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The Impact of Solar Cell Technology on Planar Solar Array Performance

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Introduction

This paper presents the results of a study into the potential impact of advanced solar cell technologies on the characteristics (weight, cost, area) of typical planar solar arrays designed for low, medium and geosynchronous altitude earth orbits. The study considered planar solar array substrate designs of lightweight, rigid-panel graphite epoxy and ultra-lightweight Kapton. The study proposed to answer the following questions:

Do improved cell characteristics translate into array-level weight, size and cost improvements?

What is the relative importance of cell efficiency, weight and cost with respect to array-level performance?

How does mission orbital environment affect array-level performance?

Important features of the study were: comparisons were made at the array level including all mechanisms, hinges, booms, harnesses. Array designs were sized to provide 5kW of array power (not spacecraft bus power, which is system dependent but can be scaled from given values). The study used important "grass roots" issues such as use of the GaAs radiation damage coefficients as determined by Anspaugh [ref. 1]. Detailed costing was prepared, including cell and cover costs, and manufacturing attrition rates for the various cell types.

The Solar Cell Technologies

Five solar cell types were studied (see table 1). The low cost, 200 μm (8-mil) thick, back surface reflector (BSR), nontexturized cell, at 12.3% efficiency represents the industry standard against which the other designs were compared. This "generic" silicon cell technology is reasonably well understood so that it was used as a control and a benchmark case study. Thin silicon cells were also included. These devices were assumed to be 66 μm (2.6 mils) thick with a boron back surface field and a back surface reflector.

Three GaAs cell technologies were studied, as follows: standard GaAs cells grown on 300 μm (12-mil) GaAs substrates, GaAs cells grown on 200 μm (8-mil) Germanium (Ge) substrates, and GaAs cells grown on 75 μm (3-mil) Ge substrates. The existence of technologies to grow GaAs cells on thinner, yet rugged substrates is the key which prompted this trade study. The effect of variable GaAs cell substrate thickness on radiation fluence at the junction was included in this study.

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It was assumed, and recent data supports this, that cell substrate type has no effect on cell conversion efficiency. It was further assumed that the radiation response of these three GaAs cell types were identical after backside shielding effects are incorporated.

The Orbital Environments and Their Impacts

The study considered three orbits which, taken as a set, encompass most earth orbit missions. A mission life of 10 years was assumed.

The low earth orbit (LEO) mission selected for study was 520 km (280 n.mi) altitude, 28.5° inclined. This is typical of Shuttle/Space Station related missions and the Advanced X-Ray Astronomy Facility (AXAF). This orbit has a relatively benign radiation environment, but has high aerodynamic drag. EOL cell efficiency (low array area) will be a key design driver for this orbit. The LEO atomic oxygen environment is a driver in the selection of array materials and components but does not significantly effect the characteristics at the array level.

The mid-altitude earth orbit (MEO) selected was 6500 km (3500 n.mi) altitude, 60° inclined to demonstrate the effects of flying in a high radiation (trapped protons) environment. This type of orbit is geo-magnetically shielded from solar flare protons. In this type of orbit, a strong trade exists between coverglass thickness and array characteristics (weight, area and cost). The array characteristics are very sensitive to orbital altitude in this regime, as EOL radiation dose (but not species) changes by orders of magnitude with varying altitude.

The geosynchronous (GEO) altitude orbit, 35760 km/0° inclined (19300 n.mi/0° inclined), was considered due to the large number of missions flying this orbit. The orbital environment is rich in high energy trapped electrons, and high energy solar flare protons. The rigid particle spectra as well as the launch cost premiums make array weight a significant driver and preclude thick coverglasses.

The Array Technologies

Two planar array types were studied: flat rigid panel substrate and flat flexible blanket substrate. The rigid substrate characteristics are based upon 125 μm (5 mil) graphite/epoxy facesheets. The flexible substrate design is based upon the JPL/TRW Advanced Photovoltaic Solar Array (APSA) design [ref. 2]. Both technologies were being produced by TRW for flight or protoflight applications.

The rigid panel array configuration is shown in figure 1. The design assumed two wings were used for the rigid-panel, flat, accordion-fold array. The study did not include the solar array drive assembly (SADA) characteristics, and the simplifying assumption was made that the array would be sun-pointed about two axes for normal incidence. No provision was made for retraction or orbital change-out mechanisms.

