GALLIUM ARSENIDE (GaAs) POWER CONVERSION CONCEPT

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The Rockwell Satellite Power System concept utilizes gallium arsenide (GaAs) solar cells and flat plate concentrators (CR=2) to generate 9.52 GW of power at the array sufficient for the satellite microwave antenna system to deliver 5 GW at the utility interface. The solar array bay configuration and design factors are shown in Figure 1. This concept shows a 3-bay by 10-bay matrix 3,900 m wide by 16,000 m long exclusive of the antenna. Each bay contains two panels 600 m by 750 m, providing a voltage string of 45.7 kV. The 600-m width consists of 24 rolls each 25-m wide.

The solar array is sized for worst conditions using summer solstice values (1311.5 W/m^2), end of life reflector values (CR effective = 1.83), solar cell degradation allowance (4% non-annealable loss), operating temperature of 113^{o}C at summer soltice (solar cell temperature coefficient of $\Delta\eta/\Delta T$ = 0.0282%/^{o}C), north-south seasonal inclination (altitude tipping of the SPS configuration accounts for 9.05^o of the nominal misorientation of 23.5^o, resulting in a seasonal factor of 0.968), packaging and array voltage mismatch factor of 0.89, and switch gear factor of 0.997. Array power output is calculated to be 352.6 W/m^2. The solar cell array area of 27 x 10^6 m^2 provides a 1.7% margin.

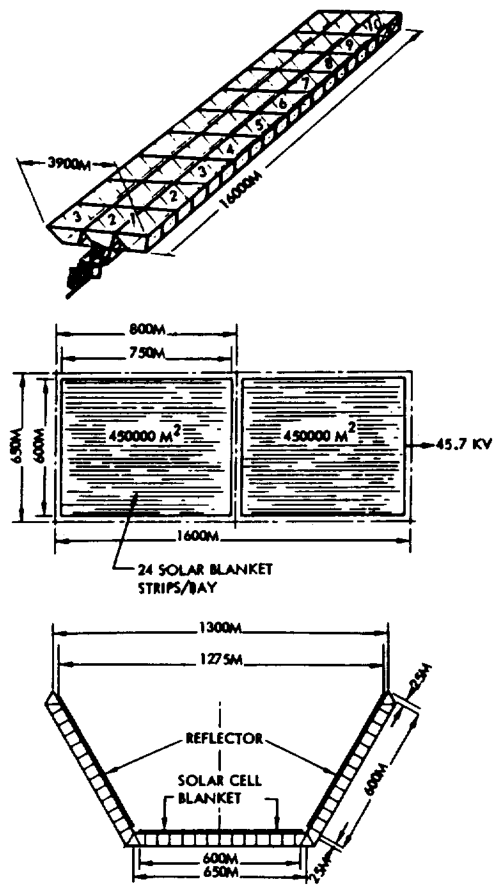
Key functional requirements include: delivery of 5 GW at constant power (except during solar eclipse) to the utility network; operation in geosynchronous orbit for 30 years (size for end of life); and cost-competitiveness with ground-based power generation. The last requirement (cost competitive with ground-based power generation) has driven the Rockwell design toward use of higher technology hardware.

The solar cell used in the satellite system design is a GaAs cell having a nominal efficiency of 20% (AMO, 28^{o}C). Based on today's technology, 20% cell efficiency is expected by the year 1990. The best laboratory GaAs cells are presently around 18% (Hughes, Rockwell International). The basic SPS cell concept is an inverted GaAs/sapphire design having a specific mass of 0.252 kg/m^2 (Figure 2). This cell design has a 20 μm sapphire (Al_2O_3) substrate upon which is grown a 5 μm single crystal GaAs junction. The Electronic Research Center (ERC) of Rockwell has supported this effort with investigations of the development and mass producibility requirements of the baseline GaAs/Al_2O_3 cells using a metallic oxide-chemical vapor deposition (MO-CVD) process. Figure 3 shows a production model of inverted structure GaAs/Al_2O_3 continuous ribbon solar cell. Trade studies by Rockwell on the system level have shown GaAs to be the preferred cell material compared to silicon. This is based on its higher efficiency (20% versus 17.3%); potential for cell efficiency improvements (the multi-bandgap concept is essentially a gallium arsenide cell with potential of 25-30% or greater); lower space radiation degradation damage (125^{o}C threshold temperature for annealing versus >500^{o}C); lower specific mass (0.252 kg/m^2 versus 0.427 kg/m^2); better compatibility with concentrators (improved temperature coefficient, $\Delta\eta/\Delta T$ = 0.028%/^{o}C versus 0.043%/^{o}C); and lower overall SPS cost.

