Solar Power Satellite
System Definition Study

Volume VII
PHASE I FINAL BRIEFING
SPS and Rectenna Systems Analyses
D180-25037-7

Approved By: G. R. Woodcock
C. R. Woodcock
Study Manager

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

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

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

This report includes a total of seven volumes:

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

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

**THURSDAY, DEC 14TH**

* 0900 EXECUTIVE SUMMARY
  TOPICAL REPORT I: SPACE OPERATIONS
    ▶ 1045 CONSTRUCTION LOCATION ANALYSIS
    1200 (LUNCH)
    ▶ 1300 SATELLITE CONSTRUCTION ANALYSIS
    ▶ 1430 ALUMINUM SATELLITE STRUCTURE
  TOPICAL REPORT II: GROUND OPERATIONS
    ▶ 1500 INDUSTRIAL INFRASTRUCTURE
    ▶ 1530 RECTENNA SITING

**FRIDAY, DEC 15TH**

TOPICAL REPORT III: SATELLITE & RECTENNA SYSTEMS
  ▶ 0900 SOLAR ARRAYS AND ANNEALING
  ▶ 0930 ONBOARD POWER HANDLING
  ▶ 0945 ONBOARD DATA & COMMUNICATIONS
  ▶ 1015 POWER TRANSMISSION SYSTEM
  ▶ 1100 POWER RECEPTION SYSTEM
  1200 (LUNCH)

TOPICAL REPORT IV: DEVELOPMENT PLANNING
  * 1300 TECHNOLOGY ADVANCEMENT
  ▶ 1330 FLIGHT PROJECTS

* = VOLUME V
▶ = VOLUME VI
● = VOLUME VII
STUDY
ALUMINUM STRUCTURE
10 GW SOLAR
POWER SATELLITE
GROUNDRULES

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

- MASS DATA
  - SOLAR ARRAYS $5.178 \times 10^7$ kg
  - MW ANTENNAS $2.521 \times 10^7$ kg
  - WT GROWTH $2.051 \times 10^7$ kg
  - TOTAL $9.75 \times 10^7$ kg

- SOLAR ARRAY BLANKET UNIT WEIGHT – $0.427$ kg/m$^2$

- T/W IN TRANSPORT FROM LEO TO GEO – $0.0001$

- SPS NATURAL FREQUENCY INCLUDING SOLAR CELLS & ANTENNAS – $0.0012$ Hz

- SOLAR BLANKET NATURAL FREQUENCY – $0.0024$ Hz

- SOLAR BLANKET PRELOAD NEEDED TO OBTAIN FREQUENCY = $4.285$ N/m ($0.0245$ LB./IN.)

- FACTOR OF SAFETY – 1.4

- 30 YEAR SERVICE LIFE
DESIGN CONDITIONS

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

- SOLAR BLANKET PRE-LOAD
- TEMPERATURES & THERMAL GRADIENT TIME HISTORIES
- TRANSPORT ACCELERATION TO GEO
- ATTITUDE CONTROL & STATION KEEPING TORQUES
- STIFFNESS
- INTERFACE LOADS BETWEEN MODULE & CONSTRUCTION BASE; BEAM HANDLING
The LEO baseline configuration utilizes a four bay wide construction base to fabricate the 4 bay by 8 bay module. During module construction, the 15 meter wide solar array blankets are installed on the two end bays of the 8 bay length as shown. The 15 meter arrays are interconnected along their lengths and uniaxially pretensioned such that the blanket natural frequency is 8.64 cph. Bending moments, caused by the pretension result in high axial compression loads in the caps of the 667.5 m beam. This condition gives the critical load in the cap.
SOLAR ARRAY PRE-LOAD DESIGN CONDITION

DIRECTION OF PRE-LOAD ON SOLAR ARRAY

CONSTRUCTION BASE

DIRECTION OF MAJOR AXIS OF SPS

FREQUENCY OF UNIAXIALLY LOADED MEMBRANE

\[ f_n = \frac{3600}{2\pi} \sqrt{\frac{S}{W}} \text{ cph} \]

- \( \xi \) = LENGTH METERS
- \( S \) = TENSION PER UNIT WIDTH
- \( W \) = ARRAY UNIT WEIGHT

REQUIRED \( f_n = 8.64 \) cph
LOADS APPLIED TO BEAM BY SOLAR ARRAY
4 BAY BY 8 BAY MODULE

THRUSTERS

DIRECTION OF CONSTRUCTION

SOLAR ARRAY BLANKET ON EACH END BAY ONLY

MODULE MASS = 6,500,000 kg
ANTENNA MASS = 12,200,000 kg

MAXIMUM THRUST TO WEIGHT RATIO = 0.0001
The maximum compression load in the 667.5 meter member results from the module transfer from LEO to GEO. The four thruster forces are applied to the module and antenna masses as shown in the figure. A dynamic magnification factor of 2.0 and a factor of 1.4 are applied to the member loads. The maximum compression load in the 667.5 meter beam is -7544 lbs.
DESIGN LOADS ON MODULE

CONDITION: SELF-TRANSPORT TO GEO

- TOTAL THRUST = 1.8349 x 10^4 N (4123 LB) LIMIT
- DYNAMIC MAGNIFICATION FACTOR = 2
- FACTOR OF SAFETY = 1.4 FOR ULTIMATE
- FORCE PER THRUSTER = 2886 LB
- ANTENNA INERTIA FORCE = 7532 LB ULT.
- MODULE INERTIA FORCE = 4013 LB ULT.
- ANTENNA SUPPORTED AT POINTS A, B, C, D
SUMMARY TRUSS LOADS DUE TO ORBIT TRANSFER FROM LEO TO GEO

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

- INCLUDES MODULE & ANTENNA MASSES
VARIATION OF CRITICAL CAP COMPRESSION LOAD VS BEAM DEPTH

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

LOAD IN H & I
LB x $10^3$
ULTIMATE

$0.0246$ LB/IN.

$0.866b$

$C_{H, L} = \frac{MG}{1.732b}$

$H$

$G$

$b$

$M$

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

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

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

The roll formed cap incorporates longitudinal stiffening beads near the corner sections in order to provide a high compression capability in the corners. Between the lightening holes, beads are rolled into the section for stiffening. The section is formed on a mandrel which is used for support during the attachment operation. The lower attachment on the centerline is not completed until after the battens are connected. The gap between flanges permits the mandrel support to extend inward to the beam machine; the mandrel support ends, and the two flanges are joined.
ALUMINUM BEAM DESIGN (7.5 METERS)

7.5 m CROSS-SECTION

LIGHTENING HOLE
BATTEN

ROLL FORMED ALUMINUM CAP WITH STIFFENING BEADS
MATERIAL 2024-T3

0.19 m (7.5 IN.)
BEAM CAP SECTION ROLL-FORMED ALUMINUM ALLOY
BATTEN SECTION ROLL-FORMED
# CANDIDATE MATERIAL PROPERTY DATA

<table>
<thead>
<tr>
<th>Property</th>
<th>2024-T3</th>
<th>2219-T6</th>
<th>6061-T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{TU}$ ksi</td>
<td>64</td>
<td>54</td>
<td>42</td>
</tr>
<tr>
<td>$F_{TY}$ ksi</td>
<td>47</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>$F_{CY}$ ksi</td>
<td>39</td>
<td>38</td>
<td>35</td>
</tr>
<tr>
<td>$E_C$ ksi</td>
<td>$10.7 \times 10^3$</td>
<td>$10.8 \times 10^3$</td>
<td>$10.1 \times 10^3$</td>
</tr>
<tr>
<td>$\rho$ LB/IN.$^3$</td>
<td>0.100</td>
<td>0.102</td>
<td>0.098</td>
</tr>
<tr>
<td>$\alpha$ IN./IN./$^\circ$F $\times 10^{-6}$ @ 200°F</td>
<td>12.9</td>
<td>12.4</td>
<td>13</td>
</tr>
<tr>
<td>$K$ BTU/(HR) (FT)$^2$ ($^\circ$F)/FT</td>
<td>80</td>
<td>74</td>
<td>96</td>
</tr>
<tr>
<td>$C$ BTU/(LB) ($^\circ$F) @ 200 °F</td>
<td>0.22</td>
<td>0.23</td>
<td>0.23</td>
</tr>
</tbody>
</table>
ALUMINUM CLOSED SECTION BEAM CAP THICKNESS & DEPTH VS CRITICAL LOAD; L = 7.5 m
CANDIDATE TRUSS CONFIGURATIONS

WEIGHT/UNIT LENGTH kg/m

15 m

COMPRESSION-TENSION DIAGONAL

7.8

COMPRESSION-TENS DIAGONAL

6.4

PRE-TENSIONED CROSS CABLES
PRELIMINARY ESTIMATE OF MODULE SLOPES FOR VARIOUS THERMAL GRADIENTS

\[
\Delta T \, ^\circ F
\]

\[
Q \text{ METERS} \times 10^3
\]

\[
\ell \text{ MODULE LENGTH}
\]
An estimate of the solar array module slopes and deflections was calculated for various temperature gradients. The analysis was based on the following assumptions:

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

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

Updated thermal data will be used to reevaluate these estimates.
PRELIMINARY ESTIMATE OF MODULE DEFLECTIONS FOR VARIOUS THERMAL GRADIENTS

CONSTRUCTION BASE

MODULE STRUCTURE

$\Delta T = T_2 - T_1$

DEFLECTION $\delta$ METERS

EXPECTED $\Delta T \approx 120^\circ F$

0
20
40
60
80
100
120

0
1
2
3
4
5
6

$\delta$ METERS x $10^3$
ORBITAL ATTITUDE DURING CONSTRUCTION

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

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

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

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

For this study, the inside of the elements are coated with black anodize (\( \varepsilon = 0.83, \alpha = 0.86 \)) and the outside surface with Z-93 white paint (\( \varepsilon = 0.90, \alpha = 0.17 \)).
ORBITAL ATTITUDE DURING CONSTRUCTION

V
NADIR
O° ORBIT ANGLE
SUN
HORIZONTAL BEAM
SUN
SUN
SUN
SUN
ELEMENT ORIENTATION AT O° ORBIT ANGLE
EARTH
EARTH
EARTH
REMAINING TASKS:

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

The SPS efficiency chain has undergone two minor revisions during this contract period. The regulation, auxiliary, and annealing power factor of 0.983 is lower than the 0.99 factor used previously. The inter-subarray loss factor of 0.976 is an improvement over the 0.956 factor used in the Part III System Definition Study.

The changes to the efficiency chain result in a slight decrease in the solar cell area requirement (0.6 km²).
## Updated Efficiency and Sizing

### Efficiency and Megawatts Per Link

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
<th>MEGAWATTS</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Bus $I^2R$</td>
<td>0.934</td>
<td>8,876</td>
<td>Solar Array Output</td>
</tr>
<tr>
<td>Rotary Joint</td>
<td>1.0</td>
<td>8,290</td>
<td>Total Input to Antenna</td>
</tr>
<tr>
<td>Antenna Power Distribution and Processing</td>
<td>0.97</td>
<td>8,290</td>
<td>Total RF Power</td>
</tr>
<tr>
<td>DC-RF Conversion</td>
<td>0.85</td>
<td>8,041</td>
<td>Total Radiated Power</td>
</tr>
<tr>
<td>Waveguide $I^2R$</td>
<td>0.985</td>
<td>8,836</td>
<td></td>
</tr>
<tr>
<td>Ideal Beam</td>
<td>0.965</td>
<td>6,733</td>
<td></td>
</tr>
<tr>
<td>Inter-Subarray Losses</td>
<td>0.976</td>
<td>6,497</td>
<td></td>
</tr>
<tr>
<td>Intra-Subarray Losses</td>
<td>0.981</td>
<td>6,341</td>
<td></td>
</tr>
<tr>
<td>Atmosphere Losses</td>
<td>0.98</td>
<td>6,221</td>
<td></td>
</tr>
<tr>
<td>Intercept Efficiency</td>
<td>0.95</td>
<td>6,097</td>
<td></td>
</tr>
<tr>
<td>Rectenna RF-DC</td>
<td>0.89</td>
<td>5,792</td>
<td>Incident on Rectenna</td>
</tr>
<tr>
<td>Grid Interfacing</td>
<td>0.97</td>
<td>5,155</td>
<td>NET TO GRID</td>
</tr>
<tr>
<td></td>
<td>0.563</td>
<td>5,000</td>
<td></td>
</tr>
</tbody>
</table>

### Solar Input
- **1,353 W/m²**
- **Solar-Cell Conversion Efficiency (0.173)**: 234.1
- **Blanket Factors (0.9483)**: 221.3
- **Thermal Degradation (0.954)**: 211.1
- **Orientation Loss (0.919)**: 194.0
- **Aphelion Intensity (0.9675)**: 187.7
- **Nonannealable Radiation Degradation (0.97)**: 182.1
- **Orbit Transfer Compensation (0.99)**: 180.2
- **Regulation, Auxiliary Power, and Annealing (0.983)**: 177.2

### EOL Blanket Output
- **177.2 W/m²**

### Total Solar-Cell Area
- **50.1 km²**

### Solar Array Output
- **8,876 MW**
The configuration of the 5000 megawatt SPS is basically that of one-half of the 10,000 megawatt SPS developed in the Part III System Definition Study. This description shows the revised dimensions from the updated efficiency chain, structural resize, and implementation of array shadowing diodes.

Using 12.7 meter beams for array attachment necessitated changing the internal bay dimensions to compensate for increased lost area, for 667.5 x 667.5 meter bay centerlines. In addition to this dimension change, the beam/array clearance for the catenary support system was increased from 2 meters to 3 meters at each bay end.

Incorporation of shadowing diodes in the array panels (to be shown on a later chart) created more lost area on the blanket. To compensate for the combined lost area effects it was necessary to add two array strings to each bay, one string to each end segment.
5000 Megawatt Reference Photovoltaic System Description

- **128 BAYS**
  - $667.5 \times 667.5 \text{m}
- **TOTAL SOLAR CELL AREA** = 50.1 km²
- **TOTAL ARRAY AREA** = 63.7 km²
- **TOTAL SATELLITE AREA** = 57.3 km²
- **MINIMUM POWER TO SLIPRINGS** = 8.29 GW

**DIMENSIONS**
- **INTERMEDIATE SEGMENT**: 44 - 15m SEGMNTS/BAY
- **TYPICAL BAY**: 598 STRINGS/BAY
- **END SEGMENT**: 811 PANELS/BAY
- **STRING LENGTH**: 9.68m
- **BEAM CHORD**: 12.7m
- **BEAM**: 7.5m
- **LENGTH**: 15m
- **INTERMEDIATE SEGMENT**: 10 cm
REFERENCE PHOTOVOLTAIC SYSTEM DESCRIPTION

The basic blanket panel configuration has changed slightly. To compensate for the shorter length available within the bay, the solar cell length was degraded from 6.55 cm to 6.48 cm. This was sufficient to allow for the 12.7 meter beams and 3 meter catenary support discussed previously.

The only other change that was made to the basic blanket panel was the incorporation of two shadowing diodes (shunts) per panel. Each panel maintains the 16 cells in series and 14 cells in parallel configuration except on the two end rows where there are 13 cells in parallel. The 13 parallel cells will allow only 3 cell failures, instead of 4 allowed by the other rows, and still pass string current without reverse bias operation.
Reference Photovoltaic System Description

- 14 CELLS IN PARALLEL WILL TOLERATE 4 CELL FAILURES IN ANY ROW
- 1.059 m SHUNT DIODE
- 16 CELLS IN SERIES
- 0.25 cm SHUNT DIODE
- 1.059 m INTERCONNECT
- 0.25 cm LONGITUDINAL TAPE 1.5 cm x 40 μm
- 1.059 m TAPE 1.6 cm x 40 μm
- NO SCALE
- 6.48 cm ELECTRICAL INTERCONNECT
- 0.01 cm TYP.
- 1.0568 m INTERCONNECT
- 7.44 cm INTERCONNECT PATTERN (BACKSIDE)
- 12.5 μm COPPER 10% AREA FACTOR
- 0.75 x 4 cm #CELLS/PANEL : 222
- PANELS/BAY : 365,378
- PANELS/SATELLITE : 9,353,678
- .5 cm SECT A-A
- .5 cm 175 μm
- .5 cm
IMPLEMENTATION OF ARRAY SHADOWING DIODES

A large shadow moving across an array string could cause the shadowed cells to operate in a reverse-biased mode. This operation can cause "hot spots" (energy consumption instead of generation) and can lead to string failure. To prevent this problem from causing array damage it is necessary to incorporate shadowing diodes to shunt the power around shadowed panels and prevent reverse-bias operation. The rationale and design criteria used to incorporate the shadowing diodes on the SPS blanket are noted on this chart.

Two, redundant, shadowing diodes were added to each blanket panel as shown. The electrical equivalent of a blanket panel with the shadowing diodes is also shown. This configuration will protect array panels from reverse-bias operation. The individual parallel sets of cells on the panel receive their protection by the "four out of fourteen" cell loss method.

Since the shadowing diodes occupy space that would normally be used for solar cells, an increase in the "lost area" of the blanket panel results. If the diodes were placed in another location packaging for transportation penalties would result. Therefore, to compensate for the new "lost area", extra array was added to the system with mass and area penalties shown.
Implementation of Array Shadowing Diodes

RATIONALE:
PREVENTS ARRAY DAMAGE CAUSED BY UNEVEN ILLUMINATION AND SHADOWING EFFECTS
PROVIDES MORE GRACEFUL POWER DEGRADATION FROM BLANKET PANEL FAILURES AND
SHADOWING EFFECTS

DESIGN CRITERIA:
REVERSE-BIAS PROTECTION FOR BLANKET PANELS
LOW REVERSE LEAKAGE CURRENT
LOW FORWARD-VOLTAGE DROP
HIGH RELIABILITY
COMPATIBLE WITH BLANKET PANEL CONFIGURATION

REDUNDANT (PARALLEL) SHUNT DIODES
INCREASE IN SYSTEM SIZE = 0.461 km²
INCREASE IN SYSTEM MASS = 192.3 MT

PHYSICAL ARRANGEMENT OF SHUNTING DIODES ON BLANKET PANEL
ELECTRICAL EQUIVALENT
SOLAR ARRAY SUPPORT STRUCTURE EVOLUTION

Illustrated here were the original and revised baseline hexahedral solar array support structure concepts. In the original system the edge cells of each of the eight modules making up the entire SPS used the configuration illustrated. The interior cells employed an absolute minimum of structure. Further analysis indicated that the edge cells were not stable with the result that the entire system was not stable. Further, the 7.5 meter beams were not adequate for solar blanket tension when the solar blanket tension was changed to uniaxial. As a result, the system was revised to the configuration indicated with 12.7 meter beams for solar blanket tension support and all cells incorporating the structural concept shown. The lower-deck-to-upper-deck diagonal provides structural stability.
Solar Array Support Structure Evolution

**ORIGINAL**
ALL 7.6M BEAMS

**REVISED**
ALL 7.6M BEAMS
EXCEPT AS NOTED

**INTERIOR CELL**

**PROBLEMS:**
- NOT STABLE
- 7.6M BEAM INADEQUATE FOR SOLAR BLANKET TENSION
SOLAR POWER SATELLITE STRUCTURAL BAY CONFIGURATION

The revised bay configuration including an index of the location and types of beams used in a typical bay is shown. A loads analysis resulted in using three types of beams in the satellite structure. For construction purposes, type B and C beams differ only in their batten spacing. This will allow the use of only two types of beam machines in the construction facility.

