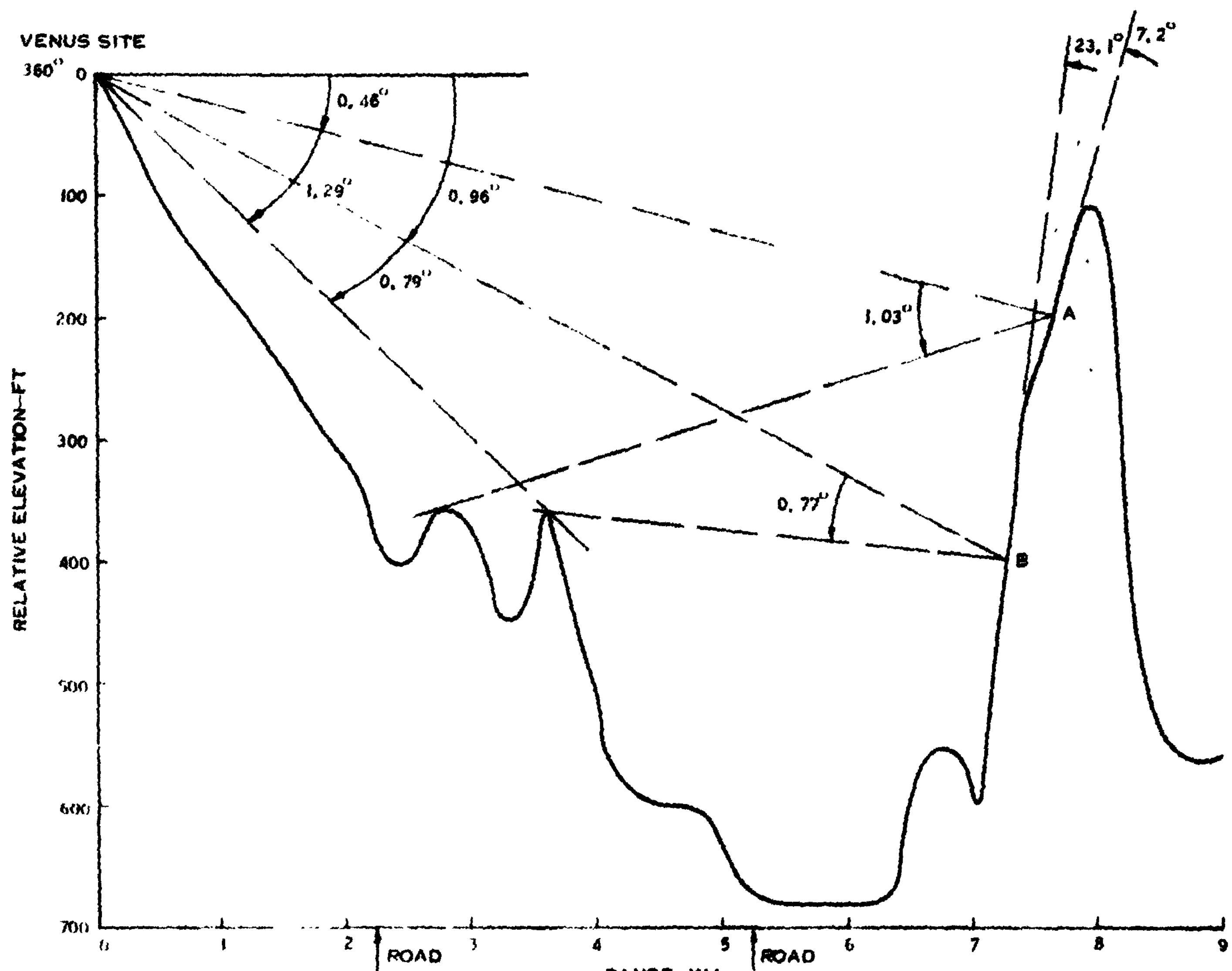


Figure 13-9. MPTS Ground Test Siting Profile Phase III - Goldstone

13.4 CRITICAL TECHNOLOGY DEVELOPMENT

The critical development areas identified in Section 11 risk assessment that directly bear on the ground test are the dc-rf converter and phase control technologies. Waveguide and structural materials are critical but are more appropriately identified with a flight test program to be covered in Section 14.

13.4.1 AMPLITRON

The amplitron development involves three sequential tasks:

Task 1

Design, fabricate and cold test three to five models for evaluation of efficiency and noise; build test equipment and optimize the design.

Task 2

Build 10 to 15 models to obtain a statistical evaluation of performance, to determine filter requirements, and to iterate the design.

Task 3

Design and test the power control and filter circuits; conduct interface tests; design tooling for production of ground test models.

13.4.2 KLYSTRON

Similar tasks cannot be started for the klystron MPTS converter candidate until further theoretical study is carried out to obtain solutions to the heat transfer problem and to better define characteristics for the highest efficiency design, involving a second harmonic cavity and collector depression. Technology requirements include cathode emitters with 30 year life (a cold cathode might be feasible) and heat pipes with a 30 year life.

13.4.3 PHASE CONTROL

The phase control technology program consists of a series of system analyses and simulation tasks and circuit development tasks:

a. Analysis and Simulation - Define methodology, simulate uplink and downlink propagation, model thermal distortion, develop ground algorithms, refine hardware modeling, evaluate closed loop response, investigate transient conditions (start up, eclipse), review and incorporate ground test results in models.

b. Circuit Development - Define circuit hardware, breadboard and test in discrete components; design for microwave integrated circuits, breadboard and test.

13.5 SCHEDULE AND COST

The project schedule is shown in Figure 13-10. The testing system is complete through Phase III in six years from go-ahead, with each phase design and installation taking two years. The critical technology development is presumed to start concurrently and is planned to have achieved a technical maturity with acceptable risk at each of the Critical Design Review (CDR) milestones sufficient to warrant release of major procurement items for each phase. Delays in the technology program will stretch out the ground testing proportionally.

The rough order of magnitude (ROM) costs expressed in 1975 dollars are given below.

1975 DOLLAR ROM COSTS, $K

Year	1	2	3	4	5	6	Totals
Critical Technology							
Amplitron	480	600	435	435	435	435	2820
Phase Control	350	435	330	240	240	-	1595
Ground Test	2390	2470	2190	3300	5325	7045	22720
Total	3220	3505	2955	3975	6000	7480	27135

The cost of the ground test portion includes funds for development and production of the rectenna array, including diode elements for accommodating the lower power densities appropriate for the MPTS.

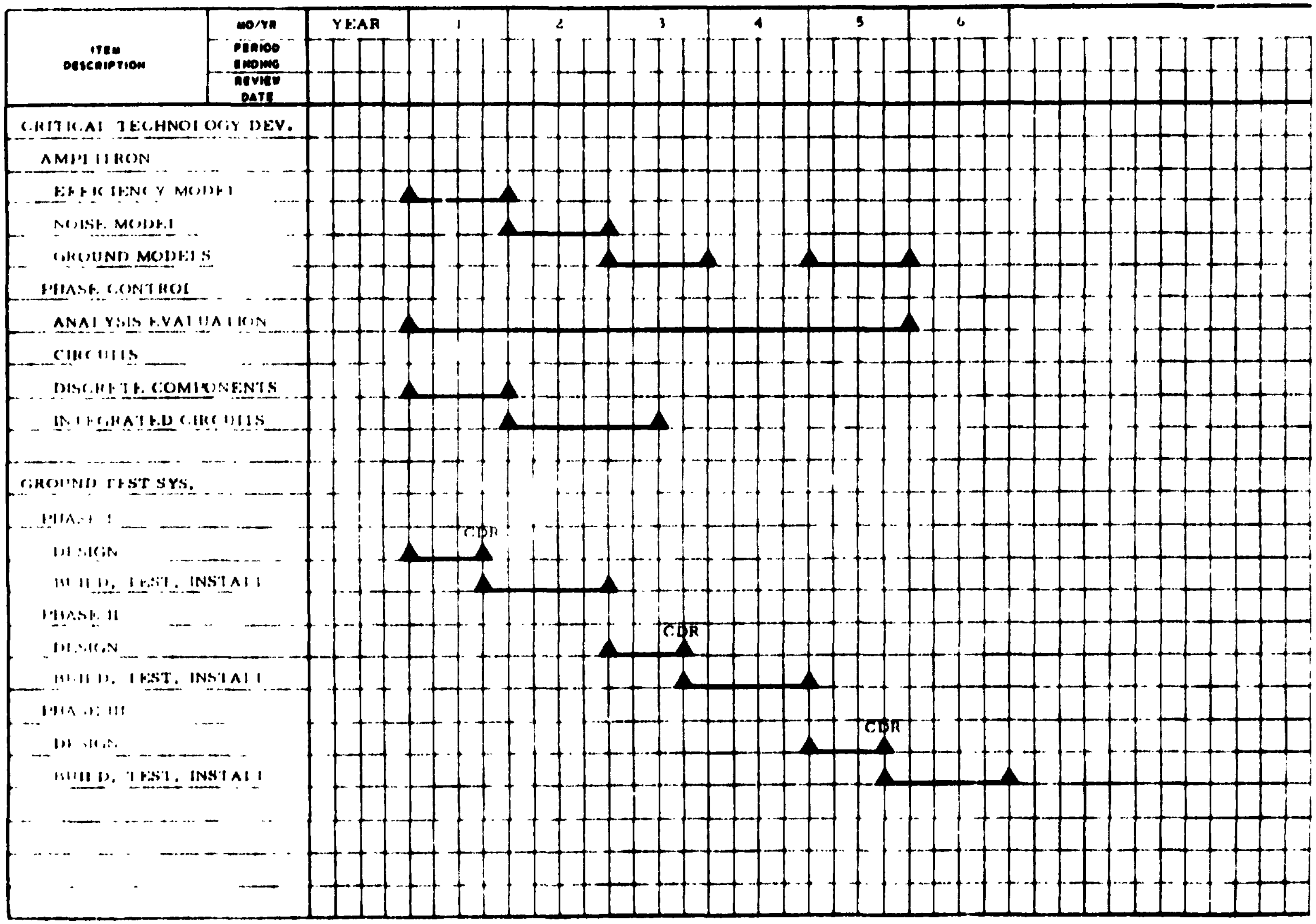


Figure 13-10. Technology Development and Ground Test System Schedule

13.6 CONCLUSIONS AND RECOMMENDATIONS

The proposed technology development and integrated ground test program is recommended to be considered to advance the technology and establish technical feasibility in support of the orbital test program and its more directly associated technology.

The following conclusions are pertinent when considered in conjunction with those for the orbital test program.

a. Initial technology development is needed for dc-rf converter, materials, and phase control subsystem.

b. Test program will provide data on controllability and radio frequency interference.

c. Transmitting antenna phased array and rectenna are required for integrated ground testing.

d. Rough order of magnitude costs are $4M for technology and $23M for the integrated ground test.

SECTION 14

CRITICAL TECHNOLOGY AND ORBITAL TEST PROGRAM

The orbital test program builds upon the technology developed and demonstrated in the ground program phases. It carries the technology development and demonstration forward to the space environment and provides a base upon which to plan and build a prototype or more appropriately a pilot plant in synchronous orbit that would have gigawatt level power transmission capability.

The orbital test program is planned to accomplish the mandatory and highly desirable objectives given below. It results in three elements: critical technology, a small satellite in geosynchronous orbit, and a low earth orbit test facility. The low earth orbit test facility may be considered for use at geosynchronous altitude to further develop the system and/or to serve as a nucleus for a later pilot plant.

Appendix K provides additional detail considerations to aid in detail planning of the ground and orbital test program.

14.1 ORBITAL TEST OBJECTIVES

The test objectives have been organized into mandatory, highly desirable and desirable categories as listed below:

a. Mandatory

M1. Convert power from dc to rf radiating it in progressive magnitudes measuring performance, noise, harmonics and functional characteristics including those associated with normal and malfunctioning conditions.

M2. Provide verification data to support the integrated proof of concept for the Microwave Power Transmission System (MPTS). Supporting data are to be provided for the operational system equipment concepts and flow of activities from ground based manufacturing through orbital manufacturing, assembly, operations and maintenance. Verify that the resulting procedures and equipments function and perform properly at the range of rf power densities anticipated for the operational equipment and systems.

M3. Demonstrate, at geosynchronous altitude, the starting of the dc to rf generator in its appropriate environment.

M4. Demonstrate, at geosynchronous altitude, satisfactory functioning and performing of the high voltage elements as they interact with the plasma and other appropriate elements.

M5. Verify, through a learning process, that the proposed design, processes and procedures including assembly, operations and maintenance, for the operational equipment are such that progressively estimated costs and schedules can be attained.

b. Highly Desirable

H1. Determine the nature of the effects of and on the critical portion of the ionosphere "F" layer (250 to 300 km) that might be experienced by the microwave power beam, associated references and controls. Determine effects that might apply to HF communications systems. Investigate the power density range of 20 to 50 milliwatts/cm^2. Determine effects that might apply to the pilot beam. Determine the nature of possible rf noise and harmonics induced by the ionosphere.

H2. Determine the effects of the 20 to 50 mW/cm^2 microwave power beam on the critical portion of the ionosphere "D" layer (70 km). In particular determine effects on existing or contemplated VLF navigation systems such as Omega and LORAN.

H3. Determine the effects of thermal cycling of the structure, waveguides and phase control components.

H4. Assess the critical elements that contribute to orbital operations life limitations.

H5. Establish a building block from which the prototype should be developed.

c. Desirable

D1. Demonstrate acquisition, lock-on pointing and focusing of the microwave beam from low orbit and demonstrate control as limited in the environment experienced from low orbit.

D2. Demonstrate microwave power transmission from low orbit to a ground rectifying antenna with a goal of efficiency, dc on orbit to dc on ground, in excess of 50 percent. The goal should be to achieve momentary power transfer, under conditions that assure beam pointing and focusing, converted on the ground by a large rectenna in the high power region of the main lobe and analytical integration based on small distributed rectenna outputs representing the low power regions.

The orbital test program has been conservatively defined in that the scope is broad and the quantities of equipments with the associated missions are large with respect to the detailed orbital test requirements of the microwave power transmission system.

The technology points of the orbital test objectives can be largely implemented in a thoroughly defined ground program; however, a flight test program is considered important to bring to focus the integrated elements, particularly when it is recognized that significant orbital assembly if not manufacturing will be involved. Equipment technology associated with assembly, operations and maintenance must be developed which is closely related to the projected operational equipments and situations.

The quantities of equipments deemed appropriate for the orbital test program are at this time uncertain. Further in-depth investigations should be conducted from which the quantities and scope should be progressively revised. In particular, those objectives associated with the high power microwave beam effects on the ionosphere warrant in-depth investigation and independent assessment. This should be done before accepting them as requirements that will play a major role in formulating the orbital test program.

14.2 IMPLEMENTATION

The quantities and scope of the following defined orbital test program are conservative for the microwave power transmission equipments, and the power source as well as transportation system orbital test objectives are beyond the scope of this investigation. To be consistent with the intent of the full breadth requirement for this study, the following orbital test program is therefore presented as being representative of scope with the resulting cost and schedule implications.

A summary of the mandatory and highly desirable items is given in Figure 14-1 together with the related payload and certain intermediate benefit aspects of the implementing orbital test program. The implementation of intermediate benefits can be significant in establishing the details of the design and missions, but this study necessarily concentrated on satisfying the MPTS requirements. As further in-depth studies and technology developments are matured, the implementation should be reassessed and redefined as appropriate.

14.2.1 GEOSATELLITE (MISSION 1)

Figure 14-2 illustrates the geosynchronous satellite concept. The payload consists of the dc-rf converters which were assumed to consist of a 5 kW amplitron and spares with power conditioning equipment as shown in Figure 14-3. See Figure 14-5 for the proposed schedule.

The 18M interferometer simulates the hardware at the center of the MPTS transmitting array which serves as the most precise attitude measurement for mechanical pointing. The particle detectors measure plasma conditions which may have some effect on converter performance. It would be attractive to have the pilot beam sent through a disturbed region of the ionosphere. This might be done in a joint or co-located experiment with the NSF Arecibo transmitter in Puerto Rico, which is recommended for consideration in determining lower ("D" layer) ionospheric effects of the power beam.

The mission weight estimate together with the performance of the Interim Upper Stage (IUS) to be used with the Shuttle are given in Figure 14-4. We see that a 28.5 degree inclination orbit (needed for Arecibo participation) provides more payload margin.

Definition of the antenna can depend upon [illegible] mediate benefits selected - radar or communications - but it is recommended that the converter payload drive a waveguide feed and array (could be an illuminator for a larger deployable antenna) to simulate the MPTS arrangement as closely as possible.

14.2.2 SHUTTLE SORTIES (MISSIONS 2 THROUGH 11)

A series of sortie missions is scheduled to develop the technology of space fabrication and to assemble in low earth orbit the building blocks needed for the Orbital Test Facility. The proposed schedule for the sortie missions is included in Figure 14-5. It begins with the availability of hardware developed in the ground based program.

Mission Class	Objectives		Microwave Payload	Intermediate Benefits
	Mandatory	Highly Desirable		
Geo-synchronous	• dc-rf Converter Starting and Operation • High voltage plasma interaction	• Ionosphere Effects on Pilot Beam • Interferometer Accuracy • Orbital Life Test	• DC-RF Converter • 18 Meter Interferometer • Particle Detectors	• Communications • Bistatic Radar • Ionosphere Data • Observation of LEO Sorties Effects
Low Earth Orbit (LEO) Sorties	• Zero "G" Mfg. and Assembly Flow Development - Structure - Microwave - Interface • Operations and Maintenance Development • Initial Verification of Cost and Schedule Projections	• Controllability Demonstration • Thermal Cycling Effects - Large Structures • Preprototype Building Block • Orbital Life Test • Upper Ionosphere Heating Effects	• Build-up to 18M x 18M Power Sub-arrays • Spares to be provided along with Command-Control Sub-array and Orbital Support Equipment • Juxtapositioning to be possible	• Communications • Bistatic Radar - Earth - Planetary • Orbital Microwave Power Transfer • Ionosphere Data

Figure 14-1. Microwave Orbital Program

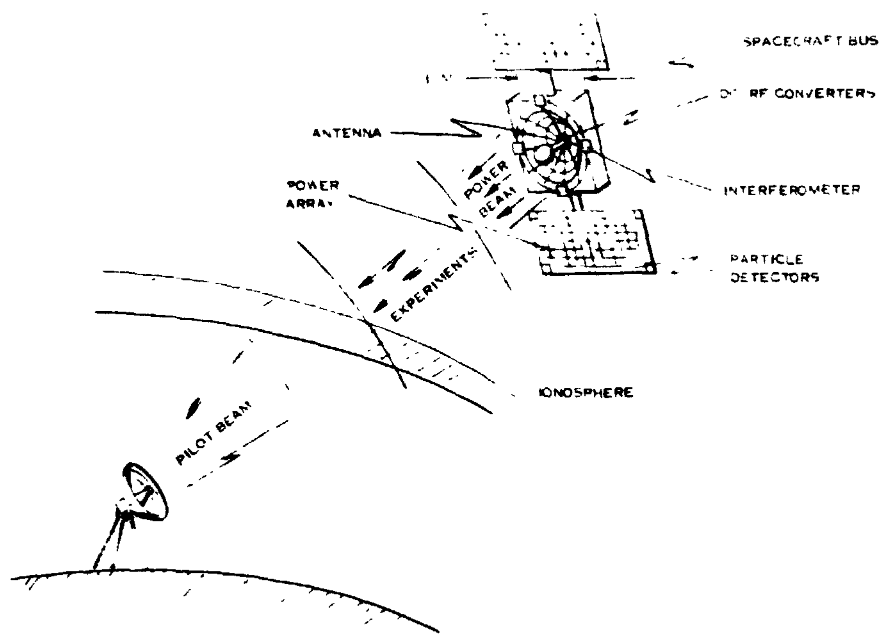


Figure 14-2. Geosatellite Concept

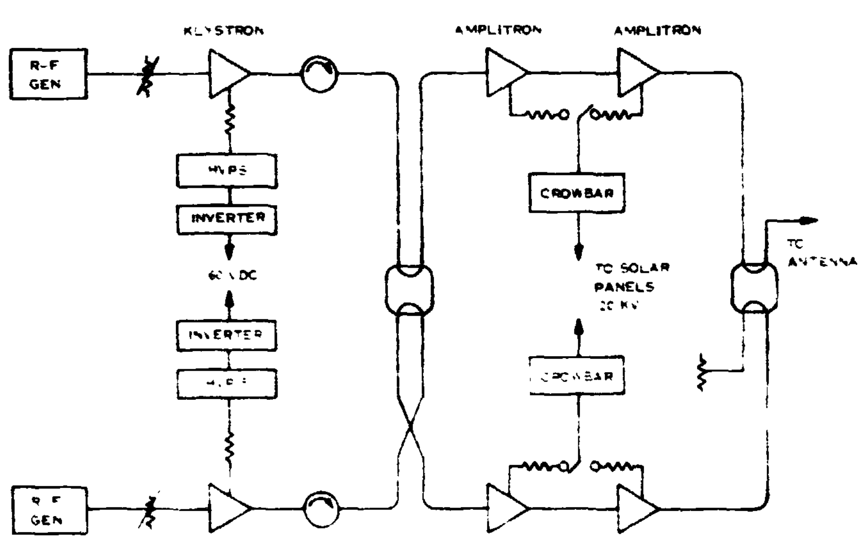


Figure 14-3. Five Kilowatt Geosatellite Payload

GEO SATELLITE WEIGHT ESTIMATE AND PREDICTED INTERIM UPPER STAGE PERFORMANCE

EARTH VIEWING MODULE	2000 LB	(907 KG)
ANTENNA	180 LB	(82 KG)
SOLAR ARRAY	400 LB	(182 KG)
P/L	350 LB	(159 KG)
	2930 LB	(1330 KG)
CONTINGENCY (20%)	586 LB	(266 KG)
	3516 LB	(1596 KG)