A comparison of GaAs solar cell annealing effects after proton irradiation is presented in Figure 4. Over 400 small-area (0.4-cm-square) solar cells were tested by Rockwell.[1] Both typical and best cell annealing results are shown in Table 1. The SPS design assumes that nearly all radiation damage can be self-annealed out or annealed out with sufficient time and proper temperature.

A cost comparison was made of single-crystal GaAs, single-crystal silicon (Si), and amorphous silicon (A-Si). The baseline GaAs configuration was utilized at a mass of 0.252 kg/m^2, the single-crystal silicon cell stack configuration was taken from the DOE/NASA reference system report[2] 0.427 kg/m^2, and an amorphous silicon configuration was modeled from an RCA paper.[3] It was assumed that the A-Si cell stack weight was equivalent to 1-mil glass (0.143 kg/m^2) and that the blanket configuration was the same as in the baseline GaAs. Figure 5 summarizes results and shows that A-Si must achieve near theoretical efficiency (~15%) and low cell cost (~\$20/m^2) to provide a cost-competitive SPS system. Single-crystal silicon (even at the high efficiency of 17.3%) appears to result in a significantly higher SPS cost (Δ cost ~2.13 B) compared to the GaAs CR=2 baseline.

[1] Gallium Arsenide Solar Concentrator Hardness Study, Rockwell International, Technical Report AFAPL-TR-78-30 (May 1978).
[2] Concept Development and Evaluation Program, U.S. Department of Energy and NASA Reference System Report (October 1978).
[3] Twelfth IEEE Photovoltaic Specialist Conference, p 893.

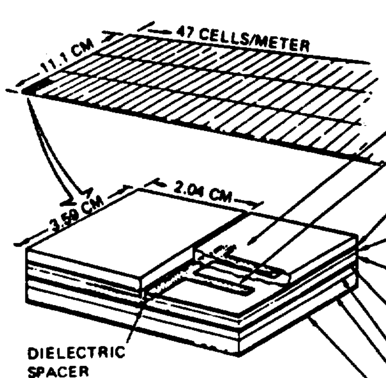


SOLAR ARRAY DESIGN FACTORS

SOLAR INPUT	1311.5 WATTS/M²
ENERGY ONTO CELL (CR = 1.83)	2400.1
OPERATIONS TEMPERATURE	113 C
n(T)	435.9
DESIGN FACTOR (0.89)	387.9
SEASONAL FACTOR (0.968)	375.5
DEGRAD. FACTOR (0.96)	360.5
SG FACTOR (0.997)	359.4
MARGIN (0.983)	352.6

SOLAR ARRAY POWER OUTPUT = 352.6 W/M² X 27.0 (10⁶) M² = 9.52 GW

Figure 1. Solar Array Configuration



ITEM	WEIGHT (MG/CM²)
20 μM Al_2O_2	7.98
INTERCONNECTS & TOP GRID CONTACTS	3.4
0.3-0.5 μM GaAlAs	0.03
1.5 μM P TYPE GaAs / 4-6 μM N-TYPE GaAs (6 μm)	2.66
0.5-1 μM OHMIC CONTACT	4.0
13 μM FEP	2.7
25 μM KAPTON (BLANKET)	3.6
6 μM POLYMER THERMAL COATING	0.9
	25.25 (.252 KG/M²)

Figure 2. GaAs on Sapphire Solar Cell Blanket Cross-Section

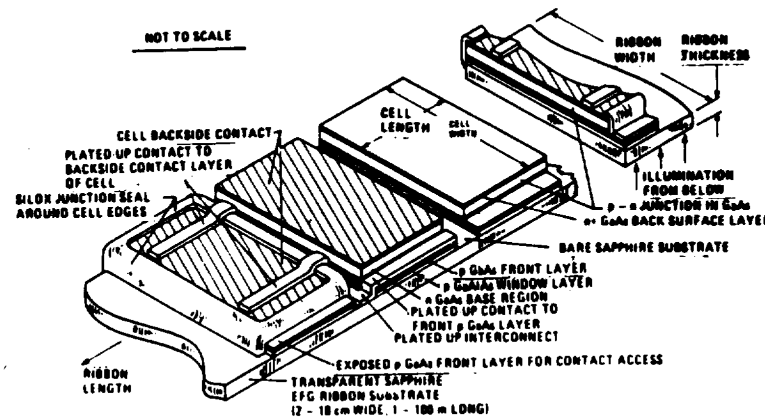
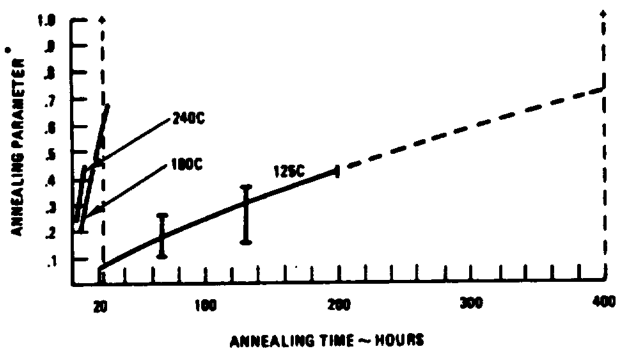