Radiation Degradation

The method used to estimate the damage equivalent normal incidence 1 MeV electron fluence is given in detail in reference 1, chapter 6 and will not be further described. Fluences were calculated over a wide range of front side shield densities (coverglass thicknesses) for weight optimization. Silicon solar cell conversion efficiency vs. fluence was taken from reference 1. Similar GaAs properties were taken from reference 3.

The radiation models used for the three orbits are given in table 2, as are some of the assumptions used in the analyses. Most important among these is that, for the region of interest, a value of 1500 was used for the conversion from DENI 10 MeV protons to DENI 1 MeV electrons for the GaAs devices, whereas a value of 3000 was used for the Si devices. A comparison of observed relative damage coefficients observed by three different experimenters is shown in figure 2. This comparison lent credibility to the data from reference 3, as used in this study, as the measured data is repeatable by other experimenters [refs. 4 and 5].

The rigid panel substrate had an areal mass density of 1.5 kg/m^2 (0.3 lb/ft^2) which, when added to the cell adhesive mass, represented an equivalent fused silica shield thickness of 736 μm (29 mils). The flexible substrate and the cell adhesives represented a fused silica equivalence of 75 μm (3 mils).

On-Orbit Operating Temperature

Operating temperatures were calculated using steady state energy balance considerations. Albedo and earth emission heating were considered only for the LEO cases. The temperatures were calculated based upon their end of life cell conversion efficiencies and the solar cell absorptance values given in table 1. Geometry, temperature coefficients and method are shown in figure 3.

Cost Estimates

The array costs were based upon the unit prices given in table 3. The substrate cost, as well as the cost of the balance of the hardware, was per recent TRW hardware experience. This data is presented as relative values only to protect the underlying proprietary information.

Array Weight

Array weight was the sum of the weights for: cells, covers, cover adhesive, cell adhesive, substrates, hinges, tie down/release/deployment mechanisms, harnesses, booms.

A cover thickness was selected for each condition that would optimize the array performance in terms of area and weight. For LEO and GEO, the optimum cover turned out to be the thinnest cover possible - 75 μm (3 mil) ceria-doped glass. For MEO, the cover thickness optimized at 500 to 750 μm (20 to 30 mil) fused silica cover (cell type dependent).

The weight for the rigid panel array included all wing components outboard of the solar array drive and power transfer assembly. Boom and mechanisms were taken as 30% of the cell-covered substrate weight. Panel wiring and boom harnesses were taken as 0.3 kg/m^2 (0.0615 lb/ft^2). Substrate area and weight were based upon cell area requirements, and the packing factor (pf=0.85) was taken at ~1100 2×4 cm cells/m^2 (100 cells/ft^2).

Summary

Tables 4, 5 and 6 compare the characteristics of the array types of a graphite/epoxy structure rigid panel planar solar array as a function of cell type for three types of 10 year, 5kW end-of-life (EOL) missions.

Relative cost figures are included in the last two columns to provide an initial indication of the cost effectiveness of the cell type. Cost is included because it will always be a key factor for both NASA and military missions. In many instances cost will be equal in importance to weight, with array size considerations being of secondary importance. Only for high radiation belt orbit missions or for existing designs where array size is limited does array size begin to have an equivalent importance with weight and cost.

One key conclusion that should be drawn is that there is never one "typical" value for specific power or power density that can be used. For a given cell type it is highly dependent on the orbit because of the order-of-magnitude variation in natural space radiation and cell degradation that will occur. Except for the very high natural radiation missions (MEO), the currently available 50 μm (2-mil) thick silicon cell provides superior EOL specific power performance relative to the currently available 300 μm (12-mil) thick GaAs/GaAs cell at a reduced cost, even though the GaAs cell array is 1/3 smaller in area. For LEO and GEO missions, the advanced GaAs/Ge cell must be substantially less than 200 μm (8-mil) thick or have efficiency characteristics above 18% in order to provide better specific power performance. Even then there will be a cost penalty when using the GaAs cells. In high radiation belt orbits (MEO), GaAs cell arrays show superior specific power performance primarily because the radiation resistance of those cells relative to silicon, in conjunction with their higher BOL efficiency characteristics, permits the array size to be also half that for silicon cell arrays. Also the cost differentials are smaller.