IUS PERFORMANCE ESTIMATE

WEIGHT	
– DRY LB (KG)	3609 (1636)
– PROPELLANT LB (KG)	23362 (10,594)
– TOTAL LB (KG)	27356 (12,405)
ISP	311 SEC
PERFORMANCE LB (KG)	
– 24 HR – EQUATORIAL	4100 (1859)
– 24 HR – 28.5 DEG INC	5480 (2487)

Figure 14-4. Geosatellite Weight Estimate and Predicted Interim Upper Stage Performance and IUS Performance Estimate

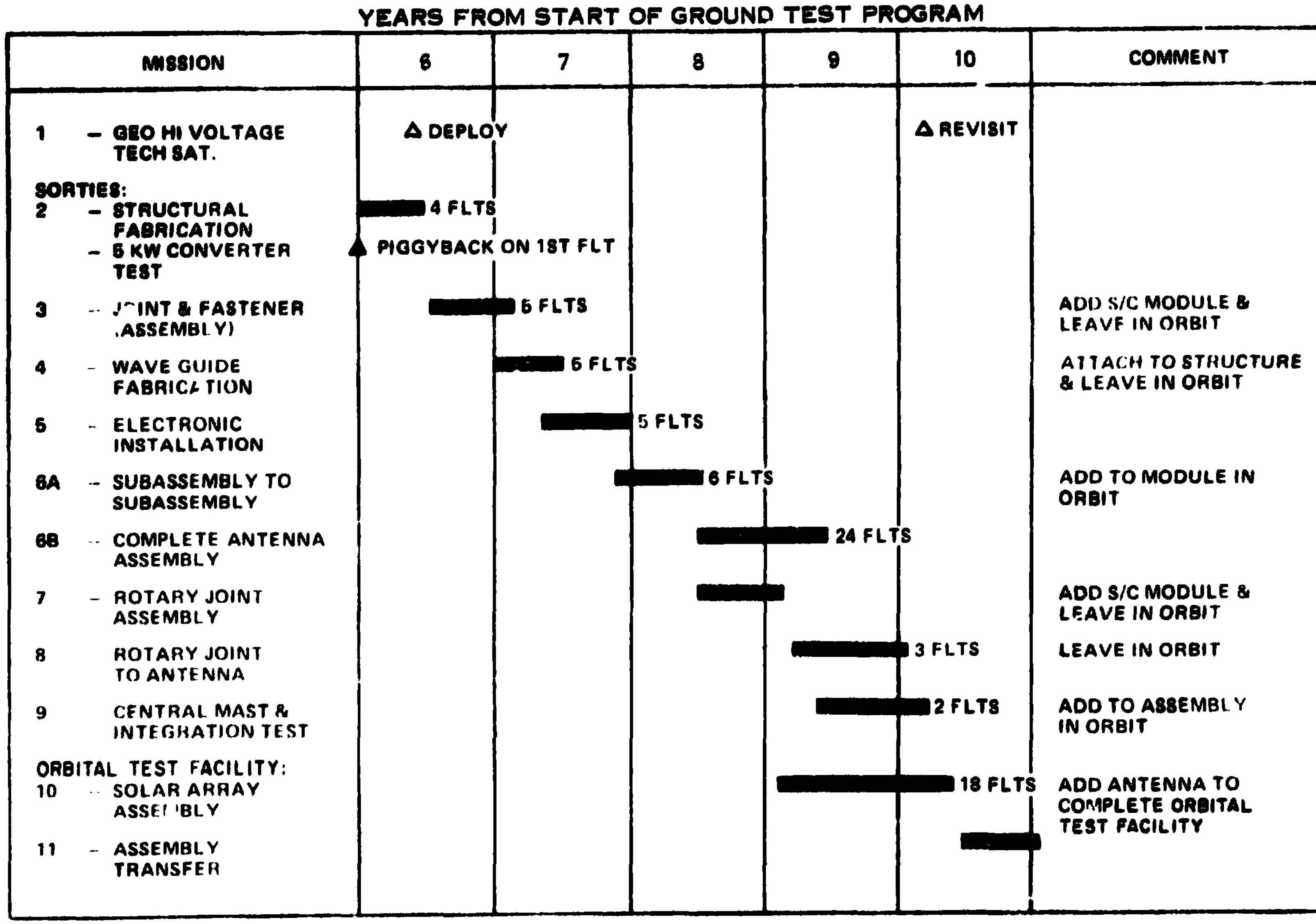


Figure 14-5. Mission Schedule

The mission descriptions are given in the following paragraphs.

Mission 2 - Structural Fabrication Technology Sortie

The objective of Mission 2 is to demonstrate the space fabrication of Satellite Power Station components which have low deployed densities. The mission will demonstrate fabrication of structural beams in aluminum, composites (e.g., graphite/polyimide) and dielectrics. Demonstration of beams, in lengths that are projected for the operational satellite (greater than 250 mils), will be needed. Structural test of the strength and alignment of the beams is also required. The length and buckling characteristics of these members may preclude ground tests and may force an active spaceborne test program.

Figure 14-6(a) is a schematic of the experiment package interfaced with the Shuttle. The equipments included in these missions are: fabrication modules, deployable structures, and jigs and fixtures. Shuttle auxiliary equipments required include: the RMS, Pallet, Airlock, and Spacelab. Instrumentation for testing the accuracy and strength of the fabricated structural elements will be included in the flight test articles inventory.

Figure 14-6(b) is a matrix of test objectives and Shuttle flights. It is estimated that four flights would be adequate to meet the stated objectives.

The first flight will test deployable structures in terms of packaging efficiency, accuracy and strength after deployment. The second and third flights will test man's skill in fabricating structural elements in a space environment and the fourth flight will evaluate the automated fabrication of elements in the candidate materials.

Mission 3 - Joint and Fastener Technology

The objective of Mission 3 is to demonstrate the method of assembling structural elements, and the selection of joints and fasteners. Demonstration of joint and fastener methods on a small scale will lead to selection of the more favorable approaches for assembling 18 x 18 m antenna structural bays. Demonstration of methods of assembly (i.e., teleoperators, EVA, etc.) will provide

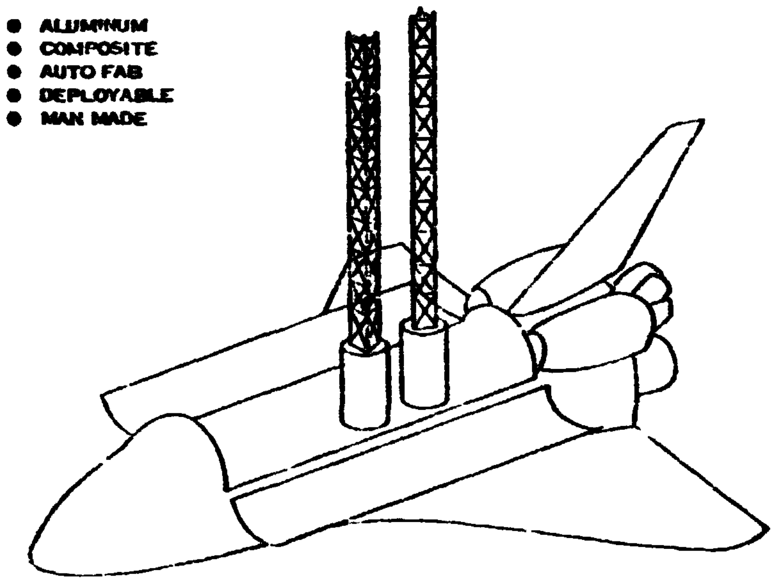


Figure 14-6(a). Mission 2 - Structural Fabrication Technology

FLIGHT	MATERIAL			FABRICATION TECHNIQUE		
	ALUM	COMPOSITE	DIELECTRIC	DEPLOYABLE	MANNED IN ORBIT	FABRICATE
1	X	X	X	X		
2	X				X	
3		X	X		X	
4	X	X	X			X

Figure 14-6(b). Mission 2 - Test Matrix

the basic data for determining the feasibility of structural assembly. Tests of production rate, structural alignment and strength will be required.

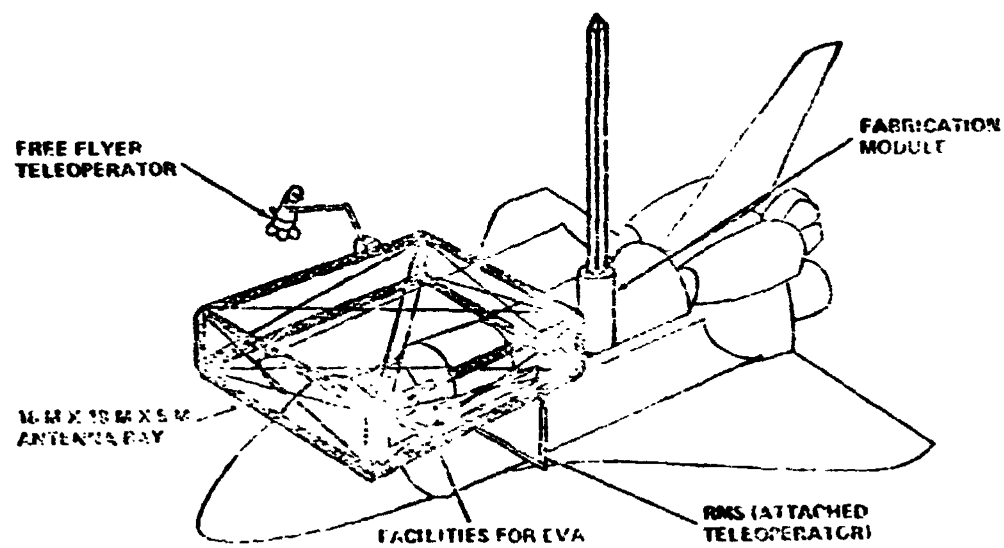
Figure 14-7(a) is a schematic of the equipments used in Mission 3. The payload will consist of manufacturing facilities to fabricate the basic structural elements, teleoperators (both attached and free flying) and the tools and equipments necessary in an EVA mode of assembly. The Shuttle support equipments required are: the RMS, Pallet, Airlock, and Spacelab. A Stationkeeping/Docking Module, which is attached to the assembled Structural Bay, is used to maintain the assembly until the next mission, in which waveguides are attached to the supporting structure.

Figure 14-7(b) is a matrix of Shuttle flights and test requirements broken down into options for materials, scale, joint method and assembly techniques. Flight 1 is designed to provide basic data on fasteners using small scale models. The objective is to determine production rate and joint integrity. The second and third flights construct 18 x 18 m antenna structural bays in aluminum using candidate assembly methods. Flights 4 and 5 perform similar operations on a composite structure.

Mission 4 - Waveguide Fabrication Technology

The objective of this mission is to demonstrate the fabrication and/or deployment of a waveguide subarray. Demonstration of this function in both aluminum and composite is necessary. Mating of the fabricated and/or deployed waveguide subarray to the structure assembled in Mission 3 will also be demonstrated. Tests will include: measurements of mechanical accuracy of the waveguide, assessment of production rates, and tests for structural integrity, before and after mating to the free-flying structure.

Figure 14-8(a) is a schematic of equipment required in Mission 4. Included are deployable waveguide sections, waveguide fabrication modules (composite and aluminum), assembly jigs, and teleoperators. Shuttle support equipments include the RMS, Pallet, Spacelab, and Auxiliary Power and Heat Rejection Module, the latter required because the waveguide assembly fixture blankets the Shuttle radiators.



MATERIAL OPTIONS
- ALUMINUM
- COMPOSITE

JOINT OPTIONS
- WELD
- BOND
- MECHANICAL

ASSEMBLY OPTIONS
- EVA
- FREE FLYER TELEOPERATOR
- ATTACHED TELEOPERATOR

Figure 14-7(a). Mission 3 - Joint and Fastener Technology

	MATERIAL		SCALE		JOINT			ASSEMBLY TECH		
FLIGHT	ALUM.	COMPOSITE	SMALL	18x18x5M	WELD	BOND	MECH	EVA	FREE FLYER	TELE ATTACH
1	X	X	X		X	X	X			
2	X			X	X		X	X		
3	X			X	X		X		X	X
4		X		X		X	X	X		
5		X		X		X	X		X	X

Figure 14-7(b). Mission 3 - Test Matrix

The 18 x 18 m structural bays and Stationkeeping/Docking Modules left in orbit by Mission 3 will be used as the test bed for mating demonstrations. Instrumentation for aligning the waveguide jigs, and measuring the alignment of the finished waveguide will be required.

Figure 14-8(b) summarizes the flight sequence for Mission 4. The first flight will test various waveguide fabrication options on a small scale. Flights 2 and 3 evaluate the two leading candidate approaches to deployment and fabrication of aluminum waveguides; while Flights 4 and 5 demonstrate and collect data on fabrication of composite waveguides.

Mission 5 - Electronics Integration

The objective of Mission 5 is to demonstrate possible methods for installing electronics and wiring. This includes installation of amplitrons, their radiators, the power distribution system, and the command electronics. Tests will include a low level electronic checkout and a measurement of production rate.

Figure 14-9(a) is a sketch of an automated approach to electronics integration. Equipments include: hold arms to support the assembly from Mission 4, and tracks required for an automated electronics integration module. In addition to the electronics (amplitrons, command electronic boxes, power distribution system switches), teleoperators and EVA, equipments for selected installations may be required. Shuttle support equipments include the RMS, Pallet, Airlock and Spacelab. Instrumentation would include an electronics checkout facility.

Figure 14-9(b) is a matrix which relates Shuttle flights to test objectives. The first flight is configured to test installation methods on a small scale, using small sections of aluminum and composite waveguides. Flights 2 and 3 install electronics on the aluminum subarray left in orbit on Mission 4. Flights 4 and 5 install electronics on the composite subarray left in orbit, with a supporting stationkeeping/docking module.

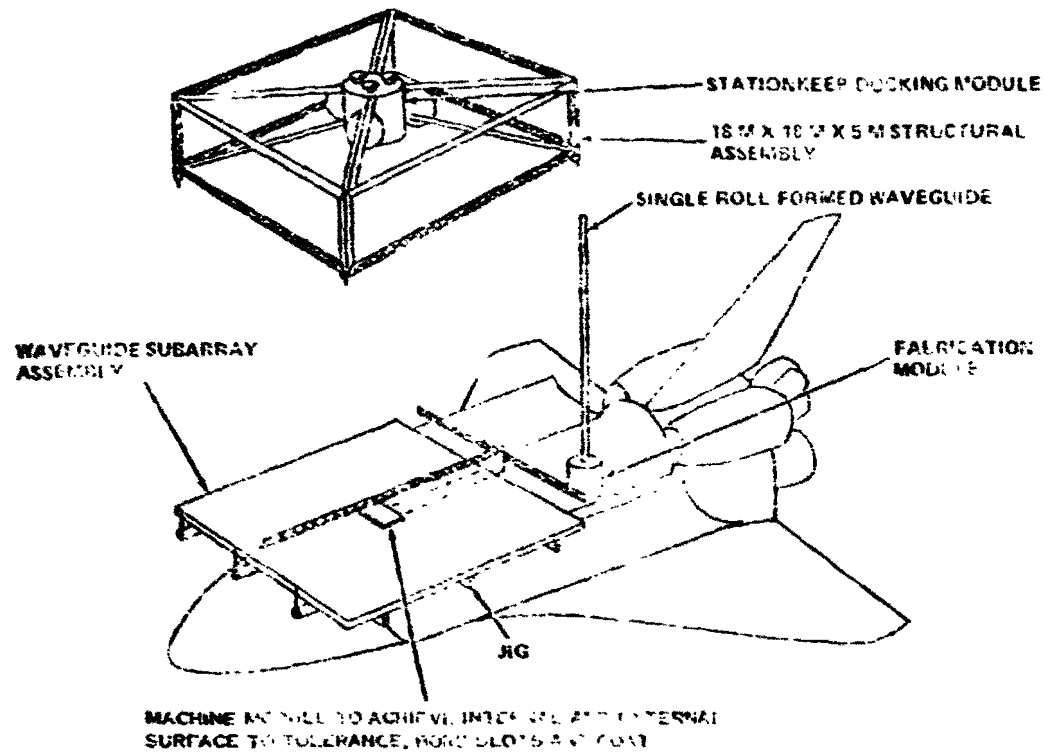


Figure 14-8(a). Mission 4 - Waveguide Fabrication Technology Sortie

FLIGHT	MATERIAL		SCALE		FABRICATION TECH				ASSEMBLE TO[illegible]
	ALUM.	COMPOSITE	SMALL	18 X 18	DE[illegible]	A	B	C	
1	X	X	X			X	X	X	
2	X			X	X				X
3	X				X		X		X
4	X				X		X		X
5		X			X			X	X

Figure 14-8(b). Mission 4 - Test Matrix

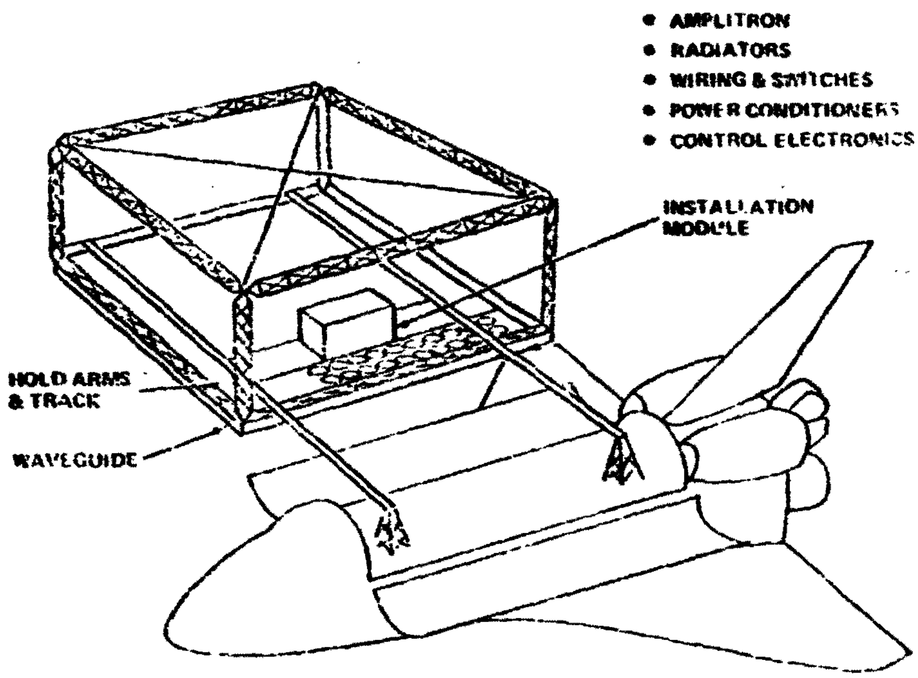


Figure 14-9(a). Mission 5 - Electronics Integration

FLIGHT	MATERIAL		SCALE		INSTALLATION TECH			CHECKOUT
	ALUM	COMPOSITE	SMALL	18 X 18	EVA	MANNED FACIL	AUTO	
1	X	X	X		X		X	X
2	X			X	X			
3						X	X	X
4		X		X	X			
5						X	X	X

Figure 14-9(b). Mission 5 - Test Matrix

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Mission 6 - Subassembly and Buildup

Figure 14-10(a) is a schematic of Mission 6. This mission combines the operations of Missions 3, 4, and 5, in a repetitive fashion, up to the number of subarrays needed for the Orbital Test Facility.

The number of flights required in Mission 6 is directly proportional to the number of subarrays required by the Orbital Test Facility. Figure 14-10(b) illustrates a four-subarray antenna, 36 x 36 m.

Mission 6A completes a 2 by 2 subarray antenna and provides the base from which the remaining 60 antenna subarrays and structure are added in Mission 6B.

Mission 7 - Rotary Joint Assembly

The objective of Mission 7 is to demonstrate assembly of the large diameter rotary joint. This includes assembly of the structure, installation of slip rings, drive mechanisms, wiring and flex cables. Tests of structural accuracy, integrity and a checkout of electrical systems are required.

Figure 14-11(a) is a sketch of the potential Rotary Joint Assembly sortie. Equipments include: a fabrication module for structure, optional deployable elements, slip rings and brushes, drive mechanisms and cables. Teleoperators and EVA support tools would be required. Shuttle support equipments include the RMS, Pallet, Airlock and Spacelab. An additional stationkeeping/docking module is required to maintain the assembled rotary joint for eventual mating to the antenna in Mission 8.

Figure 14-11(b) is a test matrix of Mission 7 Shuttle flights. The first flight will test elements of the joint constructed as a deployable structure. The remaining flights use one rotary joint assembly to test the various approaches to construction.

Mission 8 - Antenna to Rotary Joint Interface

The objective of Mission 8 is to demonstrate methods for mating and integrating large subassemblies. The antenna array assembled in Mission 6 is mated to the rotary joint assembled in Mission 7. The interface structure is fabricated and assemblied in Mission 8.

