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SSP Power Management and Distribution

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ABSTRACT

Space Solar Power is a NASA program sponsored by Marshall Space Flight Center. The Paper presented here represents the architectural study of a large power management and distribution (PMAD) system. The PMAD supplies power to a microwave array for power beaming to an earth rectenna (Rectifier Antenna). The power is in the GW level.

INTRODUCTION

The Space Solar Power PMAD (Power Management & Distribution) is designed to process power from a solar array to the microwave planar antenna. This paper will describe an architecture for the PMAD. The power beaming and rectenna are beyond the scope of this paper.

The following Figure 1 shows one of the system concepts as a tower of solar arrays feeding a microwave planar array. Other array structures have been proposed but not analyzed to this extent.

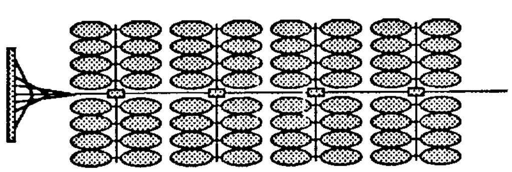


Figure 1. Sun Tower Concept

The power level for this study is 3GW. It is generated by 340 solar arrays, approximately 10MW each.

System Description

The PMAD system is comprised of power processing electronics starting at the solar array farm and ending with the microwave

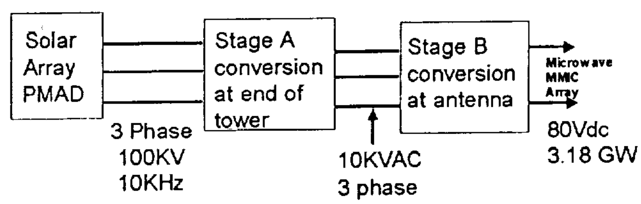


Figure 2
Space Solar Power PMAD Block Diagram

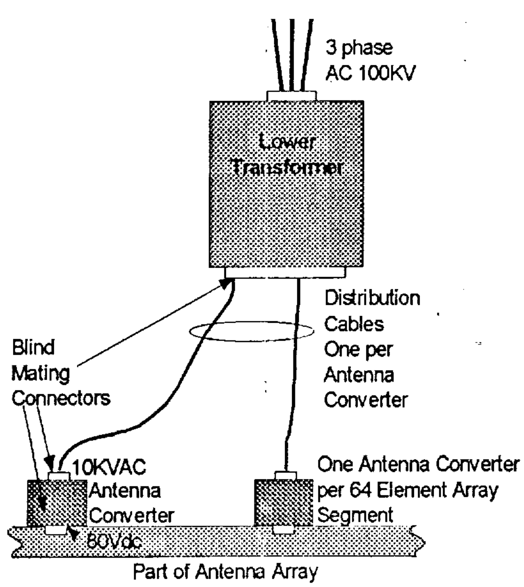
antenna as shown in the following Figure 2. The solar array produces DC at a level of approximately 5000V. A resonant bridge converter generated a 10KHz sinusoid, three phase at 100KV for the 15 km down link cable. At the bottom of the cable, the three phase AC is transformer reduced in two steps to feed 80 VDC to the microwave antenna.

Trade Studies

The PMAD was designed to achieve minimum mass from the Solar array to the MMIC antenna array. Cable weight depends upon current and to lower the weight we are driven to high voltages.

The cable weight drove the selection of cable voltage. Weight is inverse with voltage. The design utilizes 100KV, three phase AC. This approach simplifies the upper and lower PMAD interface. A transformer can be used to transform the voltage without using solid state power conversion. An approach was show using conventional DC to DC infrastructure equipment. This has a very heavy weight penalty. Other approaches using Super Conductor cable is under study.

At the lower end of the tower, the transformer we encountered a second cable distribution weight problem. The Lower Transformer was elevated by 100 meters above the Antenna Array to avoid obstructing the antenna thermal radiation field of view by the size/temperature of the transformer module [See Figure 3]. With 3GW of power transmission, the transformer was estimated to be 300 degree C because of 5MW of internal dissipation.



Fiqure 3 Antenna Arrav

This transformer dissipation is primarily core loss at the chosen frequency of 10KHz. There is a trade of transformer core weight and loss versus frequency. Through an iterative design process, we chose 10KHz as the bus power frequency. Higher frequencies will have serious phase loss. Lower frequencies will increase the transformer coupling sizes.

With 1KVDC distribution, the cables were too massive, almost equal to the Antenna Converter weight total. This drove a choice of 10KVAC for the distribution cables. The lower transformer had included a 12 pulse rectifier. This was now placed in the Antenna Converter. The Antenna Converter grows slightly (16%) versus a Distribution cable gain of 90%.

The Antenna Converter sizing is based on the power required by the smallest replaceable segment. We used some design rules to establish the sizes and weights. This is shown in table 1.

Efficiency	95%
Density	500 w per lb
Volume	50 w per in^3

Table 1 Power Supply Design Factors

The assumption of 95% efficiency is possible with steady state operation with SSP. It is also necessary to reduce the thermal rise within the electronics. The density and volume factors preclude use of active cooling hardware. The module must be designed to radiate upward away from the antenna array.