Figure 3. Production Model Inverted Structure $GaAs/Al_2O_3$ Continuous Ribbon Solar Cell



*ANNEALING PARAMETER

$$\frac{P_A - P_R}{P_I - P_R} = f(1 - e^{-\frac{t}{\tau}})$$

P_A = POWER AFTER ANNEAL
P_R = POWER AFTER IRRADIATION
P_I = POWER INITIAL
t = ANNEALING TIME
τ = RECOVERY TIME
f = RECOVERY FACTOR

Figure 4. GaAs Solar Cell Annealing Effects

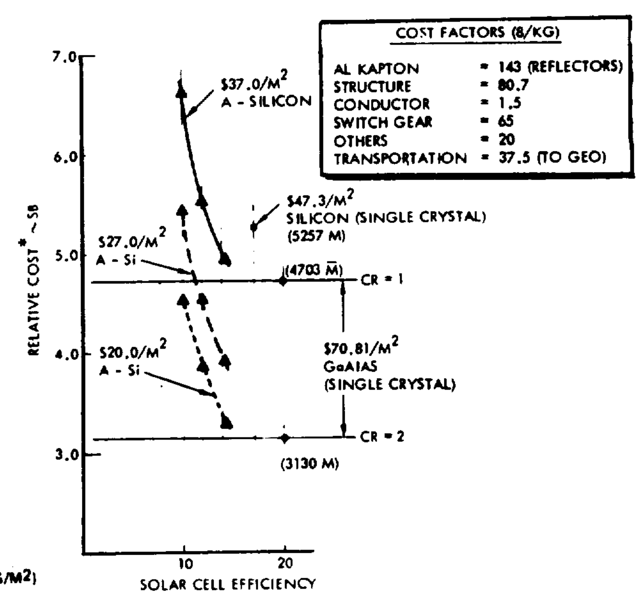


Figure 5. Solar Array Cost Comparison

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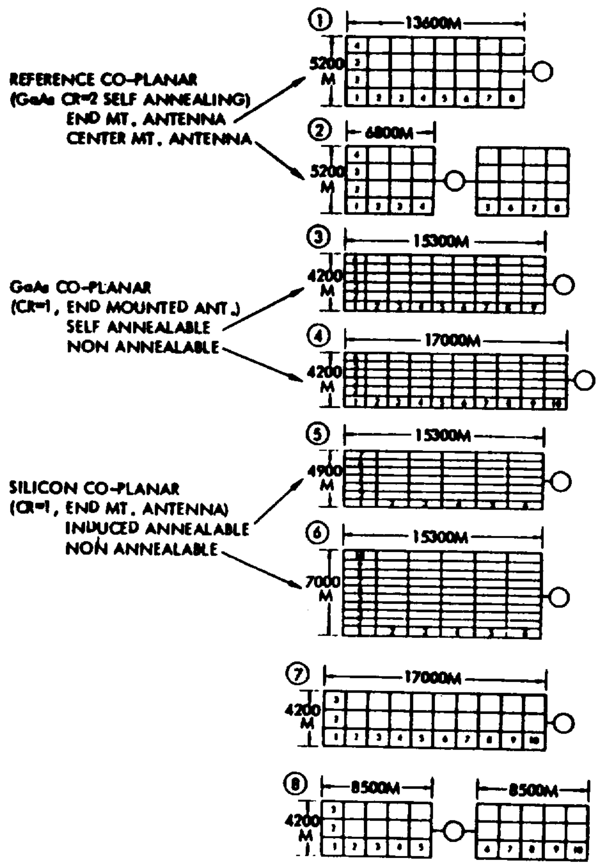