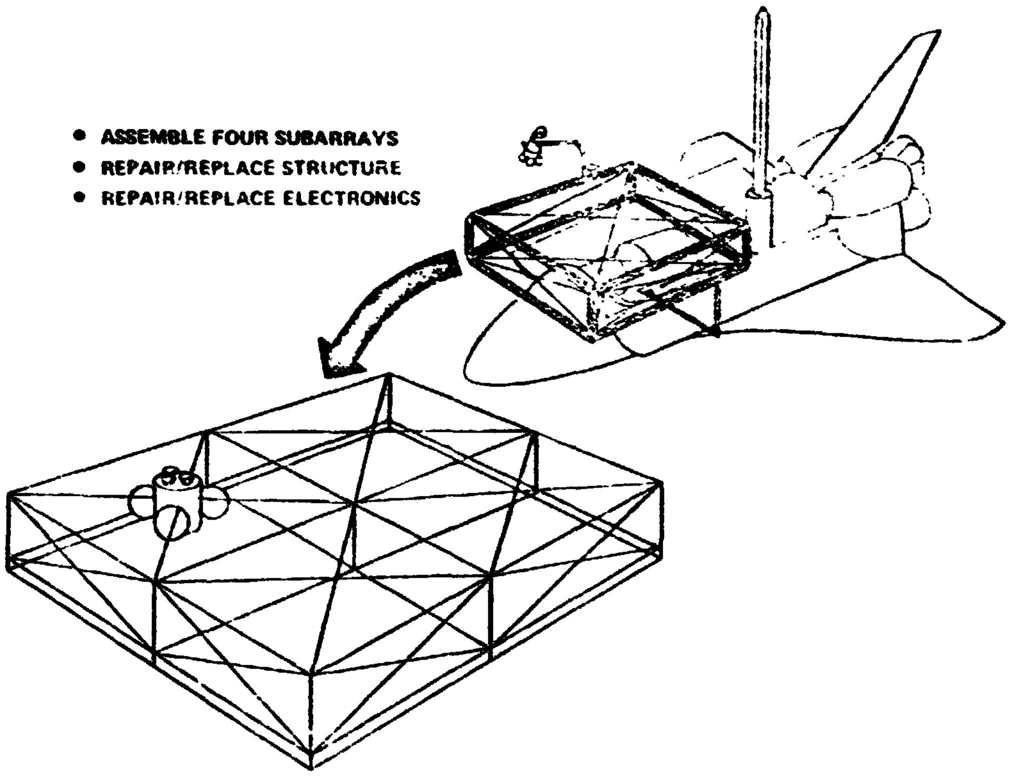

Figure 14-10(a). Mission 6 - Subassembly Build-Up

FLIGHT	OPERATION	ASSEMBLY OPTION	
		SUBASSEMBLE AND MATE TO CORE	EXPAND FROM CORE
1	STRUCTURE ASSEMBLY	X	
2	STRUCTURE ASSEMBLY		X
3	WAVEGUIDE FAB & MATE	X	
4	WAVEGUIDE FAB & MATE	X	
5	ELECTRONICS INSTALLATION		X
6	ELECTRONICS INSTALLATION		X

Figure 14-10(b). Mission 6A - Test Matrix

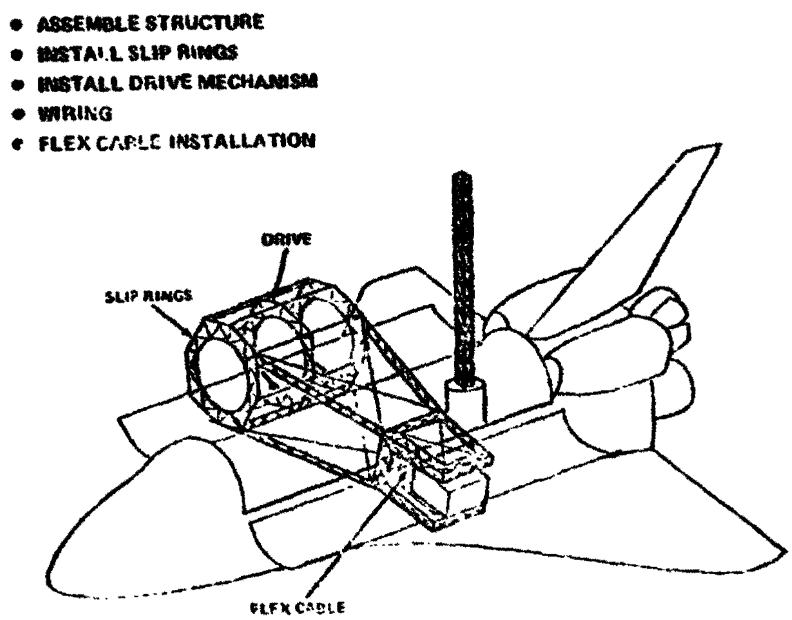

Figure 14-11(a). Mission 7 - Rotary Joint Assembly

FLIGHT	STRUCTURE			SLIP RING		DRIVE		WIRE		FLEX CABLE	
	DEPLOY	REMOTE	EVA	REMOTE	EVA	REMOTE	EVA	REMOTE	EVA	REMOTE	EVA
1	X										
2		X	X								
3				X	X	X	X				
4								X	X	X	X

Figure 14-11(b). Mission 7 - Test Matrix

Figure 14-12(a) is a conceptual drawing of the elements requiring assembly in Mission 8. The antenna (Mission 6) is interfaced to the rotary joint (Mission 7). The interface structure can be assembled using the rotary joint as an assembly base and mating the antenna to the interface structure's five points via a docking maneuver.

Figure 14-12(b) is a schedule of Mission 8 flights which assemble the interface structure (Flight 1) and mates the antenna and rotary joint to the interface structure. Interface wiring and electronics integration is performed on Flight 3.

Mission 9 - Central Mast Assembly and Integrated Test

The objective of Mission 9 is to assemble the middle section (roughly 210 meters) of the orbital test facility satellite central mast and interface the mast to the rotary joint. After assembly, an integration test is performed to demonstrate system operation.

Fig ·e 14-13(a) is a conceptual drawing of the integration test proposed for Mission 9. After assembly and mating of the central mast to the rotary joint, an interface to the Shuttle power supply could be used to perform limited tests of the antenna by "lighting-up" individual amplitrons. To provide sufficient power, a solar array and additional heat rejection has been added to the Shuttle cargo manifest. Holding tanks for fuel-cell water are added in an effort to minimize contaminants.

As summarized in Figure 14-13(b), the first flight in Mission 9 will assemble the 213m conducting central mast and mate it to the rotary joint. The test objectives can be accomplished by using the indicated options during assembly on different segments of the mast. The second flight is designed to test the integrated microwave subassembly at lower than operational power levels.

Mission 10 - Solar Array Assembly

The objective of Mission 10 is to demonstrate assembly of a large solar array and establish methods for achieving required assembly rates. The details of assembly include: construction of the support structure, installation of the solar blanket, with the required tension spring interface and the support structure to minimize the impact of large temperature variations expected in low earth orbit. The installation of the aluminized Kapton mirrors and power distribution systems

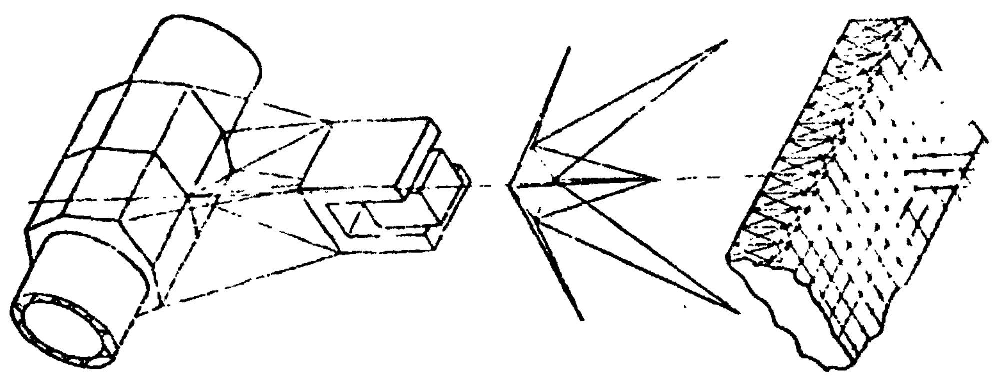

Figure 14-12(a). Mission 8 - Antenna to Rotary Joint Interface

FLIGHT	ASSEMBLE INTERFACE		WIRING		ASSEMBLE ROTARY JOINT TO ANTENNA	
	REMOTE	EVA	REMOTE	EVA	REMOTE	EVA
1	X	X				
2			X	X		
3					X	X

Figure 14-12(b). Mission 8 Test Matrix

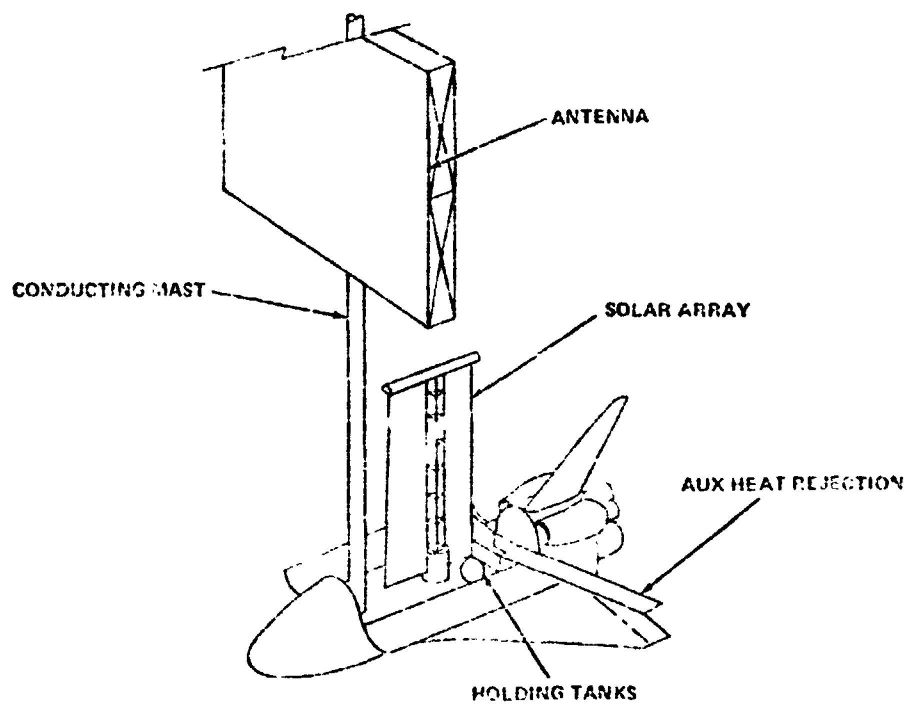

Figure 14-13(a). Mission 9 - Central Mast Assembly and Integration Test

FLIGHT	METHOD OF ASSEMBLY		
	DEPLOY	AUTO	MANUAL
1	X	X	X
2	INTEGRATION TEST		

Figure 14-13(b). Mission 9 - Test Matrix (Conducting Mast Assembly)

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requi-- unique assembly methods to achieve the needed production rates. The integration of the power-bus system to the central mast and eventual mating to the antenna subassembly follows. This mission supported by the preceding missions is considered to offer one way of obtaining the flight test data pertinent to the implementation of objective M2. Although more or less complex implementation may be recommended as the program definition matures, these mission concepts are therefore used as the basis to scope the characteristics of an orbital test facility as described in the following paragraphs.

The conceptual design results in a 15 MW power source requirement to fully implement the currently defined highly desirable objective for ionosphere "F" layer irradiation. The configuration builds up in Missions 2 through 10. The solar array is assumed to have a concentration ratio of two.

The silicon solar blanket efficiency was established using the projected efficiency for the SEPS array (12 percent) and degrading efficiency for the operating temperature at a concentration ratio of two. A power distribution system efficiency of 92 percent was assumed and the projected microwave conversion efficiency of 82 percent was utilized to compute the array output power requirement.

The array weight estimates used the projected SEPS solar blanket weights (0.525 kg/m^2) and the 0.5 mil aluminized Kapton weights projected for the operational mirror system. The weight per unit length of structure for the operational satellite was used to establish the non-conducting structural weights. The column lengths for this design are approximately the same as the operational system. The weight of the conducting structure and central mast are sized by electrical requirements in the operational system; but are sized by structural requirements in this system.

The rotary joint is scaled down (1/10 size) from the operational system.

The total weight of the orbital test facility is 228,343 kg (503,148 lb). The transmitting antenna, however, is 3.6 times heavier than the solar array. This introduces unique control problems compared to the operational system. The antenna should be used as the base for the spacecraft reaction control system and the rotary joint used to steer the array. This combination may lead to problems meeting the objective, to point to a ground rectenna, and complicating ionospheric testing to an even greater extent.

Mission 11 - Assembly Transfer

The objective of Mission 11 is to demonstrate transferring a fully assembled large structure from one orbit position to another, and testing the structural loads incurred by the operation.

Figure 14-14 indicates the need for two Shuttle launches to deploy the transfer stages; mate them to the demonstration satellite; and checkout the interface for the actual transfer.

14.2.3 ORBITAL TEST FACILITY

Sizing of the Orbital Test Facility (OTF) antenna described above came about from a consideration of the power densities desired both in the ionosphere and on the ground, with altitudes taken as 352 km (190 nmi) for assembly and 556 km (300 nmi) as a reasonable maximum for sustained operations. The relation for power density is

$$P_d = \frac{P_o A_T}{\lambda^2 D^2}$$

where

P_d = peak power density at D

A_T = transmitting antenna area

λ = wavelength

D = distance from transmitter

P_o = total radiated power

We see that the radiated power x area product will be determined by the requirements for a given power density at a given distance, and that, given the maximum power available, the smallest antenna size is established. The desired peak power densities are 50 mW/cm^2 for ionospheric tests and 20 mW/cm^2 for ground level tests.

The 144m x 144m antenna selected consists of 64 subarrays (18m x 18m) as shown in Figure 14-15. Of these 53 are active. The power densities achieved at various ranges are shown in Figure 14-16. The ionospheric "F" layer and the ground power densities are about as desired. However, the lower "D" layer ionosphere test is below the desired level and it is suggested that a ground facility be used such as Arecibo which has the largest aperture (700 ft diameter) at S-band. Even so, it must be upgraded in power from 0.4 MW to about 5 MW.

FLIGHT	DEPLOY PROPULSION STAGE	MATE PROPULSION STAGE	C/O STAGE	MANEUVER STAGE
1	X	X		
2	X	X	X	X

Figure 14-14. Mission 11 - Test Matrix

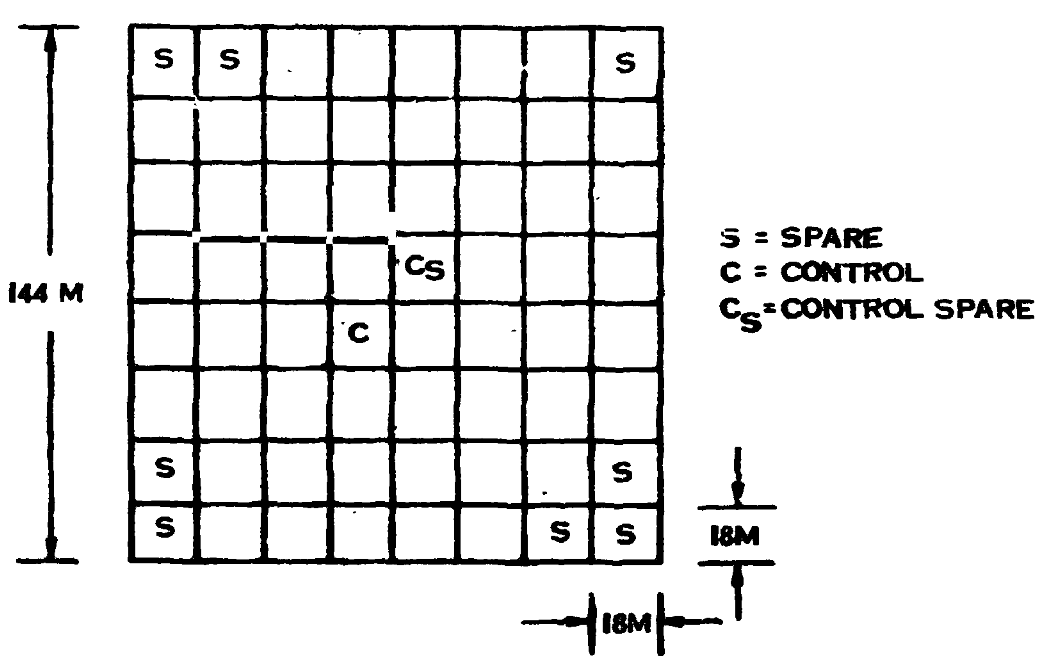

Figure 14-15. OTF Antenna

Condition	D KM	P_d mW/cm^2	Objectives (See para. 14.1)
Alt. = 190 nmi			
= 352 KM			
(a) To Ground	352	15.2	D-1 and D-2
(b) To "D" Layer	282	23.6	Use Arecibo for [H-2] Long Term (minutes)
(c) To "F" Layer	102	184	Exceeds H-1 Requirements
Altitude or Range = 240 nmi = 444 KM			
To "F" Layer	194	50.0	H-1
To Ground	444	9.5	D-1 and D-2
Altitude or Range = 236 nmi = 435 KM	435	10.0	D-1 and D-2

Figure 14-16. OTF Power Densities

Potential problems with the OTF in low orbit are the high rates relative to the earth and the short acquisition and viewing periods for a rectenna power transfer demonstration. The high rates become a problem for the attitude control design for the satellite and also for design of the electronic phase control system. These difficulties will exceed those in a geosynchronous MPTS and should be considered in evaluating the merits of power beam control and transfer demonstrations in low earth orbit.

14.3 COST AND SCHEDULE

The ground rules established for arriving at rough order of magnitude (ROM) costs were to (1) use previously established levels of cost per kilogram for the development phase, (2) to use a learning curve factor of 85 percent to work backward from the MPTS estimates for subsystems made previously, and

(3) use 1975 dollars. This learning curve consideration establishes quantitative cost goals that are important in implementing objective H3.

The microwave figure of merit for development cost was $62K/lb. The MPTS-OTF learning ratios for key subsystems were:

Subarray Cost Multiplier = 2.15 (64 units vs. 1670 units)
Amplitron Cost Multiplier = 2.88 (15,876 units vs. 1,442,000 units).

Demonstration that multipliers of this sort actually hold is a key aspect of the test program to build confidence in operational system estimates. This also holds for the structures and in particular for the orbital assembly operations which can be major cost contributors.

A summary of the MPTS Orbital Test Program is given in Figure 14-17. It can be seen that a major part of the cost is the Shuttle launch costs. A management and integration charge of 40 percent has been applied to the non-Shuttle costs. This would be for the prime or integrating contractor role and responsibility. A 20 percent contingency is placed on the final figures.

The critical technology (ground based part of flight test program) schedule is shown in Figure 14-18 and the flight test schedule has been shown in Figure 14-5. The time phased ROM cost projection based on these schedules is summarized in Figure 14-19. The Arecibo upgrading is included in the ionosphere technology portion at an estimated cost of $11M.

	NON-REC	UNIT REC	NO UNITS	REC TOTAL	NON-REC & REC TOTALS
CRITICAL TECHNOLOGY					
MICROWAVE (NOTE 1)	32	-	-	-	32
ORBITAL ASSEMBLY (NOTE 2)	126	-	-	-	126
OTHER	32	-	-	-	32
SUBTOTAL	190				190
GEOSATELLITE					
PAYLOAD	22	3	1	3	25
SPACECRAFT	(NOTE 3)	16	1	16	16
INTERIM UPPER STAGE	-	10	1	10	10
SHUTTLE	-	13	1	13	13
SUBTOTAL	22			42	64
ORBITAL TEST & FACILITY					
STANDARD SUBARRAYS	294	0.411	62	26	320
COMMAND-CONTROL SUBARRAYS (DELTA)	49	9.6	3	29	78
RECTENNA	(NOTE 4)	36	1	36	36
GROUND COMMAND-CONTROL	(NOTE 4)	26	1	26	26
MICROWAVE SUBTOTAL	343			117	460
ORBITAL ASSEMBLY (NOTE 5)	222	-	-	169	391
SOLAR ARRAY	(NOTE 6)	20	1	20	20
SHUTTLE	-	13	78	1014	1014
SHUTTLE AUX-EQUIP	-	2	78	156	156
SPACELAB MODIFICATION	103	-	1	-	103
ASSY & TRANS SUBTOTAL	325			1359	1684

Figure 14-17. MPTS Orbital Test Program ROM Costs (Rough Order of Magnitude in Millions of 1975 Dollars) (Page 1 of 2)

	NON-REC	UNIT REC	NO UNITS	REC TOTAL	NON-REC & REC TOTALS
MANAGEMENT & INTEGRATION (NOTE 7)	352	-	-	139	491
CONTINGENCY (20%)	246	-	-	331	577
PROGRAM TOTAL	$1478			$1988	$3466

NOTE 1: Includes upgrading Arecibo facility for ionospheric tests.

NOTE 2: Covers effort through Phase B.

NOTE 3: Use designs developed for ATS-6.

NOTE 4: Covered in Ground Demonstration Program and Critical Technology (above)

NOTE 5: Phase C hardware and operations.

NOTE 6: Assumed covered in separate power source development program.

NOTE 7: NASA or industry prime at 40% of total program less shuttle costs.