For the SPS constructed at GEO, the type "B" beams are replaced by type "C".
Solar Power Satellite
Structural Bay Configuration

A: TYPE "A" BEAMS - 12.7M
B: TYPE "B" BEAMS - 7.5M
   7.6M BATTENS
C: TYPE "C" BEAMS - 7.5M
   12.7M BATTENS
The three types of beams in the satellite primary structure are shown. Also listed for each type of beam are their section and beam characteristics. In previous satellite designs the beams were sized for the "worst case" load condition resulting in a mass penalty on the majority of members which had a significantly lower load. This updated configuration has started to reduce that penalty by having three types of members. The savings can be shown by the difference in mass/length between the 12.7 meter, type A, beam and the 7.5 meter, type C beam. The majority of beams in the satellite are type C beams.
Solar Power Satellite Structural Update Beam Configurations

<table>
<thead>
<tr>
<th>ITEM</th>
<th>TYPE A</th>
<th>TYPE B</th>
<th>TYPE C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UPPER SURFACE</td>
<td>UPPER AND LOWER SURFACE</td>
<td>BEAM USED IN ALL OTHER LOCATIONS</td>
</tr>
<tr>
<td></td>
<td>LONGITUDINAL BEAM</td>
<td>LATERAL BEAM</td>
<td></td>
</tr>
<tr>
<td>SECTION</td>
<td>CLOSED</td>
<td>OPEN</td>
<td>OPEN</td>
</tr>
<tr>
<td>REF. SIDE LENGTH</td>
<td>36 CM</td>
<td>38CM</td>
<td>38CM</td>
</tr>
<tr>
<td>MAT'L THICKNESS</td>
<td>0.86 MM</td>
<td>0.71 MM</td>
<td>0.71 MM</td>
</tr>
<tr>
<td>EIX</td>
<td>3.39 E8 N/CM²</td>
<td>1.80 E8 N/CM²</td>
<td>1.80 E8 N/CM²</td>
</tr>
<tr>
<td>BEAM WIDTH</td>
<td>12.7M</td>
<td>7.5M</td>
<td>7.5M</td>
</tr>
<tr>
<td>BATTEN SPACING</td>
<td>15.0M</td>
<td>7.6M</td>
<td>12.7M</td>
</tr>
<tr>
<td>CRITICAL LOAD</td>
<td>17480N (CRIP. CHORD)</td>
<td>19000 N (BUCK. BEAM)</td>
<td>7090 N (BUCK BEAM)</td>
</tr>
<tr>
<td>MASS/LENGTH</td>
<td>7.48 KG/M</td>
<td>5.12 KG/M</td>
<td>4.11 KG/M</td>
</tr>
</tbody>
</table>
MULTIPLE BUS SPS POWER DISTRIBUTION

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

A redesign of the main power distribution bus system was accomplished to decrease the possibility of loss of all power to the antenna and to limit potential fault currents. The overall multiple bus system concept is shown.
Multiple Bus SPS Power Distribution

- B POWER SOURCE
- A POWER SOURCE

- MAIN B BUSES
- 4 SUPPLY
- 4 RETURN
- 38,700V TO SLIPRINGS

- MAIN A BUSES
- 6 SUPPLY
- 6 RETURN
- 40,800 TO SLIPRINGS
- 1 MM AL SHEET CONDUCTOR
- PASSIVELY COOLED

- STRING-TO-STRING INTERBAY JUMPERS
- STRIP-TO-STRIP TURNAROUND JUMPERS
  (6 STRIPS = 3 COMPLETE STRINGS PER BAY WIDTH)

- 5.5 MEGAWATT DC/DC PROCESSORS (228/ANTENNA)
- WITH ISOLATION SWITCH GEAR AND ACTIVE THERMAL CONTROL

- FLEX CABLES ACROSS SOFT YOKE JOINT

- TWENTY SLIP RINGS
  15 M. MAX. DIA.
  MULTIPLE BRUSHES 10A/CM² MAX

- DC SWITCHGEAR (2140AMP)
  EACH STRIP TO MAIN BUS
MULTIPLE BUS/ARRAY CONNECTION

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

NOTE: CONNECTIONS SHOWN ARE TYPICAL FOR BAY CONNECTIONS TO MAIN POWER BUSES
MULTIPLE BUS CONDUCTOR SUMMARY

This table shows a breakdown of the number of buses for each power source, the number of array power sectors per power source, and the normal bus current per bus for each power source. Also shown is the number of DC-DC converters per bus in power source B and the number of klystrons supplied by each bus of each power source.
## Multiple Bus Conductor Summary

<table>
<thead>
<tr>
<th>SATELLITE</th>
<th></th>
<th>ANTENNA</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER</td>
<td>NO. OF</td>
<td>ARRAY</td>
<td>NORMAL</td>
<td>NO. OF</td>
</tr>
<tr>
<td>SOURCE</td>
<td>BUSSES</td>
<td>POWER SECTORS</td>
<td>BUS CURRENT</td>
<td>CONVERTERS</td>
</tr>
<tr>
<td>A</td>
<td>4 (+)</td>
<td>31</td>
<td>15,966</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>4 (-)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>6 (+)</td>
<td>65</td>
<td>22,783</td>
<td>16,925</td>
</tr>
<tr>
<td></td>
<td>6 (-)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SLIP RING ASSEMBLY FOR MULTIPLE BUS
POWER DISTRIBUTION SYSTEM

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

The concept shown was developed based on the following requirements:

1. Twenty separate slip ring assemblies
2. Normal slip ring current capabilities
3. Maximum brush current density of 10 amperes per square centimeter
4. Brush feeder current density of 400 amperes per square centimeter
5. Brush pressure of 25.9 Kpa (4 psi)
6. Coin silver slip ring (90% silver and 10% copper)
7. Silver-molybdenum disulfide-graphite (85% Ag 12% MOS₂ and 3% Graphite) brushes
8. Maximum outside diameter of 16 meters (fits inside HLLV payload bay)
9. Earth assembled
10. Minimum spacing between different conductor systems of 0.7 meters
11. Positive retraction of the brush assembly from the slip ring contact surface.
12. All feeder conductors to have maximum surface exposure to free space for thermal dissipation purposes.
Slip Ring Assembly for Multiple Bus Power Distribution System

CONDUCTOR RING (TYP. OF 20)
RING BEARING SUPPORT TRUSS (SECTION TYPE OF 8)
RING BEARING
SATELLITE INTERFACE TRUSS (SECTION TYP. OF 8)
CENTER BEARING
YOKE INTERFACE TRUSS (SECTION, TYPE OF 8)
FEEDER TYP. OF 10 EACH SECTION (LOCATIONS ONLY)
FEEDERS (TYP. OF 10 EACH SECTION TOTAL 80 EACH INTERFACE) (DIAGRAM LOCATIONS ONLY)
FOR BRUSH ASSEMBLY SEE DETAIL DWG A

11.7M
8.0M
16.0M
MULTIPLE SLIP RING BRUSH ASSEMBLY

Details of the brush assembly and slip ring arrangement is shown.
Multiple Slip Ring Brush Assembly

END VIEW

SLIP RING SUPPORT TRUSS

BRUSH SUPPORT TRUSS

2.63M

.75M

.36M

.4M

75M

1.1M

SIDE VIEW

SLIP RING (TYP OF 20, RADIUS VARIES FOR EACH)

SLIP RING (TYP OF 20, RADIUS VARIES FOR EACH)

ALUMINA INSULATOR

ALUMINA INSULATOR (TYP)

.57M

.55M

1.1M

D180-25037-7
ITEMIZED DC/DC CONVERTER LOSSES—NEW DESIGN

The critique of the reference concept (task 4.1.1) raised the issue of DC to DC converter life based on corona induced failures within transformers and inductors used in filters. The reference DC to DC converter concept was derived by selecting a converter chopping frequency of 20 kilohertz in order that the overall satellite mass was minimized. However, the reliability analysis was performed using failure rate data based on 400 hertz. Corona-induced failures within transformers are dependent upon the total number of AC cycles to which the transformer is subjected. The mean-time-to-failure at 20 kilohertz is 50 times shorter than at 400 hertz.

As a result of the critique, an analysis was accomplished to investigate the following three approaches to increasing the predicted life of the converter.

a) Reduce the converter system chopping frequency

b) Increase the transformer life by derating the dielectric material (i.e., operate at a lower voltage stress)

c) Redesign the transformer to increase its operating life.

Reducing the converter system chopping frequency incurs a significant mass penalty. The converter specific mass including thermal control at 1 kilohertz is approximately 2.9 kg/kw and is approximately 1.7 kg/kw at 20 kilohertz. Derating the dielectrics in the converter results in a converter specific mass (including thermal control) of 2.0 kg/kw.

In order to increase the overall converter lifetime dielectrics were derated for all filters in the converter. The losses for the revised converter are tabulated as a function of frequency in the table.
## Itemized DC/DC Converter Losses – New Design

<table>
<thead>
<tr>
<th>CONVERTER SECTION</th>
<th>1 KHZ</th>
<th>10 KHZ</th>
<th>20 KHZ</th>
<th>30 KHZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT FILTER</td>
<td>30</td>
<td>42</td>
<td>48</td>
<td>54</td>
</tr>
<tr>
<td>COND</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>SWITCHING SW</td>
<td>2.4</td>
<td>12</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>DRIVE AND SUPPRESSION</td>
<td>2.2</td>
<td>5.6</td>
<td>11</td>
<td>16.5</td>
</tr>
<tr>
<td>TRANSFORMER</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>RECTIFIERS</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>OUTPUT FILTERS</td>
<td>60</td>
<td>120</td>
<td>138</td>
<td>149.5</td>
</tr>
<tr>
<td>TOTAL LOSSES</td>
<td>178.8</td>
<td>263.7</td>
<td>305.2</td>
<td>340.2</td>
</tr>
<tr>
<td>EFFICIENCY (%)</td>
<td>96.8</td>
<td>95.3</td>
<td>94.7</td>
<td>94.1</td>
</tr>
</tbody>
</table>
DC/DC CONVERTER SWITCHING FREQUENCY SELECTION

In order to select the chopping frequency for the long life processor, the curves shown were developed for the baseline converter design, the baseline converter with de-rated dielectrics, and the baseline converter with de-rated dielectrics in all filters and a liquid cooled transformer as a replacement for the baseline transformer. It is apparent from the curves in this figure that the minimum mass system occurs when the liquid cooled transformer is used (with de-rated dielectrics in all filters) at a chopping frequency in the 15 to 20 kilohertz range. The converter concept selected to replace the baseline converter concept is shown as the lower of the three curves.
DC/DC Converter Switching Frequency Selection

\[
\text{MASS} = \text{CONVERTER MASS} + \text{THERMAL CONTROL MASS} + \text{ARRAY MASS} \quad \text{(REQUIRED TO MAKE UP FOR CONVERTER LOSSES)}
\]

- PART II CONVERTER (BASELINE)
- PART II CONVERTER WITH DERATED DIELECTRIC MATERIALS (TRANSFORMER & FILTERS)
- PART II CONVERTER WITH NEW TRANSFORMER AND DERATED DIELECTRIC MATERIALS

**Diagram:**

- X-axis: CONVERTER CHOPPING FREQUENCY ~ KILOHERTZ
- Y-axis: MASS IN METRIC TONS

Graph showing different lines representing various converter configurations at different chopping frequencies.
LIQUID COOLED TRANSFORMER

An effort is underway by Thermal Technology Labs (funded by the USAF Aero Propulsion Laboratory) to develop lightweight transformers for airborne power supplies. A computer program has been developed, and a 50 KVA prototype fabricated to verify the computer optimized design, to enable the design of lightweight liquid cooled transformers. The computer optimization was used to develop a design for a 6,000 kw liquid cooled transformer. The selected DC/DC converter transformer characteristics are shown in this table.
Liquid Cooled Transformer

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWER IN</td>
<td>5610 KW</td>
</tr>
<tr>
<td>POWER OUT</td>
<td>5540 KW</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>98.73%</td>
</tr>
<tr>
<td>WEIGHT</td>
<td>170 KG</td>
</tr>
<tr>
<td>INTERNAL SIZE</td>
<td>$(14 \text{ in})^3$</td>
</tr>
<tr>
<td>OPERATING FREQUENCY</td>
<td>20 KHZ</td>
</tr>
</tbody>
</table>
KLYSTRON MODULE THERMAL CONTROL SYSTEM CHARACTERISTICS

A revision to the Part III heat pipe thermal control system for the klystron module is an active (pumped) thermal control system with the characteristics shown on this chart. There are several reasons for the proposed change to an active thermal control system, but they are highlighted by lower mass and less fault impact.

Using an active thermal control system with the characteristics shown could result in a mass advantage of over 570 MT per antenna.

There is a possibility of micrometeoroid penetration or mechanical failure causing a tube leak in the radiator of the module thermal control system. Using the heat pipe system of Part III, such a leakage could cause severe, long-lasting electrical problems in the vicinity of the radiator leak because conductive fluids were used in the heat pipes. Thus a leak could have contaminated high voltage electrical insulators with a conductive film of heat pipe fluid. At reasonable pressure, the only heat pipe fluids found to operate in the 500°C temperature range were conductive (i.e., NaK, Hg, CS, etc.).

The active thermal control system adapted for SPS uses air (or Nitrogen) for the high temperature (500°C) section and Dowtherm-A for the low temperature (300°C) section. Both of these fluids are nonconductive.

This work was accomplished by Mr. Ray French of the Vought Corporation, an independent contributor not under contract on this project.
# Klystron Module
## Thermal Control System Characteristics

| Material | Fluid          | $T_{in}$ | $T_{out}$ | Length x Width | Tube Spacing | Tube Diameter | Tube Thickness | Fin Thickness | Emissivity | Absorptivity | $T_{sink}$ | Pump Effy. | Fin Effectiveness | Mass/Module |
|----------|----------------|---------|----------|---------------|--------------|---------------|----------------|---------------|-------------|-------------|-------------|------------|-------------|----------------|-------------|
| Copper   | Steam @ 20 ATM | 477°C   | 413°C    | 0.57m x 1.61m | 3.7 cm       | 5.6 mm        | 0.886 mm       | 0.163 mm      | 0.8          | 0.3         | 36.3°C     | 0.3        | 0.894        | 7.96 kg      |
| Copper   | Dowtherm-A     | 277°C   | 260°C    | 1.04m x 1.61m | 2.84 cm      | 1.27 mm       | 0.71 mm        | 0.086 mm      | 0.8          | 0.3         | 36.6°C     | 0.3        | 0.920        | 6.13 kg      |

Current Mass/Module: 13.18 kg
Part III Mass/Module: 18.88 kg
KLYSTRON PUMPED FLUID THERMAL CONTROL SYSTEM

Shown here is the basic layout of the components of the revised active thermal control system adopted for the klystron module.
The next three charts show some of the results of a Boeing (IR&D) test program to investigate the possibilities of thermal (bulk) annealing radiation damage from unglassed 50 μm (2-mil) silicon solar cells. The unglassed cells were irradiated with 2 MeV protons and annealed in a laboratory oven at the temperatures and times noted. The cells were also subjected to repeated radiation damage and annealing.

The results of these tests are by no means conclusive but do show recovery of radiation damage. It is anticipated that continued work in this area could lead to the optimization of the thermal (bulk) annealing processes for the type of solar blanket baselined for SPS.
Thermal Annealing of Proton Damage
In Silicon: Boeing Test Data

SOLAREX 50 μm SILICON SOLAR CELL

IRRADIATION:
2 MeV PROTONS
10^{12} PROTONS/CM²
(~1.5 \times 10^{16} 1 MeV ELECTRON EQUIV./CM²)

ANNEAL: 500°C
20 MIN

CURRENT (mA)

VOLTAGE (V)
Thermal Annealing of Proton Damage In Silicon Cells: Boeing Test Data

SOLAREX 50 μm SILICON SOLAR CELL

IRRADIATION:
- 2 MeV PROTONS
- 10^{12} PROTONS/CM^2
- (~1.5 \times 10^{16} 1 MeV ELECTRON EQUIV./CM^2)

ANNEAL:
- 500°C
- 20 MIN
BOEING

SPS

Thermal Annealing of Proton Damage In Silicon Solar Cells: Boeing Test Data

SOLAREX 50 μm SILICON SOLAR CELL

IRRADIATION:
- 2 MeV PROTONS
- $10^{12}$ PROTONS/CM$^2$
- (~$1.5 \times 10^{16}$ 1 MeV ELECTRON EQUIV./CM$^2$)

ANNEAL:
- 450°C
- 20 MIN.

FIRST ANNEAL
SECOND ANNEAL
ORIGINAL CURVE
FIRST IRRADIATION
SECOND IRRADIATION

CURRENT (ma)

VOLTAGE (V)
FIRST LASER ANNEALING TEST OF A PROTON IRRADIATED 50 μm SILICON SOLAR CELL

The first laser annealing test results for this contract are shown. The cell that was tested was an unglased 50 μm (2-mil) silicon solar cell. This cell was irradiated with $1 \times 10^{12}$ 2 MeV protons/cm$^2$ ($\sim 1.5 \times 10^{16}$ 1 MeV electron equiv./cm$^2$). The cell was then annealed using a 10.6 μm wavelength CO$_2$ laser. The time/temperature plots for this test are on the next chart.

After irradiation the cell degraded to approximately 74 percent of its initial output. By annealing the cell the output increased back to 83 percent of its initial power. The small amount of recovery was considered very good considering the fact that no optimization of the laser annealing parameters was accomplished prior to this test.
First Annealing Test of Proton Irradiated 50 μm Silicon Solar Cell
In the first attempt to laser anneal a 50 μm (2-mil) silicon solar cell two heating cycles were used. The reason for this is that on the first attempt the duration of the laser pulse was too short. The maximum cell temperature achieved was on the order of 400°C. The second pulse, of longer duration, achieved a cell temperature of 550°C. The time that the cell was above 500°C was on the order of 0.5 seconds. Considering the short "time at temperature" of this test the results are encouraging.
First Annealing Test
Temperature – Time Data

POWER DENSITY – 42 W/cm$^2$

# 1  TIME – 1.020 SEC
# 2  TIME – 1.183 SEC
LASER ANNEALING CONCEPT

The concept of how the annealing process would be accomplished is shown. Each laser gimbal would have 8-500 watt CO₂ lasers installed. The laser beams would be optically tailored to provide the desired illumination pattern and energy density.

