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COMPARATIVE VALUES OF ADVANCED SPACE SOLAR CELLS

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Goddard Space Flight Center
Greenbelt, Maryland 20771

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ABSTRACT

This paper presents a methodology for deriving a first order dollar value estimate for advanced solar cells which consists of defining scenarios for solar array production and launch to orbit and the associated costs for typical spacecraft, determining that portion affected by cell design and performance and determining the attributable cost differences. Break-even values are calculated for a variety of cells; confirming that efficiency and related effects of radiation resistance and temperature coefficient are major factors; array tare mass, packaging and packing factor are important; but cell mass is of lesser significance. Associated dollar values provide a means of comparison.

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COMPARATIVE VALUES OF ADVANCED SPACE SOLAR CELLS

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INTRODUCTION

Generally, advanced solar cell research and development is justified on the basis of improved performance, such as high efficiency, radiation resistance, temperature insensitivity, etc. Whether the improved performance will be worth the cost of the advanced cell is not addressed until the cell has been fully developed into a flightworthy device. Its value is then determined in the design trade-off phase for specific spacecraft on a case-by-case basis. Obviously, it would be preferable to have a value or cost benefit estimate for the advanced cell in addition to performance benefit estimates to aid in the decision process for investment of precious research and development funds. This can be done, at least to a first order of approximation, by hypothesizing the use of the advanced cell in several typical future spacecraft applications and evaluating the cost impact of the cell's design or performance improvements over state of the art cells in the same applications. These estimates can be readily updated at any stage of the development process, whenever performance goals are modified or as actual performance features are confirmed. Thus, in addition to performance targets, cost targets can be made available during the research and development stages for advanced cells. This paper will describe this methodology in further detail and will derive current (June 1982) value estimates for a variety of cells presently under development.

METHODOLOGY

The methodology consists of four interrelated steps. The fundamental step is the selection and definition of the hypothetical scenarios for space application of the solar cells. Each scenario consists of the following elements:

Solar cell option

Solar array configuration

Solar array production

Spacecraft mission (configuration, location, lifetime)

Transportation of the spacecraft to orbit

The second step is the determination of a reference orbital performance capability and a reference cost. This is accomplished by incorporating a reference (currently applied technology) cell into the scenarios.

The third step is the definition of the equivalent scenario required to accomplish the same orbital performance using the advanced cell. In this step only those changes that directly impact the cost and that are directly related to cell design or performance are considered. Secondary factors, such as interactions with other power subsystem components, other subsystems or the spacecraft, are not included.

The final step is the determination of the cost differential resulting from the changes. This cost differential is prorated on a per-cell basis and represents an added value for the advanced cell. When added to the cost of the reference cell, it provides a first order approximation for the break-even value of the advanced cell.

SCENARIOS

As noted above, selection and definition of scenarios are fundamental to the methodology. Selection of the scenarios is made so as to assure inclusion, with reasonable coverage, of the range of significant conditions expected in potential applications while minimizing the number of evaluations required. Definition of the scenarios is made in sufficient detail to insure inclusion of factors of primary significance, without requiring excessive sophistication in the calculations. Thus, the selection and definition are made to maintain a generic nature for the results by inclusion of elements of a mission-specific nature covering a broad range.

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Solar Cell Options

The solar cell options considered are listed in Table 1.

Table 1
Characteristics of Solar Cell Options (2X4cm; 25°C)

Cell Option	Eff. (%)	Power (mw)	Thickness (microns)	Mass (gm)	T Coeff. (%P/°C)	Assembled Eff. (%)	Assembled Power (mw)	Degraded (GEO) 10^{15} Eq. 1 Mev (% Power)
Reference	11.4	123	200	0.373	−0.5	10.8	117	0.75
Thin Silicon	14.0	152	50	0.0932	−0.5	13.3	144	0.75
Thin GaAs	14.0	152	10	0.0425	−0.2	13.3	144	0.80
High Eff. Si	18.0	195	200	0.373	−0.5	17.1	185	0.75
GaAs on Si	18.0	195	55	0.114	−0.2	17.1	185	0.80
GaAs	22.0	238	200	0.850	−0.2	20.9	226	0.80
Multibandgap	30.0	325	200	0.850	−0.2	28.5	308	0.80
50% Cell	50.0	541	200	0.850	−0.2	47.5	514	0.80