Figure 14-17. MPTS Orbital Test Program ROM Costs (Continued) (Rough Order of Magnitude in Millions of 1975 Dollars) (Page 2 of 2)

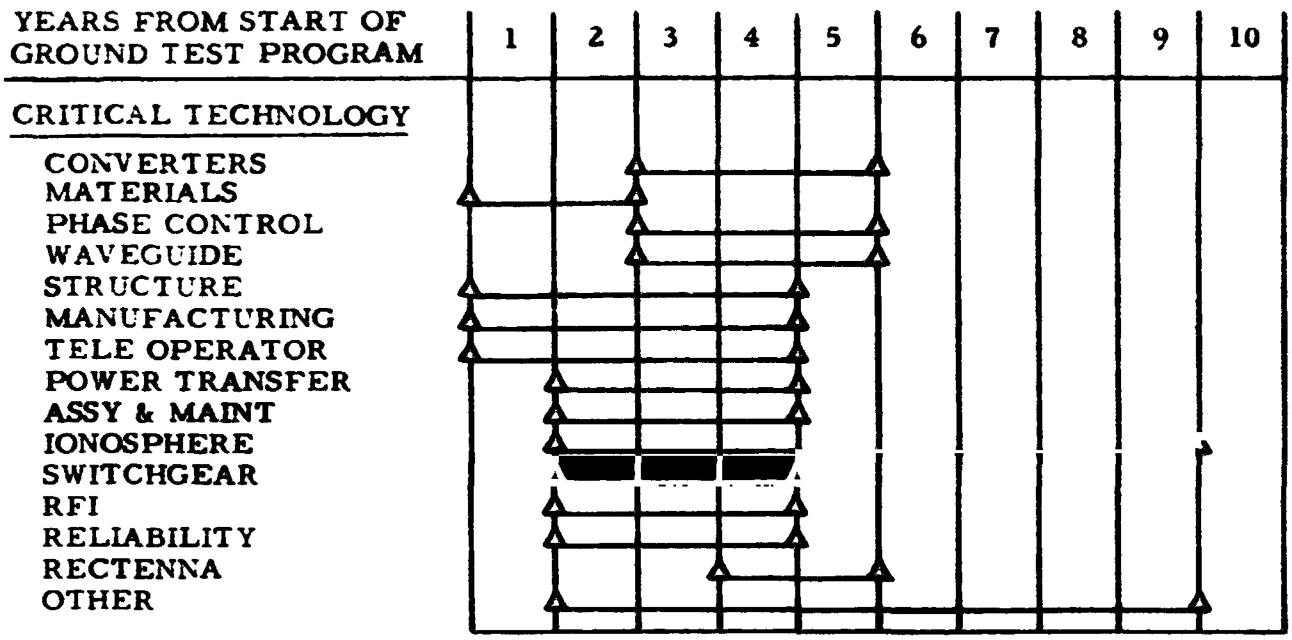

Figure 14-18. Critical Technology Schedule

	YEARS FROM START OF GROUND TEST PROGRAM										
	1	2	3	4	5	6	7	8	9	10	TOTAL
CRITICAL TECHNOLOGY	27	59	77	109	13	9	8	8	8		318
GEOSATELLITE			17	17	25	37					96
ORBITAL TEST & FACILITY				50	344	536	610	620	627	265	3052
TOTALS	27	59	94	176	382	582	618	628	635	265	3466

* INCLUDES MANAGEMENT AND INTEGRATION (40%), SHUTTLE COSTS, AND CONTINGENCY (20%)

Figure 14-19. MPTS Orbital Test Program ROM Cost Summary*
(Rough Order of Magnitude in Millions of 1975 Dollars)

14.4 CONCLUSIONS AND RECOMMENDATIONS

The proposed technology development and orbital test program is recommended to be considered to build upon the integrated ground test program to advance the technology and establish technical, cost and schedule feasibility in support of decisions to advance to a larger scale pilot plant or prototype.

The following conclusions are pertinent when considered in conjunction with those for the integrated ground test program.

a. Orbital test is needed to develop and demonstrate dc-rf converter startup and operation, zero "G" assembly and operations, and learning with respect to projected costs and schedule.

b. Requirements are satisfied by a geosynchronous test satellite and by a series of Shuttle sortie missions that lead to an orbital test facility.

c. A low earth orbital test facility can be sized to determine the effects on the upper ionosphere of high microwave power densities.

d. Modified ground based facilities, such as at Arecibo are best suited to determine the effects on the lower ionosphere of high microwave power densities.

APPENDIX H

ESTIMATED ANNUAL OPERATIONS AND MAINTENANCE COST
(5 GW System)

M$/Year

1. **Personnel, Staff and Support**

Primary:	27		
Support, 1st tier:	75		
Support, 2nd tier:	54		
	156 at \$1.2k/wk	=	\$ 9.73

2. **Maintenance**

Hardware

$$\frac{(3\%)\ (\text{Capital Investment})}{30\ \text{years}}$$

$$= \frac{(0.03)\ (\$5200)\times 10^6)}{30} \quad = \quad 5.20$$

3. **Transportation**

2 shuttle flights/year at 10.5M/flight
+ \$1.8M amortization/flight

= 2 (\$10.5M + 1.8M) = 24.60

2 tug flights/year at 1.0M/flight = 2.24

4. **Consumable Modules, Repairs, Delivery**

a. **Hardware**

$$\frac{(1.5\%\ \text{Hardware Capital Investment})}{30\ \text{years}}$$

$$= \frac{(0.015)\ (\$5200 \times 10^6)}{30} \quad = \quad 2.60$$

b. **Transportation**

$$\frac{(1/2\%\ (\text{Total Weight})\ (\text{Cost/Flight}))}{65{,}000\ \#/\text{flight}} + \begin{matrix}\text{one}\\ \text{extra}\\ \text{flight}\end{matrix}$$

$$= \frac{(0.005)\ (19.0\times 10^6\ \text{kg})\ (\$12.3\times 10^6/\text{flight}}{(0.454\ \text{kg/lb})\ (65{,}000\ \text{lb/flight})}$$

$$+\ \$12.3\times 10^6/\text{flight} \quad = \quad 51.90$$

\$96.27 M/yr.

		M$/Year
First-year O & M cost:	=	$19.25/kW
Second-year (1st year x 0.75)	=	14.44
Third-year (2nd year x 0.80)	=	11.55
Fourth-year (3rd year x 0.85)	=	9.82
Fifth-year (4th year x 0.90)	=	8.84
Sixth-year (5th year x 0.95)	=	8.40
Average annual O & M for first 6 years:		$12.05/kW
Seventh to 30th year:		8.40/kW
Average annual O & M over 30 year life:		$ 9.13/kW

APPENDIX I

ANNUAL OPERATIONS AND MAINTENANCE COST
(10 GW System)

M$/Year

1. **Personnel, Staff and Support**

Primary:	27		
Support, 1st tier:	149		
Support, 2nd tier:	108		
	284 at \$1.2k/wk	=	\$ 17.72

2. **Maintenance**

$$\frac{(3\%)\ (\text{Hardware Capital Investment})}{30\ \text{years}}$$

$$= \frac{(0.03)\ (\$9300 \times 10^{6})}{30} \qquad = \qquad 9.30$$

3. **Transportation**

3 shuttle flights/year at 10.5 M/flight
+ \$1.8M amortization/flight

= 3 (\$10.5M + \$1.8M) = 3 (\$12.3M) = 36.90

3 tug flights/year at \$1.0M/flight
+ \$1.2M amortization/flight = 3.36

4. **Consumable Modules, Repairs, Delivery**

   a. **Hardware**

$$\frac{(1.5\%)\ (\text{Hardware Capital Investment})}{30\ \text{years}}$$

$$= \frac{(0.015)\ (\$9300 \times 10^{6})}{30} \qquad = \qquad 4.65$$

   b. **Transportation**

$$\frac{(1/2\%)\ (\text{Total Weight})}{60{,}000\ \#/\text{flight}} + \text{cost of one extra flight}$$

$$= \frac{(0.005)\ (37.5 \times 10^{6}\ \text{kg})\ (12.3 \times 10^{6}/\text{flight})}{(0.454\ \text{kg/lb})\ (65{,}000\ \text{lb/flight})}$$

$$+\ 12.3 \times 10^{6}/\text{flight} \qquad = \qquad 90.45$$

\$162.38 M/yr.

		M$/Year
First-year O & M cost:	=	$16.24/kW
Second-year (1st year x 0.75)	=	12.18
Third-year (2nd year x 0.80)	=	9.74
Fourth-year (3rd year x 0.85)	=	8.28
Fifth-year (4th year x 0.90)	=	7.45
Sixth-year (5th year x 0.95)	=	7.08
Average annual O & M for first 6 years		$10.16/kW
Seventh to 30th year:		7.08/kW
Average annual O & M over 30 year life:		$ 7.70/kW

APPENDIX J

SYSTEM ANALYSIS EXAMPLES

J.1 INTRODUCTORY ANALYSIS OF INITIAL OPERATIONAL SYSTEM WITH MINIMUM SIZE TRANSMITTING ANTENNA

In order to provide a readily usable analysis tool, the chart shown in Figure J-1 was developed to collect the proper set of assumptions and put them in one place to best understand the relationships of the various parts to the total cost and how this relates to sizing of the MPTS antennas.

Figure J-2 notes the set of assumptions and summarizes the cost for a case of particular interest (Initial Operational System with Minimum A_T). The following notes provide a guide to the rationale for assumptions and data sources. See paragraph 12.2.1 for the definition of terms.

P_G A value of $P_G = 5$ GW $= 5 \times 10^6$ kW is selected based on considerations discussed in paragraph 12.2.7.

K A value of K = 200 \$/kg is selected based on considerations discussed in paragraphs 12.2.2 and 12.2.8.

C_1 A value of $C_1 = 350$ \$/kW is selected based on considerations discussed in paragraphs 12.2.2 and 12.2.8.

C_2 A value of $C_2 = 1.5$ kg/kW is selected based on considerations discussed in paragraphs 12.2.2 and 12.2.8.

n The values of the elements resulting in n = 0.536 are selected based on considerations summarized in Figure 12-32.

$n_t = 0.819$
$n_b = 0.95$
$n_a = 0.988$
$n_s = 0.90$
$n_r = 0.774$
$\therefore n = 0.536$

Values for the Amplitron case, on the low side, are assumed for the initial operational system whereas values approaching the "Goal" should be expected for the average operational system.

TOTAL COST SUMMARY

FORMAT

____

Summary Title

Specific Cost = C/P_G \$/kW = $C_{PS}/P_G + C_{PD}/P_G + C_C/P_G + C_{TA}/P_G + C_{RA}/P_G$ **of total space power system.**

Assumptions

Parameters Controlled by Major Programmatic Decisions

P_G	=	Total power delivered to the ground power grid	______	kW
K	=	Orbital transportation and assembly specific cost	______	\$/kg
C_1	=	Cost of power source/power output at the power source	______	\$/kg
C_2	=	Weight of power source/power output at the power source	______	kg/kW

MPTS Efficiency Parameters driven by MPTS Technology Development

n	=	$n_t\, n_b\, n_a\, n_s\, n_r$ = total dc from the orbital power source to a-c at the ground power network	______
n_t	=	power source interface through dc to rf conversion and rf radiation out the waveguide slots	______

RF Generator ______

Antenna Basic Material ______

Figure J-1

Level of Maturity or Confidence Low(L) Medium(M) High(H)

$$C_{PS}/P_G = \frac{C_1 + K\,C_2}{n}$$ = Specific Cost of Power Source

		Low(L)	Medium(M)	High(H)
C_{PS}/P_G	\$/kW			

$$C_{PD}/P_G = \frac{(C_3 + C_4\,K)\,10^3}{(n\,P_G)^{1/2}}$$ = Specific Cost of Power Distribution

		Low(L)	Medium(M)	High(H)
C_3	$\$/\sqrt{W}$			
C_4	$kg/\sqrt{W}$	_____	_____	_____
C_{PD}/P_G	\$/kW			

$$C_C/P_G = \frac{n_t}{n}\,(C_5 + C_6\,K)$$ = Specific Cost of dc to rf Converters

		Low(L)	Medium(M)	High(H)
C_5	\$/kW			
C_6	kg/kW	_____	_____	_____
C_C/P_G	\$/kW			

$$C_{TA}/P_G = (C_7 + C_8\,K)\,A_T/P_G$$ = Specific Cost of Transmitting Antenna

		Low(L)	Medium(M)	High(H)
C_7	$\$/m^2$			
C_8	kg/m^2	_____	_____	_____
C_{TA}/P_G	\$/kW			

$$C_{RA}/P_G = \frac{C_9\,A_R}{P_G} + \frac{C_{10} \times 10^3}{P_G^{1/2}}$$ = Specific Cost of Receiving Antenna

		Low(L)	Medium(M)	High(H)
C_9	$\$/m^2$			
C_{10}	$\$/\sqrt{W}$			
A_R	m^2	_____	_____	_____
C_{RA}/P_G	\$/kW			

Total Specific Cost = Specific Capital Cost of Total Space Power System

		Low(L)	Medium(M)	High(H)
C/P_G	\$/kW			

Figure J-1 (Continued)

TOTAL COST SUMMARY

INITIAL OPERATIONAL SYSTEMS WITH MINIMUM A_T

Summary Title

Specific Cost = C/P_G \$/kW = $C_{PS}/P_G + C_{PD}/P_G + C_C/P_G + C_{TA}/P_G + C_{RA}/P_G$ of total space power system.

Assumptions

Parameters Controlled by Major Programmatic Decisions

P_G	=	Total power delivered to the ground power grid	5×10^6 kW
K	=	Orbital transportation and assembly specific cost	200 \$/kg
C_1	=	Cost of power source/power output at the power source	350 \$/kW
C_2	=	Weight of power source/power output at the power source	1.5 kg/kW

MPTS Efficiency Parameters driven by MPTS Technology Development

n	=	$n_t n_b n_a n_s n_r$ = total dc from the orbital power source to a-c at the ground power network	0.536
n_t	=	power source interface through dc to rf conversion and rf radiation out the waveguide slots	0.819

RF Generator — Amplitron

Antenna Basic Material — Aluminum

Figure J-2

Level of Maturity or Confidence		Low(L)	Medium(M)	High(H)

$$C_{PS}/P_G = \frac{C_1 + KC_2}{\iota}$$ = Specific Cost of Power Source

C_{PS}/P_G	\$/kW	1215	1215	1215

$$C_{PD}/P_G = \frac{(C_3 + C_4 K)10^3}{(n\ P_G)^{1/2}}$$ = Specific Cost of Power Distribution

C_3	\$/ $\sqrt{W}$	575	965	1330
C_4	kg/ $\sqrt{W}$	5.76	5.76	5.76
C_{PD}/P_G	\$/kW	33	41	48

$$C_C/P_G = \frac{n_t}{n}(C_5 + C_6 K)$$ = Specific Cost of dc to rf Converters

C_5	\$/kW	11.4	18.2	28.2
C_6	kg/kW	0.324	0.324	0.324
C_C/P_G	\$/kW	117	127	142

$$C_{TA}/P_G = (C_7 + C_8 K)\ A_T/P_G$$ = Specific Cost of Transmitting Antenna

C_7	\$/m^2	244	[illegible]	986
C_8	kg/m^2	5.16	5.16	5.16
A_T	m^2	541×10^3	541×10^3	541×10^3
C_{TA}/P_G	\$/kW	138	165	202

$$C_{RA}/P_G = \frac{C_9\ A_R}{P_G} + \frac{C_{10} \times 10^3}{P_G^{1/2}}$$ = Specific Cost of Receiving Antenna

C_9	\$/m^2	8.48	11.85	17.3
C_{10}	\$/ $\sqrt{W}$	158	[illegible]	[illegible]
A_R	m^2	[illegible]	[illegible]	[illegible]
C_{RA}/P_G	\$/kW	210	[illegible]	629

[illegible]

[illegible]	\$/kW	[illegible]	[illegible]	[illegible]

Figure J-2 (Continued)

n_t The value of $n_t = 0.819$ is selected as discussed on the previous page.

C_3 The values of

$$C_3 = \frac{54.6 \times 10^6}{\sqrt{9 \times 10^9}} = 575 \ \$/\sqrt{W} \quad (L)$$

$$C_3 = \frac{91.7 \times 10^6}{\sqrt{9.5 \times 10^4}} = 965 \ \$/\sqrt{W} \quad (M)$$

$$C_3 = \frac{126.0 \times 10^6}{\sqrt{9.5 \times 10^4}} = 1330 \ \$/\sqrt{W} \quad (H)$$

are taken from Figure 12-31 WBS 3.0.

C_4 The value of

$$C_4 = \frac{548.0 \times 10^3}{\sqrt{9 \times 10^9}} = 5.76 \ kg/\sqrt{W}$$

is taken from Figure 12-31 WBS 3.0 for (L), (M) and (H) cases.

C_5 The values of

$$C_5 = \frac{57.0}{5.0} = 11.4 \ \$/kW \quad (L)$$

$$C_5 = \frac{91.0}{5.0} = 18.2 \ \$/kW \quad (M)$$

$$C_5 = \frac{141.0}{5.0} = 28.2 \ \$/kW \quad (H)$$

are taken from Figure 12-31 WBS 4.5(a).

C_6 The value of

$$C_6 = \frac{1.62}{5.0} = 0.324 \ kg/kW$$

is taken from Figure 12-31 WBS 4.5(a) for (L), (M) and (H) cases.

C_7 **The values of**

$$C_7 = 115.0 + 64.0 + 1.05 + \frac{11.5 \times 10^6}{\pi \times 1000^2/4} + 46.0 + \frac{2.6 \times 10^6}{\pi \times 1000^2/4}$$

$$= 244 \ \$/m^2 \ (L)$$

$$C_7 = 231.0 + 132.0 + 2.1 + \frac{23.0}{0.784} + 92.0 + \frac{5.1}{0.784} = 493 \ \$/m^2 \ (M)$$

$$C_7 = 462.0 + 264.0 + 3.68 + \frac{46.0}{0.784} + 184.0 + \frac{10.2}{0.784} = 986 \ \$/m^2 \ (H)$$

are taken from Figure 12-31 WBS (4.1 + 4.2 + 4.3) + 4.4(a) + 5.1(a) + 5.2 + 5.3 + 6.0 for aluminum waveguides.

C_8 **The values of**

$$C_8 = \frac{35.0 + 17.2 + 22.7 + 1381.0}{324.0} + 0.26 + \frac{172.0 \times 10^3}{\pi \times 1000^2/4} + 0.184$$

$$+ \frac{775.0}{\pi \times 1000^2/4}$$

$$= 4.5 + 0.26 + 0.219 + 0.184 + 0.001$$

$$= 5.16 \ kg/m^2$$

was taken from Figure 12-31 WBS (4.1 + 4.2 + 4.3) + 4.4(a) + 5.1(a) + 5.2 + 5.3 + 6.0 for aluminum waveguides for (L), (M) and (H) cases.

A_T **The value of $A_T = 541.0 \times 10^3 \ m^2$ is determined assuming a 5 dB taper with a fully packed central portion as discussed in paragraph 12.2.7, minimum peak power density as discussed in paragraph 12.2.5, and beam collection efficiency $n_s = 0.90$. From these assumptions and referring to Figure 12-15 a diameter of 0.83 km is selected.**

$$\therefore A_T = \frac{\pi \times 830^2}{4} = 541.0 \times 10^3 \ m^2$$

C_9 **The values of**

$C_9 = 0.10 \times 4.28 + 0.10 \times 1.3 + 7.0 + 0.13 = 8.48$ \$/m^2 (L)

$C_9 = 0.25 \times 4.28 + 0.40 \times 1.3 + 10.0 + 0.26 = 11.85$ \$/m^2 (M)

$C_9 = 0.35 \times 4.28 + 1.00 \times 1.3 + 14.0 + 0.50 = 17.3$ \$/m^2 (H)

WBS item 1.1 is associated with real estate area being larger than A_R by $\frac{26.5 \times 20.4}{11.3^2} = 4.28$ as approximated in paragraph 12.2.7.

WBS item 1.2 is associated with the area projected on the ground which is 1.3 x A_R (major axis/minor axis = 1.3).

WBS item 1.3 and 1.4 are associated with A_R.

WBS item 2.0 is associated with A_R having total cost \$13.2 x 10^6, \$26.1 x 10^6, \$50.2 x 10^6 for (L), (M) and (H) respectively giving 0.13, 0.26 and 0.50 \$/m^2 respectively.

C_{10} **The values of**

$$C_{10} = \frac{112 \times 10^6}{\sqrt{5.0 \times 10^9}} = 158.0 \text{ \$/} \sqrt{W} \quad (L)$$

$$C_{10} = \frac{225 \times 10^6}{\sqrt{70.8 \times 10^4}} = 317.0 \text{ \$/} \sqrt{W} \quad (M)$$

$$C_{10} = \frac{450 \times 10^2}{70.8} = 635.0 \text{ \$/} \sqrt{W} \quad (H)$$

are taken from Figure 12-31 WBS item 1.5.

A_R **The value of $A_R = 100 \times 10^6$ m^2 is determined as follows:**

For 5 dB taper, beam collection efficiency $A_S = 0.90$, fully packed amplitrons at center of transmitting antenna from Figure 12-14, a major axis of 14.7 km is determined (not precisely the lowest cost situation). The minor axis is 11.3 km as shown in Figure 12-11.

Area projected on the ground = $\frac{\pi \times 11.3 \times 14.7 \times 10^6}{4}$ = 130.0×10^6 m^2

A_R = normal to the boresite

= $\frac{\pi\, 11.3^2 \times 10^6}{4}$ = 100.0×10^6 m^2

Check: - From Figure 12-14 for 5 dB taper and beam collection efficiency = 0.90.