The Antenna Converter contains a transformer to reduce the 10KV 3 phase AC to 500VDC with a 12 pulse rectifier. The second stage is a current fed DC-DC converter down to the 80VDC antenna grid. The converter was sized with state-of-the-art factors listed in Table 1 and the results

Transformer 3ph	4488W	
Weight	2	kg
Volume	8,503	cm3
Length	20.4	cm
Dissipation	105	Watts
Module Power	4488 W	
Weight	4.1	kg
Volume	1,471	in3
Length	28.9	cm
Dissipation	224	Watts
Total		
Weight	6	kg
Volume	9,974	cm3
Length	21.5	cm
Dissipation	329	Watts

Table 2
Antenna Converter Sizing

appear in Table 2 below.
The antenna Converter must be closely attached to the 64 element module to minimize the loss and voltage drops in the 80 volt MMIC input power bus. With the estimated power needs of the 64 element panel, we calculate a volume of 9,974 cm^2 or a cube 21.5 cm on a side. We also calculate a thermal loss of 329 watts. This thermal loss must be radiated outward, preferably away from the antenna. This is a difficult packaging problem. The first approach was to position the power converter on the 64 element array panel.

We see in Figure 4, the converter covers most of the array sub panel. This blocks the thermal radiation from the MMICs.

An idea is to reduce the aspect ratio of the converter. For example, the converter could be squeezed into half of the thickness with twice the length or 10.5 by 42 cm. This covers 29% of the radiating surface of the antenna segment. This is clearly a difficult design challenge for the high interface voltage.

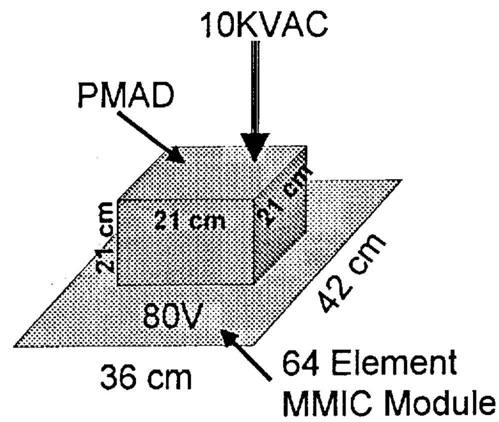


Figure 4
Placement of Antenna Converter

Results and Conclusions

Three primary challenges exist for SSP PMAD:

- **Mass** **Less than 1kg/kw**
- **Voltage** **Greater than 1KV**
- **Temperature** **300 degree C**

These challenges interact. We are driven to small boxes to keep within the mass allocation. This causes the temperature to rise because no active cooling – the mass allocation includes everything the PMAD requires.

An estimation of the overall PMAD mass is tabulated below in Table 3.

	kg	kg/kw
Array Converters	3,362,061	1.06
Upper Transformer	88,712	0.03
3 phase cable	1,463,049	0.46
Lower Transformer	88,712	0.03
Distribution Cables	390,296	0.12
Antenna Converters	2,890,909	0.91
Total	8,283,740	2.61

Table 3 PMAD Mass

The overall factor of 2.61 in the table 3, above, exceeds the allocation of 1kg/kw.

Clearly we have a challenge to reduce mass. A beginning challenge is to build a 300 degree C power converter with less than 1kg/kw density. The Array Converters and the Antenna Converters are the largest components of the mass distribution.

PMAD for SSP is a difficult challenge but no less than the other issues for SSP. We have 20 years to full deployment to work through the myriad of issues and design challenges.

Acknowledgements

This worked was done under funding of Space Solar SERT contract from MSFC through Boeing, Huntington Beach. I wish to thank Mark Henley, Seth Potter and James McSpadden (Boeing Seattle) for the many hours of technical discussions.

List of Acronyms

PMAD	Power Management And Distribution
SSP	Space Solar Power
MMIC	Monolythic Microwave Integrated Circuit
GW	Gigawatt, 10^9 watts

[redacted]

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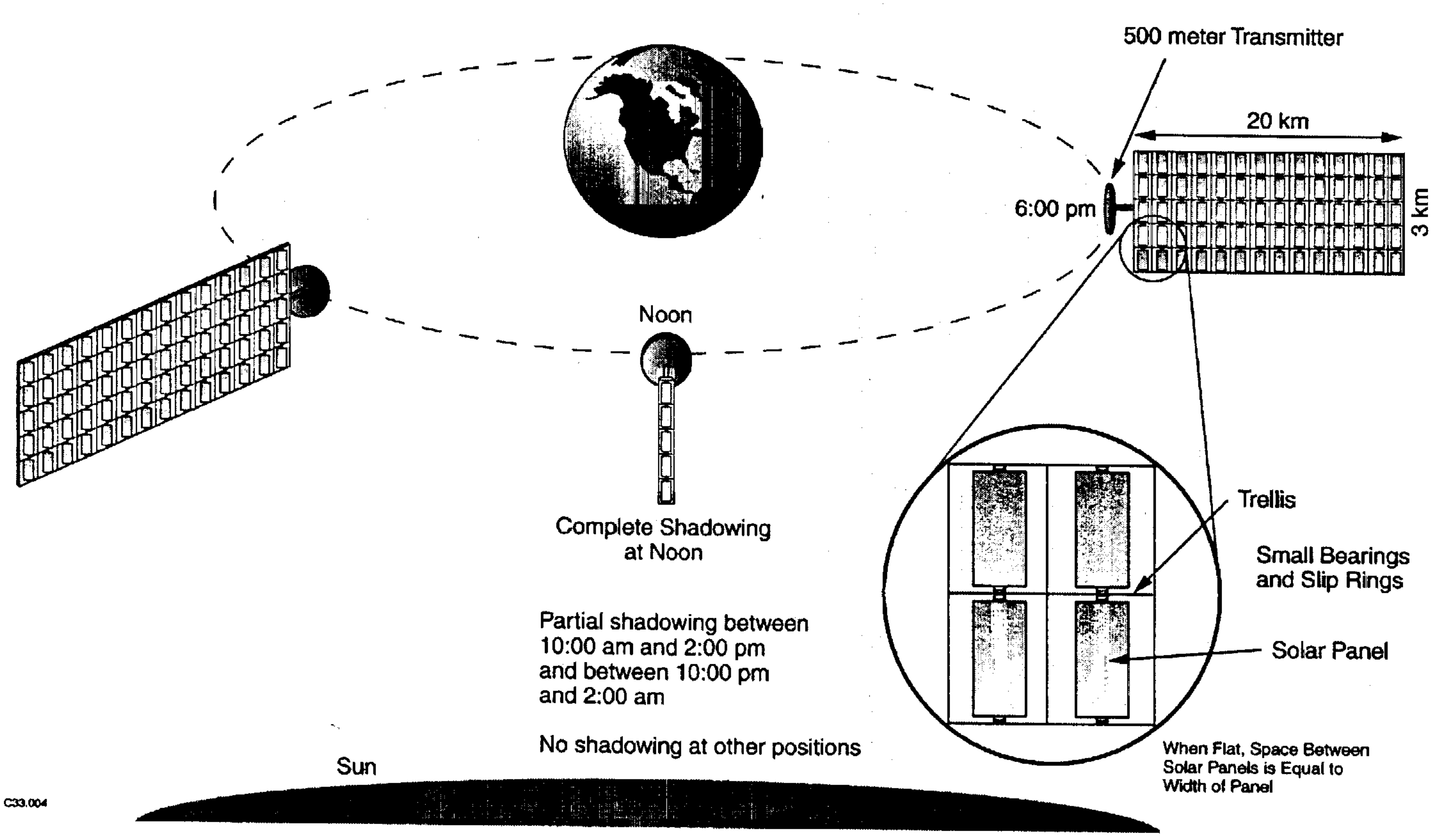
- Architecture & Concepts
- Backside Thermal View
- Solar Array Interface
- Transformer design & risks
- Twelve pulse rectifier
- Antenna(80V) Converters
- Distribution Cables
- Weight analysis
- Summary & Conclusions