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

DETAIL A
TYPICAL 667.5m BAY

DETAIL B
TYPICAL LASER ANNEALER
GIMBALED SCANNING LASER CHARACTERISTICS - UPDATE

As a result of the laser annealing tests being conducted under our current contract and after analyzing the SPIRE annealing test results from the Part III contract, the laser annealing power density and amount of equipment has been decreased by a factor of eight. Shown here are the revised laser annealing system characteristics.
Gimbaled Scanning Laser Characteristics Update

- ANNEALING ENERGY DENSITY: 16 W-sec/cm²
- POWER DENSITY: 8 W/cm²
- T_MAX (ACTIVE REGION): 550°C
- LASERS/GIMBAL: 8
- SCANNING SPOT SIZE: 500 cm² (44.0 x 11.4 cm)
- SPOT SWEEP RATE: 5.7 cm/s
- POWER REQUIRED/LASER GIMBAL: 26.7 kW
- POWER REQUIRED/GANTRY: 1.17 MW
- NUMBER OF GANTRIES/SATELLITE: 8 (1/SATELLITE MODULE)
- TOTAL ANNEALING POWER REQUIREMENT: 9.4 MW
- TIME REQUIRED TO ANNEAL ARRAY: 147 DAYS
LARGE FLARE EFFECT ON ARRAY PERFORMANCE

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

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

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

Probability of a flare large enough to cause array damage, provided a flare larger than $10^6$ protons/cm$^2$ occurs.
Shown here is a comparison of the radiation degradation characteristics of the Boeing/JSC baseline 50 μm silicon solar cell and the published RI/MSFC baseline GaAlAs/GaAs solar cell. It can be noted that very little difference in the degradation characteristics can be seen on this plot. This comparison is significantly different than the comparison made in the Rockwell documentation. The data that Rockwell used for the 2 mil silicon cell could have been that published in the TRW Radiation Handbook which is not a textured surface cell and shows significantly greater degradation.

For a proper system level trade between the Boeing and Rockwell baselines it is necessary to resolve the degradation characteristics issue.
Degradation Comparison For Electron Irradiation

- ROCKWELL GaAlAs/GaAs SOLAR CELL
- BOEING 50 µm SILICON SOLAR CELL

\[ \frac{P}{P_0} \]

1 MeV ELECTRON EQUIV. FLUENCE

0.6
0.7
0.8
0.9
1.0

0
10^{14}
10^{15}
10^{16}
DEGRADATION COMPARISON FOR PROTON IRRADIATION

This chart further shows the differences that exist between the two major SPS contractors. From this chart it would appear that silicon would have less degradation than GaAs solar cells. It is not being suggested that this is the case, however. The point that is being made is that it appears that there is not a significant difference in radiation degradation characteristics between a 50µm silicon (texturized surface) solar cell and the published Rockwell GaAs solar cell data.
Degradation Comparison For Proton Irradiation

BOEING 50 μm SILICON SOLAR CELLS
(1-10 MeV PROTON ≈ 3750 - 1 MeV ELECTRONS)

ROCKWELL GaAlAs/GaAs SOLAR CELL
(1-10 MeV PROTON ≈ 8600 - 1 MeV ELECTRONS)
Another apparent inconsistency that exists between the two major SPS contractors has to do with the model that is being used to predict the fluence \( t \) the cell will be subjected to during its 30 years of operation.

This table shows the baseline blankets for both systems in terms of amount of shielding afforded in each case. With the silicon being shielded almost twice as much as the gallium system it is doubtful that it could be subjected to a larger fluence unless the environmental models being used are significantly different.

Using the Boeing method for fluence calculations, the Rockwell 5\textmu m GaAlAs solar cell equivalent 1-MeV electron fluence would be approximately \( 6 \times 10^6 \) instead of the \( 4.9 \times 10^5 \) shown.

Again, a system level trade between the two systems should require both systems to be weighed on the same scale.
### 30 Year Fluence Comparison

<table>
<thead>
<tr>
<th>ITEM</th>
<th>BOEING</th>
<th>ROCKWELL</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELL THICKNESS (mils)</td>
<td>2.0</td>
<td>0.2</td>
</tr>
<tr>
<td>FRONT SHIELD (COVER, THICKNESS (mils)</td>
<td>BOROSILICATE GLASS</td>
<td>A12O3 (SAPPHIRE)</td>
</tr>
<tr>
<td>MASS/AREA (g/m²)</td>
<td>3.0</td>
<td>0.8</td>
</tr>
<tr>
<td>BACK SHIELD (SUBSTRATE) THICKNESS (mils)</td>
<td>BOROSILICATE GLASS</td>
<td>FEP/KAPTON</td>
</tr>
<tr>
<td>MASS/AREA/(g/m²)</td>
<td>167.6</td>
<td>79.6</td>
</tr>
<tr>
<td>30 YEAR FLUENCE (1-MeV ELECTRON EQUIV./cm²)</td>
<td>2 x 10^{16}</td>
<td>4.9 x 10^{15}</td>
</tr>
</tbody>
</table>

⚠️ BOEING MODEL WOULD PREDICT APPROX. 6 x 10^{16} 1-MeV ELECTRON EQUIV./cm²
This figure summarizes the telemetry requirements estimated for the spacecraft (solar array) portion of the satellite up to and including the slip rings, and for the MPTS antenna from the slip rings on. The estimates were prepared by examining the satellite design in detail and estimating the instrumentation required to determine the satellite state of health and to make decisions concerning commands in the event of anomalies.

For those subsystems on which very little design information exists, estimates were made based on knowledge of requirements for typical subsystems of existing satellites which were then extrapolated to a system of the magnitude of SPS.
# SPS Telemetry Requirements

## Satellite Subsystem

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Telemetry Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analog</td>
</tr>
<tr>
<td>Spacecraft</td>
<td></td>
</tr>
<tr>
<td>Solar Array</td>
<td>89,152</td>
</tr>
<tr>
<td>Attitude Control &amp; Determination</td>
<td>26</td>
</tr>
<tr>
<td>Electric Propulsion</td>
<td>656</td>
</tr>
<tr>
<td>Chemical Propulsion</td>
<td>112</td>
</tr>
<tr>
<td>Command &amp; Data Handling</td>
<td>4,805</td>
</tr>
<tr>
<td>Communications</td>
<td>30</td>
</tr>
<tr>
<td>Power Control</td>
<td>426</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>95,407</td>
</tr>
</tbody>
</table>

| MPTS Antenna                                    |        |         |         |
| Central Power Distribution                      | 1,648  | 4,120   |         |
| Power Sectors                                   | 4,560  | 131,708 | 1,140   |
| Klystrons                                       | 970,560| 485,280 |         |
| Phase Control/RF Drive                          | 679,372| 388,224 |         |
| Attitude Control & Determination                | 26      | 28      | 4       |
| Control Moment Gyros                            | 48      | 24      | 24      |
| Command and Data Handling                       | 9,194   | 18,388  | 45,970  |
| Communications                                  | 30      | 48      | 6       |
| Thermal Control                                 | 200     | 400     |         |
| **Total**                                       | 1,665,638| 1,028,220| 47,144  |
SPS COMMAND REQUIREMENTS

This figure summarizes the command requirements estimated for the satellite using the same techniques as used for estimating the telemetry requirements. This process necessitates many decisions concerning the component level to which each subsystem will be instrumented and the level to which a command capability will be provided. For example, voltage will be measured on each string in each bay and each string will have a command disconnect capability at the main power bus.

As these figures indicate, the requirements of the SPS are much greater than those of the spacecraft, however, in both cases they are much greater than those of current satellites. The magnitude of these requirements suggest that unusual measures must be taken to keep the data transmission rates relatively low.
**SPS COMMAND REQUIREMENTS**

<table>
<thead>
<tr>
<th>SATELLITE SUBSYSTEM</th>
<th>COMMAND TYPE</th>
<th>Pulse</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SPACECRAFT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOLAR ARRAY</td>
<td></td>
<td></td>
<td>19,200</td>
</tr>
<tr>
<td>ATTITUDE CONTROL &amp; DETERMINATION</td>
<td></td>
<td>84</td>
<td>32</td>
</tr>
<tr>
<td>ELECTRIC PROPULSION</td>
<td></td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>CHEMICAL PROPULSION</td>
<td></td>
<td>224</td>
<td></td>
</tr>
<tr>
<td>COMMAND &amp; DATA HANDLING</td>
<td></td>
<td>220</td>
<td>2,400</td>
</tr>
<tr>
<td>COMMUNICATIONS</td>
<td></td>
<td>54</td>
<td>200</td>
</tr>
<tr>
<td>POWER CONTROL</td>
<td></td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>THERMAL CONTROL</td>
<td></td>
<td></td>
<td>400</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>1,672</td>
<td>22,328</td>
</tr>
<tr>
<td><strong>MPTS ANTENNA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CENTRAL POWER DISTRIBUTION</td>
<td></td>
<td></td>
<td>1,848</td>
</tr>
<tr>
<td>POWER SECTORS</td>
<td></td>
<td>1,140</td>
<td>485,280</td>
</tr>
<tr>
<td>ATTITUDE CONTROL &amp; DETERMINATION</td>
<td></td>
<td>8;</td>
<td>32</td>
</tr>
<tr>
<td>CONTROL MOMENT GYROS</td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>COMMAND AND DATA HANDLING</td>
<td></td>
<td>18,388</td>
<td>9,194</td>
</tr>
<tr>
<td>COMMUNICATIONS</td>
<td></td>
<td>54</td>
<td>200</td>
</tr>
<tr>
<td>THERMAL CONTROL</td>
<td></td>
<td></td>
<td>400</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>19,690</td>
<td>496,954</td>
</tr>
</tbody>
</table>
SPS COMMAND & DATA HANDLING SYSTEM (CDHS) CONSIDERATIONS

The impact of the large numbers of telemetry points and commands required by the satellite is to make unsatisfactory the usual practice of sending all data to the ground for information and action. If this practice were followed for SPS, the data rates would be unacceptably large. In addition the data would either have to be processed, commands generated and then sent automatically after it reached the ground or extremely large numbers of ground personnel would be required.

In the recommended concept, a large amount of the automatic data processing and generation of predetermined commands will take place at the local component level in the satellite, with only summary information and configuration changes transmitted to the ground. This concept reduces the amount of data to be transmitted (hence data rates) and also reduces the number of ground personnel required.
SPS COMMAND & DATA HANDLING SUBSYSTEM (CDHS) CONSIDERATIONS

- Conventional techniques (i.e., all data to ground for processing and command decision generation) unsatisfactory due to large numbers of telemetry and command requirements
  - Extreme amounts at data through satellite and between ground and satellite
  - Large ground crews required or computer aided data review and command decision generation

- Recommended concept characteristics
  - Perform routine data review and generate predetermined commands aboard satellite with microprocessors near equipment (e.g., limit check data and switch off faulty equipment)
  - Send limited real-time data to ground when system is operating satisfactorily. All data available to ground upon request.
PRINCIPAL FEATURES OF CDHS

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

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

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

The use of fiber optics is recommended for data transmission because such a system is of lighter weight, is more fault tolerant (because it is a non-conductor it does not propagate faults), has a wide-band multiplexing capability, is inherently immune to EMI and arc discharges, and the raw materials required are in ready supply and inexpensive. It is recognized, however, that a considerable amount of development in fiber optics will be required.

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

- Performs selected data processing and command generation locally aboard Satellite using tiered system of microprocessors
- Consists basically of two systems, one for spacecraft, one for MPTS antenna, with limited data link through slip rings
- Each system has separate ground communication link
- Utilizes fiber optics for data transmission aboard Satellite
- Utilizes code format, such as Manchester II bi-phase code, which includes the clock
SPACECRAFT CDHS USING FOUR TIERS OF PROCESSORS

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

The CPU manages data traffic to and from the ground, formats telemetry for transmission and checks commands for bit errors. Other functions of the CPU include maintaining stored commands for operating and testing the data subsystem in the absence of ground control and control of telemetry data storage for later transmission.

Each tier monitors operation of the tier below, instigates check on subordinate units and establishes priority for upward communication. The lowest tier interfaces the CDHS to other subsystems through sensor readings, digital data transfers and command outputs. An upper tier may also override a command by a lower tier in order to restore operation or diagnose apparent failures if its information on the status of the RTU involved, or information from another RTU, warrants such action.
SPACECRAFT CDHS USING FOUR TIERS OF PROCESSORS

NOTES:
- RTU - REMOTE TERMINAL UNIT
- 4800 RTU's REQUIRED FOR SOLAR ARRAY
- 8 RTU's REQUIRED FOR REMAINDER OF SPACECRAFT
MPTS ANTENNA CDHS USING FIVE TIERS OF PROCESSORS

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

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

TRW

NOTES:
- RTU - Remote Terminal Unit
- RTU CONT - RTU Controller

6 SUB MODULE CONTROLLERS
UNDER MODULE CONTROLLERS #1, #2, #3
228 RTU CONTROLLERS
649 RTU'S
COMMUNICATION SUBSYSTEM CHARACTERISTICS

Separate systems for the spacecraft and MPTS antenna are recommended not only because there are separate CDHS systems which must communicate with the ground, but because the nature of the system mission (i.e., continuous provision of electrical power to the ground) demands high reliability which suggests this redundancy.

Alternative systems considered for MPTS communication were use of the retrodirective beam for the command uplink and modulation of the output of one of the klystrons for the downlink. Both of these techniques have certain advantages, however, since in the event of a relatively minor attitude control system deviation the MPTS antenna beam is deliberately despoiled, the result would be severe degradation of the communication link at a critical period of operation. For this reason a separate antenna which provides earth coverage is recommended.

As the figures indicate, the necessary performance is readily provided by an S-Band system using a 20 watt transmitter.
COMMUNICATION SUBSYSTEM CHARACTERISTICS

- SEPARATE SYSTEMS FOR SPACECRAFT AND MPTS ANTENNA
- EACH SYSTEM HAS 2 FOOT PARABOLIC ANTENNA PROVIDING EARTH COVERAGE GAIN OF 18 dB AT S-BAND
- SPACECRAFT SYSTEM ALSO HAS OMNI-ANTENNA FOR COMMAND RECEPTION IN EVENT OF LOSS OF ATTITUDE CONTROL
- TELEMETRY DOWNLINK CAPABILITY 1-10 MBPS (1 REQUIRED) AT 2.2-2.3 GHZ
- COMMAND UPLINK CAPABILITY 1-5 MBPS (1 REQUIRED) AT 2.05-2.15 GHZ
- KLYSTRON WIDE-BAND NOISE ~ 40 dB BELOW COMMAND RECEIVER THRESHOLD
SPS COMMUNICATION SUBSYSTEM

This figure shows the recommended subsystem and its interface with the CDHS. This system is very similar to existing S-Band systems hence most of the components are currently available. Information to date indicates that little or no development will be required for an SPS communication system.
SPS COMMUNICATION SUBSYSTEM

- **Central Processor Unit**
  - TLM
  - CMDS

- **Command Demodulator**
  - S-Band Receiver
  - Baseband Assembly Unit

- **S-Band Receiver**
  - Diplexer
  - Earth Coverage Antenna (2' Dish)

- **Transmitter**
  - 20 Watts
  - Spacecraft

- **MPTs Antenna**

- **SLIP RING**

---

D180-25037-7
CDHS FAILURE MODES AND EFFECTS ANALYSIS RECOMMENDATIONS

The status of hardware design of the CDHS is such that it was not possible to make such an analysis at the hardware level, however, a preliminary system analysis was made. This analysis resulted in the processor redundancy recommendations shown. At the RTU level it was recommended that the data be distributed among the RTU's such that the condition of a component can be determined from the data on two different RTU's. For example one RTU can monitor the on/off switch position of an electrical component. The temperature of that component could be monitored by another RTU. In the event one RTU failed, the status of that component could still be determined from the data of the remaining RTU. This technique also provides for a cross-check by the next level processor monitoring the RTU's.

This analysis also was an important factor in the recommendation to use fiber optics as well as the provision of earth-coverage antennas and the omni antenna.
CDHS FAILURE MODES AND EFFECTS ANALYSIS RECOMMENDATIONS

- **PROCESSOR REDUNDANCY**
  - Processors in standby redundancy at CPU and module controller level
  - Bank of spare processors at levels between RTU's and module controllers
  - Non-redundant RTU's - redundancy provided by data distribution

- **DATA BUS**
  - Use fiber optics
  - Redundant parallel bus between module controllers and CPU

- **PROCESSOR POWER SUPPLY** - Use bus with local regulation

- **SATELLITE/GROUND COMMUNICATIONS** - Use wide band (earth coverage) antenna
ELECTROMAGNETIC INTERFERENCE SOURCES CONSIDERED

The sources listed are considered to be the most likely sources of internal EMI. Very preliminary consideration of these sources indicated that corona effects and inrush currents were likely to be less severe sources than the others. Since it is not planned to operate high voltage disconnects unless the power has been interrupted previously by circuit breakers it was felt that this source would be less than would otherwise be the case. The status of information on slip rings of the size considered here and on 70 Kw klystrons is such that analysis would be of little value at this time.

Since some data is available on the DC/DC converters, and since they are a continuous EMI source, this source was selected for analysis. This very preliminary analysis indicated that the mean electric field at a distance of 6 meters from the conductors would be 20 volts/meter at 20 Khz, declining at higher frequencies. Current equipment must be designed for 10 volts/meter from 14 Khz to 35 Mhz. The mean magnetic field at the same distance would be 36 milliamperes/meter at 20 Khz. The current requirement on equipment is 2.6 microamperes per meter.
ELECTROMAGNETIC INTERFERENCE SOURCES CONSIDERED

* DC/DC CONVERTERS
  * HIGH VOLTAGE SWITCH GEAR
  * ROTARY JOINTS
  * CORONA EFFECTS
  * INRUSH CURRENTS
  * 70 KW KLYSTRONS

* SELECTED FOR ANALYSIS
MPTS Phase I Review

Erv Nałos
December 1978
MPTS STUDY AREAS

Primary areas of emphasis in Part 4, Phase I, SPS Microwave Power Transmission System studies were in the three areas defined on the attached chart. The first two high leverage items contribute to the baseline design verification, and the third item, due to its potential impact on r.f. transmitter reliability, offers a viable alternate SPS design worthy of refinement.
• PHASE CONTROL
• FAILURE ANALYSIS
• SOLID STATE SPS
MPTS PHASE CONTROL

The major accomplishments in the phase control area are summarized on this chart. A comprehensive dialogue has been established through the SPS Program Office with Lincom Inc., the designer of the baseline phase control system. A number of circuit refinements and model simulations were carried out to arrive at an improved compromise design.

The failure analysis of a 4 node system defined in conjunction with General Electric Space Division was accomplished, yielding a 3.8% efficiency degradation due to MPTS system availability.