γ = 1.62

A_T = 54.1×10^4 m^2

λ = 0.1225 m

D = 37×10^6 m.

$$A_R = \frac{\gamma^2 \lambda^2 D^2}{A_T} = \frac{1.62^2 \times 0.1225^2 \times 37^2 \times 10^{12}}{54.1 \times 10^4}$$

= 100.3×10^6 m^2

$\therefore D_R$ = 11.35 km

Calculations for (Initial Operational System) with Minimum A_T (summarized in Figure J-2)

$$C_{PS}/P_G = \frac{350 + 200 \times 1.5}{0.536} = 1215 \text{ \$/kW} \qquad \text{(L, M, H)}$$

$$C_{PD}/P_G = \frac{(575 + 5.76 \times 200)\ 1000}{(0.536 \times 5 \times 10^9)^{1/2}} = 33.1 \text{ \$/kW} \qquad \text{(L)}$$

$$= \frac{(965 + 1152)\ 1000}{\sqrt{26.8 \times 10^8}} = 40.7 \text{ \$/kW} \qquad \text{(M)}$$

$$= \frac{(1330 + 1152)\ 1000}{52{,}000} = 47.7 \text{ \$/kW} \qquad \text{(H)}$$

$$C_C/P_G = \frac{0.819}{0.536} (11.4 + 0.324 \times 200) = 116.5 \text{ \$/kW} \quad (L)$$

$$1.52 (18.2 + 64.8) = 127.0 \text{ \$/kW} \quad (M)$$

$$1.52 (28.2 + 64.8) = 142.0 \text{ \$/kW} \quad (H)$$

$$C_{TA}/P_G = (244 + 5.16 \times 200) \frac{541 \times 10^3}{5 \times 10^6} = 138.0 \text{ \$/kW} \quad (L)$$

$$= (493 + 1032)\ 0.1082 = 165.0 \text{ \$/kW} \quad (M)$$

$$= (986 + 1032)\ 0.1082 = 202.0 \text{ \$/kW} \quad (H)$$

$$C_{RA}/P_G = \frac{8.48 \times 100 \times 10^6}{5 \times 10^6} + \frac{158 \times 10^3}{\sqrt{5 \times 10^6}}$$

$$= 170.0 + 70 = 240.0 \text{ \$/kW} \quad (L)$$

$$\frac{11.85 \times 100 \times 10^6}{5 \times 10^6} + \frac{317 \times 10^3}{\sqrt{5 \times 10^6}}$$

$$= 237.0 + 141 = 378.0 \text{ \$/kW} \quad (M)$$

$$\frac{17.3 \times 100 \times 10^6}{5 \times 10^6} + \frac{625 \times 10^3}{\sqrt{5 \times 10^6}}$$

$$= 346.0 + 283 = 629.0 \text{ \$/kW} \quad (H)$$

J.2 ANALYSIS OF THE FINAL OPERATIONAL SYSTEM AND THEIR GOALS

Figure J-3 notes the set of assumptions and summarizes the cost for a case of interest to establish goals for design and technology development of the MPTS.

Operational System (Goal)

P_G A value of $P_G = 5$ GW $= 5 \times 10^6$ kW is selected based on considerations discussed in paragraph 12.2.7.

K A value of K = 200 \$/kg is selected based on considerations discussed in paragraphs 12.2.2 and 12.2.8.

C_1 A value of $C_1 = 350$ \$/kW is selected based on considerations discussed in paragraphs 12.2.2 and 12.2.8.

TOTAL COST SUMMARY

OPERATIONAL SYSTEM (GOAL)

Summary Title

Specific Cost = C/P_G \$/kW = $C_{PS}/P_G + C_{PD}/P_G + C_C/P_G + C_{TA}/P_G + C_{RA}/P_G$ **of total space power system.**

Assumptions

Parameters Controlled by Major Programmatic Decisions

P_G	=	Total power delivered to the ground power grid	5×10^6	kW
K	=	Orbital transportation and assembly specific cost	200	\$/kg
C_1	=	Cost of power source/power output at the power source	350	\$/kW
C_2	=	Weight of power source/power output at the power source	1.5	kg/kW

MPTS Efficiency Parameters driven by MPTS Technology Development

n	=	$n_t n_b n_a n_s n_r$ = total dc from the orbital power source to a-c at the ground power network	0.6348
n_t	=	power source interface through dc to rf conversion and rf radiation out the waveguide slots	0.87

RF Generator	Amplitron
Antenna basic Material	Aluminum

Figure J-2

Level of Maturity or Confidence		Low(L)	Medium(M)	High(H)

$$C_{PS}/P_G = \frac{C_1 + K\,C_2}{n}$$ = Specific Cost of Power Source

C_{PS}/P_G	\$/kW	1023	1023	1023

$$C_{PD}/P_G = \frac{(C_3 + C_4\,K)\,10^3}{(n\;P_G)^{1/2}}$$ = Specific Cost of Power Distribution

C_3	\$/ $\sqrt{W}$	575	965	1330
C_4	kg/ $\sqrt{W}$	5.76	5.76	5.76
C_{PD}/P_G	\$/kW	30	37	43

$$C_C/P_G = \frac{n_t}{n}\,(C_5 + C_6\,K)$$ = Specific Cost of dc to rf Converters

C_5	\$/kW	11.4	18.2	28.2
C_6	kg/kW	0.324	0.324	0.324
C_C/P_G	\$/kW	104	114	128

$$C_{TA}/P_G = (C_7 + C_8\,K)\,A_T/P_G$$ = Specific Cost of Transmitting Antenna

C_7	\$/m^2	244	493	986
C_8	kg/m^2	5.16	5.16	5.16
A_T	m^2	64.7×10^4	64.7×10^4	63.7×10^4
C_{TA}/P_G	\$/kW	164	197	261

$$C_{RA}/P_G \quad \frac{C_9\,A_R}{P_G} + \frac{C_{10} \times 10^3}{P_G^{\;1/2}}$$ = Specific Cost of Receiving Antenna

C_9	\$/m^2	8.18	11.88	17.3
C_{10}	\$/$\sqrt{W}$	158	317	635
A_R	m^2	$83.[illegible] \times 10^6$	63.4×10^6	83.4×10^6
C_{RA}/P_G	\$/kW	[illegible]	[illegible]48	572

Total Specific Cost = Specific Capital Cost of [illegible] Space Power System

C/P_G	\$/kW	[illegible]	[illegible]	2027

Figure J-3 (Continued)

C_2 A value of C_2 = 1.5 kg/kW is selected based on considerations discussed in paragraph 12.2.2 and 12.2.8.

n The values of the elements resulting in n = 0.6348 are selected based on considerations summarized in Figure 12-27.

$$\left.\begin{aligned} n_t &= 0.87 \\ n_b &= 0.97 \\ n_a &= 0.988 \\ n_s &= 0.90 \\ n_r &= 0.846 \\ \therefore n &= 0.6348 \end{aligned}\right\}$$

Value of 0.90 for n_s is assumed rather than the 0.95 which would be more appropriate for the 10 dB taper design.

n_t The value of n_t = 0.87 is selected as discussed above.

C_3 The values of

$$C_3 = \frac{54.6 \times 10^6}{\sqrt{9 \times 10^9}} = 575.0 \ \$/\sqrt{W} \quad \text{(L)}$$

$$C_3 = \frac{91.7 \times 10^6}{\sqrt{9 \times 10^9}} = 965.0 \ \$/\sqrt{W} \quad \text{(M)}$$

$$C_3 = \frac{126.0 \times 10^6}{\sqrt{9.5 \times 10^4}} = 1330.0 \ \$/\sqrt{W} \quad \text{(H)}$$

are taken from Figure 12-31 WBS 3.0.

C_4 The value of

$$C_4 = \frac{548.0 \times 10^3}{\sqrt{9 \times 10^9}} = 5.76 \ \text{kg}/\sqrt{W}$$

is taken from Figure 12-31 WBS 3.0 for (L), (M) and (H) cases.

C_5 The values of

$$C_5 = \frac{57}{5} = 11.4\ \$/kW \quad (L)$$

$$C_5 = \frac{91}{5} = 18.2\ \$/kW \quad (M)$$

$$C_5 = \frac{141}{5} = 28.2\ \$/kW \quad (H)$$

are taken from Figure 12-31 WBS 4.5(a).

C_6 The value of

$$C_6 = \frac{1.62}{5.0} = 0.324\ kg/kW$$

is taken from Figure 12-31 WBS 4.5(a) for (L), (M) and (H) cases.

C_7 The values of

$$C_7 = 115 + 64 + 1.05 + \frac{11.5 \times 10^6}{\pi 1000^{2/4}} + 46 + \frac{2.6 \times 10^6}{\pi 1000^{2/4}} = 244\ \$/m^2 \quad (L)$$

$$C_7 = 231 + 132 + 2.1 + \frac{23}{0.784} + 92 + \frac{5.1}{0.784} = 493\ \$/m^2 \quad (M)$$

$$C_7 = 462 + 264 + 3.68 + \frac{46}{0.784} + 184 + \frac{10.2}{0.784} = 986\ \$/m^2 \quad (H)$$

are taken from Figure 12-31 WBS (4.1 + 4.2 + 4.3) + 4.4(a) + 5.1(a) + 5.2 + 5.3 + 6.0 for aluminum waveguides.

C_8 The values of

$$C_8 = \frac{35.0 + 17.2 + 22.7 + 1381.0}{324.0} + 0.26 + \frac{172 \times 10^3}{\pi 1000^{2/4}} + 0.184 + \frac{775}{\pi 1000^{2/4}}$$

$$= 4.5 + 0.26 + 0.217 + 0.184 + 0.001$$

$$= 5.16\ kg/m^2$$

for aluminum waveguides and for (L), (M) and (H) cases.

A_T The value of $A_T = 64.7 \times 10^4 \ m^2$ is determined as follows:

For the operational system (goal) the transmitting antenna should be evolved from the earlier configurations. However, it is expected that it will approach the near optimum area as defined in paragraph 12.2.1.

$$A_T = \lambda D \gamma \left[\frac{C_9}{C_7 + C_8 K}\right]^{1/2}$$

Check: - From Figure 12-4 for edge taper = 5 db and $n_s = 0.90$.

γ = 1.62

λ = 0.1225 m for f = 2.45 GHz

D = 37×10^6 m

C_9 = 11.85 $\$/m^2$ is the medium value for the purposes of estimating the transmitting and receiving antenna sizes (derivation shown later).

C_8 = 5.16 kg/m^2 (derivation shown later)

K = 200 \$/kg as discussed earlier

$$A_T = 0.1225 \times 37 \times 10^6 \times 1.62 \left[\frac{11.85}{493.0 + 5.16 \times 200}\right]^{1/2} = 64.7 \times 10^4 \ m^2 \text{ i.e.,}$$

D_T = 910 m

Letting

C_9 = take on the most expensive (H) value: 17.3 $\$/m^2$ rather than 11.85 would increase A_T by:

$$\sqrt{\frac{17.3}{11.35}} = \sqrt{1.455} = 1.21 \text{ i.e.,}$$

A_T = $1.21 \times 64.7 \times 10^4 \ m^2$

= $78.2 \times 10^4 \ m^2$

$\therefore D_T$ = 1000 m

Letting

C_9 = retain the medium value of 11.85 a..1

C_7 = 244 \$/m^2 (L) low value rather th.. ..e (M) value of 493

C_8 = 5.16 kg/m^2 would increase the ar.a above the 64.7 x 10^4 m^2 by:

$$\sqrt{\frac{493.0 + 5.16 \times 200}{244.0 + 5.16 \times 200}} = \sqrt{\frac{1525}{1276}} = \sqrt{1.2} \text{ i.e.,}$$

A_T = 75.4 x 10^4 m^2

$\therefore D_T$ = 985 m

Letting

C_9 take on the most expensive (H) value 17.3 \$/m^2 i.e., most expensive ground antenna and

C_7 take on the low value 244 \$/m^2

C_8 retain the low value 5.16 kg/m^2 would give:

$$A_T = 7.34 \times 10^6 \sqrt{\frac{17.3}{244 + 5.16 \times 200}}$$

$$= 7.34 \times 10^6 \times 11.7 \times 10^{-2}$$

$$= 86.0 \times 10^4 \text{ m}^2$$

$$D_T = \sqrt{\frac{4}{\pi} \times 86 \times 10^4} = \sqrt{109.9 \times 10^4}$$

$$= 1050 \text{ m}$$

From Figure 12-9 it is evident that for the 5 GW case a 910 m diameter antenna would not give a converter packing problem, i.e., thermal control of the amplitron would be relieved in addition to relief associated with the higher efficiency for the amplitron. It does not appear to be prudent to press the thermal limit too closely so the 910 m diameter is a welcome relief. The 1000 m, 985 m or the 1050 m diameters would be yet better in this regard and give a significant design margin for thermal control near the center of the antenna.

Peak Power Density Considerations

The peak power density on the ground is discussed in paragraph 12.2.5.

$$P_D = \frac{P_o A_T^2}{\lambda^2 D^2} \left[\frac{1 - 10^{-dB/20}}{0.115\ dB}\right] n_a\ n_b$$

P_o = 21.7 kW/m^2 for the fully packed amplitron case as discussed in paragraph 12.2.7. This would be for a 5 GW system with 5 dB taper having a 0.83 km diameter transmitting antenna.

$$A_T = \frac{\pi \times 830^2}{4} = 54 \times 10^4\ m^2$$

For A_T different from this value the associated P_o would vary inversely proportional to the area. Thus for

$$P_D = \frac{P_o\ A_T^2}{0.1225^2 \times (37 \times 10^6)^2} \left[\frac{1 - 10^{-5/20}}{0.115 \times 5}\right] 0.988 \times 0.97$$

$$= \frac{P_o\ A_T^2}{20.6 \times 10^{12}} \times 0.958 \left[\frac{1 - 10^{-0.25}}{0.115 \times 5}\right]$$

$$= P_o\ A_T^2 \times 4.65 \times 10^{-14} \left[\frac{1 - 0.56}{0.575}\right]$$

$$= P_o\ A_T^2 \times 3.56 \times 10^{-14}\ kW/m^2$$

$$P_D = 3.56\ P_o\ A_T^2 \times 10^{-12}\ mW/cm^2$$

D_T m	A_T m^2	P_o kW/m^2	A_T^2	$P_o\ A_T^2$	P_D mW/cm^2
830	54.0×10^4	21.7	2900×10^8	630×10^{10}	22.0
910	64.7×10^4	18.2	4150×10^8	754×10^{10}	27.0
1000	78.0×10^4	15.0	6080×10^8	910×10^{10}	33.0
985	75.4×10^4	15.5	5700×10^8	883×10^{10}	31.0
1050	86.0×10^4	13.6	7350×10^8	1000×10^{10}	36.0

The critical value for power density with respect to causing electron temperature increases in the lower D-region of the Ionosphere is defined as:

$$S_c = f_e^2 \text{ MW/m}^2 \quad \text{(see Appendix C)}$$

where

$$f_e = 2450 \text{ MHz}$$

$$\therefore S_c = 15 \text{ mW/cm}^2.$$

The electron temperature for a range of P_D between 22 and 36 would be in excess of 1000°K and less than 2000°K. The specific temperatures and what their effects on the environment and on other users will be, should be the subject of detailed investigation. Assuming that effects in this range of density are not significantly adverse then any of the values of A_T could be acceptable (reference Appendix C).

Sidelobes

Paragraph 6.1, Figure 6-4 shows the first sidelobe to be 20 dB down from the peak.

The second sidelobe is 26 dB down from the peak.

The power density at the first sidelobe then ranges between 0.22 and 0.36 mW/cm^2. For the second sidelobe, it will range between 1/400 th of 22 to 36, i.e., 0.05 to 0.09 mW/cm^2 which should be acceptable assuming a 0.1 mW/cm^2 limit outside the guard ring.

In summarizing considerations for A_T there appears to be advantage to tend toward the larger areas for the transmitting antenna if there is concern about the specific costs of the rectifying antenna tending toward the high values while those for the transmitting antenna tend toward the low value. There does not appear to be a real argument to support those specific cost concerns at this time.

There are concerns, not yet thoroughly founded, with respect to increasing power densities at the main lobe in the ionosphere and on the ground, similarly at the sidelobes on the ground.

The value of $A_T = 65.7 \times 10^4 \text{ m}^2$ and the associated diameter $D_T = 910$ m should therefore be selected at this time.

C_9 The values of

$$C_9 = 0.10 \times 4.28 + 0.10 \times 1.3 + 7.0 + 0.13 = 8.48 \ \$/m^2 \qquad (L)$$

$$C_9 = 0.25 \times 4.28 + 0.40 \times 1.3 + 10.0 + 0.26 = 11.85 \ \$/m^2 \qquad (M)$$

$$C_9 = 0.35 \times 4.28 + 1.0 \times 1.3 + 14.0 + 0.50 = 17.3 \ \$/m^2 \qquad (H)$$

are taken from Figure 12-31 WBS 1.0. WBS item 1.1 is associated with real estate area being larger than A_R by $\frac{26.5 \times 20.0}{11.3^2} = 4.28$ as approximated in paragraph 12.2.7. WBS item 1.2 is associated with the area projected on the ground which is 1.3 A_R. WBS items 1.3 and 1.4 are associated with A_R. WBS item 2.0 is associated with A_R having total cost $\$13.2 \times 10^6$, $\$26.1 \times 10^6$, $\$50.2 \times 10^6$ for (L), (M) and (H) respectively giving 0.13, 0.26 and 0.50 $\$/m^2$ respectively.

C_{10} The values of

$$C_{10} = \frac{112 \times 10^6}{\sqrt{5 \times 10^9}} = 158 \ \$/\sqrt{W}$$

$$C_{10} = \frac{225 \times 10^6}{70.8 \times 10^4} = 317 \ \$/\sqrt{W}$$

$$C_{10} = \frac{450 \times 10^2}{70.8} = 635 \ \$/\sqrt{W}$$

are taken from Figure 12-31 WBS item 1.5.

A_R The value of A_R is determined as follows:

For 5 dB taper, beam collection efficiency $\eta_s = 0.90$, Figure 12-3 gives $v = 1.62$

$$v = \frac{\sqrt{A_T A_R}}{\lambda D}$$

using

$$A_T = 64.7 \times 10^4 \ m^2$$

$$\lambda = 0.1225 \ m$$

$$D = 37 \times 10^6 \text{ m}$$

$$A_R = \frac{\gamma^2 \lambda^2 D^2}{A_T}$$

$$= \frac{1.62^2 \times 0.1225^2 \times 37^2 \times 10^{12}}{64.7 \times 10^4}$$

$$= 83.4 \times 10^6 \text{ m}^2$$

$$D_R = \sqrt{\tfrac{4}{\pi}\ 8340 \times 10^4}$$

$$= \sqrt{10,620 \times 10^4}$$

$$= 10,300 \text{ m}$$

$$= 10.3 \text{ km}$$

$$C_{PS}/P_G = \frac{350 + 200 \times 1.5}{(0.6348 \times 5 \times 10^9)^{1/2}} = 1023 \text{ \$/kW}$$

$$C_{PD}/P_G = \frac{(575 + 5.76 \times 200)\ 10^3}{(0.6348 \times 5 \times 10^9)^{1/2}} = \frac{1727}{57.4} = 30 \text{ \$/kW} \quad \text{(L)}$$

$$= \frac{965 + 1152}{57.4} = \frac{2117}{57.4} = 37 \text{ \$/kW} \quad \text{(M)}$$

$$= \frac{1330 + 1152}{57.4} = \frac{2482}{57.4} = 43 \text{ \$/kW} \quad \text{(H)}$$

$$C_C/P_G = \frac{0.87}{0.6348} (11.4 + 0.324 \times 200) = 104.5 \text{ \$/kW} \quad \text{(L)}$$

$$= 1.37 (18.2 + 64.8) = 114 \text{ \$/kW} \quad \text{(M)}$$

$$= 1.37 (28.2 + 64.8) = 128 \text{ \$/kW} \quad \text{(H)}$$

$$C_{TA}/P_G = (244 + 5.16 \times 200) \frac{64.7 \times 10^4}{5 \times 10^6} = 164.5 \text{ \$/kW} \quad \text{(L)}$$

$$(493 + 1032)\ 0.1295 = 197 \text{ \$/kW} \quad \text{(M)}$$

$$(986 + 1032)\ 0.1295 = 261 \text{ \$/kW} \quad \text{(H)}$$

$$C_{RA}/P_G = 8.48 \times \frac{83.4 \times 10^6}{5 \times 10^6} + \frac{158 \times 10^3}{\sqrt{5 \times 10^6}} = 141 + 70 = 211$$

$$= 11.85 \times 16.68 + 317 \times 0.445 = 198 + 140 = 338$$

$$= 17.3 \times 16.68 + 635 \times 0.445 = 289 + 283 = 572$$

C/P_G

(L)	(M)	(H)
1023	1023	1023
30	37	43
104	114	128
164	197	261
211	338	572
1532	1709	2027

For the operational system goal a total specific cost goal should be 1532 \$/kW. Taking out the 1023 for the power source this would make the goal for the MPTS 509 \$/kW or about 0.332 of the total cost would be attributed to the MPTS.

Assuming the technology is developed to achieve the maximum efficiency n = 0.6348 and that orbital transportation and assembly costs will be ≤ 200 \$/kg the specific costs associated with the MPTS would range between 509 \$/kW and 1004 \$/kW.

J.3 ANALYSIS OF THE INITIAL OPERATIONAL SYSTEM BASED ON THE FINAL SYSTEM CONFIGURATION

Figure J-4 notes the set of assumptions and summarizes the cost for a case of particular interest (Initial Operational System using $A_T = 64.7 \times 10^4 \text{ m}^2$ (910 m diameter) i.e., near the optimum area for the transmitting antenna as may be sized for the operational fleet of MPTS systems.