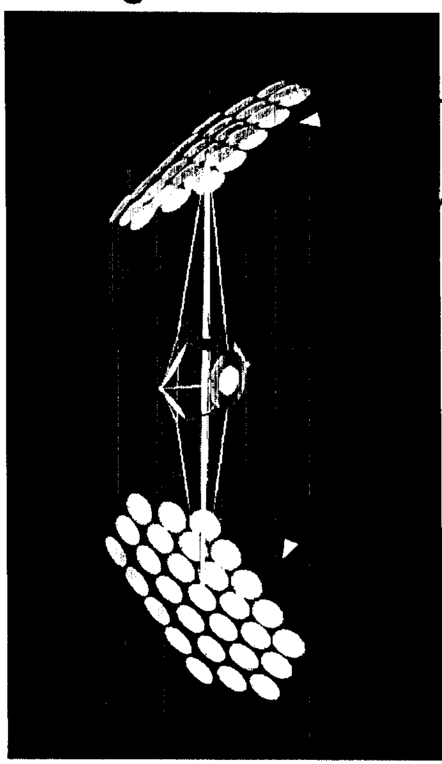
[redacted]

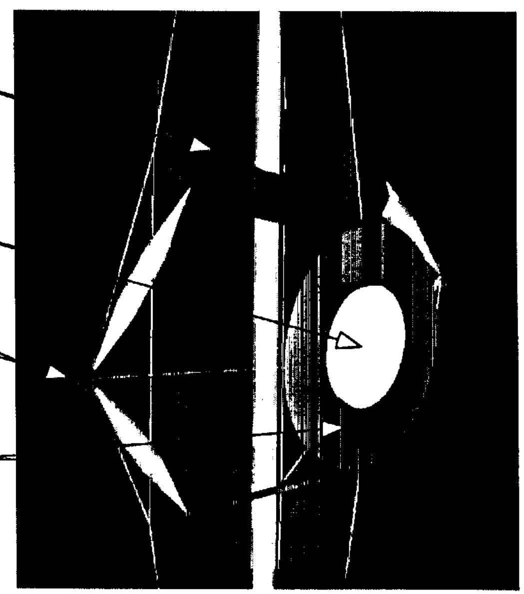
- Transmitter always faces Earth
- Trellis framework fixed to transmitter
- Individual panels rotate to face Sun