Figure 6. Configuration Options

Table 1. Proton Test Data

Test	Configuration*					
	1		2		3	
	Best	Typ	Best	Typ	Best	Typ
Initial						
Voc (V)	0.987	0.87	0.90	0.85	0.89	0.85
Isc (MA)	0.62	0.61	0.66	0.63	0.34	0.44
After Irradiation						
Voc (%)	98.6	93.7	98.5	96.0	68.1	64.0
Isc (%)	90.1	76.4	91.3	85.3	54.1	45.8
Recovery						
Voc (%)	99.3	97.2	99.2	97.8	83.6	73.1
Isc (%)	95.1	88.3	94.2	93.1	80.0	75.2

*Test Configurations:

	1	2	3
Radiation (protons/cm^2)	10 MEV (6.6×10^{10})	3 MEV (3.3×10^{10})	1 MEV (1×10^{12})
Annealing Temp (^{o}C)	130	130	180
Annealing Time (hr)	65	65	17

Eight different satellite configuration options (Figure 6) were studied to obtain a better understanding of the impact of solar cell selection (GaAs versus Si), antenna mounting location (end versus center), number of troughs (range 3 to 10), concentration ratio (CR=2 versus non-concentrated), and radiation degradation assumption (annealable versus non-annealable). For these studies, solar cell and power distribution efficiencies were held constant, as was antenna mass. The data are summarized in Table 2.

Very little SPS mass difference was calculated between configurations with different numbers of troughs; however, construction considerations strongly favor a narrow configuration. A relatively small mass savings is indicated for a center-mounted antenna (0.4 kg/kW$_{ut}$); similarly, a relatively small difference in mass was shown between GaAs annealable and non-annealable CR=1 configurations (0.36 kg/kW$_{ut}$) and between GaAs CR=1 and CR=2 (0.89 kg/kW$_{ut}$).

Figure 7 shows a plot of SPS mass estimates made over the last few years. A mass curve was prepared which normalized to an early estimate made by Dr. Peter Glaser in 1974 (~2.3 kg/kW utility power). As shown, SPS mass estimates have grown by a factor of approximately 2.3 for GaAs configurations and 3.5 for Si configurations (NASA reference concepts). The GaAs concept falls near the nominal range of uncertainty established initially by NASA/JSC in-house studies conducted in 1975. Various alternative concepts are compared, including solid-state (SS) configurations which replace klystrons with solid-state power amplifiers for the dc to RF microwave system and multi-bandgap (MBG) solar cells replacing the reference GaAs single function cells. The impact felt by cell efficiency improvements is demonstrated by the MBG concepts, which use a 30% nominal cell efficiency.

GaAs solar array major technology needs for the SPS program are identified in Table 3. Assumed values are given for critical parameters used in the satellite concept definition. Impacts on the SPS design from a failure to achieve the design values also are given in the table. These technology requirements are to be addressed as part of the Ground-Based Exploratory Development (GBED) activities.[4]

Table 2. Configuration Comparison Data

CONFIGURATION	①	②	③	④	⑤	⑥	⑦	⑧	FIRST Q BASELINE
CELL MATERIAL	GaAs	→	→	→	Si	→	GaAs	→	→
CONC RATIO	2	→	1	→	→	→	2	→	→
ANT MOUNT	END	CENTER	END	→	→	→	→	CENTER	→
RADIATION DEGRAD FACTOR	.96	→	→	.84	.96	.70	.96	→	→
CELL OUTPUT (W/M²)	362.7	→	218.2	190.9	182.9	133.4	362.7	→	336.6
SOLAR CELL AREA (10^6 M²)	28.4	→	47.2	53.95	56.3	77.2	28.4	→	30.6
REFLECTOR AREA (10^6 M²)	57.6	→	—	—	—	—	57.6	→	61.2 (650)
BAY DIMENSIONS (M)	700 X 1700	→	→	→	700 X 2550	→	750 X 1700	→	600 X 1600
NUMBER SOLAR CELL BAYS	4 X 8 = 32	→	6 X 9 = 54	6 X 10 = 60	7 X 6 = 42	10 X 6 = 60	3 X 10 = 30	→	3 X 12 = 36 (1350)
REFL BAY DIMENSION (M)	1300 X 1700	→	—	—	—	—	1400 X 1700	→	1250 X 1600
PLAN FORM (M)	5200 X 13600	→	4200 X 15300	4200 X 17000	4900 X 15300	7000 X 15300	4200 X 17000	→	3850 X 19200
PLAN FORM AREA (10^6 M²)	70.72	→	64.3	71.4	74.97	107.1	71.4	→	73.92
NO. SWITCHGEAR (ON ARRAY)	1120	→	1890	2100	2436	3480	1140	→	1260
COLLECTOR ARRAY (10^6 KG)									
STRUCTURE & MECH	2.156	→	2.043	2.168	2.230	2.791	2.156	→	3.825
SOLAR PANELS	7.258	→	11.897	13.595	23.988	34.506	7.258	→	7.722
SOLAR REFLECTORS	1.182	→	—	—	—	—	1.182	→	1.108
POWER DISTRIBUTION	2.719	1.55	2.879	2.545	3.058	3.87	3.00	1.272	1.081
ATT CONTROL/IMS/ROT JT	.385	→	.350	.389	.408	.583	.385	→	.385
	(13.699)	(12.53)	(17.259)	(18.697)	(29.684)	(41.750)	(14.011)	(12.253)	(14.127)
ANTENNA SECTION	16.297	→	→	→	→	→	→	→	→
SUBTOTAL	29.996	28.827	33.556	34.994	45.981	58.047	30.388	28.55	30.424
25% GROWTH	7.499	7.206	8.389	8.749	11.495	14.512	7.577	7.137	7.606
TOTAL	37.495	36.033	41.945	43.743	57.476	72.559	37.965	35.687	38.029