The initial operational system costs will tend toward the high side, i.e., toward the (H) values 2391 \$/kW whereas the final operational systems will tend toward the (L) values 1532 \$/kW for a fleet of about 100. The average of the 100 systems costs should not approximate the mean, i.e., 1961 \$/kW, but approach the goal.

It should be noted that these costs would be significantly modified, increased or decreased, if the weight and costs of the power source were to increase or decrease from K = 200 \$/kg. The cost of the power source would be $\frac{350}{n}$ \$/kW

TOTAL COST SUMMARY

INITIAL OPERATIONAL SYSTEM USING $A_T = 64.7 \times 10^4\ m^2$

Summary Title

Specific Cost $= C/P_G$ \$/kW $= C_{PS}/P_G + C_{PD}/P_G + C_C/P_G - C_{TA}/P_G + C_{RA}/P_G$
of total space power system.

Assumptions

Parameters Controlled by Major Programmatic Decisions

P_G	=	Total power delivered to the ground power grid	4.22×10^6 kW	
K	=	Orbital transportation and assembly specific cost	200	\$/kg
C_1	=	Cost of power source/power output at the power source	350	\$/kW
C_2	=	Weight of power source/power output at the power source	1.5	kg/kW

MPTS Efficiency Parameters driven by MPTS Technology Development

n	=	$n_t\, n_b\, n_a\, n_s\, n_r$ = total dc from the orbital power source to a-c at the ground power network	0.536
n_t	=	power source interface through dc to rf conversion and rf radiation out the waveguide slots	0.819

RF Generator — Amplitron

Antenna Basic Material — Aluminum

P_G - Recognizing the efficiency n may be as low as n = 0.536 for initial operational systems and for the Goal it would be n = 0.6348, the result in P_G initially may be as low as $5.0 \times \frac{0.536}{0.6348} = 4.22$ GW = 4220 kW.

n_t - May be as low as 0.819 initially

Figure J-4

C_{PS}/P_G would increase to $1023 \times \frac{5}{4.22} = 1215$

C_{PD}/P_G would increase by $\sqrt{\frac{0.6348}{0.536}} = \sqrt{1.19} = 1.09$ to 33(L), 41(M), 48(H)

C_C/P_G would increase by $\frac{0.6348}{0.536} \times \frac{0.819}{0.87} = 1.12$ to 117(L), 127(M), 142(H)

C_{TA}/P_G would increase by $\frac{5}{4.22} = 1.18$ to 194(L), 234(M), 309(H)

C_{RA}/P_G would increase by $\frac{5}{4.22} = 1.18$ to 249(L), 400(M), 677(H)

The total specific cost would increase to 1,808(L); 2,017(M); 2,391(H), i.e., about the inverse ratio of output power $\frac{5}{4.22} = 1.18$.

Figure J-4 (Continued)

Level of Maturity or Confidence		Low(L)	Medium(M)	High(H)

$C_{PS}/P_G = \dfrac{C_1 + K\,C_2}{n}$ = Specific Cost of Power Source

C_{PS}/P_G	\$/kW	1215	1215	1215

$C_{PD}/P_G = \dfrac{(C_3 + C_4\,K)\,10^3}{(n\,P_G)^{1/2}}$ = Specific Cost of Power Distribution

C_3	\$/ W			
C_4	kg/ W			
C_{PD}/P_G	\$/kW	33	41	48

$C_C/P_G = \dfrac{n_t}{n}\,(C_5 + C_6\,K)$ = Specific Cost of dc to rf Converters

C_5	\$/kW			
C_6	kg/kW			
C_C/P_G	\$/kW	117	127	142

$C_{TA}/P_G = (C_7 + C_8\,K)\,A_T/P_G$ = Specific Cost of Transmitting Antenna

C_7	\$/m^2			
C_8	kg/m^2			
A_T	m^2	64.7×10^4	64.7×10^4	64.7×10^4
C_{TA}/P_G	\$/kW	194	234	309

$C_{RA}/P_G = \dfrac{C_9\,A_R}{P_G} + \dfrac{C_{10} \times 10^3}{P_G^{1/2}}$ = Specific Cost of Receiving Antenna

C_9	\$/m^2			
C_{10}	\$/$\sqrt{W}$			
A_R	m^2			
C_{RA}/P_G	\$/kW	[illegible]	400	677

Total Specific Cost = Specific Capital Cost of Total Space Power System

C/P_G =	\$/kW	[illegible]	[illegible]	[illegible]

Figure J-4 (Continued)

delivered ground power, i.e., $\frac{350}{.6348}$ = 551 \$/kW or $\frac{551}{2391}$ = 23% of the total for the initial operational system and $\frac{250}{.536}$ = 466 \$/kW or $\frac{466}{1532}$ = 30% of the total cost for the final operational systems.

The cost of the transportation and assembly of both the power source and the MPTS system would be proportional to their weights.

J.4 WEIGHT AND COST ANALYSIS FOR THE INITIAL AND FINAL OPERATIONAL SYSTEMS

Power source weights would be:

$$W_{PS} = C_2 \times \frac{P_G}{n}.$$

Transmitting orbital antenna weights would be:

$$W_{TA} = C_4 \sqrt{P_G \times \frac{n_t}{n}} + C_6 P_G \frac{n_t}{n} + C_8 A_T.$$

	Final Operational System
P_G	5×10^6 kW
n	0.6348
C_2	1.5 kg/kW
W_{PS}	11.8×10^6 kg
C_4	5.76 kg/$\sqrt{W}$
n_t	0.87
C_6	0.324 kg/kW
C_8	5.16 kg/m^2
W_{TA}	6.02×10^6 kg
$W_{PS} + W_{TA}$	17.82×10^6 kg

The transportation and assembly costs would be:

$$200 \times 11.8 \times 10^6 = \$2.360 \times 10^9 \text{ for the power source}$$

$$200 \times 6.02 \times 10^6 = \underline{\$1.205 \times 10^9} \text{ for the orbital antenna}$$

$$\$3.565 \times 10^9 \text{ for the total station.}$$

In the case of the initial operational system this would be:

$$\frac{3.565 \times 10^9}{4.22 \times 10^6} = 845 \text{ \$/kW delivered ground power}$$

or

$$\frac{845}{2391} = 35\% \text{ of the total.}$$

In the case of the final operational system this would be:

$$\frac{3.565 \times 10^9}{5.0 \times 10^6} = 713 \text{ \$/kW delivered ground power}$$

or

$$\frac{713}{1532} = 47\% \text{ of the total.}$$

Of direct importance to those developing the MPTS, its transportation and assembly costs, alone would be:

$$\frac{1.205 \times 10^9}{4.22 \times 10^6} = 286 \text{ \$/kW}$$

or

$$\frac{286}{2391} = 12\% \text{ of the total}$$

and

$$\frac{1.205 \times 10^9}{5.0 \times 10^6} = 242 \text{ \$/kW}$$

or

$$\frac{242}{1532} = 16\% \text{ of the total.}$$

for the initial and final systems respectively.

These data are summarized in Figure J-5.

J.5 ENERGY COST

Assume ground fabrication and orbital operations time of 3 years

Assume rate of return of 15 percent.

Assume 80 percent utilization.

Referring to Figure J-6 developed from the analysis in paragraph 12.2.8

$$\text{mils/kW Hr/1000 \$/kW} = 26 \times \frac{95}{80} = 30.8$$

∴ for capital cost = 2391 $/kW (initial system)

energy cost = 74 mils/kW hr

for capital cost - 1532 $/kW (final system)

energy cost = 47 mils/kW hr

The data shown in Figures 51, 52, 53 and 54 of the executive summary and Section 12, Figures 12-27, 12-28, 12-29 and 12-30, have been replotted in Figures J-7, J-8, J-9 and J-10 respectively, using 54 percent efficiency for the initial system, 63 percent for the final system. An 80 percent utilization factor is assumed rather than the 95 percent associated with availability. It should be pointed out that for this system if the available power is not utilized on the ground the difference namely available power - utilized power is largely reflected and completely wasted. This conceivably could be limited to some extent by purposely cutting off some of the power at the solar array on orbit and simply not transmitting it but this gives similarly wasted power. The utilities on the ground should be configured to make use of all available power by making available loads that can absorb the power when available recognizing that it would otherwise be lost. If this approach can be established, then the utilization would approach the availability number of 95 percent and the average energy cost would reduce from those shown in Figures J-8, J-9 and J-10 by a factor of $\frac{0.80}{0.95} = 0.84$.

For the specific set of assumptions which define the Initial Operational System and the Final Operational System, the data points are plotted on the figures for reference. If the 95 percent utilization was used it would give an initial system energy cost of 62 mils/kW hr and a final system energy cost of 43 mils/kW hr. Although the average of these is 52 mils/kW hr, the average over a fleet of 100 should approach the goal of 43 mils/kW hr.

	Initial Operational System	Final Operational System
Power Source		
Cost of Power on Orbit	350 $/kW	350 $/kW
Power on Orbit	7.9 GW	7.9 GW
Specific Weight	1.5 kg/kW	1.5 kg/kW
Weight on Orbit	11.3×10^6 kg	11.8×10^6 kg
Microwave Power Transmission System		
Diameter on Orbit	910M	910M
Area on Orbit	64.7×10^4 M^2	64.7×10^4 M^2
Weight on Orbit	6.02×10^6 kg	6.02×10^6 kg
Efficiency (Overall)	54%	63%
Rectenna		
Minor Axis	10.3 km	10.3 km
Major Axis	13.4 km	13.4 km
Power Density (Peak) at Ground Main Beam	23 mW/cm^2	27 mW/cm^2
Power Density (Peak)		
At First Sidelobe	0.19 mW/cm^2	0.22 mW/cm^2
At Second Sidelobe	0.05 mW/cm^2	0.05 mW/cm^2
Transportation and Assembly		
Specific Cost	200 $/kg	200 $/kg
Weight to be Transported & Assembled		
Power Source	11.8×10^6 kg	11.8×10^6 kg
Antenna	6.02×10^6 kg	6.02×10^6 kg
Total	17.8×10^6 kg	17.8×10^6 kg
Cost of Transportation & Assembly with Respect to Power Delivered on Ground		
Power Source	559 $/kW	472 $/kW
Antenna	286 $/kW	241 $/kW
Total (% of Total)	845 $/kW (65 %)	713 $/kW (47%)
Total System		
Weight	17.8×10^6 kg	17.8×10^6 kg
Ground Power Output	4.22 GW	5.0 GW
Cost Including Transportation and Assembly		
Power Source	[illegible]	[illegible]
Microwave Power Transmission	[illegible]	[illegible]
Total	[illegible]	[illegible]

Figure J-5. Summary of Initial and Final Operational System Characteristics

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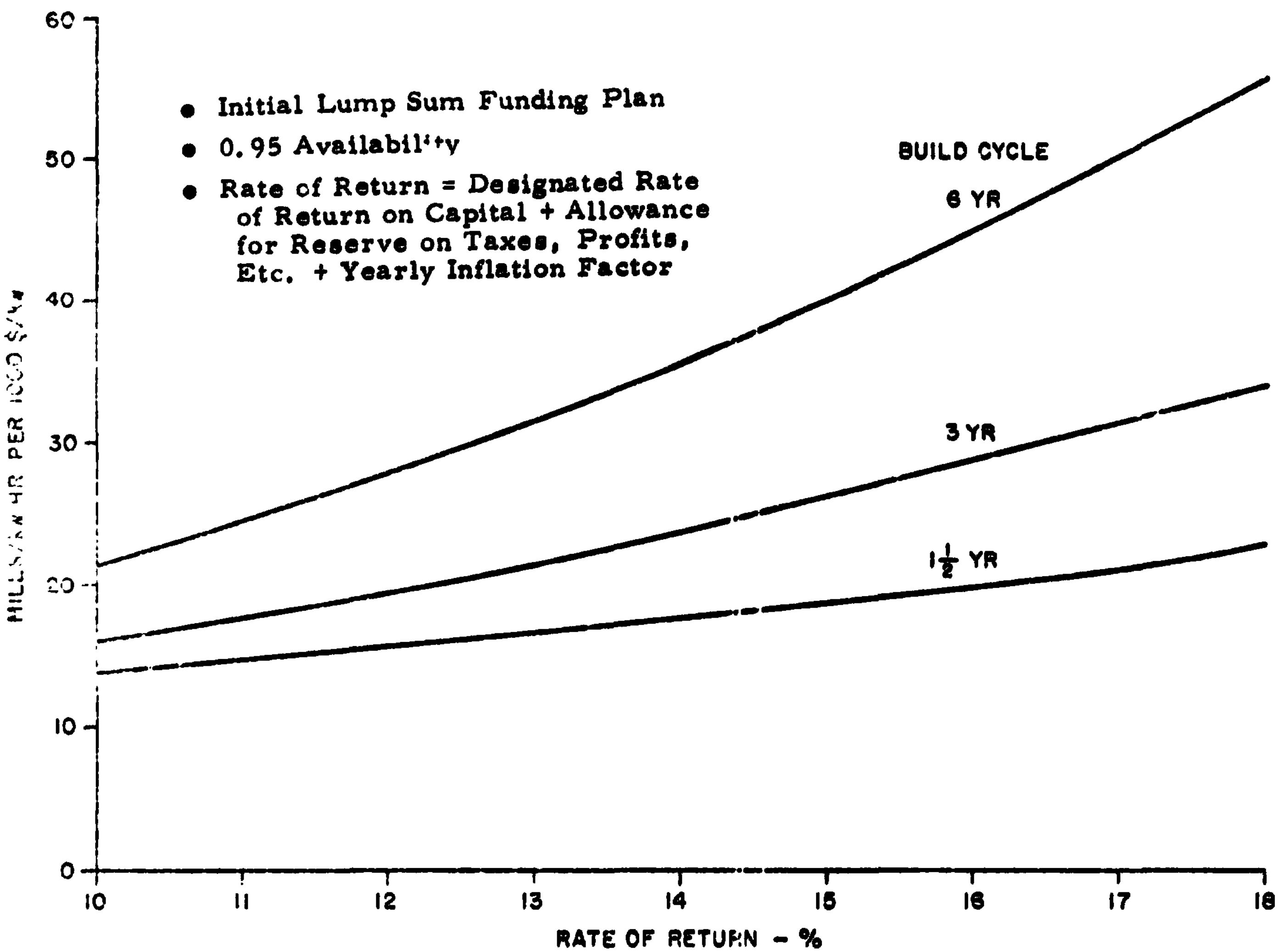
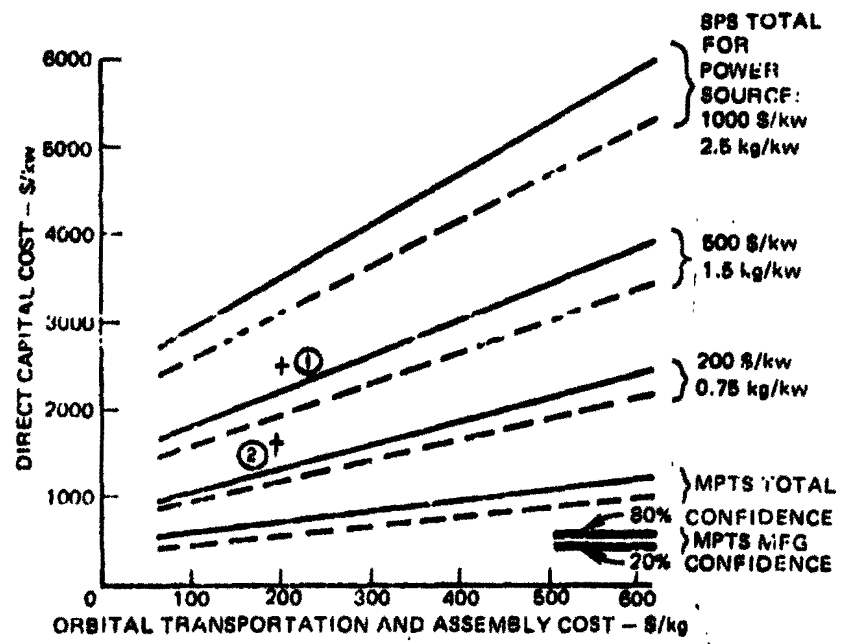


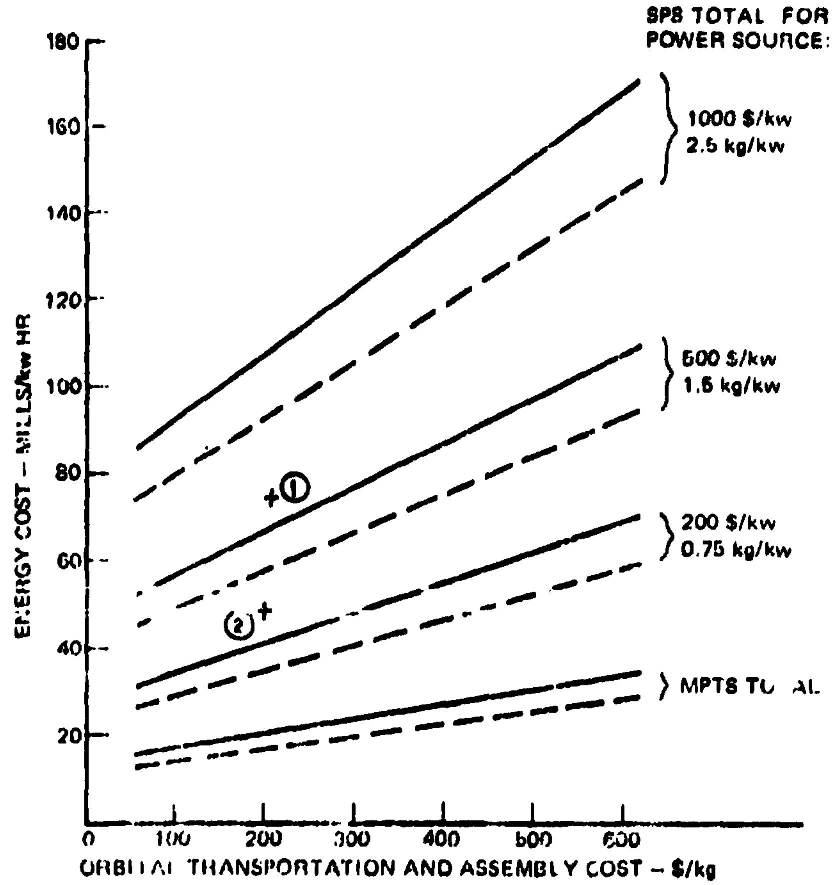
Figure J-6. Capital Cost to Energy Cost Conversion versus Rate of Return



Symbol	MPTS Efficiency (Percent)	Delivered Power to Ground Grid	Power Source	
			Cost	Weight
——— Initial	58	5.0 GW	Noted	Noted
– – – Final	63	5.0 GW	Noted	Noted
① Initial	58	4.22 GW	350 $/kW	1.5 kg/kW
② Final	63	5.0 GW	350 $/kW	1.5 kg/kW

1975 Dollars

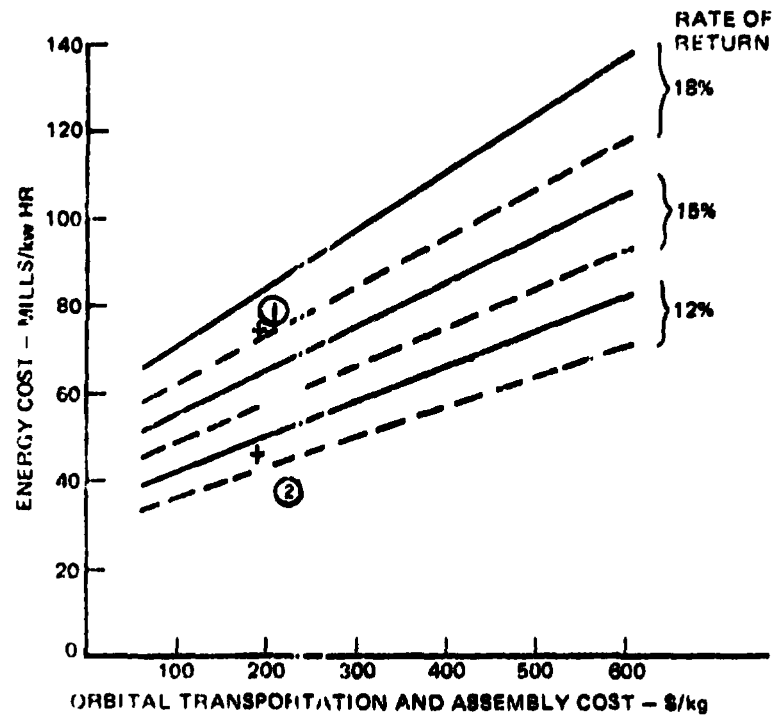
Figure I-7. SPS Capital Cost/Transportation Cost for Various Power Source Characteristics



Symbol	MPTS Efficiency (Percent)	Delivered Power to Ground Grid	Power Source		Rate of Return (Percent)	Construction Cycle	
			Cost	Weight		Ground Fabrication (Years)	Orbital Operation (Years)
—— Initial	[illegible]	5.0 GW	Noted	Noted	15	2	1-1/2
- - - - Final	[illegible]	5.0 GW	Noted	Noted	15	2	1-1/2
(1) Initial	[illegible]	4.22 GW	350 $/kW	1.5 kg/kW	15	3	
(2) Final	[illegible]	5.0 GW	350 $/kW	1.5 kg/kW	15	3	