Initial definition of a fiber-optic cabling system was defined in a supporting IR&D effort, yielding a potential 20:1 reduction in phase error due to cable temperature fluctuations. Laboratory verification is required using coherent and possibly non-coherent GaAs LED's.
MPTS Phase Control

- PHASE CONTROL CRITIQUE
  - CIRCUIT IMPLEMENTATION
  - COMPUTER PROGRAM VERIFICATION
  - DISTRIBUTION TREE LAYOUT

- FAILURE MODE ANALYSIS
  - BASELINE SYSTEM DEFINED
  - REDUNDANCY LEVEL DEFINED
  - IMPACT ON EFFICIENCY

- FIBER OPTIC CABLING FEASIBILITY
  - CONCEPT AND LINK CALCULATIONS
SPS ARRAY COMPUTER SIMULATION

In the computer simulation area, routine use is now being made of the "Tiltmain" array program in checking grating lobe levels with systematic and random tilt. The "Modmain" program, which overcomes some of the storage limitations of Tiltmain is now 65% complete, and will ultimately enable modeling the SPS array to the klystron module level (100,000 elements). The program flow of each are indicated on the attached chart, and the status of each is indicated below.

- **"TILTMAIN"**
  - Phase Control Verification
  - Grating Lobe Levels, Tilt

- **"MODMAIN"**
  - Capability to Access NASA-JSC Computer
  - Set up files for main program and subroutines

Modmain will have the following features:

- Capability to model the spacetenna down to the power module level without excessive storage requirements.
- Incorporation of variable spacing between modules.
- Capability to define level of phase control.
- More accurate modeling of grating lobe behavior

So far "Modmain" has been matched to a no-error "Tiltmain" run for a 10 m x 10 m subarray and plan for Phase 2 is to:

- Incorporate the "error" subroutine into "Modmain" and match to Tiltmain runs.
- Detail the model by changing the size and spacing of the modules. There will be ten different sizes of klystron modules corresponding to the ten step quantized illumination taper.
Computer Program Flow Comparison

CURRENT "TILTMAIN" FLOW CHART

1. INPUT (READ)
2. EXCITE ALL SUBARRAYS
3. INCORPORATE ERRORS & TILT (STORE)
4. PICK ONE GROUND POINT
5. CALCULATE PATTERN CONTRIBUTION AT EACH GROUND POINT
6. PROCEED TO NEXT POINT
7. PRINT ELECTRIC FIELD
   - NO
   - FINAL GROUND POINT
     - NO
     - CALCULATE EFFICIENCIES
     - PRINT EFFICIENCIES
     - STOP
   - YES
   - PRINT ELECTRIC FIELD
   - STOP

"MODMAIN" PROGRAM FLOW CHART

1. INPUT (READ)
2. PICK GROUND POINTS
3. EXCITE MODULE
4. INCORPORATE ERRORS & TILT
5. CALCULATE PATTERN CONTRIBUTION AT "A" GROUND POINT
6. NO
7. FINAL MODULE
8. PRINT ELECTRIC FIELD
9. CALCULATE EFFICIENCIES
10. PRINT EFFICIENCIES
11. STOP
Typical grating lobe level amplitudes are illustrated as a function of distance from the rectenna. The design requirement of 1 arcmin. of systematic tilt are derived from these, to meet the Soviet microwave level standard at the first grating lobe. The random tilts have only second order effect on grating lobe levels and affect primarily the array scanning loss.

The baseline 1 arcmin. random tilt, combined with the above systematic tilt, will combine to give a 0.5% efficiency loss for a 10 m x 10 m subarray. Going to a 5 m x 5 m subarray would allow the tilt requirement to be relaxed to 2 arcmin. systematic and 2 arcmin. random for the same scanning loss of 0.5%.
Grating Lobe Peaks Produced by Systematic Spacetenna Tilt

Grating Lobe Number

dB Down from Main Beam

Rectenna Radial Distance in Kilometers

441.5 ± 0.5 km

4 arc min

2 arc min

1 arc min

0.5 arc min
A number of "Tiltmain" runs were made to check some available aspects of the Lincom "Solarsim" program, of which the attached curve is typical. For the use of a 10 m x 10 m subarray, both one dimensional and two dimensional "Tiltmain" runs checked well with the Lincom results, provided that surface irregularity error were accounted for in a similar manner.
Comparison of Array Performance Degradation with Tilt

Legend

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

- BOEING "TILTMAIN" RESULTS
  1. 3 arcmin SYSTEMATIC TILT
     3 √2 arcmin RANDOM TILT
  2. 3 √2 arcmin SYSTEMATIC TILT
     3 √2 arcmin RANDOM TILT
  3. 3 √5 arcmin SYSTEMATIC TILT
     3 √2 arcmin RANDOM TILT
     Surface ε = .01λ corresponds to 1/2% power loss
EFFECT OF PHASE ERROR AND TILT ON BEAM SHAPE

From the designer's point of view, it is important to estimate the effects of various phase control system errors near the rectenna. The attached chart does this in a qualitative manner. One fallout is the fact that correlated phase errors may not be of great importance in a system that has more than, say, ten branches per node.
Effect of Phase Error and Tilt on Beam Shape

PHASE ERROR BUILDUP

- UNCORRELATED ERRORS
  - NO EFFECTS ON MAIN BEAM SHAPE
  - FAR-OUT SIDELOBE LEVEL PLATEAU INCREASED

- CORRELATED PHASE ERRORS
  - FEW BRANCHES (4) AT FIRST/SECOND LEVEL
    - SLIGHT RANDOM WANDER OF MAIN Beam
    - BEAM BROADENED BY 4% (95% CONFIDENCE)
  - MANY BRANCHES
    - PROBABLY NEGLIGIBLE

ANTENNA TILT

- SYSTEMATIC TILT
  - MAIN BEAM SHAPE UNAFFECTED BUT
    - POWER REDUCED BY SCAN LOSS WHICH APPEARS AT GRATING LOBES

- RANDOM TILT
  - MAIN BEAM SHAPE UNAFFECTED;
    - RESULTING AMPLITUDE MODULATION CAN RAISE ERROR PLATEAU
• Failure Analysis

• Impact On Efficiency
POTENTIAL PHASE DISTRIBUTION TREE LAYOUTS

The detailed layout of the phase distribution system will depend on the results of a trade study of correlated and uncorrelated phase error buildup per node; redundancy/reliability/ and level at which phase control is exercised. The nine node system suffers from poor reliability, poor phase randomization (i.e., resulting correlated phase errors which produce beam pointing errors) and lowest allowable phase error per node. The four node system may be a viable candidate if 10 m x 10 m subarrays are retained and phase control is exercised down to the klystron level. A three node system may be possible if phase control is exercised at the subarray level only, and subarray size is reduced to 5 m x 5 m.

To reduce phase correlation effects, i.e., beam steering errors, the number of branches at the lower levels should be kept high. This also allows higher random phase error per level in the error budget. Even with 4 m x 4 m subarray, the 4-level system will require a total (1 GHz) phase accuracy of 2° per level to achieve a 96% efficiency including tilt. This will require stringent design criteria. A possible 3 m x 3 m subarray could be accommodated by a 32 x 16 x 16 x 8 four node distribution system. Phase error buildup affects only far-out low level sidelobes, i.e., does not constitute a major environmental problem.
Potential Phase Distribution Tree Layouts

- **4-NODE SYSTEM — 7,220 SUBARRAYS, 100,000 KLYSTRON MODULES**
  - 10 m SUBARRAY
  - 9.5 db TAPER
  - 4:1 @ EDGE (6.9 m AVG. CABLE LENGTH)
  - 36:1 @ CENTER
  - 250 m ~250 m
  - TRIPPLY REDUNDANT
  - DOUBLY REDUNDANT
  - PRINTED CIRCUIT N-WAY DIVIDERS

- **3-NODE—32 BRANCH SYSTEM — 28,880 SUBARRAYS**
  - 5 m SUBARRAY
  - 9.5 db TAPER
  - 32
  - 9 NODE — 4 BRANCH SYSTEM

- **4-NODE—13 BRANCH SYSTEM — 28,880 SUBARRAYS**
  - 13
  - 262,144 ELEMENTS
FOUR NODE PHASE DISTRIBUTION SYSTEM LAYOUT

Three sections are shown of the 4 node system selected for reliability analysis by the General Electric Co. This layout uses 20 triply redundant sections at the first level, 19 doubly redundant paths at the second level, and 19 non-redundant paths (cable and electronics) at the third level (i.e., 7220 subarrays). The fourth level provides power dividers down to the klystron module (4:1 at the center and 36:1 at the array edge), to accommodate the quantized 10 db Gaussian power taper indicated in the chart.
LOCATION OF REFERENCED PHASE REPEATER STATIONS OF SECTORS AND GROUPS
RELIABILITY CALCULATIONS

The MTBF values assigned to each component in the phase distribution path are indicated. These values, together with the redundancy level selected, and the selected maintenance procedure assumed, lead to availability numbers detailed in the Part 4, Phase I, Final Report, Dec. 14, 1978, General Electric Space Division. The overall impact of the failure analysis on efficiency is summarized in the table below.

<table>
<thead>
<tr>
<th>Component</th>
<th>Availability, %</th>
<th>Efficiency, η</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Control</td>
<td>.989</td>
<td>.978</td>
<td>Power &amp; Beam Loss</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Redundant 1st, 2nd Level</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Conjugator, Receiver</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6 Months Maintenance</td>
</tr>
<tr>
<td>Klystron &amp; Driver</td>
<td>.98</td>
<td></td>
<td>No Redundancy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Previous</td>
<td>25 Year MTBF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Budget</td>
<td>6 Month Maintenance</td>
</tr>
<tr>
<td>Rectenna</td>
<td>.984</td>
<td>.984</td>
<td>Diodes Non-redundant</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DC Panel Open/Short Circuit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Continuous Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.8%</td>
<td></td>
<td>Microwave Related</td>
</tr>
<tr>
<td></td>
<td>5.1%</td>
<td></td>
<td>Total MPTS</td>
</tr>
</tbody>
</table>

Note that for the phase control system failure, there is a double penalty: array thinning (% availability), and associated loss of power, since the klystrons are not radiating in the main beam direction. The 5.1% figure includes efficiency degradation due to bussbar failures on the space antenna and the rectenna.
BLOCK DIAGRAM FOR
RELIABILITY CALCULATIONS

FAILURES ARE SHOWN
IN ONE FAILURE PER
10^6 HRS UNITS
For purposes of illustration, a layout of the klystron module is indicated. It shows possible locations of the solid state phase control modules for good thermal distribution. The selection of a pilot receiving antenna has not been finalized and is indicative of an approach to be considered to achieve good isolation in a system in which the power beam and pilot beam are at the same frequency. The radiator is indicative only and is not representative of an alternate lower mass active cooling system under consideration.
MECHANICAL LAYOUT OF A TYPICAL KLYSTRON MODULE IN THE OUTER RING OF THE SPACE ANTENNA
KLYSTRON MODULE THERMAL CONTROL SYSTEM

CHARACTERISTICS

Failure analyses also indicated a problem with the heat-pipe-cooled klystron. The difficulty was that the $500^\circ$C segment would utilize a mercury vapor heat pipe. In the event of a meteoroid puncture or other leak, the liquid metal would be released into the high voltage environment of the transmitter system and lead to arcing and damage. Plating of liquid metals on insulators might lead to a permanent damage situation that would require repair and replacement. Vought Corporation examined a circulating fluid cooling option and found that a mass reduction was possible and that fluids could be selected that would minimize risk of arcing. Their analysis indicates that a circulating fluid system can be made as reliable as the heat pipe system and certainly more reliable than the expected lifetime of the klystron themselves. The facing page shows principal features of the circulating fluid system for the klystron cooling circuit.
## Klystron Module Thermal Control System Characteristics

### Table: Thermal Control System Characteristics

<table>
<thead>
<tr>
<th></th>
<th>500°C</th>
<th>300°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MATERIAL</strong></td>
<td>COPPER</td>
<td>COPPER</td>
</tr>
<tr>
<td><strong>FLUID</strong></td>
<td>STEAM @ 20 ATM</td>
<td>DOWTHERM-A</td>
</tr>
<tr>
<td><strong>INLET TEMP</strong></td>
<td>477°C</td>
<td>277°C</td>
</tr>
<tr>
<td><strong>OUTLET TEMP</strong></td>
<td>413°C</td>
<td>260°C</td>
</tr>
<tr>
<td><strong>LENGTH X WIDTH</strong></td>
<td>0.57m x 1.61m</td>
<td>1.04m x 1.61m</td>
</tr>
<tr>
<td><strong>TUBE SPACING</strong></td>
<td>3.7 cm</td>
<td>2.84 cm</td>
</tr>
<tr>
<td><strong>TUBE DIAMETER</strong></td>
<td>5.6 mm</td>
<td>1.27 mm</td>
</tr>
<tr>
<td><strong>TUBE THICKNESS</strong></td>
<td>0.886 mm</td>
<td>0.71 mm</td>
</tr>
<tr>
<td><strong>FIN THICKNESS</strong></td>
<td>0.163 mm</td>
<td>0.066 mm</td>
</tr>
<tr>
<td><strong>EMISSIVITY</strong></td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>ABSORPTIVITY</strong></td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>TSINK</strong></td>
<td>36.3°C</td>
<td>36.8°C</td>
</tr>
<tr>
<td><strong>PUMP EFFY.</strong></td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>FIN EFFECTIVENESS</strong></td>
<td>0.894</td>
<td>0.920</td>
</tr>
<tr>
<td><strong>AREA</strong></td>
<td>0.91 m²</td>
<td>1.67 m²</td>
</tr>
<tr>
<td><strong>MASS/MODULE</strong></td>
<td>7.95 kg</td>
<td>5.13 kg</td>
</tr>
</tbody>
</table>

**Current Mass/Module:** 13.18 kg  
**Part III Mass/Module:** 18.88 kg
ANTENNA WAVEGUIDE MATERIAL

Although the plated composite approach is probably a high risk based on today's knowledge because of potential breaks or delamination of the plating under thermal cycling or high RF power conditions, the cost advantages of a low-coefficient-of-thermal-expansion material are sufficient that development of a suitable such approach for waveguides should be identified as a priority development item for SPS.
Antenna Waveguide Material

- Low CTE-plated composite detuning loss is 0.2% compared to 1.3% for aluminum.

- Cost of 1% efficiency loss is $75 million per 5-GW SPS.

- Plated composite as high-risk, based on today's knowledge.

- Recommend using low-CTE characteristics for waveguide performance and mass; flag development of suitable material as high-priority research item.
Included in the analysis of aluminum structural options was the analysis of use of aluminum for the waveguides in the transmitting antenna. Aluminum has a high coefficient of thermal expansion compared to the graphite used in the earlier baseline. As a result, due to expected temperature changes, the aluminum waveguides will be significantly detuned resulting in power losses as tabulated on the facing page.
Comparison of Losses for Metal & Composite Waveguide

- AVERAGE STICK = 2.76 METERS
- $\Delta T = 55\,^\circ\text{C}$

<table>
<thead>
<tr>
<th>PERCENT POWER LOSS</th>
<th>ALUMINUM</th>
<th>COMPOSITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>STICK LENGTH</td>
<td>.67</td>
<td>.02</td>
</tr>
<tr>
<td>STICK WIDTH</td>
<td>.42</td>
<td>.12</td>
</tr>
<tr>
<td>CROSS GUIDE LENGTH</td>
<td>.17</td>
<td>.02</td>
</tr>
<tr>
<td>CROSS GUIDE WIDTH</td>
<td>.11</td>
<td>.03</td>
</tr>
<tr>
<td></td>
<td>1.37%</td>
<td>.19%</td>
</tr>
</tbody>
</table>
COMMENTS ON NOMINAL EFFICIENCY CHAIN - MPTS

The effect on the overall MPTS efficiency is summarized for the case of aluminum waveguide and the baseline tilt requirements. (1 arcmin systematic tilt to control grating lobe levels, and 1 arcmin random tilt to limit total scanning loss to .5%). The additional efficiency reduction due to metal waveguide and failures in the baseline design is \((1.18 + 3.8) = 4.98\)% for the 10 m x 10 m subarray if tilt remains as above. Further refinements in the rectenna subsystem efficiency values are indicated as subject for Phase 2 studies.
Comments on Nominal Efficiency Chain—MPTS

- CURRENT BUDGET BASED ON COMPOSITE WAVEGUIDE

- SYSTEMATIC TILT 1.75 ARCMIN, NO RANDOM TILT

<table>
<thead>
<tr>
<th></th>
<th>EFFICIENCY DEGRADATION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10M X 10M</td>
</tr>
<tr>
<td>ALUMINUM WAVEGUIDE</td>
<td></td>
</tr>
<tr>
<td>TILT</td>
<td></td>
</tr>
<tr>
<td>2 ARC MIN SYSTEMATIC</td>
<td>1.18%</td>
</tr>
<tr>
<td>2 ARC MIN RANDOM</td>
<td>2.7%</td>
</tr>
<tr>
<td>RECTENNA</td>
<td>TBD</td>
</tr>
<tr>
<td>FAILURES</td>
<td>3.8%</td>
</tr>
<tr>
<td>( \Delta \eta )</td>
<td>7.68%</td>
</tr>
</tbody>
</table>
The potential advantages of a fiber optic cable for phase distribution are indicated, possibly with the use of a coherent laser emitter or a non-coherent LED emitter. The elements are identified below, with a sample link calculation.
Fiber Optic Design Considerations for SPS Phase Control Distribution

- INCOHERENT LIGHT EMITTING DIODE
  - ONE EMITTER CAN ILLUMINATE BUNDLE OF >100,000 FIBERS
  - REDUNDANT LED EASY TO IMPLEMENT

- MULTIMODE GRADED INDEX FIBER
  - LOSS OF 10 DB/KM COMPATIBLE WITH SPS ($6 PER METER)
  - POTENTIALLY GOOD RADIATION RESISTANCE
  - CABLE BUNDLE ≈ 2.5” FOR DUAL FIBER REDUNDANCY (~200,000 FIBERS)

- SAMPLE LINK CALCULATION

  POWER DIVISION LOSS ≈ 55 db
  FIBER LOSS ≈ 5 db
  FOR 1 mw RADIATED POWER, RECEIVED POWER IS = -60 dbm = 1 nwatt
  AVALANCHE DIODE RECEIVER WILL HAVE S/N > 20 db @ THIS LEVEL FOR 5 MHz BANDWIDTH.
A potential layout, suitable for accommodating up to 200,000 fibers is indicated, illuminated by a LED or semiconducting (GaAs) laser array of several milliwatts output.
Fiber Optic Distribution System Concept

IF REFERENCE SIGNAL
@ CENTER ARRAY

REdundant Array of Light Emitting Diodes
(20 Diodes 0.1 mw EC
(20 Diodes 0.1 mw EACH TYP.)