Figures 4 and 5 plot the GEO specific power results, respectively, for rigid panel and flexible blanket arrays as a function of AM0 cell efficiency to better illustrate some key points. Included on Figure 4 are zones for the advanced technology multi-bandgap (MBG) cells that are still in the early development stages. The 200 μm (8-mil) GaAs/Ge cell at 18% efficiency is equivalent to the 50 μm (2-mil) silicon cell and the cost differentials are small. The 200 μm (8-mil) GaAs/Ge cell is assumed to be the immediate successor to the 300 μm (12-mil) GaAs/GaAs cell because of performance, cost and ruggedness. The results show that the 75 μm (3 mil) GaAs/Ge cell is a very attractive alternative to thin silicon cells for most orbit conditions if weight is a key issue, especially if the BOL efficiency is in the 18 to 21 percent range. Because of the expected high cost for MBG cells they must be made very thin 150 to 200 μm (6 to 8 mils), if they are going to be competitive with the thin GaAs/Ge cell.

References

[1] Anspaugh, Downing, et al, *Solar Cell Radiation Handbook*, third edition, JPL publication 82-69, November 1, 1982

[2] R.M. Kurland et. al., "Advanced Photovoltaic Solar Array Development," *9th Space Photovoltaic Research and Technology Conference Proceedings*, 19-21 April 1988 at NASA/LeRC, Cleveland, Ohio.

[3] Anspaugh and Downing, *Radiation Effects in Silicon and Gallium-Arsenide Solar Cells*, JPL publication 84-61, September 1, 1984

[4] G. Moreno et al, "Analysis of Low Energy Proton GaAs Solar Cell Degradation", *Photovoltaic Generators in Space, Proceedings of the Fifth European Symposium (ESA SP-267)*, November 1986, pp 313-316

[5] Takata, et al, "Energy Dependance of Proton Irradiation Damage in GaAs Solar Cells and Combined Radiation on Them,"*Photovoltaic Generators in Space, Proceedings of the Fifth European Symposium (ESA SP-267)*, November 1986, pp 425-432

Table 1. Cover and Cell Characteristics

Covers

- Fused silica or CMX (thickness dependent)
- Thickness orbit optimized
  - Front shielding from 3 to 60 mils
  - Highest EOL W/kg determined thickness
- Efficiency optimized shielding not practical (too heavy)

Cell Types	Thickness (mil)	Efficiency at 28°C AMO (%)	Solar Absorptance	Type
Silicon*	8.0	12.3	0.75	BSR
Thin Silicon	2.6	13.5	0.72	BSR/B-BSF
Gallium-arsenide	12.0	18.0	0.78	–
GaAs/Germanium	8.0	18.0	0.78	–
Thin GaAs/Ge	3.0	18.0	0.78	–

*Cell type selected showed highest EOL efficiency at operating temperature of all production thick silicon cells available

Table 2. Space Radiation Data

Free field environments

- GEO: AE8MAX, Pruett flare
- MEO: AP8MAX, flares not significant
- LEO: AP8MIN, geomagnetically shielded

Equivalent fluence approach and Si degradation per Reference 1

GaAs damage coefficients and degradation per Reference 2 agree with Reference 3 and 4

10 MeV proton in GaAs equals 1500 1 MeV electrons (Si = 3000)

Cell substrate included in backside shielding for GaAs cells

References

1. **Solar Cell Radiation Handbook,** Third edition, JPL Publications 82-69, November 1, 1982, By Anspaugh, Downing, et al.
2. **Radiation Effects in Silicon and Gallium Arsenide Solar Cells,** JPL publication 84-61, September 1, 1984, by Anspaugh, Downing
3. **Analysis of Low Energy Proton GaAs Solar Cell Degradation,** by Moreno, et al.
4. **Energy Dependence of Proton Irradiation Damage in GaAs Solar Cells,** by Takata, et al.