1975 Dollars, [illegible] 80 Percent

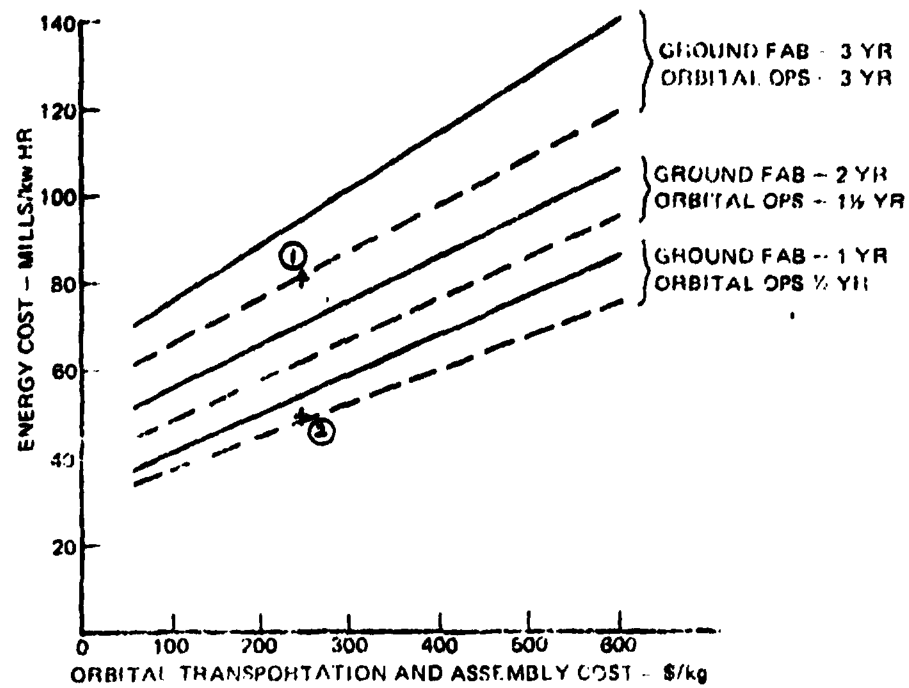
Figure J-8. SPS Energy Cost/Transportation Cost for Various Power Source Characteristics



Symbol	MPTS Efficiency (Percent)	Delivered Power to Ground Grid	Power Source		Rate of Return (Percent)	Construction Cycle	
			Cost	Weight		Ground Fabrication (Years)	Orbital Operation (Years)
——— Initial	58	5.0 GW	500 $/kW	1.5 kg/kW	Noted	2	1-1/2
– – – – Final	63	5.0 GW	300 $/kW	1.5 kg/kW	Noted	2	1-1/2
① Initial	58	4.22 GW	350 $/kW	1.5 kg/kW	15	3	
② Final	63	5.0 GW	350 $/kW	1.5 kg/kW	15	3	

1975 Dollars, Utilization 80 percent

Figure J-9. SPS Energy Cost/Transportation Cost for Various Rates of Return



Symbol	MPTS Efficiency (Percent)	Delivered Power to Ground Grid	Power Source		Rate of Return (Percent)	Construction Cycle	
			Cost	Weight		Ground Fabrication (Years)	Orbital Operation (Years)
─ ─ ─ Initial	58	5.0 GW	500 $/kW	1.5 kg/kW	15	Noted	Noted
─·─ Final	63	5.0 GW	500 $/kW	1.5 kg/kW	15	Noted	Noted
(1) Initial	-	4.22 GW	350 $/kW	1.5 kg/kW	15	3	
(2) Final	63	5.0 GW	350 $/kW	1.5 kg/kW	15	3	

1977 Dollars, Utilities [illegible] percent

Figure J-10. SPS Energy Cost/Transportation Cost for Various Construction Cycles

APPENDIX K

DETAILS OF GROUND AND ORBITAL TEST PROGRAM

K.1 INTRODUCTION

This appendix documents an activity undertaken to review the ground and orbital test programs as defined in separate tasks and to modify them as necessary to represent an integrated program. In addition, it is anticipated that this material will be useful in formulating future definitions of the programs as detailed studies and technology developments are matured. Insight into the test equipment requirements to meet the detailed objectives may be useful if the objectives which currently define the maximum size of the orbital test system are progressively relaxed.

The resulting currently defined objectives for both the ground and orbital programs as modified are given in Sections 13 and 14.

K.2 OBJECTIVES IMPLEMENTATION EQUIPMENT AND CHARACTERISTICS

Figure K-1 summarizes the ground test objective implementation by program phase.

Figure 14-1 summarizes the orbital program objectives and indicates the nature of the microwave payload required to implement them. It also indicates the sort of equipment that might be associated with the concurrent implementation of suggested intermediate benefit areas.

Figure 14-2 illustrates the geosynchronous satellite and Figure 14-3 shows the functional block diagram to implement the associated currently defined mandatory and highly desirable objectives which require geosynchronous altitude test operations, namely: M3, M4, and H4.

The approaches considered to implement the rest of the objectives from low earth orbit and from a ground based system warrant more detailed discussion.

Objective	Phase I (Low Power-Single Axis)	Phase II (Amplitrons-Single Axis)	Phase III (Amplitrons-Two Axes Rectenna Array)
Primary			
1. Phase Control Accuracy	X	X	X
2. System Controllability	X	X	X
3. RFI Characteristics		X	X
Secondary			
1. Transmitting Array Integration	X	X	X
2. Power Source Interface	X	X	X
3. Rectenna Array Integration			X
4. Power Load Interface			X
5. Rectenna Environmental Protection		X	X
6. Component Producibility		X	X
7. Large Sample Efficiency and Performance Data		X	X
8. Cost Learning Curve Data		X	X
9. Efficient DC-DC High Power Transmission		X	X
10. Efficient DC-DC Long Range Power Transmission			X

Figure K-1. Summary of Ground Test Objectives/Implementation

K.3 IMPLEMENTATION OF OBJECTIVES H1, H2, D1 AND D2 USING LOW EARTH ORBIT SORTIE MISSIONS

Figure K-2 summarizes the concerns regarding effects on the ionosphere. It indicates the height of the region of concern and also indicates the part of the region where testing in the F and D layers would be required to implement the highly desirable objectives H1 and H2.

It has become evident tha radiation of the D layer from low earth orbit at the desired power densities . ıe times of interest is not as practical as conducting the test from an upgraded ground facility such as at Arecibo. Figure K-3 summarizes the characteristics of the Arecibo facility in this regard. It indicates that an upgrading by an order of magnitude would be required to irradiate the D region. Similarly, it would have to be upgraded by two orders of magnitude to irradiate the F region. It appears that testing the D region from the ground may be practical and it is therefore recommended. It also appears that further investigation into testing the F region from low earth orbit is warranted.

Detailed test requirements for the "F" layer are summarized in Figure K-4. Building blocks and assembly options for meaningful orbital tests are shown in Figure K-5. The power levels associated with the sections of an operational power transmitting array are shown in Figure K-6. The progressively increasing input power and the opportunity for test are indicated. This should permit a properly phased program to address objectives M1, M2, M5 to a small degree, H3 to a limited degree, H4 and H5.

Figure K-7 presents more detailed technology development objectives in the currently defined order of technology risk ranking. Figure K-8 presents a progressive set, a through j, of configurations to be investigated on orbit at the subarray and below level of assembly. This set should permit progressive implementation of objectives M1, M2, M3, M5, H3, H4, H5 and of the technology development detailed objectives associated with the technology areas in rank order 1, 2, 4, 6, 7, 13, 14, 15, 16, and 20. The degree to which these are implemented will depend in large part on the number of each configuration developed and tested on orbit: however, each step will contribute significantly to the understanding of the issues and the total set will form a good basis for the development of the MPTS subarrays. Objective M1 and rank order item 1 will be relatively

Region	Height km	Concern
F	150-340 (250-300)	Effects on HF communications Effects on pilot beam Possible rf noise and harmonic generation
E	90-150	———
D	60-90 (70)	Effects on VLF navigation, Omega and Loran

( ) for test program sizing purposes.

Figure K-2. Ionospheric Effects

Existing Characteristics

P = 400 kW

λ = 0.125 M

G = 72 dBi (700' diameter at 55% efficiency)

3 dB BW = 3.2 min arc

Resulting Performance on Axis

Height km	Power Density mW/cm^2	Required Power MW to Achieve 20 mW/cm^2	50 mW/cm^2
73	3.8	2.1 MW	5.3 MW
250	.8	10.0 MW	25.0 MW
300	.55	14.5 MW	26.4 MW

Figure K-3. Utilization of Arecibo to Accomplish Ionosphere Test Requirements

Power Density	20 to 50 MW/cm^2
Minimum Duration of Heating	5 seconds
Dwell Required	≥10 ms
Maximum Revisit Interval	100 ms
Volume to be Heated	100m Dia. x 1 km
Altitude (F layer)	250 - 300 km

Figure K-4. Ionosphere Test Requirements for F Layer

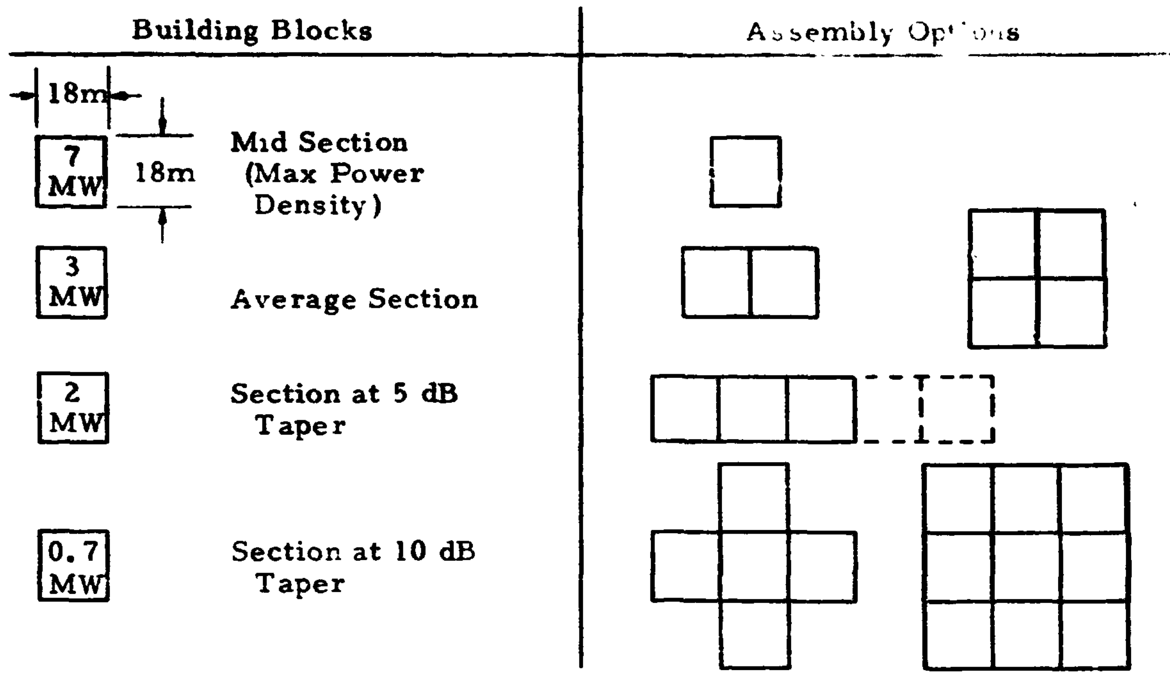


Figure K-5. Power Subarray Assembly Options for Meaningful Orbital Tests

Step	Configuration		Input Power	Rationale
1	CCS	Command Control Subarray	TBD	Provides: • Attitude reference • Phase reference • Telecommunications • Test Equipment • Component spares
2	OSE	Orbital Support Equipment	TBD	
3	CCS, 0.7 MW, OSE	Low Power Module	0.9 MW	• Lowest power density • Difficult waveguide assembly task
4	0.7 MW; CCS, 0.7 MW, OSE	High Power Module	8.5 MW	• Highest power density • Difficult tube - waveguide assembly task
5	CCS, 0.7 MW, 0.7 MW Spare; 0.7, 7 MW, 0.7 MW; OSE, 0.7 MW, 7 MW Spare	High Power Array	12.0 MW	• Mechanical manufacturing and assembly • Operations and maintenance development

Figure K-6. Recommended Microwave Payload Assemblies Build-Up

Rank Order	Technology Area	Development Objective
1	DC-RF Converters and Filters	Develop high efficiency (.85 and greater), long life (30 years and greater), low controlled noise and harmonics device for low cost hard vacuum space operations.
2	Materials - Metallics and Non-Metallics Including Propellants	Develop materials and conduct a program of investigation to select materials and define their characteristics for performance, availability, produceability and general utilization on orbit. In particular, determine the nature of their outgassing products as they effect their and other equipments life.
3	Phase Control	Develop circuits and analyze associated system performance under simulated atmospheric and ionospheric conditions. Specify ground and space born equipment functional and performance requirements.
4	Waveguide	Develop waveguides with thickness of 0.02 inches and less using aluminum and composites commensurate with required ground based or space based manufacturing and assembly techniques.

Figure E-7 Critical Technology Required for Defined Microwave Power Ground and Orbital Test Program (Sheet 1 of 5)

Rank Order	Technology Area	Development Objective
5	Structure	Develop basic structural element with thickness of 0.02 inches and less using aluminum and composites commensurate with required ground based and/or space based manufacturing and assembly techniques.
6	Manufacturing Modules	Develop module(s) for on orbit manufacturing of waveguides and structure.
7	Remote Manipulators	Develop remote manipulator module(s) for the assembly, installation, removal, replacement, maintenance and operations.
8	Biological	To be identified in supplemental program.
9	Attitude Control	To be identified in supplemental program.
10	Ionosphere	Study effects of high power microwave beam on the ionosphere and predict the impact on the pilot beam, other ionosphere users and possible radio frequency noise or harmonics generation.
11	Power Transfer	Develop power transfer techniques and equipment for the transfer of high power across relatively rotating

Figure K-7. Critical Technology Required for Defined Microwave Power Ground and Orbital Test Program (Sheet 2 of 5)

Rank Order	Technology Area	Development Objective
11	Continued	interfaces between the power source and the microwave power transmitting antenna.
12	Switch Gear	Develop switch gear and possibly associated crowbars advancing the technology from existing high current terrestrial applications to achieve long life space borne performance.
13	Radio Frequency (Allocation Process Required Technology)	Determine RFI impact within the microwave power transmission system and on other users for the required power, data, and control frequency and band widths.
14	Support Modules	Develop the orbital life support, monitoring, command and control, maintenance, repair, storage, and other capabilities required to develop in low earth orbit the largely remotely controlled capabilities essential to the operational system.
15	Orbital Assembly Operations	Develop processes for orbital assembly operations from the support modules and from the ground.

Figure E-7. Critical Technology Required for Defined Microwave Power Ground and Orbital Test Program (Sheet 3 of 5)

Rank Order	Technology Area	Development Objective
16	Reliability	Contribute to technology and equipment development to achieve reliable operation of ground and space borne elements.
17	Solar Electric Propulsion Stage	To be identified in supplemental program.
18	Transportation Operations	To be identified in supplemental program.
19	SPS Flight Mechanics	To be identified in supplemental program.
20	Operations and Maintenance	Develop operations and maintenance requirements and techniques in support of economical, safe, and reliable operational life (in excess of 30 years) requirements.
21	Power Source	To be identified in supplemental program
22	Heavy Lift Launch Vehicle	To be identified in supplemental program.
	Socio-Economic Considerations	To be identified in supplemental program.
24	Re-supply	To be identified in supplemental program.

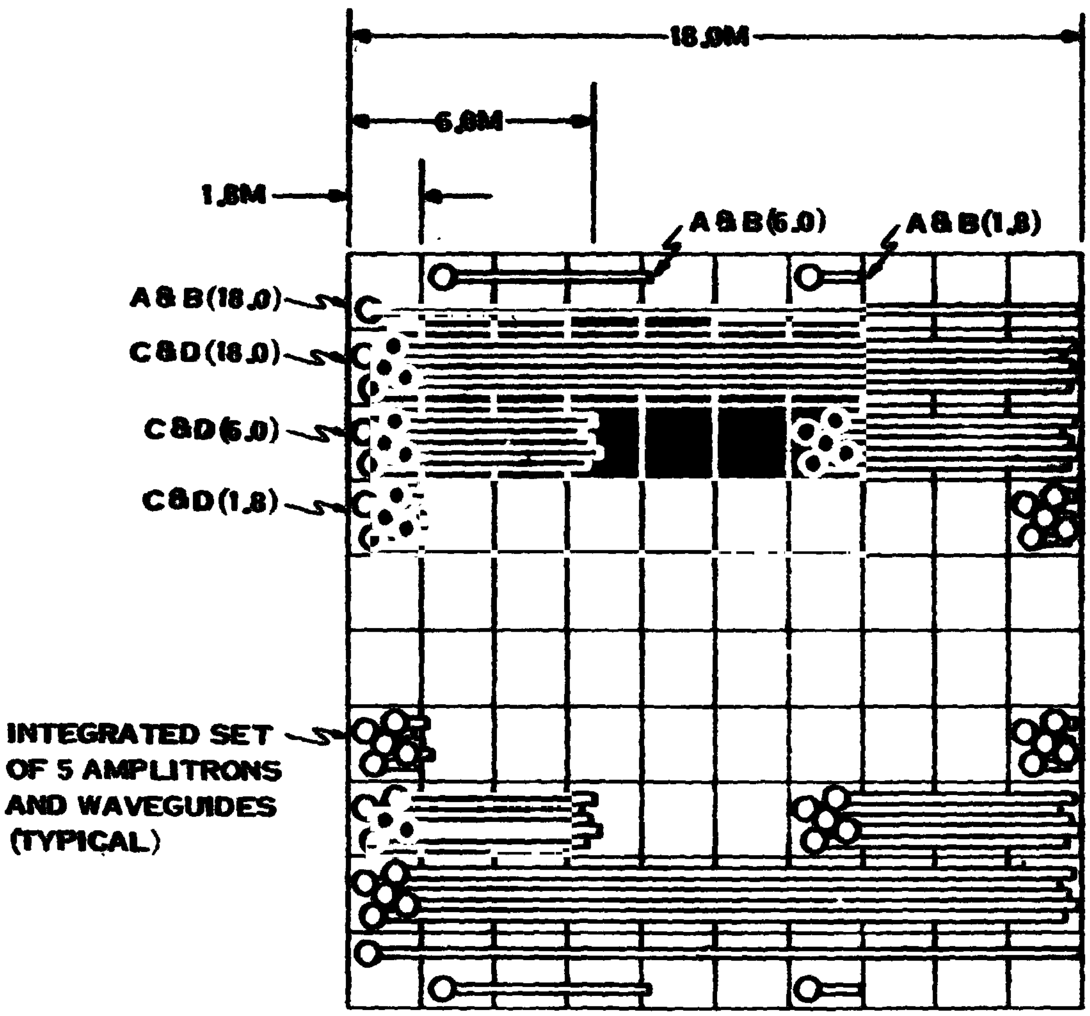
Figure K-7. Critical Technology Required for Defined Microwave Power Ground and Orbital Test Program (Sheet 4 of 5)

Supplemental Critical Technology Required for Operational System	
23 - Socio-Economic Considerations	18 - Transportation Operations
21 - Power Source	24 - Re-Supply
20 - Operations and Maintenance	14 - Support Modules
19 - SPS Flight Mechanics	15 - Assembly Operations
17 - Solar Electric (SEPS) Propulsion Stage	8 - Biological
23 - Heavy Lift Launch Vehicle (HLLV)	

Figure K-7. Critical Technology Required for Defined Microwave Power Ground and Orbital Test Program (Sheet 5 of 5)

Configuration	No. Meters of Slotted Waveguide Per RF Generator	Power (RF) Density Radiated kW/m²	Total (RF) Power to be Radiated kW	Power DC Input kW
a. 1/3 power for 1 5 kW amplitron	1.8, 6.0, 18.0	9.1, 2.72, 0.91	2.0	2.5
b. Full power for 1 5 kW amplitron	1.8, 6.0, 18.0	27.2, 8.17, 2.72	6.0	7.5
c. 1/3 power for 5 5 kW amplitrons	1.8, 6.0, 18.0	39.5, 11.8, 3.95	8.7	11.0
d. Full power for 5 5 kW amplitrons	1.8, 6.0, 18.0	118.0, 35.4, 11.8	26.0	32.0
e. 1/3 power for 10 dB down full subarray	18.0	0.756	245.0	300.0
f. Full power for 10 dB down full subarray	18.0	2.27	736.0	900.0
g. 1/3 power for 5 dB down full subarray	6.0	2.53	818.0	1000.0
h. Full power for 5 dB down full subarray	6.0	7.57	2455.0	3000.0
i. 1/3 power for 0 dB down full subarray	1.8	7.57	2455.0	3000.0
j. Full power for 0 dB down full subarray	1.8	22.1	7360.0	9000.0

Figure K-8. Configurations to be Investigated on Orbit (Subarray and Below)



Total No. RF Generators (shown) = 56

No. Required = 147

Add 6 More Configuration C&D (18.0)

Add 6 More Configuration C&D (6.0)

Add 6 More Configuration C&D (1.8)

Add 1 More Configuration A&B (18.0)

Total No. RF **Generators to be Incorporated** = 147

Clear Areas Remaining for Control and Support Equipment = 50×1.8^2

$= 162.0\ m^2$ i.e.,

$\frac{162}{18^2} = 50\%$

Figure K-9. **Development Configuration** (Subarray and Below Incorporating Control and Support Equipment) completely implemented while the rest will be partially implemented. Multiple subarrays integrated into a functional phased array will be required to approach full implementation.