Hexagonal Bundle
Contains 61 Hexagons (.045" Dia)
Each with 61 Fibers (.005 Each)
5 MILS EACH

HEMISPHERICAL SECTION
61 CABLES, 226,981
.005"
D = d (.94 + \sqrt{\frac{N - 3.7}{.907}}) = 2.27"

Constant Length Fiber Optic Cable

61 Fibers

3721 Fibers

30 Groups of 2 Fibers

Avalanche Diode Envelope Detector
Recovered IF Reference Signal
A comparison of phase delay for a conventional cable and fiber optic cable indicates a potential reduction in phase change of nearly 20:1, as well as cabling mass and cost reductions.
Comparison of Coaxial and Fiber Optic System

<table>
<thead>
<tr>
<th>ATTENUATION (100 Milz)</th>
<th>COAXIAL CABLE</th>
<th>OPTICAL FIBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RG-58 SOLID DIEL.</td>
<td>~5 MIL DIA (85 µm ACTIVE CORE)</td>
</tr>
<tr>
<td>db/km</td>
<td>180 db</td>
<td>5</td>
</tr>
<tr>
<td>MASS (kg/km)</td>
<td>43</td>
<td>.5</td>
</tr>
<tr>
<td>COST ($/km)</td>
<td>2,000</td>
<td>1500 (1978)</td>
</tr>
<tr>
<td>PHASE DELAY (120°/METER)</td>
<td>(ε=1.0, λg=3m)</td>
<td>(ε=1.5 λg=2m)</td>
</tr>
<tr>
<td>LINEAR EXPANSION</td>
<td>18.5x10^-6/k</td>
<td>5.5x10^-7/k</td>
</tr>
<tr>
<td></td>
<td>(COPPER)</td>
<td>(QUARTZ)</td>
</tr>
<tr>
<td>PHASE CHANGE FOR ΔT=450°C L=300m</td>
<td>89.1°</td>
<td>4.46°</td>
</tr>
</tbody>
</table>
SOLID STATE DEVICE ASSESSMENT FOR SPS

Progress in Part 4, Phase I, emphasized areas dealing with:

- Device Assessment
  - GaAs FET
  - Switched Mode
  - Initial Noise Analysis

- Power Module Concept
  - Strip Line Cavity Radiator
  - Low Loss Combiner
  - 3-Stage Amplifier Design

- SPS Integration
  - Subarray Layout
  - SPS Sizing Trade Study
  - Power Conditioning Initiated
  - Initial Reliability Assessment
FINDINGS

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

ISSUES

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

The device selection of a GaAs Field Effect Transistor (FET) was based on a thorough review of the state of the art of various solid state devices, discussions with NASA-JSC, RCA, and other industries. The power level of 5 watts per device is considered realistic for the SPS time frame.
Solid State CW Power Status—1978

**Legend**

- **2 Terminal Devices**
  - IMPATT—Multi-Mesa
  - IMPATT
  - GUNN

- **3 Terminal Devices (Transistors)**
  - GaAs MESFET
  - Silicon Bipolar

**Graph**

- **CW Power, Watts** vs **Frequency, GHz**
- **Single Packaged Devices**
- **Legend**
  - **η**
    - < 36%
    - < 10%
    - ≈ 67%
    - ≈ 50%
SWITCHING AMPLIFIER STATUS

To achieve efficiencies in excess of 70%, it will be necessary to consider the switched mode of operation where efficiencies in excess of 90% were obtained below 100 MHz. The implementation of these techniques at microwave frequencies will have to be accomplished as part of a proposed experimental task.
Switching Amplifier Status

EFFICIENCY:  

- > 95% AT 10 MHZ
- > 90% AT 100 MHZ

ACTIVE DEVICE:  

CAN USE BIPOLAR TRANSISTOR OR FET

MICROWAVE IMPLEMENTATION

NEEDS LABORATORY VERIFICATION
MICROSTRIP WITH COMMERCIAL FET INTO TERMINATION
MEASURE EFFICIENCY, SPECTRUM, AND SENSITIVITY TO POWER SUPPLY VARIATIONS.
The failure statistics indicated in the attached chart show that at a channel temperature of 135°C, 98% of the devices will still be operating after 30 years. This suggests that a no-maintenance mode of operation may not be unfeasible. Even if a single FET failure in a power module consisting of 8 output FET's (say 4 watts each) constituted a total loss of the entire module (no graceful degradation), the operation of such modules at 125°C would result in 2% loss after 30 years, compatible with SPS failure rate budget.
Solid State Device Lifetime

- GaAs FET
- 30 YEAR MAINTENANCE
- LOG NORMAL FAILURE DISTRIBUTION

$\sigma = 1$

JUNCTION TEMPERATURE, °C

DEVICES MTBF, HOURS

1978 RELIAB. PHYSICS SYMP.
With a 70% production rate improvement curve (i.e., units produced at the rate of $2n$ per year cost 70% as much as units produced at the rate of $n$ per year), cost per unit power for GaAs FETS is about the same as the projected cost per unit power for klystrons.
Solid State Device Mature Industry Costing

The graph illustrates the relationship between the number of devices per year and the specific cost per watt. It shows two lines representing different cost reductions: 0.7/OCTAVE and 0.8/OCTAVE. The projected SPS is indicated by a shaded area. The x-axis represents the number of devices per year, ranging from $10^2$ to $10^{10}$, and the y-axis represents the specific cost, ranging from $10^2$ to $10^3$. The graph indicates that as the number of devices increases, the specific cost decreases.
A proprietary module was identified in an associated IR&D program, in which low-loss combining in a cavity type microstrip radiator was achieved. Such a module would use 6 three-stage amplifiers with a 5 watt output stage, totaling 30 watts per module. Further module feasibility tests have been proposed.

A subarray would consist of 144 panels, each panel consisting of 3 strings in parallel, each string consisting of 12 rows in series, and each row of 4 modules in parallel. The subarray would operate at approx. 2 Kv and radiate 622 Kw of r.f. power.
30W POWER MODULE
15V, 59 λ x .59 λ

ROW = 4 MODULES IN PARALLEL

PANEL = 3 STRINGS IN PARALLEL
LEAST REPLACEABLE UNIT
4.32 kW
180 V
3.07 KG
.75 M²

STRING = 12 ROWS IN SERIES

SUBARRAY = 144 PANEL MATRIX
LEAST SWITCHABLE UNIT
2.16 KV, 622 KW, 442 KG

COMPONENT MASS PER UNIT AREA (KGM⁻²)

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>MASS PER UNIT AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃ DIELECTRIC</td>
<td>1.99</td>
</tr>
<tr>
<td>Al, INCLUDING RADSHIELD</td>
<td>1.39</td>
</tr>
<tr>
<td>PHASE FEED AND INTRASUBARRAY STRUCTURE</td>
<td>.70</td>
</tr>
<tr>
<td>MPTS SECONDARY STRUCTURE</td>
<td>.72</td>
</tr>
<tr>
<td>MPTS PRIMARY STRUCTURE</td>
<td>.07</td>
</tr>
<tr>
<td>TOTAL</td>
<td>4.87</td>
</tr>
</tbody>
</table>
A nomograph has been developed as a useful design tool to determine potential solid state SPS design parameters. For an 80% efficient GaAs FET and a device temperature of 125°C, a thermal limit of 3-5 kW r.f. radiated per m² is indicated. A nominal design of 2 GW with a 1.5 km diameter space antenna corresponds to this value, for the ionospheric heating limit of 23 mW/cm² and the nominal SPS efficiency chain. Uniform illumination would not be of any advantage in such a design.
COMPARATIVE CALCULATION OF GROUND NOISE

A preliminary noise analysis near the operating frequency does not indicate a significant advantage for the solid state design, since good oscillators are about at the same level of -160 dBc/Hz as are electron tubes of the klystron type. It is, however, possible to spread this ground noise over a larger area, since the solid state module can be made smaller than a klystron module, and the noise is incoherent (i.e., radiates independently from each module). The attached table shows calculations of the type made by NASA-JSC for the klystron, and indicates a level 14 dB lower for the solid state design for the parameters chosen. Harmonic radiation was not considered in this analysis.
Comparative Calculation of Ground Noise

**SOLID STATE**

\[ P_N = 3.5 \times 10^5 \times 10^{-16} = 3.5 \times 10^{-7} \text{ W/Hz} \]

\[ G_N = 4\pi AN/\lambda^2 = 308 \]

\[ N = 0.5 \text{ COHERENCY FACTOR} \]
\[ \text{AREA} = (7\lambda)^2 \]

**NOISE SPECTRAL DENSITY**

\[ P_N G_N / 4\pi R_0^2 \]

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

**EXTERNAL FILTER CAN PROVIDE ADDITIONAL ATTENUATION**

**KLYSTRON**

\[ P_N = 7 \times 10^9 \times 10^{-16} = 7 \times 10^{-7} \text{ W/Hz} \]

\[ G_N = 3650 \text{ FOR AV. AREA PER KLYSTRON OF 8.7 m}^2 \]

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

**MULTIPLE CAVITY DESIGN PROVIDES 24db/OCTAVE ATTENUATION**
The footprint of the incoherent noise contributions is indicated and compared with that of a klystron module.
Incoherent Noise Power Distribution

KLYSTRON DESIGN—5 GW, 1 km
CENTER MODULE FOOTPRINT 3.6° (1.73 m)
EDGE MODULE FOOTPRINT 1.2° (5.2 m)

SOLID STATE—2.5 Gw, 1.4 km
4.32 Kw PANEL GROUP FOOTPRINT (144–30 WATT UNITS) 7° (.85 m)

RECTENNA

SPS-2346
SOLID STATE POWER SUPPLY OPTIONS

Solid state devices suitable for microwave power amplification operate at voltages on the order of 25 volts. Distribution voltages suitable for SPS application range from 20,000 to 40,000 volts. If it were necessary to process all this power down to a voltage of 25 volts, the cost and efficiency of power processing combined with the $I^2R$ losses and conductor mass for such operations might be prohibitive. Therefore, an approach to elimination of power processing is highly desirable and constitutes the first option identified, Direct High Voltage DC (DHV DC). An aspect of this approach is series-parallel connection of the microwave power amplifiers (as regards DC power supply) similar to that used for solar cells in generation of the DC power. Aggregate sets of microwave power generators can then be supplied at comparatively high distribution voltages. This option raises concerns regarding stability, matching, and balance of the power supply and control network.

The minimum risk option is use of DC/DC converters but this will result in significantly greater SPS mass and cost.

AC power distribution may provide a means of minimizing distribution losses and reducing solar array voltage. Mass and cost penalties will be similar to those for full DC/DC processing.
DIRECT HIGH VOLTAGE DC

REQUIRES SUBARRAYS IN SERIES
CONNECTION TOPOLOGY A PROBLEM
HIGH E-FIELDS NEAR ADJACENT SUBARRAYS
MAY CAUSE ARCS, WILL SUSTAIN THEM

DC-DC CONVERSION CON MPTS

PERFORMANCE PENALTIES
DC-DC CONVERTERS ≈ 1kg/kw
POWER LOSSES IN CONVERTERS
SERIES/PARALLEL CONNECTIONS WITHIN
SUBARRAYS STILL REQUIRED

AC POWER DISTRIBUTION

CONVERT
DC/AC ON SOLAR ARRAY
AC/DC AT SUBARRAY
REQUIRES S/P TO SOME EXTENT ON SUBARRAY
SERIES - PARALLEL INTERCONNECTION

RELIABILITY ASPECTS

The assumptions for an initial reliability analysis are stated and concerns dealing with AC transients and stability are defined for further effort.
Series -Parallel Interconnection
Reliability Aspects

- Direct current reliability
  - Single or double failures must not take system down
  - Adequate reliability if devices can take 20% overvoltage

- Turn-on transients
  - Strings of panels like transmission line
  - No problem with $\tau > 10^{-6}$ s

- Alternating current stability
  - Oscillations due to coupling between modules
  - Suppress via damping
STRING RELIABILITY ANALYSIS CONFIGURATION

The string configuration is defined for the reliability analysis as consisting of 96 amplifiers, in 12 rows of 4 modules, where each module has 2 output amplifiers, each with 3 output devices.
String Reliability Analysis Configuration

SERIES STRINGS OF 12 ROWS
4 MODULES PER ROW
2 AMPLIFIERS PER MODULE

SINGLE AMPLIFIER FAILURE PROBABILITY = \( F_p \)

IF \( > N \) AMPLIFIERS PER ROW FAIL STRING GOES DOWN

DESIRED RESULT IS STRING FAILURE PROBABILITY, \( F_S \), AS A FUNCTION OF \( F_p \) AND \( N \)

REWORK DESIGN UNTIL \( F_S << F_p \)
SERIES - PARALLEL STRING FAILURE

The initial results of the reliability analysis indicate that, for the case where 2 amplifiers per row may fail and still maintain an acceptable overvoltage, the string failure rate can be made much lower than the amplifier failure rate for cases where the amplifier is highly reliable. For example, the probability of string failure is 10X lower than amplifier failure at F_p = 0.04. This will be even more dramatic for lower F_p's.
Series—Parallel String Failure

PROBABILITY OF AMPLIFIER FAILURE \( F_p \)

PROBABILITY OF STRING FAILURE \( F_S \)

1 AMPLIFIER MAY FAIL

2 AMPLIFIERS MAY FAIL
Further progress in the reliability analysis is contingent upon understanding of how overvoltages/overcurrents in a string are to be managed. The matrix chart illustrates some options which are currently being investigated and are subject for further studies in Phase 2.
<table>
<thead>
<tr>
<th></th>
<th>MODULE</th>
<th>ROW</th>
<th>STRING</th>
<th>PANEL</th>
<th>SUBARRAY</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNDERVOLTAGE</td>
<td>NO RESPONSE</td>
<td>NO RESPONSE</td>
<td>NO RESPONSE</td>
<td>NO RESPONSE</td>
<td>NO RESPONSE</td>
</tr>
<tr>
<td>OVERVOLTAGE</td>
<td>NO RESPONSE</td>
<td>OPEN ON 1.2X LOAD ON 1.05X</td>
<td>NO RESPONSE</td>
<td>OPEN AND LOAD ON 1.2X</td>
<td>OPEN AND LOAD ON 1.15X</td>
</tr>
<tr>
<td>CURRENT LOW</td>
<td>NO RESPONSE</td>
<td>NO RESPONSE</td>
<td>NO RESPONSE</td>
<td>NO RESPONSE</td>
<td>NO RESPONSE</td>
</tr>
<tr>
<td>EXCESSIVE CURRENT</td>
<td>FUSE ON 3X</td>
<td>NO RESPONSE</td>
<td>FUSE ON 2X OPEN ON 1.5X LOAD ON 1.4X</td>
<td>OPEN ON 1.6X</td>
<td>OPEN ON 1.6X</td>
</tr>
</tbody>
</table>

All failures should become open or soft.
TURN-ON TRANSIENTS

It has been ascertained by the use of a small computer program, that turn-on transients will not be troublesome, provided turn-on times of $>10^{-6}$ seconds are used.

The assumed unbalanced reactance $C^* = 2C$ and values of $R, L, C$ selected are estimates considered representative of current knowledge of the solid state module.
**Turn-On Transients**

- **CONSIDER STRINGS OF AMPLIFIERS AS RLC NETWORK**

  4 MODULE STRING, $V_0 = 60$ V

  ![RLC Network Diagram](image)

- **ROUGH ESTIMATES FOR SOLID STATE MODULES**

  ARE $C = 500$ PF, $L = 3\mu$ H, $R = 7.5$ Ω.

- **IF REACTANCES ARE UNBALANCED (FOR INSTANCE, IF $C = 2C$) AND TURNON IS FAST ($\tau = 10^{-8}$ s) RINGING AT SEVERAL MHZ OCCURS. SLOWER TURN-ON TIMES ($\tau = 10^{-6}$ s) LARGELY ELIMINATE THIS PROBLEM.**

- **SINCE $L/R >> \sqrt{L/C - C}$ MAXIMUM VOLTAGE ACROSS $R$ DOES NOT EXCEED NOMINAL.**

- **HOWEVER, RINGING MODULATES VOLTAGES ON WAY UP TO FULL VOLTAGE. MAY CAUSE SIDEBANDS DURING TURNON.**
The solid state transmitter is limited by maximum allowable device temperature to a thermal dissipation of roughly 1.5 kilowatts per square meter. At a conversion efficiency of 80% with a 10 dB Gaussian taper, the thermal constraints and ionosphere power density constraints follow characteristics curves as illustrated on this map of SPS power cost indicators versus transmitter diameter and power level. As can be seen, the solid state system is constrained to a total power level of approximately 21 gigawatts with a transmitter aperture of 1.4 kilometers. Thus, this system is well-suited to the smaller size lower power SPS application and, in fact, may be limited to such lower power transmitter links.
Representative Solid State SPS Costs and Sizing

COST OF SPS ELECTRICITY (mils/kwh)

MAXIMUM THERMAL RADIATION

\[ \eta_{DC-RF} = 0.8 \]

ASSUMPTIONS:

- DC-RF = 0.8
- Power processing

TRANSMITTING ANTENNA DIAMETER (km)
MPTS Phase II Recommendations

- **PHASE CONTROL**
  - Optimum Subarray Size
  - Firm up Distribution Tree
  - Refine Failure Analysis
  - Laboratory Feasibility
  - Fiber optic demonstration
  - Waveguide stick tests
  - Develop "MODMAIN" computer simulation

- **SOLID STATE**
  - Integrate power module into SPS design
  - Structural Interface
  - Complete development plan
  - Alternate circuit/radiator concepts
  - Lightweight substrate
  - Reliability of interconnection methods

- **RECTENNA**
  - Define RF collection circuit criteria
  - Select best option
  - Define collection efficiency chain
  - Complete failure mode analysis
  - Improved development plan
PART 4 - PHASE 1 PRESENTATION

- SPACE ANTENNA
  - DC POWER DISTRIBUTION AND RF PHASE CONTROL LAYOUT
  - PHASE CONTROL SYSTEM FAILURE MODES AND EFFECTS ANALYSIS
  - PHASE DISTRIBUTION SYSTEM MAINTENANCE ANALYSIS
- RECTENNA SYSTEM
  - ANTENNA LAYOUT
  - POWER CONDITIONING LAYOUT
  - FAILURE MODES AND EFFECTS ANALYSIS
  - MAINTENANCE ANALYSIS
SPACE ANTENNA DC POWER DISTRIBUTION AND RF REFERENCE PHASE DISTRIBUTION SYSTEM

The conceptual mechanical layout of the DC power distribution and RF reference phase distribution was developed during the Part IV, Phase I Study. The summary displays some of the most important results.
SPACE ANTENNA DC POWER DISTRIBUTION
AND RF REFERENCE PHASE DISTRIBUTION SYSTEM