Table 3. Unit Cost Data

2 x 4 cm cells

- Silicon – \$12; thin silicon – \$36
- GaAs/GaAs – \$125
- GaAs/Ge – \$100; thin GaAs/Ge – \$100

Covers

- 2 mil CMX – \$5; 20 mil fused silica – \$10; 30 mil FS – \$15

Coverage

- 100 cells/ft^2

Attrition rates

- Varies with cell type (based on TRW production line experience)

Manufacturing, integration, and test costs based on TRW experience

Table 4. Comparative Performance, Rigid Panel Deployable Solar Array (LEO Mission, 5 kW EOL Power)

10 Year Orbit	Cell Type	Optimum Cover Thickness (mils)	EOL Specific Power (W/Kg)	EOL Power Density (W/m^2)	Array* Weight (kg)	Array** Area (m^2)	Cell Stack Material Relative Cost	Array Relative Recurring Cost
	8 mil silicon	2	30	101	167	49.3	0.97	0.98
LEO	2 mil silicon	2	38	112	133	44.7	2.31	1.30
280 nmi	12 mil GaAs	2	34	170	146	29.5	5.02	1.73
28.5° i	8 mil GaAs/Ge	2	40	170	124	29.5	3.73	1.42
	3 mil GaAs/Ge	2	49	170	103	29.5	3.73	1.42

η_0 - 12.3% at 28°C for 8 mil silicon cell (10 Ω-cm BSR, DAR; α_s - 0.75)
η_0 - 13.5% at 28°C for 2 mil silicon cell (10 Ω-cm BSR/B-BSF; DAR; α_s - 0.72)
η_0 - 18% at 28°C for all GaAs or GaAs/Ge cells (α_s - 0.78)
Substrate - 10 mil graphite/epoxy facesheets and 0.75-in aluminum honeycomb core (≈29 mil equivalent fused silica shielding)

*Weight includes all wing components exclusive of SADA
**Array area is total panel area for two multi-panel wings

Table 5. Comparative Performance, Rigid Panel Deployable Solar Array (MEO Mission, 5 kW EOL Power)

10 Year Orbit	Cell Type	Optimum Cover Thickness (mils)	EOL Specific Power (W/Kg)	EOL Power Density (W/m2)	Array* Weight (kg)	Array** Area (m2)	Cell Stack Material Relative Cost	Array Relative Recurring Cost
MEO 3500 nmi 60° i	8 mil silicon	20	11	52	440	95.3	2.42	1.76
	2 mil silicon	20	13	55	385	91.6	5.31	2.26
	12 mil GaAs	30	15	105	330	47.7	8.75	2.86
	8 mil GaAs/Ge	30	16	100	310	50.2	6.96	2.42
	3 mil GaAs/Ge	20	17	82	290	61.2	8.11	2.76

η_0 = 12.3% at 28°C for 8 mil silicon cell (10 Ω-cm BSR, DAR; α_s = 0.75)
η_0 = 13.5% at 28°C for 2 mil silicon cell (10 Ω-cm BSR/B-BSF; DAR; α_s = 0.72)
η_0 = 18% at 28°C for all GaAs or GaAs/Ge cells (α_s = 0.78)
Substrate = 10 mil graphite/epoxy facesheets and 0.75-in aluminum honeycomb core (≈29 mil equivalent fused silica shielding)

*Weight includes all wing components exclusive of SADA
**Array area is total panel area for two multi-panel wings

Table 6. Comparative Performance, Rigid Panel Deployable Solar Array (GEO Mission, 5 kW EOL Power)

10 Year Orbit	Cell Type	Optimum Cover Thickness (mils)	EOL Specific Power (W/Kg)	EOL Power Density (W/m2)	Array* Weight (kg)	Array** Area (m2)	Cell Stack Material Relative Cost	Array Relative Recurring Cost
GEO	8 mil silicon	2	29	98	173	51.0	1.00	1.00
	2 mil silicon	2	37	110	135	45.4	2.40	1.33
	12 mil GaAs	2	32	159	156	31.5	5.37	1.83
	8 mil GaAs/Ge	2	37	158	134	31.6	4.00	1.50
	3 mil GaAs/Ge	2	45	158	112	31.6	4.00	1.50