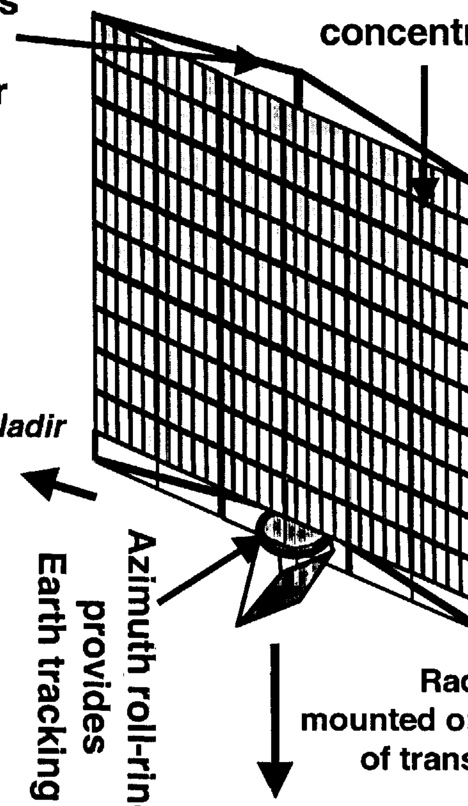
Integrated Symmetrical Concentrator

1.2 gW Delivered





Abacus Concept



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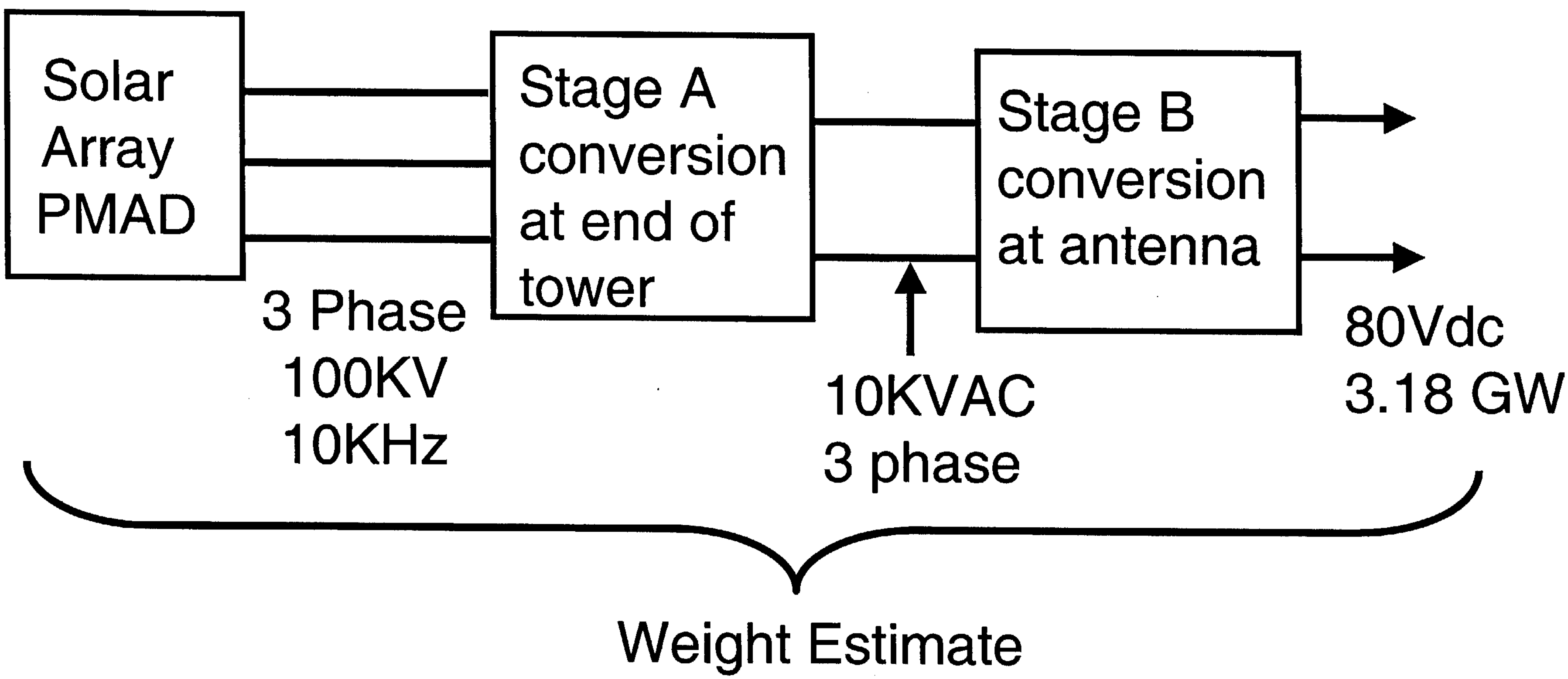
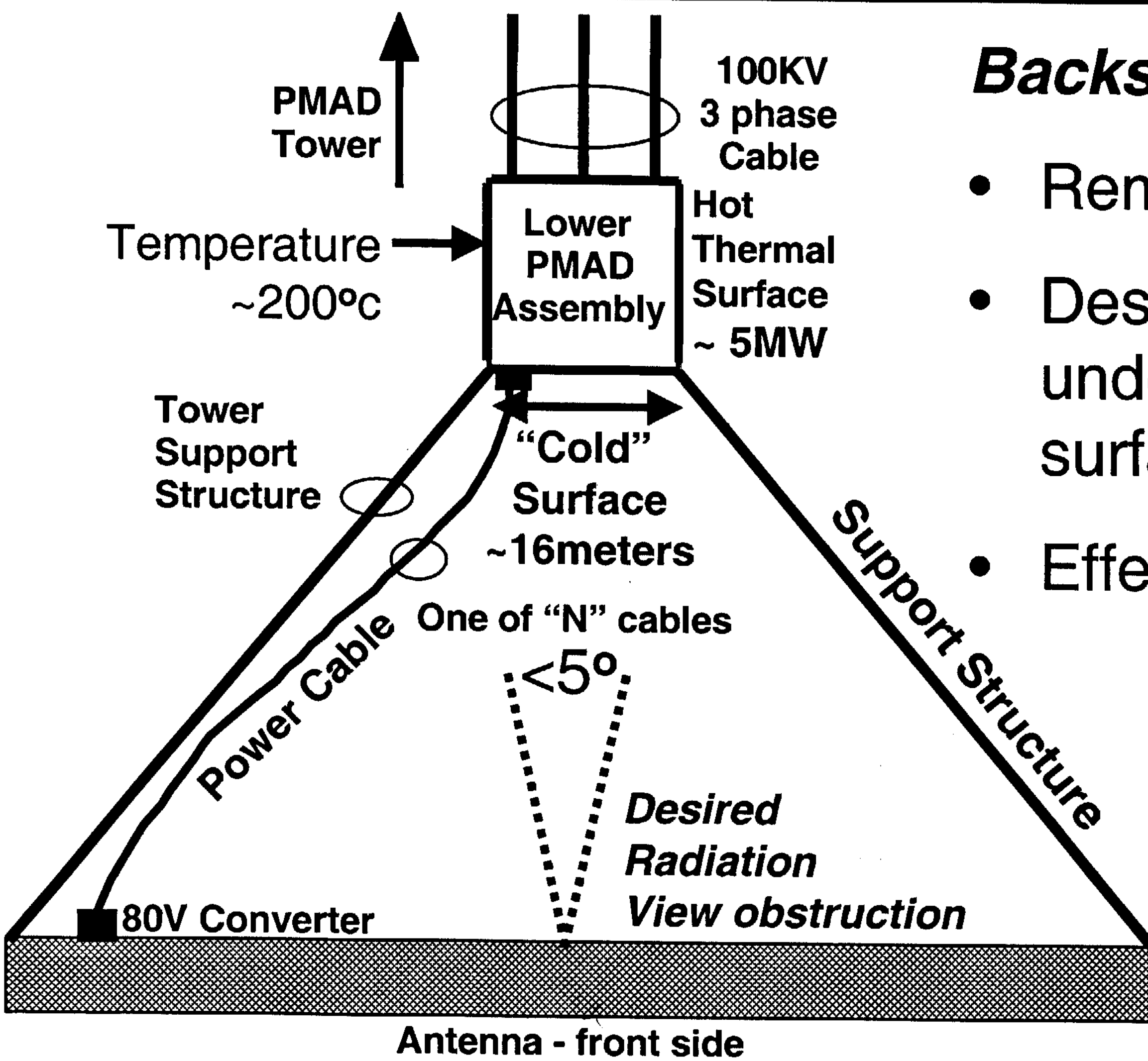