SUMMARY

- DC DISTRIBUTION IS USING 228 MAIN SECTOR LINES AND AN AVERAGE OF 446 KLYSTRON LINES ATTACHED TO EACH SECTOR LINE.
- DC TO DC CONVERTERS MUST BE REDUNDANT FOR ACCEPTABLE DC POWER AVAILABILITY.
- FOUR LAYER REFERENCE PHASE DISTRIBUTION NETWORK IS USED WITH 20, 19 AND 19 BRANCHES AT THE CONSECUTIVE NODES (SECTOR, GROUP, SUBARRAY, KLYSTRON). THE POWER DIVISION AT THE LAST (KLYSTRON) LEVEL IS DETERMINED BY THE NUMBER OF KLYSTRONS PER SUBARRAY.
- THE PHASE DISTRIBUTION AND CONJUGATION PROCESS IS COMPLETELY SEPARATED.
- TRIPLE REDUNDANCY IS USED IN THE FIRST AND DOUBLE REDUNDANCY IN THE SECOND LAYER OF THE PHASE DISTRIBUTION TREE.
- THE ELECTRONIC CIRCUIT CONCEPT IS AS PER RECOMMENDATIONS OF THE LINCON REPORT.
DISTRIBUTION OF DC SECTOR LINES FOR THE SPACE ANTENNA

A total of 228 main DC lines enters into the space antenna each carrying about 35 MW power. On the average 11.4 lines serve an 18° wide pie sector of the aperture.
DISTRIBUTION OF DC SECTOR LINES FOR THE SPACE ANTENNA

1 DC INPUT LINE

11 DC INPUT LINES

20 SECTORS

361 SUBARRAYS PER SECTOR

11.4 D-C LINES PER SECTOR

114 DC INPUT LINES

114
The DC sector lines and their $J_1$ end junctions within a typical sector of the space antenna are distributed in such a manner that the density of the junctions correspond to the density of the klystrons over the antenna area. On the average a main DC line serves 31.67 subarrays or 446 klystrons.
DISTRIBUTION OF DC SECTOR LINES WITHIN 1 OF 20 SECTORS

SECTOR INPUT LINES

116

- 114

114

112

NOMENCLATURE

N WAY DIVIDER TOWARD SUBARRAYS (JUNCTION)
SA/I = SUBARRAY PER SECTOR LINE
KL/I = KLYSTRON PER SECTOR LINE

118

116

114

112

110

108

106

104

102

100

98

96

94

92

90

88

86

84

82

80

78

76

74

72

70

68

66

64

62

60

58

56

54

52

50

48

46

44

42

40

38

36

34

32

30

28

26

24

22

20

18

16

14

12

10

8

6

4

2

0
DISTRIBUTION OF DC SUBARRAY (KLYSTRON) LINES WITHIN A TYPICAL (OUTER) PART OF A SECTOR

At the J₁ junction about 16.2% of the power goes through a redundant DC to DC converter. Both the processed and unprocessed power then is divided into subarrays or directly to klystrons. The figure shows this lower level of distribution system covering the A₁, A₂, A₃ and part of A₄ group subarrays in the outer region of a typical sector.
DISTRIBUTION OF DC SUBARRAY (KLYSTRON) LINES WITHIN A TYPICAL (OUTER) PART OF A SECTOR

JUNCTION (J₁) FOR 110 SUBARRAYS OR 440 KLYSTRONS
The figure shows the ten different types of subarray layouts, the locations of klystrons and the best reference phase distribution power dividers. Only two types of slotted waveguide radiators (sticks) are used in the system.
LAYOUT OF THE TEN DIFFERENT TYPES OF SUBARRAYS, SHOWING KLYSTRON PHASE REPEATER LOCATIONS AND WAVEGUIDE STICK SIZES

TYPE 1 SUBARRAY
TYPE 1 STICK
K = 6
N_G = 440
N_R = 56

TYPE 3 SUBARRAY
TYPE 1 STICK
K = 8
N_G = 432
N_R = 27

TYPE 2 SUBARRAY
TYPE 1 STICK
K = 6
N_G = 432
N_R = 36

TYPE 4 SUBARRAY
TYPE 2 STICK
K = 9
N_G = 648
N_R = 36

• KLYSTRON
□ PHASE REPEATER
LAYOUT OF THE TEN DIFFERENT TYPES OF SUBARRAYS, SHOWING KLYSTRON PHASE REPEATER LOCATIONS AND WAVEGUIDE STICK SIZES (Cont’d)

TYPE 5 SUBARRAY
TYPE 2 STICK
K = 12
Ns = 648
Nr = 27

TYPE 6 SUBARRAY
TYPE 1 STICK
K = 16
Ns = 432
Nr = 27

TYPE 7 SUBARRAY
TYPE 1 STICK
K = 20
Ns = 400
Nr = 22

TYPE 8 SUBARRAY
TYPE 1 STICK
K = 24
Ns = 432
Nr = 18
LAYOUT OF THE TEN DIFFERENT TYPES OF SUBARRAYS,
SHOWING KLYSTRON PHASE REPEATER LOCATIONS
AND WAVEGUIDE STICK SIZES (Cont'd)

TYPE 9 SUBARRAY
TYPE 1 STICK
K = 30
N_S = 680
N_R = 22

TYPE 10 SUBARRAY
TYPE 2 STICK
K = 36
N_S = 648
N_R = 18
DIVISION OF 7220 ELEMENT SPACE ANTENNA INTO 10 POWER LEVEL RINGS

ELEMENT SIZE 10.4 m x 10.4 m
D = 90.4 m
A = 780018.2 m²
LAYOUT OF PHASING SECTORS AND GROUPS

SECTOR A

SECTOR B

SECTOR C

GROUP 1

SUBARRAY C1, 10

LEVEL L1

LEVEL L2

LEVEL L3
The figure shows the layout of the reference phase distribution network and the location of the phase repeater stations. The phase distribution network is a four layer tree. The first, second and third layers have 20, 19 and 19 way power dividers respectively at the nodes of the network. The first layer is called sector, the second group, the third unit, the fourth subarray. The power dividers at the fourth layer correspond to the number of klystrons carried by the subarray.
LOCATION OF REFERENCED PHASE REPEATER STATIONS OF SECTORS AND GROUPS
MECHANICAL LAYOUT OF A TYPICAL KLYSTRON MODULE IN THE OUTER RING OF THE SPACE ANTENNA

The figure shows the conceptual layout of all the components which are related to a "klystron" module of the space antenna. The example shown is for a subarray, at the edge of the antenna, which carry a total of four klystrons.
MECHANICAL LAYOUT OF A TYPICAL KLYSTRON MODULE IN THE OUTER RING OF THE SPACE ANTENNA
REDUNDENCY CONCEPT OF PHASE DISTRIBUTION NETWORK
The figure shows the redundancy and failure rate assumptions in the phase distribution network. The first layer is triple, the second is doubly redundant.
The rectenna power conditioning network from input aperture plane to utility grid interface was developed conceptually including detailed geometry and conductor sizes. The summary displays some of the most important results.
MECHANICAL AND ELECTRICAL LAYOUT OF A TYPICAL RECTENNA WAS DEVELOPED FOR A TEXAS SITE.

THE FOLLOWING COMPONENTS ARE DISTINGUISHED: DIPOLE, ARRAY, PANEL, UNIT, GROUP.

A LOW VOLTAGE AND A LOW CURRENT DESIGN WAS CONCEIVED, THE LOW VOLTAGE, USING MAX. 3 KV (NOMINAL) WAS SELECTED AS THE BASELINE.

FOUR DIFFERENT TYPES OF PANELS AND SEVEN DIFFERENTLY WIRES UNITS ARE NECESSARY TO FORM THE OVERALL NETWORK.

ALL PANEL DIMENSIONS ARE IDENTICAL (3 M X 3.33 M) AND THE NS DIMENSIONS OF ALL UNITS ARE EQUAL (117.18 M).

MOST OF THE LOSS IS IN THE PANEL WIRING, MOST OF THE WEIGHT IN THE UNIT LINES. USING ALUMINUM CONDUCTORS TOTAL NETWORK LOSS IS 1.39% AND TOTAL NETWORK WEIGHT IS 225,430 METRIC TONS.

HIGH VOLTAGE DESIGN CAN CONSIDERABLY REDUCE THE NECESSARY WEIGHT OF CONDUCTORS, BUT IT INCREASES THE WEIGHT OF INSULATORS.

LOSS IN THE AC SYSTEM IS APPROXIMATELY 1.5%
RECTENNA RF POWER DISTRIBUTION

DISTRIBUTION OF INCOMING RF POWER OVER RECTANNA AS A FUNCTION OF DISTANCE FROM CENTER NORMALIZED TO MAJOR OR MINOR AXIS OF ELLIPTICAL APERTURE OF RECTANNA

NORMALIZE DISTANCE / MAX

NORMALIZE DISTANCE / MAX

RING CENTERS

RING CENTERS
Figure shows the typical dimension of a panel in the rectenna and the highest applicable voltages in the so-called "low voltage" design. There are 1849 dipoles on one panel in the middle of the rectenna. Each dipole receives over an average of 54.1 cm² area. There are $1.305 \times 10^{10}$ dipoles, $7.654 \times 10^9$ diodes, $7.06 \times 10^6$ panels in a typical rectenna.
RECTENNA PANEL LAYOUT
WITH 1849 DIPOLES AND DIODES
CHARACTERISTICS OF THE PANELS

A nominal panel size of 3m (NS) and 3.33m (EW) is assumed carrying between 1800 and 1849 dipoles. Dipoles are forming 1, 2, 4 or 8 element radiators in various rings of rectenna. Approximately $1.305 \times 10^{10}$ dipoles and $7.654 \times 10^9$ diodes are used. The voltage of panels vary between 283.5V and 772.3V.
## CHARACTERISTICS OF THE PANELS

<table>
<thead>
<tr>
<th>Ring</th>
<th>$\mu M^2$</th>
<th>$\frac{W}{cm^2}$</th>
<th>$\frac{W}{cm^2}$</th>
<th>Dipole</th>
<th>Diode $V_{DC}$</th>
<th>Diode $V_{DC}$</th>
<th>Panel $V_{DC}$</th>
<th>Panel $V_{DC}$</th>
<th>A Panel</th>
<th>$\Omega$ Panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.33</td>
<td>2333</td>
<td>.765</td>
<td>43 $x$ 43 = 1849</td>
<td>1849</td>
<td>17.96</td>
<td>.9298</td>
<td>772.3</td>
<td>2.25</td>
<td>1100</td>
</tr>
<tr>
<td>2</td>
<td>18.76</td>
<td>1876</td>
<td>.7366</td>
<td>1375</td>
<td>1849</td>
<td>16.11</td>
<td>.7437</td>
<td>692.7</td>
<td>1.90</td>
<td>1100</td>
</tr>
<tr>
<td>3</td>
<td>14.38</td>
<td>1438</td>
<td>.7255</td>
<td>1043.3</td>
<td>1849</td>
<td>14.11</td>
<td>.5642</td>
<td>406.7</td>
<td>1.72</td>
<td>1100</td>
</tr>
<tr>
<td>4</td>
<td>11.42</td>
<td>1142</td>
<td>.7251</td>
<td>828.1</td>
<td>930</td>
<td>17.73</td>
<td>.8904</td>
<td>549.6</td>
<td>1.50</td>
<td>1134</td>
</tr>
<tr>
<td>5</td>
<td>8.67</td>
<td>867</td>
<td>.7121</td>
<td>625.6</td>
<td>930</td>
<td>15.44</td>
<td>.6727</td>
<td>478.6</td>
<td>1.31</td>
<td>1134</td>
</tr>
<tr>
<td>6</td>
<td>6.72</td>
<td>672</td>
<td>.6966</td>
<td>468.1</td>
<td>930</td>
<td>13.59</td>
<td>.5033</td>
<td>421.3</td>
<td>1.11</td>
<td>1134</td>
</tr>
<tr>
<td>7</td>
<td>5.24</td>
<td>524</td>
<td>.6842</td>
<td>365.4</td>
<td>930</td>
<td>12.12</td>
<td>.3929</td>
<td>375.7</td>
<td>.973</td>
<td>1136</td>
</tr>
<tr>
<td>8</td>
<td>4.24</td>
<td>424</td>
<td>.6809</td>
<td>292.1</td>
<td>642</td>
<td>15.32</td>
<td>.6222</td>
<td>337.0</td>
<td>.866</td>
<td>1152</td>
</tr>
<tr>
<td>9</td>
<td>3.49</td>
<td>349</td>
<td>.6716</td>
<td>236.5</td>
<td>642</td>
<td>13.90</td>
<td>.5119</td>
<td>305.8</td>
<td>.773</td>
<td>1152</td>
</tr>
<tr>
<td>10</td>
<td>3.14</td>
<td>314</td>
<td>.6815</td>
<td>216.0</td>
<td>642</td>
<td>12.90</td>
<td>.5119</td>
<td>283.5</td>
<td>.755</td>
<td>1100</td>
</tr>
</tbody>
</table>
WIRING LAYOUT OF THE FOUR DIFFERENT RECTENNA PANELS

The figure shows the four different panel wiring layouts necessary in the overall rectenna. The different panel layouts are necessary to keep the received power per diode relatively constant in the gradually decreasing power density rings of the rectenna.
WIRING LAYOUT OF THE FOUR DIFFERENT RECTANNA PANELS

TYPE 1 (FOR RING 1,2,3)

TYPE 2 (FOR RING 4,5,6,7)

TYPE 3 (FOR RING 8,9)

TYPE 4 (FOR RING 10)
CHARACTERISTICS OF THE UNITS

From the panels panel strings are formed by parallel connection using between 50 to 160 panels. From the panel strings units are formed by series connections using 8 or 16 panel strings. The NS dimension of all units are identical, 117.18 m, determined by 32 rows of panels. The EW dimension varies for the different power rings of the rectenna. 7270 units are formed and their number roughly corresponds to the number of subarrays in the space antenna. The voltage of units varies between \( +1685.2 \text{ V} \) and \( +3087.4 \text{ V} \). The power output from units varies between 0.585 Mw and 1.502 Mw.
### CHARACTERISTICS OF THE UNITS

<table>
<thead>
<tr>
<th>No.</th>
<th>No. of Panels Per Unit</th>
<th>No. of Rows of Panels Per String</th>
<th>No. of Rows of Strings</th>
<th>V&lt;sub&gt;Unit&lt;/sub&gt;</th>
<th>W&lt;sub&gt;Unit&lt;/sub&gt;</th>
<th>A&lt;sub&gt;Unit&lt;/sub&gt;</th>
<th>Ohm&lt;sub&gt;Unit&lt;/sub&gt;</th>
<th>No. of Units</th>
<th>Total Power</th>
<th>Normalized Total Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>464</td>
<td>4</td>
<td>120</td>
<td>6174.8</td>
<td>1.36</td>
<td>81.4</td>
<td>718</td>
<td>778.0</td>
<td>.3590</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>431</td>
<td>4</td>
<td>120</td>
<td>5541.6</td>
<td>1.26</td>
<td>89.4</td>
<td>718</td>
<td>1008.3</td>
<td>.2061</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>462</td>
<td>4</td>
<td>120</td>
<td>4853.6</td>
<td>1.18</td>
<td>73.3</td>
<td>908</td>
<td>909.4</td>
<td>.1859</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>431</td>
<td>4</td>
<td>120</td>
<td>4394.8</td>
<td>1.08</td>
<td>76.8</td>
<td>588</td>
<td>309.3</td>
<td>.0796</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>462</td>
<td>4</td>
<td>120</td>
<td>3828.0</td>
<td>1.03</td>
<td>77.7</td>
<td>588</td>
<td>481.6</td>
<td>.0984</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1280</td>
<td>4</td>
<td>160</td>
<td>3570.4</td>
<td>.5991</td>
<td>177.7</td>
<td>820</td>
<td>491.3</td>
<td>.1004</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>800</td>
<td>2</td>
<td>50</td>
<td>4011.2</td>
<td>.2923</td>
<td>181.76</td>
<td>400</td>
<td>233.8</td>
<td>.0478</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>400</td>
<td>2</td>
<td>44</td>
<td>5532</td>
<td>.2991</td>
<td>181.76</td>
<td>400</td>
<td>233.8</td>
<td>.0478</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>512</td>
<td>2</td>
<td>44</td>
<td>5532</td>
<td>.2991</td>
<td>181.76</td>
<td>400</td>
<td>233.8</td>
<td>.0478</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>462</td>
<td>2</td>
<td>75</td>
<td>4556</td>
<td>.2297</td>
<td>175.71</td>
<td>188</td>
<td>180.7</td>
<td>.0418</td>
<td></td>
</tr>
</tbody>
</table>

Total DC Power Without Conductor Losses: 4491.4

Input Power to Receiver: 6792.7

Efficiency Without Conductor Losses: 72.012
D180-25037-7

WIRING LAYOUT OF THE SEVEN DIFFERENT RECTENNA UNITS

The figure shows the seven different unit layouts, formed from the panels. There are 7270 units in the rectenna. The NS dimension for all units are 117.18 m.
WIRING LAYOUT OF THE SEVEN DIFFERENT RECTENNA UNITS

TYPE 1 1,2...27 (FOR RING 1)
TYPE 2 1,2...32 (FOR RING 2)
TYPE 3 1,2...30 (FOR RING 3)
TYPE 4 1,2...25 (FOR RING 4)
TYPE 5 1,2...31 (FOR RING 5)
TYPE 6 1,2...40 (FOR RING 6)
TYPE 7 1,2...35 (FOR RING 7)
D180-25037-7

RECTENNA BOUNDARIES OF UNITS

The different types of units are arranged into rings. The figure shows the boundaries between these rings, the number of units in each ring, the incident RF power to the corresponding units ($P_u$) and the total RF power ($P_T$) received within the corresponding rings.
CHARACTERISTICS OF THE GROUPS

From the units groups are formed by parallel connection using four to ten units. A total of 784 groups are in the rectenna. The voltage of the groups varies between ± 1685.2V and ± 3087.4V. The power output from groups varies between 2.923 MW and 9.012 MW. The group covers a total area of 84.75 km², with a nominal 9.4 km E-W and 11.48 km N-S dimension.
## CHARACTERISTICS OF THE GROUPS

<table>
<thead>
<tr>
<th>Ring</th>
<th>Parallel Units</th>
<th>No. of Residual Units</th>
<th>( V^V )</th>
<th>( R^Q )</th>
<th>( p^{Hw} )</th>
<th>( I^A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>85</td>
<td>8</td>
<td>6175</td>
<td>13.58</td>
<td>9.012</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>179</td>
<td>0</td>
<td>5542</td>
<td>17.18</td>
<td>5.632</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>112</td>
<td>12</td>
<td>4854</td>
<td>9.166</td>
<td>8.016</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>72</td>
<td>12</td>
<td>4397</td>
<td>11.36</td>
<td>5.299</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>97</td>
<td>0</td>
<td>3829</td>
<td>8.875</td>
<td>4.965</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>82</td>
<td>0</td>
<td>3370</td>
<td>5.68</td>
<td>5.991</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>40</td>
<td>0</td>
<td>6011</td>
<td>18.18</td>
<td>2.923</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>43</td>
<td>0</td>
<td>5392</td>
<td>18</td>
<td>4.786</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>44</td>
<td>0</td>
<td>4893</td>
<td>14.4</td>
<td>4.843</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>22</td>
<td>4</td>
<td>4536</td>
<td>15.71</td>
<td>7.669</td>
</tr>
</tbody>
</table>