Figure K-9 illustrates how configurations A, B, C, and D could be incorporated into a test bed subarray in such a manner as to create progressive build-up of amplitrons and waveguides into higher density configurations to achieve a representative thermal environment for the centrally located amplitrons and waveguides. It also illustrates how the same test bed could have sufficient remaining clear areas for control and support equipment. A total of 147 amplitrons is suggested to build the power level up to that associated with a low power density subarray. This would provide for relatively complete implementation of objective M1.

K.4 DEFINING AN MPTS ORBITAL TEST FACILITY PROGRAM

This section was prepared to develop the more complete configuration for an orbital test facility based primarily on the implementation of objective H1 requiring high power density irradiation of the "F" layer of the ionosphere. Although further detailed study and testing is required to confirm this objective, it is considered sufficiently important at this time to form the basis for a first approximation of the orbital test facility MPTS configuration. It, along with the ground test program, the geosynchronous satellite and the upgraded Arecibo facility, would completely implement the currently defined objectives.

K.4.1 ASSUMPTIONS

a. On orbit facility will have dc power available for generation of rf power in a progressive build-up to a maximum of 15 MW to the rf transmitter. This is assumed to:

1. Be required for power source development and demonstration purposes.

2. Be available in steps as required for rf systems development and demonstration purposes.

3. Be available for other orbital operations in a continuing program such as orbital manufacturing, communications, sensing, and mapping.

b. On orbit facility will be assembled in 190 nm (352 km) orbit and will be able to operate between 190 nm (352 km) and 300 nm (356 km) with progressively increasing consumable penalties for the lower altitudes.

c. Ground receiving stations will be at Goldstone, WSMR, and Arecibo.

d. Low altitude operations may be between 190 nm (352 km) and 400 nm (741 km) with cross ranges from 0 to 400 nm (690 km). Total range, orbit to ground = 190 nm (352 km) to 566 nm (1048 km).

e. DC to RF conversion efficiency assumed for sizing purposes.

	Element Contribution	Integrated Effect	
Power Distribution	96%	96%	
RF Generator and Filter	85%	82%	
Phase Control	92%	75%	"D" and "F" region
Atmosphere Attenuation	99%	74%	Incident on ground
Beam Capture	81%	60%	
Rectification	85%	51%	dc on orbit to dc on ground

K.4.2 SIZING THE PHASED ARRAY ANTENNAS

a. Largest Phased Array (Objective H-2)

Size to irradiate the "D" region 38 nm (70 km) from an altitude of 190 nm (352 km) with a power density of 500 W/m^2 (50. mW/cm^2).

$$P_d = \frac{P_o D^2}{\lambda^2 R^2} \qquad D = \frac{P_d \lambda^2 R^2}{P_o}$$

P_d = Maximum power density (W/m^2) on boresite at receiving aperture assuming uniform power density on square transmitting aperture.

D = Dimension (M) of square transmitting aperture.

P_o = Transmitted rf power = $0.82 \times 15 \times 10^6 = 12.3 \times 10^6$ W.

λ = Wavelength of transmitted power (0.1225M)

R = Distance from transmitting aperture to receiving or test aperture (m).

$$D_1 = \sqrt{\frac{500 \times 0.1225^2 \times (352 - 70)^2 \times 10^6}{0.75 \times 15.0 \times 10^6}}$$

$$= \sqrt{57,200} = 239.0 \text{ m}$$

Power density on orbit

$$P_{do} = \frac{0.82 \times 15.0 \times 10^6}{57,200} = 215 \text{ W/m}^2$$

One 5 kW generator at 1/3 power would power

$$\frac{5000}{3} \times \frac{1}{215} = 7.78 \text{ m}^2$$

of slotted waveguide.

For 0.1225 m width it would be 63.0 meters long.

Operational subarrays are 12 to 24 m.

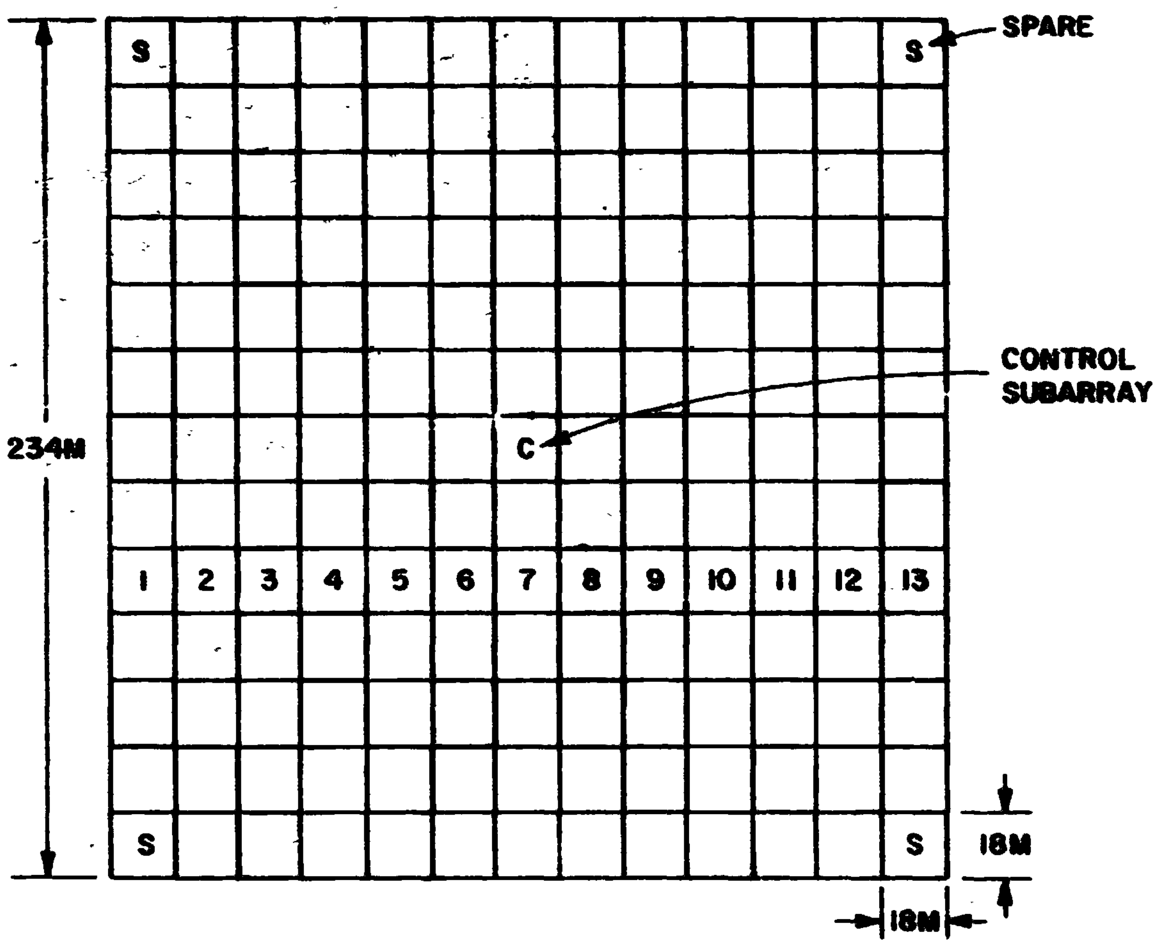
This would mean ≑ 5 to 3 splits or 4 waveguides/amplitron on average.

The configuration of a subarray (shown in Figure K-10) gives ≑ $45 \times 5/18^2$ = 0.695 kW/m² which is 0.032 or about 15 dB down from the 21.7 kW/m² maximum packing density for an 85% efficient generator.

This subarray configuration would be unique to the flight test. Operational configurations are conceived to have power densities of 21.7 kW/m² maximum (in the central region) and 5 dB to 10 dB down in the edge region or possibly as low as 2.17 kW/m² or $2.17 \times 18^2/5 = 141.0$ generators per subarray. The 0.695 kW/m² configuration would have $0.695 \times 18^2/5 = 45.0$ generators each feeding 3 slotted waveguides through a splitter that would be required for this low power density flight test configuration.

b. Smallest Phased Array (Objective H-1)

Size to illuminate the bottom of the "F" region 135 nm (250 km) from an altitude of 190 nm (352 km) with a power density of 500 W/m² (50 milliwatts/cm²).



164 Powered Subarrays

Area/Subarray = 52580/164 = 320.6 m^2

$\doteq$ 18.0 x 18.0 m

= 324 m^2

RF Power Output/Subarray $= \frac{12300}{164}$ = 75.0 kW

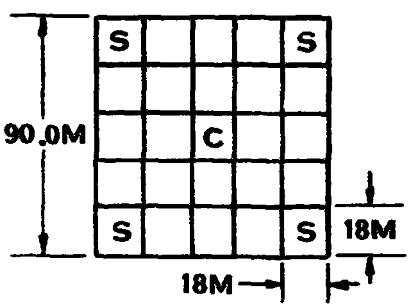
No. 5 kW Generators Operating at 1/3 Power $= \frac{75}{5/3}$ = 45

Figure K-10. Large Array and Subarray Sizes for Cost, Inertia and Performance Estimation Purposes

$$D_2 = \sqrt{\frac{P_d \lambda^2 R^2}{P_o}} = \sqrt{\frac{500 \times 0.1225^2\ (352-250)^2 \times 10^6}{0.75 \times 15.0 \times 10^6}}$$

$$= \sqrt{6{,}900.0} = \sqrt{83.3\ m}$$

Power density on orbit $P_{do} = \frac{0.82 \times 15.0 \times 10^6}{6900} = 1780.0\ w/m^2$



20 powered subarrays area/subarray = 324 m^2.

$\Sigma = 6480.0\ m^2$

RF power output per subarray

$\frac{0.82 \times 15000}{20} = 615.0$ kW

No. 5 kW generators operating at 1/3 power = 615/5/3 = 369/subarray.

This configuration of subarrays gives = $369 \times 5/18^2 = 5.69\ kW/m^2$ which is 0.26 or about 5.9 dB down from the 21.7 kW/m^2 maximum packing density for an 85% efficient generator.

Slotted waveguide area per rf generator = 324/369 = 0.878 m^2. For 0.1225 m width it would be 0.878/0.1225 = 7.17 meters long.

This would permit operating at 9 meters long with 1/3 x 9/7.17 = 0.418 of 5 kW rather than 1/3 of 5 kW/generator or would permit a smaller subarray without requiring multiple slotted waveguides per rf generator.

Assuming 18 m subarray with 0.1225 m wide waveguides there would be 147 waveguides. One rf generator per waveguide would operate at 615/147 = 4.18 kW.

c. Irradiating the "F" Region with Large Array

Using the subarray configuration from 1.0 largest phased array (0.695 kW/m^2) one would be able to irradiate the "F" region as follows:

$$P_d = \frac{P_{do} D^2 D^2}{\lambda^2 R^2} \quad \text{(Assume full array of power subarrays)}$$

$$500 = \frac{0.92 \times 695\ D^4}{0.1225^2\ (352-250)^2 \times 10^6}$$

$$D^4 = \frac{500}{0.92 \times 695} \times 0.0150 \times 102^2 \times 10^6$$

$$= 1.04 \times 10^8$$

$$D = 102.0\ \text{m.}$$

or 6 (18 meter wide subarrays)

using 6 x 6 x 75 = 2700 kW rf power

$$= \frac{2.7}{0.82} = 3.3\ \text{MW dc power}$$

d. Irradiating the Ground with Large Phased Array

Use configuration 1 (largest phased array) to illuminate the ground from an altitude of 190 nm (352 km) to implement objectives D-1 and D-2.

$$P_d = \frac{P_d D^2}{\lambda^2 R^2}$$

$$= \frac{0.74 \times 15.0 \times 10^6 \times 234^2}{0.1225^2 \times (352)^2 \times 10^6} = 327.0\ \text{W/m}^2 = 32.7\ \text{mW/cm}^2$$

This is in excess of that required for the desirable objective D. 2.

Assuming D. 2 could be implemented with $P_d = 70\ \text{W/m}^2$

$$R^2 = \frac{P_o D^2}{\lambda^2 P_d} = \frac{0.74 \times 15 \times 10^6 \times 234^2}{0.1225^2 \times 70} = 58.0 \times 10^{10}$$

$R = 765.0 \text{ km} = 413.0 \text{ nm}$

which would correspond to alt = 190 nm and $413^2 - 190^2 =$ 367 nm cross range.

e. <u>Sizing for MPTS Equipment Development</u>

For rf generator/waveguide configuration build-up implementation of objectives M1, M2, M5, H1, H3, H4, H5, D1, and D2; assume 1 rf generator radiates through 18 m length of waveguide 0.1225 m wide for minimum rf power density.

$\therefore$ 18 m x 18 m gives $\frac{18}{0.1225} = 147.0$ generators

Operate at $\frac{1}{3}$ x 5 kW/generator

$\therefore\ 147 \times \frac{1}{3} \times 5 = 245$ kW/subarray

Use 12.3 MW total rf power i.e., $\frac{12.3}{0.245} = 50.0$ subarrays

Square configuration = 7.1 subarrays use 8 subarrays wide, i.e., 64 subarrays leave 9 corners (1, 2 or 3 each corner) and 2 at center, unpowered, i.e., 53 subarrays with power operating at 50/53 x 245.0 = 232 kW/subarray average over the subarray which would allow up to 6% of area to be non-radiating and incorporate instrumentation. Total array 8 x 18 = 144.0 m wide, i.e., D = 144.0 m and P_o = 12.3 MW.

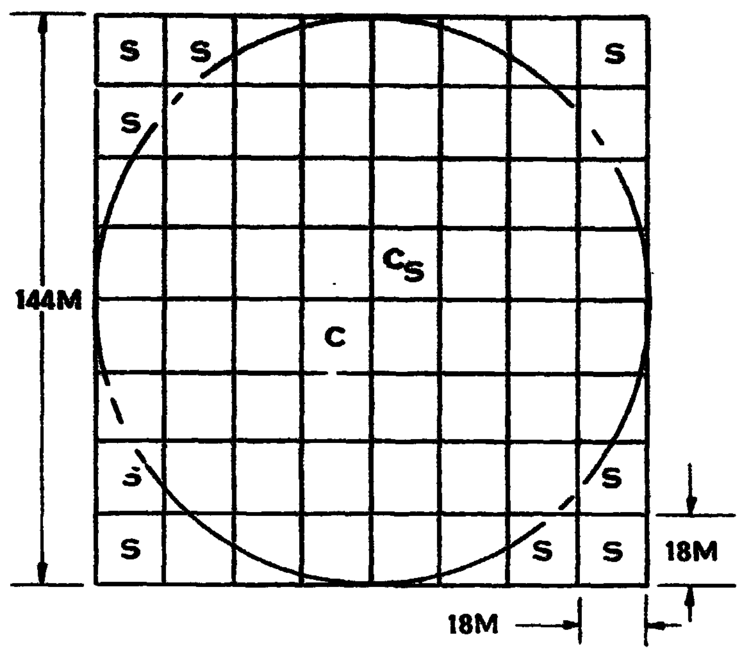
$$P_d = \frac{P_o D^2}{\lambda^2 R^2}$$

or

$$R^2 = \frac{P_o D^2}{\lambda^2 P_d} = \frac{0.75 \times 15 \times 10^{\prime} \times 144^2}{0.1225^2 \times 500}$$

$$= 3.13 \times 10^4$$

$$R = 177 \text{ km}$$



For lower "F" region irradiation S/C must be 250 + 177 =
= 427 km altitude
= 231 nm

f. Implementing Objectives D1 and D2

Using the 144 m x 12.3 MW configuration at 190 nm (352 km) radiate to the ground rectenna.

$$P_d = \frac{P_o D^2}{\lambda^2 R^2} = \frac{0.74 \times 15.0 \times 10^6 \times 144^2}{0.1225^2 \times 352^2 \times 10^6}$$

$$= 125.0 \text{ W/m}^2$$

g. Implementing Objective H2

Using the 144 m x 12.3 MW configuration at 190 nm (352 km) radiate to the "D" layer R = 352 - 70 = 282 km.

$$\frac{0.75}{0.74} \times 125 \times \left(\frac{352}{282}\right)^2 = 158.0 \text{ W/m}^2$$

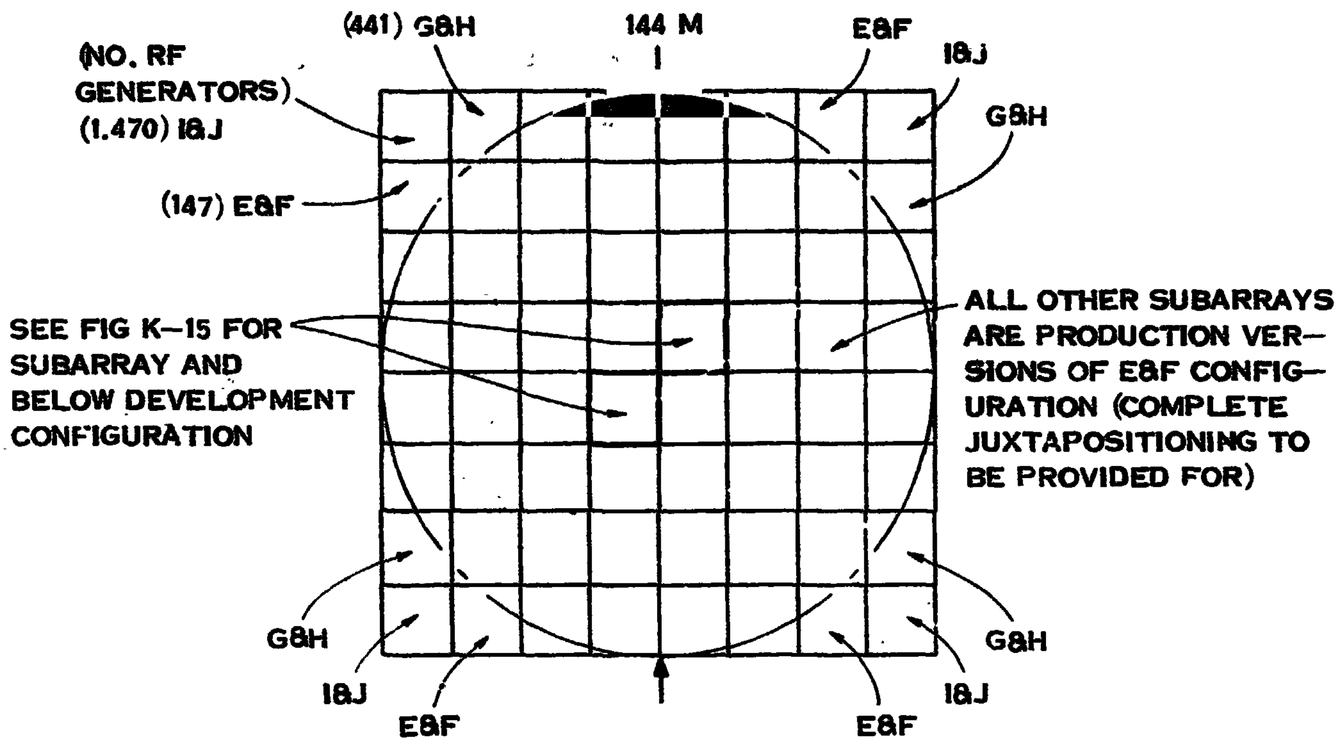
Arecibo is recommended for "D" layer illumination due to long term illumination requirement in excess of 10 minutes.

h. Summary of Phased Array Antenna Orbital Test Hardware

Figure K-11 illustrates the recommended antenna orbital test hardware to implement all of the currently defined primary and secondary objectives assuming objective H2 requiring high power density irradiation of the "D" layer for several mi. utes is implemented through the use of a ground based facility such as Arecibo (upgraded by an order of magnitude).

Figure K-12 summarizes the relationships of altitude, range, and power densities. It identifies the objectives addressed in each case and indicates that those associated with irradiation of the "F" layer can be accomplished at altitudes as low as 391 km. It advises that the "D" layer irradiation be accomplished using the Arecibo facility (upgraded). The irradiation of the ground is low but probably sufficient.

It should be pointed out that the acquisition and lock-on will be a difficult problem requiring further extensive investigation.



Total number of rf generators provided for orbital development and test.

Development	K-15	2 x	147
	E&F	4 x	147
	G&H	4 x	441
	I&J	4 x	1470
			8526
Production	E&F	50 x	147
			7350
			15876

Equivalent circular array powered at one time.

Diameter	144 m
Development Generator	2 x 147
Production Generator	50 x 147
Total	7644

Operating at $\frac{1}{3}$ x 5 kW

$\therefore$ Total rf power = 12.8 MW

DC to rf efficiency = 82%

$\therefore$ Total input power = 15.6 MW @ 200 Vdc

$\doteq$ 15.0 MW assumed to be available (see K.5.1(a)

Figure K-11 Array Flight Test Hardware

Condition	R M	P_d W/m^2	
Altitude = 190 nm			
= 352 km			
(a) to ground	352.0×10^3	98.5	Objectives D1 and D2.
(b) to "D" layer	282×10^3	125.5	Use Arecibo for (H-2) Long Term (10 minutes).
(c) to "F" layer	102×10^3	952.0	Objective H-1 (overdone).
Altitude or range = 212 nm			
= 391 km			
to "F" layer	141.0×10^3	500.0	Objective H-1
to ground	391.0×10^3	77.0	Objective D-1 and D-2
Altitude or range = 189 nm			
= 350	350×10^3	100.0	Objective D-1 and D-2

Figure K-12. Summary of Altitude Range and Associated Power Densities