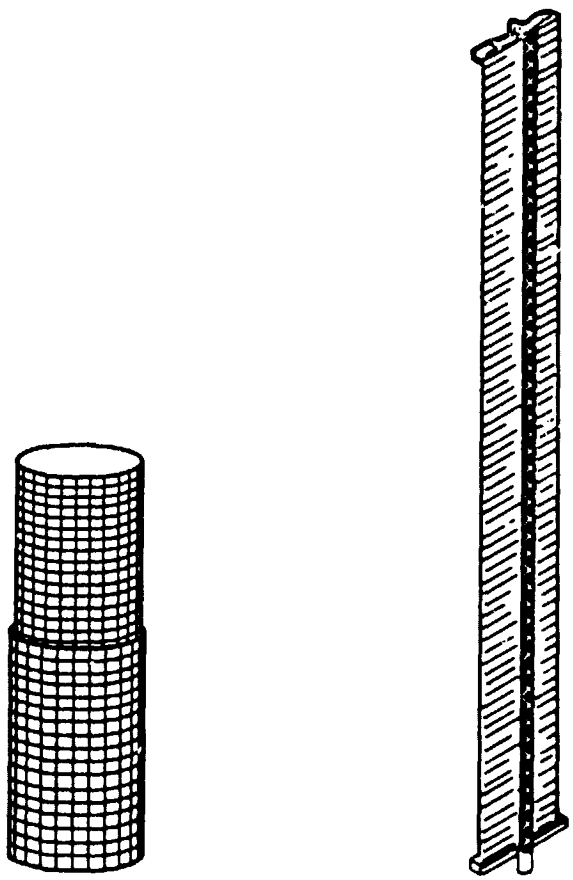
All cells are considered to be 2X4 cm in size in order to eliminate the impact of cell area on cost. (Should inclusion of the element of size be desired, the same methodology can be applied; however, added detail in the definition of the scenarios for production of the cell and the solar array would be required.) An effort was made to include most of the advanced cells currently under development. Their efficiency characteristics are selected to match the high end of the goal range set for the cells. (Lower efficiencies could, of course, be selected, affecting the final results but not the methodology.) The reference cell selected for this application is the low cost cell selected initially for the solar electric propulsion stage (SEPS) array (1,2). The cost is taken at $16 for the basic cell used on the reference drum array, with a wraparound cell, used on the wing array, costing 25 percent more, or $20.

The cell mass was determined using a density of 2.33 gm/cm^3 for Si and 5.31 gm/cm^3 for GaAs. Density of the multibandgap cell was assumed to be the same as GaAs which likely will be the primary cell material. This higher density was also assumed as a conservative figure for the 50% cell for lack of a better guess. In the case of the GaAs on Si cell, the cell consists of a 5 micron thick GaAs layer on a 50 micron thick Si substrate.

Nominal temperature and radiation damage coefficients were obtained from the literature (3,4,5,6,7) for the silicon and the GaAs cells. For other cells the coefficients are assumed to be the same as for GaAs. For temperature calculations, all cells are assumed to have an absorptivity of 0.8.

Solar Array Configuration

Two solar array configurations, a telescoping drum (Figure 1a) and a wing (Figure 1b) were considered.



a. Telescoping Drum (Extended) b. Wing (Deployed)

Figure 1. Solar Array Configurations

This selection was made, not simply because the two configurations are typical, but, more importantly, to highlight configuration dependencies of performance (incidence effects, temperature effects, etc.), production costs and transportation costs. The drum array, though much larger, is patterned after the LEASAT (8) and SBS arrays. The wing array is patterned after the SEPS array (1,2). In both cases it was assumed that total fabrication and assembly losses are 5 percent (Table 1), a nominal figure typical of SEPS. The packing factor in both configurations is 0.8. a low but typical figure for both telescoping drum and wing arrays.

Mechanical characteristics of the reference configurations are given in Table 2.

Table 2
Characteristics of Reference Arrays

	DRUM			WING
	Outer Cyl.	Inner Cyl.	Total	
Length (m)	8.84	8.84	–	31.6
Diam./Width (m)	4.27	4.19	–	3.99
Area (m^2)	118.6	116.4	235	126
Cell Area (m^2)	94.9	93.1	188	101
Cells (thousands)	118.6	116.4	235	126
Mass (kg)	355.8	349.2	705.0	189.0
Cells Mass (kg)	44.3	43.4	87.7	47.0
Tare Mass (kg)	311.5	305.8	617.3	142.0
Specific Tare Mass (kg/m^2)			2.627	1.127

These characteristics incorporate shuttle associated restrictions (9), such as bay size and a 0.152 m (6 in) dynamic clearance requirement. A 0.04 m (1.5 in) radial separation between cylinder surfaces for the drum array has been allowed to accommodate substrate thickness, telescoping tracks, etc.

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Solar Array Production

Production costs for the reference arrays were taken to be $750 per watt and $500 per watt for the drum and wing configurations respectively (Table 3).

Table 3
Reference Production Costs

	DRUM	WING
Nominal Cost ($/w)	750	500
Power (kw)	27.5	14.7
Total Cost ($M)	20.63	7.35
Specific Cost ($K/m^2)	87.76	58.33
Single Cell Cost ($)	16	20

These cost figures reflect the low cost of the reference cells. The difference reflects the differences in material and construction and also the projection that a higher degree of automation is achievable for a wing configuration than for a drum. Production of the arrays with advanced cells was assumed to be similar, resulting in the same specific cost (cost per unit area).