**Specials**

<table>
<thead>
<tr>
<th>Ring</th>
<th>Parallel Units</th>
<th>No. of Residual Units</th>
<th>( V^V )</th>
<th>( R^Q )</th>
<th>( p^{Hw} )</th>
<th>( I^A )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>6175</td>
<td>20.37</td>
<td>6.008</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>4854</td>
<td>12.22</td>
<td>6.012</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>4397</td>
<td>15.15</td>
<td>3.974</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>4536</td>
<td>20.95</td>
<td>5.752</td>
</tr>
</tbody>
</table>
The figure shows the block diagram from diodes to "groups" of the rectenna for Group 1 of Ring 1. (Example shows a group close to the center of the rectenna.)
BLOCK DIAGRAM OF A TYPICAL LOW VOLTAGE RECTANNA GROUP
(GROUP 1, RING 1)
LOW CURRENT RECTANNA WIRING LAYOUT FOR
SEVEN DIFFERENT UNIT DESIGNS

TYPE 1 1,2...27 (FOR RING 1)
TYPE 2 1,2...32 (FOR RING 2)
TYPE 3 1,2...30 (FOR RING 3)
TYPE 4 1,2...25 (FOR RING 4)
TYPE 5 1,2...31 (FOR RING 5)
TYPE 6 1,2...40 (FOR RING 6)
TYPE 7 1,2...35 (FOR RING 7)
TYPE 8 1,2...25 (FOR RING 8)
TYPE 9 1,2...32 (FOR RING 9)
TYPE 10 1,2...40 (FOR RING 10)
The table displays the loss and weight characteristics of the DC power collection system of the rectenna. Using the previously described "low voltage" design the loss can be kept at 1.393% at the cost of 253490 metric tons of aluminum conductor. The bulk of the loss is in the panel lines and the bulk of the weight in the unit lines, thus the system can be improved by further optimization. Conductor weight can be reduced to 32424MT (to 12.8%) by allowing ± 27.2 kV within the rectenna. ("High voltage" design.)
### SUMMARY OF LOSSES AND TRANSMISSION LINE WEIGHTS

<table>
<thead>
<tr>
<th>Ring</th>
<th>Loss $MW$</th>
<th>Weight $T$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Panel</td>
<td>Unit</td>
</tr>
<tr>
<td>1</td>
<td>7.40</td>
<td>1.98</td>
</tr>
<tr>
<td>2</td>
<td>9.41</td>
<td>3.54</td>
</tr>
<tr>
<td>3</td>
<td>8.44</td>
<td>2.77</td>
</tr>
<tr>
<td>4</td>
<td>4.03</td>
<td>1.59</td>
</tr>
<tr>
<td>5</td>
<td>5.03</td>
<td>3.02</td>
</tr>
<tr>
<td>6</td>
<td>4.92</td>
<td>2.48</td>
</tr>
<tr>
<td>7</td>
<td>2.30</td>
<td>.90</td>
</tr>
<tr>
<td>8</td>
<td>1.44</td>
<td>1.29</td>
</tr>
<tr>
<td>9</td>
<td>1.46</td>
<td>1.03</td>
</tr>
<tr>
<td>10</td>
<td>1.80</td>
<td>1.40</td>
</tr>
</tbody>
</table>

#### Losses and Transmission Summary

- Total DC Power at Diode Output: 4891.4
- Loss %: 1.353
- Total DC Power at Inverter Input: 4823.3
GROUND POWER COLLECTION AND TRANSMISSION SYSTEM

The integration of SPS power into electric utility power system will depend largely on the local system characteristics. The work in this area included an assessment of using AC at different voltage levels and/or using DC for long distance power transmission.

The failure characteristics and modes for the elements in the rectenna AC power collection system were developed and integrated into reliability profiles describing the availability of the various rectenna layouts studied.

The maintenance requirements both periodic and unscheduled were assessed and tabulated.
GENERAL ELECTRIC
GROUND POWER COLLECTION AND TRANSMISSION SYSTEM

TASKS IN PHASE 1

- INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

- FAILURE MODE AND RELIABILITY ANALYSIS OF RECTENNA AC POWER COLLECTION SYSTEM

- MAINTENANCE REQUIREMENTS FOR THE AC POWER COLLECTION SYSTEM – SCHEDULED AND UNSCHEDULED
INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

The critical parameters when considering what kind of transmission system and what voltage levels will be feasible for connecting SPS power plant's to the power grid is first, the distance between the SPS plant and the load centers served. The existing AC transmission system may be applicable for part of the power but stability and system reliability considerations may well indicate a mixed AC and DC system.

Since the SPS system is likely to be far more stable than a conventional power plant of the same rating the breakeven between AC and DC might well be different than in conventional systems. Due to the possibility of extreme reliability criteria being imposed on a SPS system, the conventional transmission planning contingency criteria will also need review in site specific studies.
INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

CRITICAL PARAMETERS

- LOCATION OF LOAD CENTERS RELATIVE TO SPS RECTENNA LOCATION

- EXISTING POWER TRANSMISSION SYSTEM
  - DISTANCE FROM SPS LOCATION
  - STABILITY

- TRANSMISSION PLANNING CONTINGENCY CRITERIA
INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

Previous arrangements shown using a redundant set of transmission lines has been restudied and the arrangement shown in this figure using a total of six 500 kV circuits would be applicable if the SPS would serve one major and a couple of minor load areas. It is anticipated that any two of the 6 circuits could be removed from service without reduction of the rectenna output. The remaining four circuits, together with the normal utility transmission interconnections should be capable of carrying the 5000 MW output required.
INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

CONSIDERATIONS FOR AC BULK POWER TRANSMISSION

TRANSMISSION REQUIREMENTS FOR UTILITY INTERPHASE
INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

For conventional generation stations, depending on the distance to the load center, some series capacitor compensation of the AC transmission lines would normally be expected when considering contingency line loadings. Typical line loadings versus distance and amount of series compensation for AC transmission lines is shown in this figure.

When considering contingency loadings as discussed before with 2 lines down and 4 lines carrying the full 5000 MW the line loadings would be 1.25 times the surge impedance loading (SIL). The surge impedance loading for various voltage levels are shown in the table and for 500 kV, the SIL would be about 1000 MW. From the curves it would appear that a reasonable transmission distance with no series compensation for this example would be about 200 miles, which could be increased to 350 or 400 miles with up to 70% series compensation.
INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

CONSIDERATIONS FOR AC BULK POWER TRANSMISSION

* NOTE: SERIES COMPENSATION TYPICALLY APPLIED BEYOND 150 - 250 MILES

REPRESENTATIVE LINE SURGE IMPEDANCE LOADINGS (BIL)

<table>
<thead>
<tr>
<th>LINE VOLT</th>
<th>THREE CONDUCTOR</th>
<th>FOUR CONDUCTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>kV</td>
<td>MW</td>
<td>MW</td>
</tr>
<tr>
<td>242</td>
<td>209</td>
<td>-</td>
</tr>
<tr>
<td>362</td>
<td>468</td>
<td>504</td>
</tr>
<tr>
<td>560</td>
<td>1080</td>
<td>1180</td>
</tr>
<tr>
<td>800</td>
<td>2280</td>
<td>2480</td>
</tr>
</tbody>
</table>

TYPICAL ECONOMIC LINE LOADINGS
INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

When substantial amounts of power are to be transported for distances of 400 miles or more, the consideration of a high-voltage DC (HVDC) as the transmission load is often indicated. The HVDC system is ideally suited for long distance bulk power transport since it does not suffer from stability effects and can even be used to improve the stability of the AC system to which it is connected.

There are, however, certain specific requirements to be met. At each of its terminals the DC transmission system absorbs reactive power which must be supplied by static capacitors, rotating machines, like synchronous condensers or from the connected AC network. Reactive volt-amperes equal to approximately 60% of the transmitted active power are required.

The current on the AC side of the terminals contains substantial harmonic components which must be removed, generally by shunt-connected tuned circuits.

Lastly, the DC terminal must be connected to an active AC network having a short circuit capacity (in volt-amperes) equal to a minimum of two times the transmitted power.

When the requirements for filtering, reactive supply, and short circuit capacity are met, the HVDC system is a reliable, efficient, and readily controlled power transmission medium.
INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

CONSIDERATIONS FOR DC BULK POWER TRANSMISSION

DC INDICATED FOR

- LONG TRANSMISSION DISTANCES > 400 MILES
- STABILITY PROBLEMS IN EXISTING AC SYSTEM
- RELIABILITY AND EASY CONTROLABILITY

DC REQUIREMENTS

- REACTIVE POWER SUPPLY ~ 80% OF ACTIVE POWER
  - STATIC CAPACITORS
  - SYNCHRONOUS CONDENSERS
  - CONNECTED AC NETWORK
- CONTROL OF HARMONICS BY FILTERS
- MUST BE CONNECTED TO AN ACTIVE AC NETWORK WITH SUFFICIENT SHORT CIRCUIT CAPACITY
INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

A typical HVDC power transmission circuit is shown in this figure. The synchronous condensers and AC filters are shown connected to the AC switchyard. The DC terminal consists of three phase bridge converters connected in parallel on the AC side and in series on the DC side. Although only two bridges are shown between ground and the DC conductor, it is not uncommon for four such bridges to be applied when the DC voltage exceeds \(+400\) kV.

The DC system is balanced with respect to ground and is firmly held this way by fully rated ground electrodes. In normal operation there is no current in these ground electrodes, but in an emergency if one conductor or its converters are lost, the other conductor and the ground circuit will continue to transmit half power. Such emergency use can usually be tolerated. The transformers which couple the AC system to the bridges are shown equipped with load tap changers (LTC) which insure that the converter operates at the proper voltage and firing angle regardless of normal smaller variations in the AC system voltage.
INTEGRATION OF SPS POWER INTO A TYPICAL ELECTRIC UTILITY POWER SYSTEM

CONSIDERATION FOR DC BULK POWER TRANSMISSION

ELEMENTS OF A HVDC TRANSMISSION SYSTEM
FAILURE MODES AND EFFECTS ANALYSIS

The failure modes and their effects was analyzed for the power transmission system between the elevation flexible joint on the spacecraft to the utility interface on the ground. The summary presents some of the most important results.
WITH CONVERTER REDUNDANCY THE SPACE ANTENNA DC SYSTEM HAS A MEAN AVAILABILITY OF APPROXIMATELY 99.5%.

THE PHASE CONTROL SYSTEM MEAN AVAILABILITY IS 99%. THIS CAN BE IMPROVED IF THE FOURTH LAYER IS DUPLICATED, BUT THE COST PENALTY IS VERY LARGE. ANOTHER POTENTIAL IMPROVEMENT IN AVAILABILITY (AND COST) MAY BE POSSIBLE BY OMITTING THE FOURTH LAYER ALTOGETHER.

THE MEAN AVAILABILITY OF THE KLYSTRON AND ITS DRIVER IS 97.45% WITH 20 YEAR LIFETIME TUBE AND HALF YEARLY MAINTENANCE. POWER LOSS CAN BE CUT BY NEARLY A FACTOR OF TWO IF QUARTER YEARLY MAINTENANCE IS IMPLEMENTED.

COMBINED EFFECTS OF RANDOM ERRORS IN THE APERTURE DISTRIBUTION AND LOSSES IN THE PROPAGATION MEDIA ARE COMPARABLE TO THAT OF THE KLYSTRONS.

MEAN AVAILABILITY ASSOCIATED WITH DIODE FAILURES IS APPROXIMATELY 99.45%, ASSUMING NO DIODE OR PANEL RELATED MAINTENANCE.

THE RESULTANT DC POWER COLLECTION SYSTEM CAN HAVE A MEAN AVAILABILITY OF 98.4%.

THE RESULTANT AC POWER COLLECTION SYSTEM MEAN AVAILABILITY IS 99.7%.

RESULTANT SYSTEM EQUIPMENT AVAILABILITY BETWEEN ELEVATION FLEXIBLE JOINTS AND UTILITY GRID IS APPROXIMATELY 90%, POWER AVAILABILITY IS HIGHER THAN 86%.

NUMBER OF POTENTIAL AREAS WERE DETECTED WHERE AVAILABILITY IMPROVEMENT CAN BE IMPLEMENTED IN COST EFFECTIVE MANNER.
The figure shows the availability of the spacecraft DC power distribution system. The resultant curve is shown for .075 failure/.5 year failure rate DC to DC converters in a redundant configuration. The available power for this case falls below 99.5% of its maximum in no more than 2980.4 Hrs./year or otherwise it stays above this value in 66% of the time. This value may be taken as the average (rms) value of the available DC power.
AVAILABILITY VS. PROBABILITY FOR SPACE ANTENNA D-C DISTRIBUTION SYSTEM FROM OUTPUT OF FLEXIBLE JOINT TO KLYSTRON INPUT
AVAILABILITY VS. PROBABILITY OF A STRING OF RECTENNA DIODES CONTAINING $N_{DS} = 43$ PARALLEL DIODES

$N = 43, \frac{1}{T} = 0.02 \times 10^6$ FAILURE 30 YEAR, $r = 30$ YEAR
The figure shows the availability of the spacecraft phase distribution system. The average value is 99%.
AVAILABILITY VS. PROBABILITY OF THE SPACE ANTENNA PHASE CONTROL SYSTEM FROM INPUT OF PILOT RECEIVE ANTENNA TO KLYSTRON INPUT

PERCENT OF AVAILABILITY (A)

HOURS PER YEAR

RESULTANT PHASE CONTROL SYSTEM

INPUT TO SW OUTPUT

2nd BIG OUTPUT TO Bmin OUTPUT

4 INPUT TO KLYSTRON INPUT

PERCENT OF PROBABILITY (P)

91 92 93 94 95 96 97 98 99 99.9 99.99

0.1 1 10 30 60 80 90 99 99.9 99.99
The figure shows the availability of klystrons and their associated drives. Twenty year lifetime is assumed for this assembly and refurbishment is provided half yearly. The average value of availability is 97.45%. On the average 2544.6 klystrons have to be replaced biyearly out of the 101784 operational units.
AVAILABILITY VS. PROBABILITY OF KLYSTRONS
BASED ON AVAILABILITY OF A GROUP OF $N_G = 380$
AVAILABILITY VS. PROBABILITY OF POWER OUTPUT FROM IDEAL SPACE ANTENNA DUE TO RANDOM APERTURE ERRORS AND PROPAGATION CONDITIONS

The figure shows the availability of effective antenna gain as it is influenced by random variables. Effects of aperture phase errors, aperture amplitude errors, attenuation in the media and effects caused by Faraday rotation.
AVAILABILITY VS. PROBABILITY OF POWER OUTPUT FROM IDEAL SPACE ANTENNA DUE TO RANDOM APERTURE ERRORS AND PROPAGATION CONDITIONS
The mean value of availability of a typical rectenna panel is 98.85% with state-of-the-art failure rates (.04 x 10^-6 failure/hours). A factor of 2 improvement in failure rates increases the mean availability to 99.45% at the end of the 30 year lifetime. The improved value is assumed for system availability calculations. The dipole panels will be refurbished only after 30 years.
AVAILABILITY VS. PROBABILITY OF A TYPICAL RECTENNA PANEL CONTAINING N = 1849 DIODES
The mean availability of a typical rectenna panel string (unit) is 99.38% on the account of DC bus line failures if the mean time to repair is \( r = 876 \) Hrs. Lines are continuously maintained.
AVAILABILITY VS. PROBABILITY OF A TYPICAL RECTENNA STRING OF PANELS CONTAINING
\( N_{PS} = 872 \) PANELS

\[ N_p = \frac{N_{PS}}{10} = 87, \quad N = 87240, \]

\[ \frac{1}{T} = 6.3 \times 10^{-2} \text{ failures per year} \]

\( T = 676 \) HRS

\( T = 1752 \) HRS
The mean availability of rectenna unit to group center connecting line is 99.65% if the mean time to repair is $r = 876$ Hrs. Lines are continuously maintained.
GENERAL ELECTRIC

AVAILABILITY VS. PROBABILITY OF UNIT TO GROUP CENTER LINES FOR $N_G = 784$

$N_G = 784, \frac{1}{r} = .0315$

FAILURE RATE \( r = 873 \) HRS, \( P = .00315 \)

PERCENT OF AVAILABILITY (A)

PERCENT OF PROBABILITY (P)
AVAILABILITY VS. PROBABILITY OF RECTENNA D-C POWER COLLECTION SYSTEM FOR VARIOUS FAILURE CHARACTERISTICS COMBINATIONS

The mean availability of the rectenna resultant DC power collection system is 98.4% with $0.02 \times 10^{-6}$ failure/Hrs. diodes and 876 Hrs. mean time for repair allowance on the DC lines. For the predicted failure rates a crew of 29 is necessary to maintain the DC power collection system.
AVAILABILITY VS. PROBABILITY OF RECTENNA D-C POWER COLLECTION SYSTEM FOR VARIOUS FAILURE CHARACTERISTICS COMBINATIONS
RECTENNA AC POWER COLLECTION SYSTEM

The diagram shows an idealized AC power collection network, developed during the Part III study, which can be used for availability calculations.
Mean availability of the AC power collection system is 99.7%, limited by the 20 MW stations.
AVAILABILITY VS. PROBABILITY
OF OVERALL RECTENNA
AC POWER COLLECTION SYSTEM
FAILURE MODE AND RELIABILITY ANALYSIS

The calculation of a reliability profile of the AC power collection system was performed for all three layout options. The reliability profile calculated will show the power output from a 625 MW rectenna sector as a function of the percent of time in a year. The block diagram in this figure shows the flow of the probability calculations. The failure characteristics are indicated on the figure.

Mathematically the calculations are performed by using the binomial probability function for each of the groups in each design to which it applies and then combining the probabilities of component outages and the associated power lost to develop the data needed to draw the reliability profiles. The assumptions used are:

1. The exposure period is 8760 hours
2. The switchyards and the synchronous condensers are designed not to contribute to power outages.
FAILURE MODE AND RELIABILITY ANALYSIS

BLOCK DIAGRAM FOR RECTENNA SECTOR RELIABILITY CALCULATIONS
The reliability profile for the 625 MW sector considering the elements in the AC power collection system is shown in this curve.