η_0 = 12.3% at 28°C for 8 mil silicon cell (10 Ω-cm BSR, DAR; α_s = 0.78)
η_0 = 13.5% at 28°C for 2 mil silicon cell (10 Ω-cm BSR/B-BSF; DAR; α_s = 0.72)
η_0 = 18% at 28°C for all GaAs or GaAs/Ge cells (α_s = 0.78)
Substrate = 10 mil graphite/epoxy facesheets and 0.75-in aluminum honeycomb core (≈29 mil equivalent fused silica shielding)

*Weight includes all wing components exclusive of SADA
**Array area is total panel area for two multi-panel wings

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Characteristics

- Substrate
  - 0.3 lb/ft^2 graphite/epoxy aluminum honeycomb core
  - 29 mils equivalent fused silica rear-side shielding

Array weight includes the following:

- Two wings
- Panel substrates
- Deployment mechanisms
- Hinges
- Spacecraft boom
- Solar cells/covers
- Panel wiring
- Wing harness

Array weight doesn't include the following:

- Array drive
- Retraction capability
- Orbital change-out

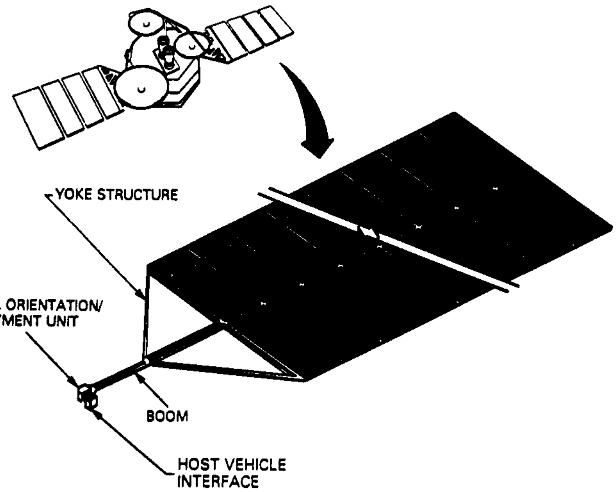
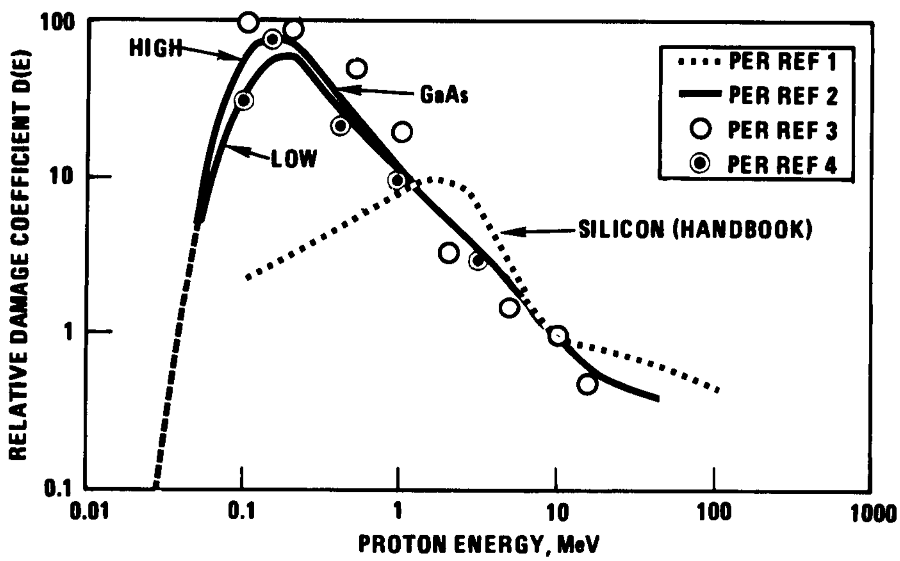