Solar Array PMAD
3 Phase
100KV
10KHz
Stage A conversion at end of tower
10KVAC
3 phase
Stage B conversion at antenna
80Vdc
3.18 GW
Weight Estimate

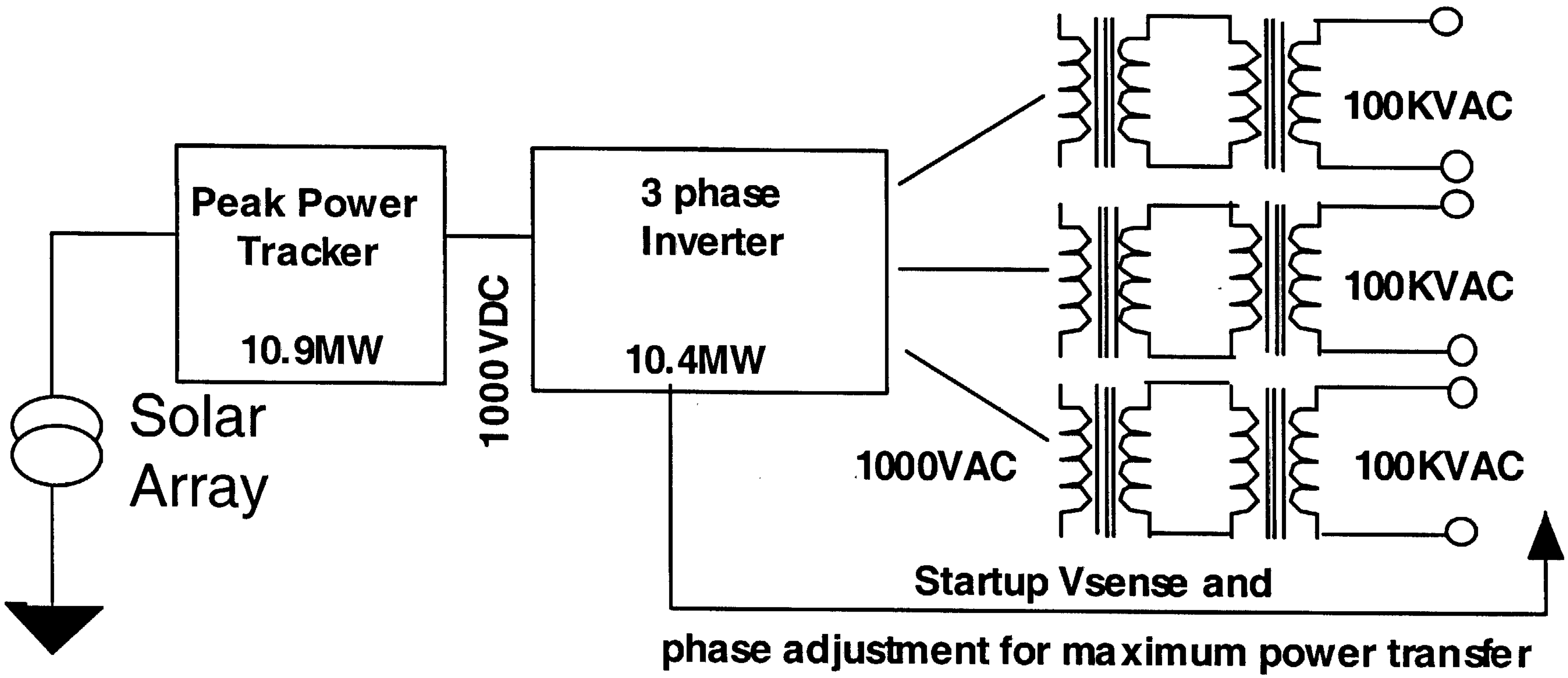
[redacted]



Backside thermal view

- Remote locate PMAD
- Design for cold underside PMAD surface
- Effect of cable heating?