Table 3. SPS Solar Cell Parameters as Design Drivers

Parameter	SPS GaAs Design Values	Description	Impact on Design (failure to achieve values)
Cell efficiency	20% (AMO, 28°C)	SPS concept (CR=2) requires 27.0 x 10^6 m² of solar cells; array output: 352.6 W/m²	Lower efficiency penalizes array area, weight, array cost, transportation cost, and construction schedule; Si performance could be as low as 123.6 W/m²
Radiation degradation	4%	Non-annealable allowance is 4% array area; current design assumes self-annealing at >125°C	Failure to achieve annealing will penalize array area 16% in GEO and 40% EOTV; Si degradation penalties are greater
Weight	0.252 kg/m²	Total SPS array weight = 7.536 x 10^6 kg; ~25% of total satellite weight	Substitution of Si penalizes system by 22.2 x 10^6 kg or more
Operating temperature	>125°C	GaAs performance at operating temperature -17.6%	Lower performance could penalize system by forcing nonconcentrated SPS ~4.06 x 10^6 kg; 18.8 x 10^6 m² solar cells
Cost	$70.8/m² solar cells	Total array cost $3130.2M̄ (basic cell/reflector cost $2320M̄) per satellite*	Si cell cost penalty adds $2126.7M̄ to array cost*
Cell thickness	5 μm active GaAs region 20 μm sapphire substrate	Gallium requirement for SPS ~375 metric tons (5 GW)	Thicker materials affect weight, cost, and availability

*Reference: Satellite Power System (SPS) Concept Definition Study (Exhibit C) First Quarterly Review. Rockwell International, SD 78-AP-0075 (June 21-22, 1978)

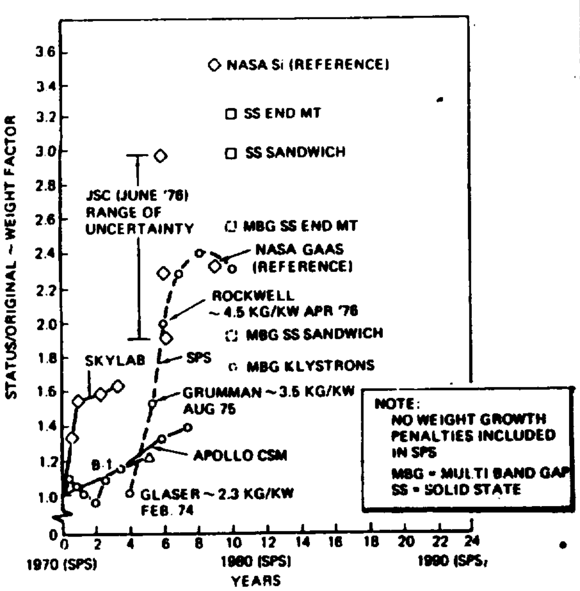

Figure 7. SPS Weight Uncertainty

[4]Satellite Power System Ground-Based Exploratory Development (GBED) System Analysis and Technology Plan. National Aeronautics and Space Administration. Rough Draft (December 1, 1979).