Figure 1. Solar Array Configuration



NORMAL INCIDENCE MAX POWER DAMAGE COEFFICIENTS
FOR Si AND GaAs

Figure 2. Solar Cell Damage Coefficients

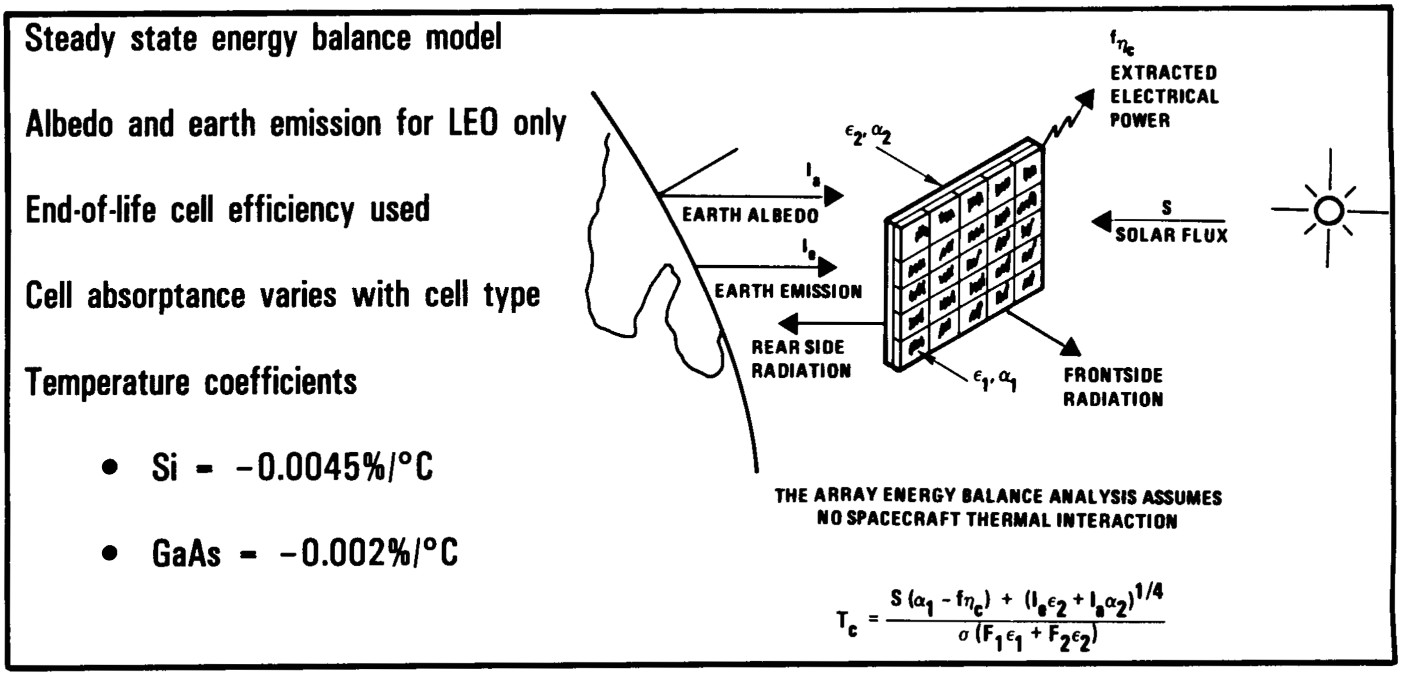


Figure 3. Solar Array On-Orbit Operating Temperature Model

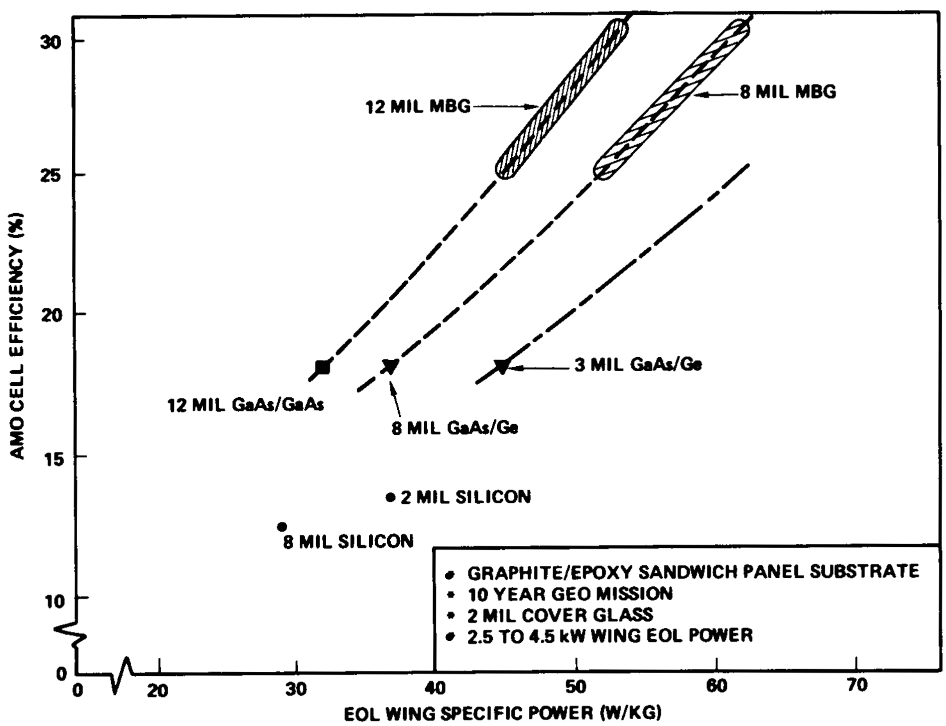