[redacted]



Peak Power Tracker
10.9MW
Solar Array
1000VDC
3 phase Inverter
10.4MW
1000VAC
100KVAC
100KVAC
100KVAC
Startup Vsense and
phase adjustment for maximum power transfer

Transformer analysis

RF at Antenna	2.86E+09 watts
Antenna efficiency	90.0%
DC to Antenna	3.18E+09 watts

$$N_p = \frac{E\,x\,10^8}{4.44\,f\,B_m\,A_e}$$

Stage1	**Conversion to 10KV**
Primary Voltage	100000 Vrms
Primary Current	93.5 Arms
Secondary Voltage	10000 Vrms
Secondary Current	934.6 Arms
Frequency	10000 Hz
Bmax	5000 gauss
Area of core	50 cm^2
Stacking Factor	80% (1 mil tape)
Effective core area	63 cm^2
Core dimension	7.9 (sq core)
Core Length	557 cm
Core volume	27835 cm^3
Steel weight	0.0161 lbs/cm^3
Core weight	359 lbs

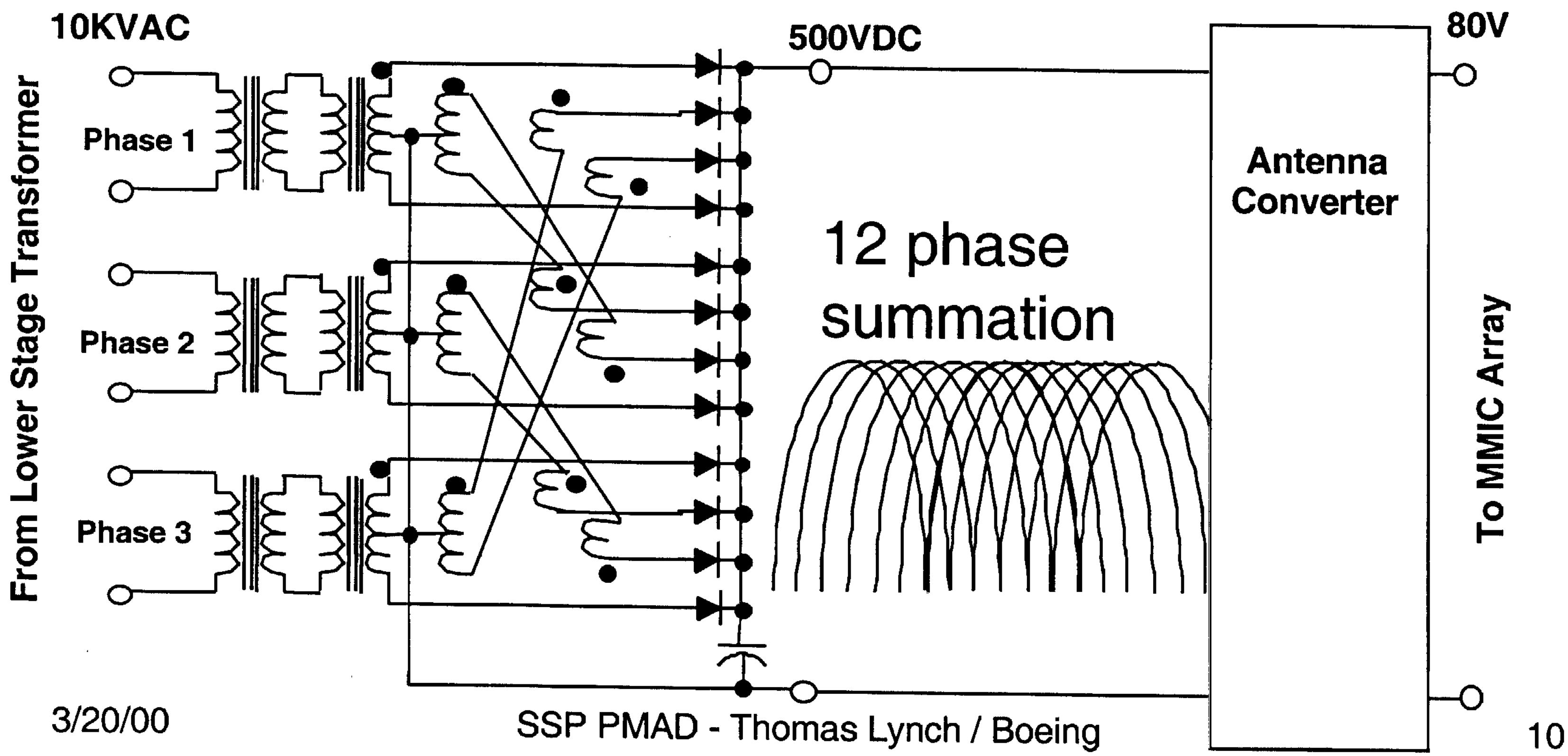
	Primary	Secondary
Turns	901	90
Wire Size	4	8 "O"s
Wire Area	0.2105	2.1
Insulation fill factor	80%	80%
Winding Area	948	954
Window Fill Factor	0.5	
Window area	3805	
Window side length	61.7	
Wire weight	0.0203	
Winding length	23.72	
wire volume	9024	
Wire Weight	183	
Transformer Weight	542	
Transformer Volume	788,316	
Core Loss, W	35,900	

- Leakage inductance of $\sqrt{10}:1$ ratios (x2)
- Corona, interwinding & distribution
- Dielectric voltage stress
- Core dissipation
- Interface to 100KV lines
- Potting or Oil filled
- Operation at 200°C

[redacted]

Advantages

- Simplicity
- Rugged & robust
- Excellent power factor



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- Architecture
  - 80 VDC output
    - 10KVAC input to 12 Pulse Rectifier
    - 500VDC into 80V converter
  - 4488 watt module for 64 MMICs
  - Current limit to 80V grid
  - Redundancy with “N+1” converters per module
  - Weinberg topology

[redacted]