The reliability profile is shown in the figure. The reliability of the rectenna AC power collection system is very high compared to current utility generating equipment, both in the baseline design as well as the other designs studied, and the choice of any of these three designs will not depend on these reliability considerations.
FAILURE MODE AND RELIABILITY ANALYSIS

RELIABILITY PROFILE FOR A 625 MW SECTOR IN THE LOW VOLTAGE BASELINE RECTANNA DESIGN
SUMMARY OF EQUIPMENT AND POWER AVAILABILITY CALCULATIONS

The table summarizes the equipment availability and AC power to utility grid availability on the account of the analyzed part of the SPS system. Input interface is at the output of a flexible DC cable on space antenna, output interface is at input to utility grid. All effects which cause statistical variation of availability (failures, errors, propagation) are included. Some of the major assumptions:

- Space antenna DC to DC converter is redundant.
- Phase control uses four layer tree, down to klystron level, only first and second layers are redundant.
- Nonredundant, 20 year lifetime klystrons are used. (This is a factor of ten better than state-of-the-art).
- Random phase and amplitude errors of space antenna are the same as calculated in Part III Study.
- Elevation angle toward satellite is 55°.
- Diode failure rate is 0.02 per million hrs. Diode is not refurbished for 30 years. (Failure rate is a factor of two better than state-of-the-art).
- Critical components in AC power collection system are redundant, rest are covered by on-site spares.
- Space antenna is refurbished within 81 hours biyearly peri.
- No power recovery is assumed when a failure occurs in space antenna aperture segment related to items 1, 2, or 3 in table.

Note that with power recovery methods the power availability (81.8% mean value) can be improved to the equipment availability (90.12% mean value).
### SUMMARY OF EQUIPMENT AND POWER AVAILABILITY CALCULATIONS

<table>
<thead>
<tr>
<th>F^2</th>
<th>10</th>
<th>66</th>
<th>80</th>
<th>90</th>
<th>99</th>
<th>99.9</th>
<th>99.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hrs/Year</td>
<td>7889</td>
<td>2980</td>
<td>1753.2</td>
<td>876.6</td>
<td>87.66</td>
<td>8.766</td>
<td>.8766</td>
</tr>
<tr>
<td>A. Space Antenna</td>
<td>97.75</td>
<td>93.20</td>
<td>91.56</td>
<td>89.59</td>
<td>84.12</td>
<td>78.62</td>
<td>71.28</td>
</tr>
<tr>
<td>1 DC Distribution</td>
<td>100.00</td>
<td>99.50</td>
<td>99.22</td>
<td>98.95</td>
<td>98.00</td>
<td>97.00</td>
<td>95.95</td>
</tr>
<tr>
<td>2 Phase Control</td>
<td>99.86</td>
<td>98.92</td>
<td>98.44</td>
<td>97.83</td>
<td>96.10</td>
<td>94.60</td>
<td>91.30</td>
</tr>
<tr>
<td>3 Klystron</td>
<td>98.90</td>
<td>97.50</td>
<td>97.02</td>
<td>96.55</td>
<td>95.48</td>
<td>94.58</td>
<td>93.60</td>
</tr>
<tr>
<td>4 Random Phase</td>
<td>99.40</td>
<td>98.50</td>
<td>98.20</td>
<td>97.82</td>
<td>96.80</td>
<td>95.75</td>
<td>94.80</td>
</tr>
<tr>
<td>5 Random Amp.</td>
<td>99.60</td>
<td>98.60</td>
<td>98.40</td>
<td>98.00</td>
<td>96.65</td>
<td>94.90</td>
<td>91.70</td>
</tr>
<tr>
<td>B. Propagation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Attenuation</td>
<td>99.05</td>
<td>98.54</td>
<td>98.28</td>
<td>97.84</td>
<td>96.24</td>
<td>94.17</td>
<td>91.77</td>
</tr>
<tr>
<td>7 Faraday Rotation</td>
<td>100.00</td>
<td>99.92</td>
<td>99.98</td>
<td>99.74</td>
<td>99.32</td>
<td>98.92</td>
<td>98.52</td>
</tr>
<tr>
<td>C. Rectenna</td>
<td>98.38</td>
<td>98.13</td>
<td>97.61</td>
<td>97.03</td>
<td>95.06</td>
<td>92.96</td>
<td>87.65</td>
</tr>
<tr>
<td>8 DC power Collection</td>
<td>99.38</td>
<td>98.45</td>
<td>98.15</td>
<td>97.81</td>
<td>97.00</td>
<td>96.38</td>
<td>95.80</td>
</tr>
<tr>
<td>9 AC Power Collection</td>
<td>100.00</td>
<td>99.68</td>
<td>99.45</td>
<td>99.20</td>
<td>98.00</td>
<td>96.45</td>
<td>91.50</td>
</tr>
</tbody>
</table>

Total Power Transmission System Equipment Availability

Power Availability at Power Grid Interface Relative to Equipment Without Failure

| 95.00 | 85.85 | 83.19 | 79.43 | 69.20 | 59.65 | 47.01 |
The chart shows the variation of equipment availability in the overall SPS power transfer system. If power recovery methods are used in the space antenna, then the output power at the power grid interface is determined by the equipment availability. Without power recovery (redirecting the available DC power for DC to RF conversion to the still available part of the space antenna radiating components) the available power at the utility interface is lower because a lost radiating component in the space antenna represents loss of power as well as loss of antenna area.

The mean availability for the two cases is approximately 90% and 86% respectively.
AVAILABILITY VS. PROBABILITY OF OVERALL SPS POWER TRANSMISSION SYSTEM FROM OUTPUT OF FLEXIBLE JOINT ON SPACE ANTENNA TO POWER GRID INTERFACE

D180-25037-7

PERCENT OF PROBABILITY (P)

PERCENT OF AVAILABILITY (A)

HOURS PER YEAR

55 0.1 1 10 30 66 90 99 99.9 99.99

56 60 65 70 75 80 85 90 95 100

7896 1036 2604 8768 4383 877 0.77 0.88

AVAILABLE POWER AT POWER GRID INTERFACE

EQUIPMENT AVAILABILITY
AVAILABILITY OF EFFICIENCY AND POWER INTO POWER GRID

Table shows the worst case efficiency and power into utility grid as a statistical variable. Using results of the availability analysis. If diode efficiency is improved by 5% and power recovery methods are successful and spacecraft then the figures shown in the table must be multiplied by 1.1.
<table>
<thead>
<tr>
<th>P (%)</th>
<th>10</th>
<th>66</th>
<th>80</th>
<th>90</th>
<th>99</th>
<th>99.9</th>
<th>99.99</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hrs/Year</td>
<td>7889</td>
<td>2980</td>
<td>1753.2</td>
<td>876.6</td>
<td>87.66</td>
<td>8.766</td>
<td>.8766</td>
</tr>
<tr>
<td>Available Efficiency (%)</td>
<td>63.33</td>
<td>57.23</td>
<td>55.46</td>
<td>52.29</td>
<td>46.13</td>
<td>39.76</td>
<td>31.34</td>
</tr>
<tr>
<td>Available Power MW</td>
<td>4513.3</td>
<td>4078.6</td>
<td>3952.3</td>
<td>3773.6</td>
<td>3287.6</td>
<td>2833.9</td>
<td>2233.4</td>
</tr>
</tbody>
</table>
EFFECT OF DEVIATION FROM BASELINE SPS ON RELATIVE OUTPUT POWER

This table shows the impact of various output power increasing options on output power and cost.
### Effect of Deviation from Baseline SPS on Relative Output Power

<table>
<thead>
<tr>
<th>Option Description</th>
<th>A</th>
<th>B</th>
<th>B/A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Option A</strong> Increase 4 and 3 by 1.068 for 23 mw/cm² max.</td>
<td>6.8</td>
<td>3.88</td>
<td>1.75</td>
</tr>
<tr>
<td>Received Power Density</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Option B</strong> Increase 4 and 3 by 1.1</td>
<td>10.0</td>
<td>5.71</td>
<td>1.75</td>
</tr>
<tr>
<td>Reduce 2 by 1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase 1 by 1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Option C</strong> Increase 1 by 1.1211 for 96.77% beam efficiency</td>
<td>1.5</td>
<td>1.73</td>
<td>.87</td>
</tr>
<tr>
<td><strong>Option D</strong> Implement klystron Maintenance in Every 3 Months</td>
<td>2.5</td>
<td>1.58</td>
<td>1.58</td>
</tr>
<tr>
<td><strong>Option E</strong> Make Last Layer of Phase Control System Fully Redundant</td>
<td>.4</td>
<td>3.0</td>
<td>.13</td>
</tr>
<tr>
<td><strong>Option F</strong> Refurbish Rectenna Panel Assembly After 15 Years</td>
<td>.58</td>
<td>3.57</td>
<td>.16</td>
</tr>
<tr>
<td><strong>Option G</strong> Reduce r to 438 Hours on Panel String Maintenance</td>
<td>.37</td>
<td>.35</td>
<td>1.06</td>
</tr>
<tr>
<td>All the above options are implemented.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Power Output (5052 MW)</td>
<td>23.88</td>
<td>26.50</td>
<td>.901</td>
</tr>
<tr>
<td>Only Cost Effective Options A, B and D are Implemented</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Power Output (6911.4 MW)</td>
<td>20.42</td>
<td>11.50</td>
<td>1.77</td>
</tr>
</tbody>
</table>
The figure shows the statistical variation of the available power of the utility interface if power recovery is not used. Improved diodes and power recovery methods can improve the predicted values by about 9%. Chart considers all random failures and scheduled maintenance of 84 Hrs./half year, however, it neglects eclipse and start up/shut down caused power output losses.
AVAILABLE SPS POWER TO UTILITY GRID

CONSIDERING RANDOM ERRORS, FAILURE MODES AND SCHEDULED MAINTENANCE. NOT CONSIDERING ECLIPSE AND START UP/SHUT DOWN TIME LOSSES.
The maintenance tasks for the SPS power transmission system were studied and preliminary manpower requirements were established both for the space and ground operation. The summary shows the manpower needs.
### MAINTENANCE REQUIREMENTS

**SUMMARY**

<table>
<thead>
<tr>
<th>Component</th>
<th>Hours Per Repair Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Distribution</td>
<td>281.2</td>
</tr>
<tr>
<td>RF Reference Phase Distribution</td>
<td>680.5</td>
</tr>
<tr>
<td>Klystrons</td>
<td>2544</td>
</tr>
<tr>
<td><strong>Total Crew Hours Per Repair Cycle</strong></td>
<td><strong>3506.3</strong></td>
</tr>
<tr>
<td><strong>Total Man Hours Per Repair Cycle</strong></td>
<td><strong>7012.7</strong></td>
</tr>
<tr>
<td><strong>Total Man Hours Per Year</strong></td>
<td><strong>14025.4</strong></td>
</tr>
</tbody>
</table>

- Rectenna DC per Year: 5762.5
- Rectenna AC per Year: 69457

*The manpower requirement is equivalent to approximately seven man years per year in space (on the average) and 64 man years per year on the ground for 5 GW SPS System.*
NUMBER OF FAILURES AND ASSOCIATED MAINTENANCE TIME REQUIREMENTS IN THE SPACE ANTENNA POWER TRANSMISSION SYSTEM

Table summarizes number of failures in space antenna power transmission system within half year period and associated total repair horns requirement. Klystron maintenance represents 72.6% of total time.
## NUMBER OF FAILURES AND ASSOCIATED MAINTENANCE TIME REQUIREMENTS IN THE SPACE ANTENNA POWER TRANSMISSION SYSTEM

<table>
<thead>
<tr>
<th>Item</th>
<th>f [\text{.5 year}]</th>
<th>N</th>
<th>F*</th>
<th>Hrs. Repair</th>
<th>Total Repair Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Convertor</td>
<td>0.075</td>
<td>456</td>
<td>34.2</td>
<td>4</td>
<td>136.8</td>
</tr>
<tr>
<td>DC Vector Line</td>
<td>0.00594</td>
<td>228</td>
<td>1.35</td>
<td>12</td>
<td>16.2</td>
</tr>
<tr>
<td>Subarray Line</td>
<td>0.000315</td>
<td>101784</td>
<td>32.06</td>
<td>4</td>
<td>128.2</td>
</tr>
<tr>
<td>SW1 Output</td>
<td>0.01859</td>
<td>60</td>
<td>1.11</td>
<td>8</td>
<td>8.9</td>
</tr>
<tr>
<td>2nd B19 Output</td>
<td>0.006048</td>
<td>380</td>
<td>2.29</td>
<td>6</td>
<td>13.8</td>
</tr>
<tr>
<td>Bmm Output</td>
<td>0.005246</td>
<td>7220</td>
<td>37.87</td>
<td>2</td>
<td>75.7</td>
</tr>
<tr>
<td>Klystron Input</td>
<td>0.007626</td>
<td>101784</td>
<td>776.2</td>
<td>.75</td>
<td>582.1</td>
</tr>
<tr>
<td>Klystron and Drive</td>
<td>0.025</td>
<td>101784</td>
<td>2544.6</td>
<td>1</td>
<td>2544.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>3429.68</td>
<td></td>
<td>3506.3</td>
</tr>
</tbody>
</table>

Man hours for two man team 7012.7
NUMBER OF FAILURES AND ASSOCIATED MAINTENANCE TIME REQUIREMENTS IN THE RECTENNA DC POWER COLLECTION SYSTEM

Table summarizes number of failures in rectenna DC power collection system within 1/10 year maintenance period and the associated repair time requirements. Approximately 29 man can maintain this part of the system.
NUMBER OF FAILURES AND ASSOCIATED MAINTENANCE TIME REQUIREMENTS IN THE RECTENNA DC POWER COLLECTION SYSTEM

<table>
<thead>
<tr>
<th></th>
<th>( f )</th>
<th>( N )</th>
<th>( P )</th>
<th>Hrs. Repair</th>
<th>Tot. Repair Hrs. Per Maintenance Cycle</th>
<th>Man Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel String</td>
<td>.0063</td>
<td>87240</td>
<td>549.6</td>
<td>5 (2 man)</td>
<td>2748</td>
<td>5496.1</td>
</tr>
<tr>
<td>Unit to Group Center Lines</td>
<td>.00315</td>
<td>784</td>
<td>2.47</td>
<td>18 (6 man)</td>
<td>44.4</td>
<td>266.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>5762.5</strong></td>
<td></td>
</tr>
</tbody>
</table>
The modular nature of the rectenna design will always contribute to the reliability of the rectenna power output.

The components used in the AC power collection system are shown in this table. The AC power collection system is based on the baseline system with the low voltage system layout.
## FAILURE MODE AND RELIABILITY ANALYSIS RECTENNA AC POWER COLLECTION SYSTEM

### FAILURE CHARACTERISTICS OF ELEMENTS IN RECTENNA AC POWER COLLECTION SYSTEM

<table>
<thead>
<tr>
<th>Component</th>
<th>Failure Rate (Failures/yr)</th>
<th>Mean Time to Repair (hrs)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC SWITCHGEAR</td>
<td>.2</td>
<td>8</td>
</tr>
<tr>
<td>DC BUS CONNECTIONS</td>
<td>.00063/BREAKER</td>
<td>13</td>
</tr>
<tr>
<td>DC CONVERTER BREAKER</td>
<td>.2</td>
<td>8</td>
</tr>
<tr>
<td>DC/AC CONVERTER</td>
<td>.33</td>
<td>10</td>
</tr>
<tr>
<td>CONVERTER TRANSFORMER</td>
<td>.003</td>
<td>75</td>
</tr>
<tr>
<td>AC CABLE</td>
<td>.00336/1000 FT</td>
<td>16</td>
</tr>
<tr>
<td>STEP-UP TRANSFORMER</td>
<td>.013</td>
<td>72</td>
</tr>
<tr>
<td>AC CIRCUIT BREAKERS</td>
<td>.0176</td>
<td>3.8</td>
</tr>
</tbody>
</table>

*ASSUMES AVAILABLE PARTS AND SPARES ON SITE*
MAINTENANCE REQUIREMENTS FOR THE AC POWER COLLECTION SYSTEM

The values for repair time given in the failure rate and effects analysis were used as a basis for developing the unscheduled maintenance requirements. The values used are typical electric industry statistical data. The values found in the SPS rectenna system may be considerably lower than the values shown due to specially trained maintenance personnel and a well stocked replacement parts supply. Particularly in the area of transformer maintenance the value of a sufficient number of spares would be quite significant. This table shows the expected values of failures per year calculated as Repair time x number of components/8760.
# Expected Values of Failures Per Year

<table>
<thead>
<tr>
<th>Part III Baseline</th>
<th>Low Current Design</th>
<th>Low Voltage Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Breakers</td>
<td>1.917</td>
<td>2.833</td>
</tr>
<tr>
<td>D/A Converters</td>
<td>0.047</td>
<td>0.205</td>
</tr>
<tr>
<td>Converter Transformer</td>
<td>0.003</td>
<td>0.014</td>
</tr>
<tr>
<td>AC Cable</td>
<td>0.004</td>
<td>0.017</td>
</tr>
<tr>
<td>Synchronous Condenser</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>AC Switchgear</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>SU Transformer</td>
<td>0.001</td>
<td>0.0008</td>
</tr>
</tbody>
</table>
MAINTENANCE REQUIREMENTS FOR THE AC POWER COLLECTION SYSTEM

The normal or scheduled maintenance requirements are defined as being inspections and performance tests causing either no curtailment of power or performed during periods in which the power from the rectenna system is zero for other reasons than rectenna AC Power Collection System maintenance.

The scheduled maintenance requirements for the components in the rectenna AC power collection system are quite nominal. There are few standard practices in this area in electric utility systems, since each user would tailor the maintenance practices to fit with his specific situation. Contamination from particles and chemicals, the impact of weather and duty cycles and manufacturers specifications would all be variables in determining frequency and maintenance activities.

Based on available survey results of maintenance activities the data given in this table shows scheduled maintenance in terms of manhours per year for the components in the rectenna AC system.
**MAINTENANCE REQUIREMENTS FOR THE AC POWER COLLECTION SYSTEM**

**SCHEDULED MAINTENANCE REQUIREMENTS**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Manhours/Year/Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC SWITCHGEAR</td>
<td>2</td>
</tr>
<tr>
<td>DC/AC CONVERTERS</td>
<td>16</td>
</tr>
<tr>
<td>CONVERTER TRANSFORMER</td>
<td>16</td>
</tr>
<tr>
<td>AC CABLE</td>
<td>2</td>
</tr>
<tr>
<td>SYNCHRONOUS CONDENSER</td>
<td>40</td>
</tr>
<tr>
<td>AC SWITCHGEAR</td>
<td>20</td>
</tr>
<tr>
<td>STEP-UP TRANSFORMER</td>
<td>16</td>
</tr>
</tbody>
</table>
SUMMARY OF MAINTENANCE HOURS REQUIREMENTS FOR THE AC POWER COLLECTION SYSTEM

The table summarizes scheduled and unscheduled maintenance time requirement with a 1/10 year maintenance period. Approximately 35 men can maintain this part of the system.
**SUMMARY OF MAINTENANCE HOURS REQUIREMENTS**

FOR THE AC POWER COLLECTION SYSTEM

<table>
<thead>
<tr>
<th></th>
<th>HRS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>UNSCHEDULED</td>
<td>495.7</td>
</tr>
<tr>
<td>SCHEDULED</td>
<td>6450</td>
</tr>
</tbody>
</table>

**Total** 6945.7