Figure 4. Cell Type Versus Wing Specific Power, Rigid Panel Deployable Solar Array

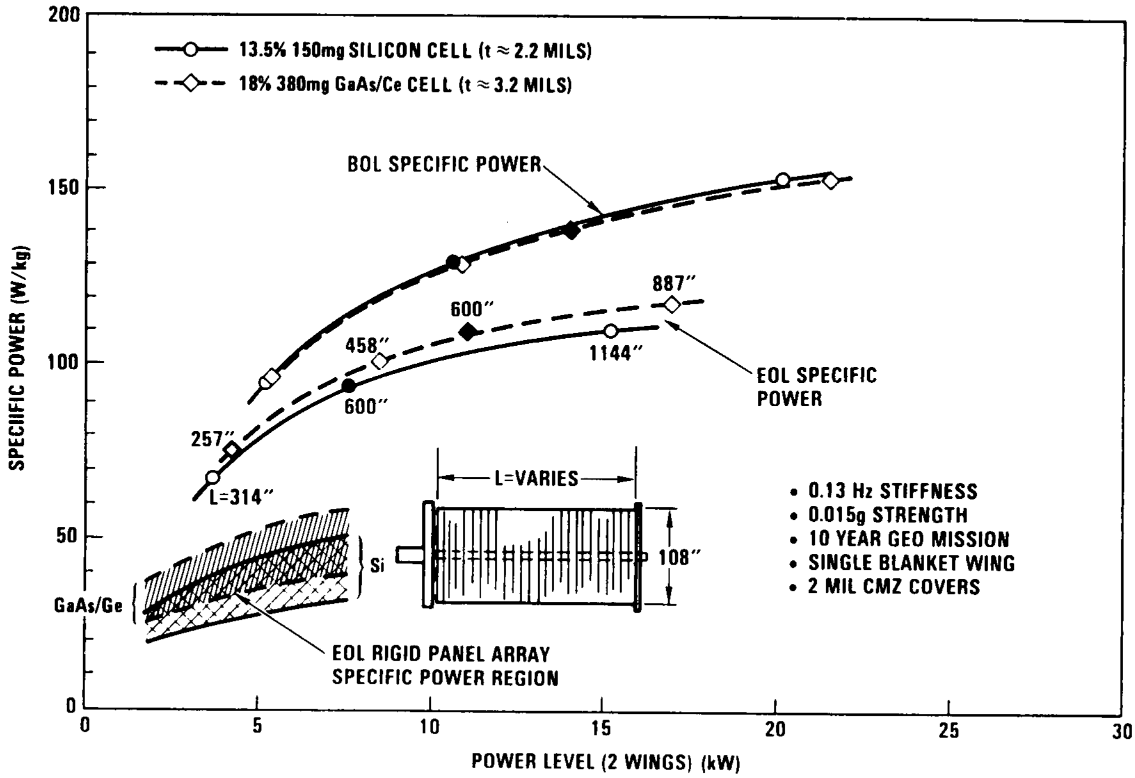


Figure 5. Effect of Power Level on Specific Power Performance for APSA Flexible Blanket Array (Thin Silicon Versus Thin GaAs/Ge Cells)