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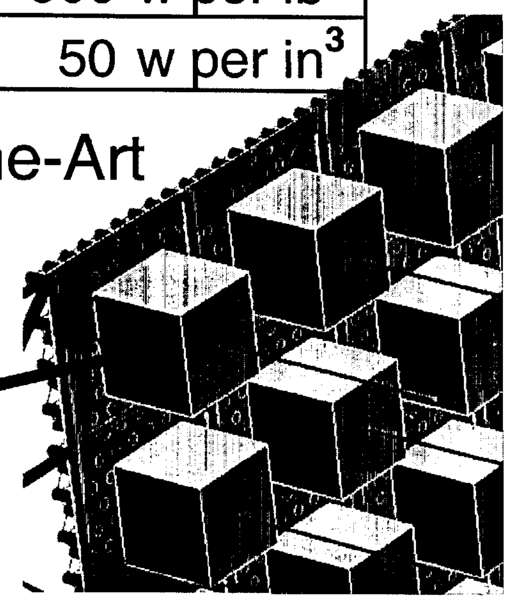
Weight	2	kg
Volume	8,503	cm3
Length	20.4	cm
Dissipation	105	Watts
Module Power	4488 W	
Volume	1,471	in3
Length	28.9	cm
Weight	9.0	lbs
	4.08	kg
Dissipation	224.4	Watts
Total		
Weight	6	kg
Volume	9,974	cm3
Length	21.5	cm
Dissipation	329	Watts

Assumptions:

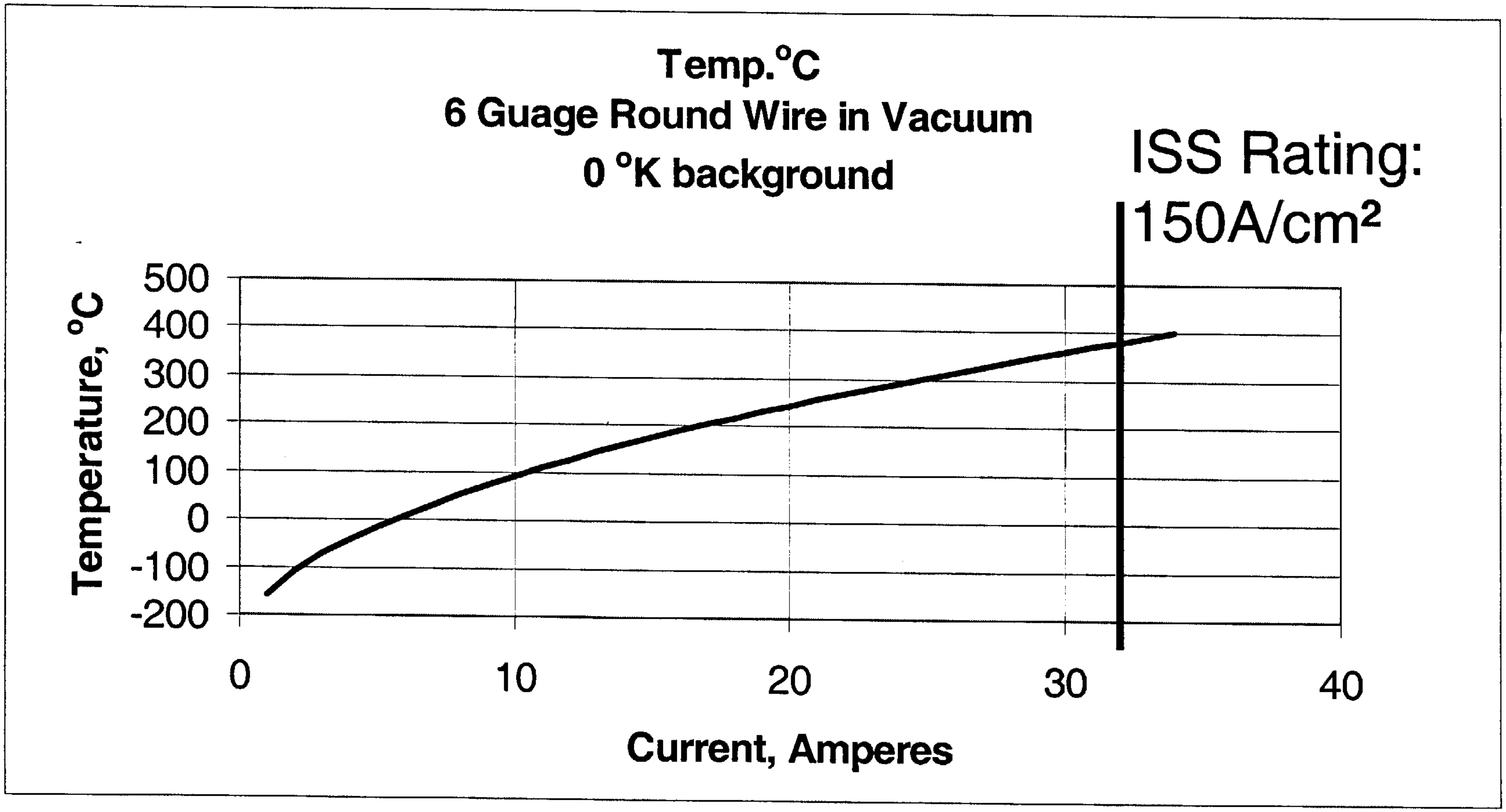
10KV 3 phase AC input
80VDC output at 4488W

Efficiency	95%
Density	500 w per lb
Volume	50 w per in^3

State-of-the-Art

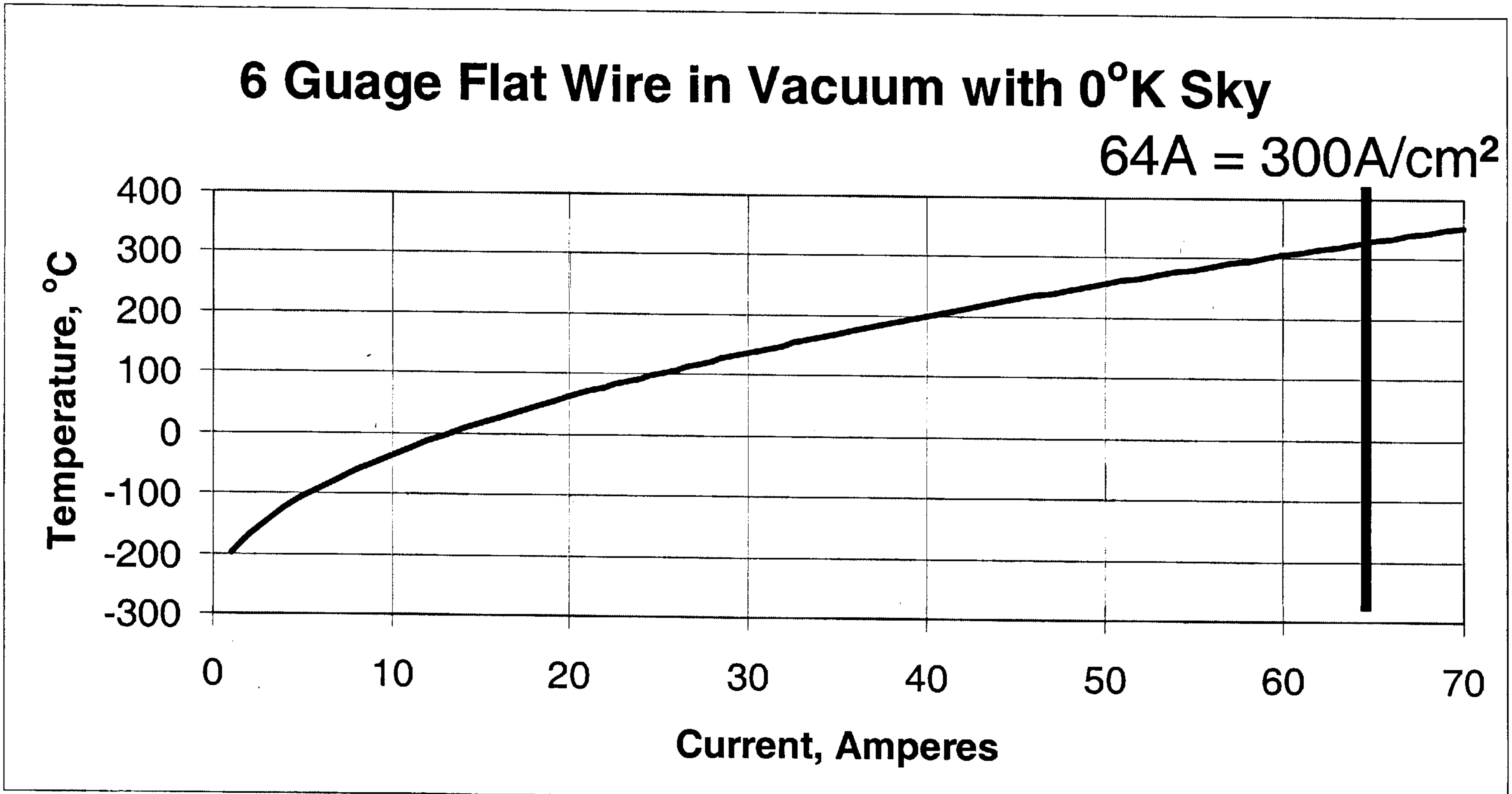


PMAD
Modules


Temp.°C
6 Guage Round Wire in Vacuum
0 °K background
ISS Rating:
150A/cm²
Temperature, °C
500
400
300
200
100
0
-100
-200
0
10
20
30
40
Current, Amperes

[redacted]

Could double ISS Current Rating with Flat Wire



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Assuming use 300A/cm^2 current density with flat wire
935 Amperes at 10KVDC per cable

Antenna Distribution Cables

	Qty	Length, m	kg per cm^3	Area, cm^2	Weight, kg	
Hot	340	200	9.21E-03	3.12	1.95E+05	kg
Return	340	200	9.21E-03	3.12	1.95E+05	kg
				Total	3.90E+05	kg

- Trade must be done to evaluate use of smaller cables
  - Radiation occlusion from dark sky from other structures
  - Adjacent cables cloud view of dark sky
  - Careful attention to termination of small cables

[redacted]

At 3.18 GW to 500 meter Antenna

	kg	kg/kw
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Upper Transformer	88,712	0.03
3 phase cable	1,463,049	0.46
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[redacted]

[redacted]

Issue	Straw man	Risks
Cable Voltage	100KV	Corona, plasma, cable weight
Power cable Topology	Single Cable, 3PH 10KHz AC drive	Weight, Spaghetti distribution, Feed access, coupling & drive
Array Voltage	1KV and higher	Corona, rotary joints
Grounding, plasma, corona	Exterior surfaces of PMAD to be at structure ground	Insulator interface degradation & failure due to voltage gradients
Command & Control	Autonomous status & control from each node	Failure analysis, distribution imbalance
MTBF & MTTR	Careful topology design trades and mechanical interface design	Connector interfaces prevent disassembly

[redacted]

Temperature .... 300°C

Mass .... 1.0 kw/kg

Voltage .... Corona

[redacted]

- Re-visit weight on all fronts
- Tower termination at antenna
  - PMAD interface & distance from antenna
  - Thermal radiation shield for antenna
  - Wire distribution to antenna
- Invest in PMAD R&D