Spacecraft Missions

The spacecraft mission largely determines the required solar array configuration which in turn defines the spacecraft configuration. For this application the two configurations are the drum configuration with drum axis perpendicular to the sun line and the winged spacecraft with the plane of the solar-oriented wing arrays perpendicular to the sun line. In addition, the size of the drum array was selected to occupy one half of the shuttle bay during transport to orbit. This selection was based on several factors. First, a high power capability, approaching that of the wing configuration was desired. Second, this is the largest size that can be transferred to geosynchronous equatorial orbit (GEO) by the Shuttle/Centaur combination because the Centaur will occupy the other half of the bay. Third, a reduction in maximum size down to one quarter of the bay length would not affect the specific (per unit length) transportation costs. Fourth, at shorter lengths the advantages of advanced cells become obscured by spacecraft instrument platform size requirements. Finally, it was desirable to have a common size for the reference drum array in both low earth orbit (LEO) and GEO. This selection also brings to bear the feature that transportation costs can be either size dependent or mass dependent as described in the next section. The large drum results in size dependent costs while the wing configuration is assumed to be compactly packaged during launch so as to result in mass dependent costs.

Two spacecraft locations, one in LEO at 300 km (160 n. mi.) altitude and 28.5° inclination and the other in GEO at 35,800 km (19,330 n. mi.) altitude, were selected. This selection assures coverage of a wide range of transportation costs and, in addition includes a range of radiation damage.

Mission lifetime of 10 years was selected. This results in a radiation damage equivalent to that caused by 10^{15} 1-Mev electrons/cm^2 (4) in GEO. In LEO the radiation damage is negligible (10) because the orbit is well under the inner Van Allen belt.

Transportation of the Spacecraft to Orbit

Transportation to LEO is accomplished by the shuttle at which point the LEO spacecraft is deployed to become a free flyer. For the GEO spacecraft, the spacecraft, attached to a Centaur orbit transfer vehicle, is deployed by the shuttle in LEO and then transferred by the Centaur to GEO.

Transportation charges (9) are shown in Table 4.

Table 4
Transportation Charges

SHUTTLE – 29,484 kg (65,000 lb.) TO 300 km (160 nmi.) LEO (28.5° INCL)

CENTAUR – 6,170 kg (13,600 lb.) LEO TO 35,800 km (19,330 nmi.) GEO

	LEO SPACECRAFT	GEO SPACECRAFT
SHUTTLE		
Standard Charge (1975)	$18.00M	$18.00M
Load Factor	0.500	1.000
Shared Load Factor	1.333	1.000
Escalation Factor (June 1982)	1.887	1.887
Charge	$22.64M	$33.97M
Specific Charge		
Drum	$2.476M/meter	
Wing	$1.536K/kg	
CENTAUR (1982 EST.)		$40M
TOTAL CHARGE		$74M
SPECIFIC CHARGE		$12.0K/kg

REFERENCE ARRAY PERFORMANCE AND COST

Performance of the reference arrays in LEO is calculated from the assembled cell characteristics (Table 1) and the reference array characteristics (Table 2). A 20°C operating temperature was selected as the nominal operating temperature for the reference drum array based on a variety of flight data. A 55° temperature was selected for the reference wing based on the SEPS design. Note that these are also the beginning of life (BOL) operating conditions for GEO. For GEO the operating temperatures after radiation degradation are calculated with respect to the BOL temperature using the equation:

$$\left(\frac{T_1}{T_2}\right)^4 = \frac{\alpha_1 - F_1 n_1}{\alpha_2 - F_2 n_2} \qquad \text{(Eq. 1)}$$

where, T is the absolute operating temperature

α is the absorptivity

F is the packing factor

n is the operating efficiency

and subscripts 1 and 2 refer to the two respective operating conditions. The results are shown in Tables 5 and 6.

Costs for the reference cells and arrays are as previously described.

Table 5
Drum Array Cells

Cell Option	LEO (8.98 kw)				GEO (6.66 kw)		
	Temp. (°C)	Power (mw)	Eff. (%)	Cells (thous.)	Temp. (°C)	Power (mw)	Cells (thous.)
Reference	20	120	11.1	235	22	89.1	235
Thin Silicon	18	149	13.8	189	21	110	190
Thin GaAs	18	146	13.5	193	20	116	180
High Eff. Si	14	195	18.0	145	18	143	146
GaAs on Si	15	189	17.5	149	18	150	139
GaAs	11	232	21.4	122	15	184	114
Multibandgap	3	322	29.7	87.6	9	255	82.1
50% Cell	−21	561	51.8	50.[illegible]	−7	411	47.4

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Table 6
Wing Array Cells

Cell Option	LEO (12.5 kw) Temp. (°C)	Power (mw)	Eff. (%)	Cells (thous.)	GEO (9.29 kw) Temp. (°C)	Power (mw)	Cells (thous.)
Reference	55	99.5	9.19	126	57	73.7	126
Thin Silicon	53	124	11.5	101	56	91.6	101
Thin GaAs	52	136	12.6	91.9	54	108	86.0
High Eff. Si	50	162	15.0	77.2	54	119	78.1
GaAs on Si	48	176	16.3	71.0	51	140	66.4
GaAs	45	217	20.0	57.6	49	172	54.0
Multibandgap	37	301	27.8	41.5	43	238	39.0
50% Cell	11	528	48.7	23.7	25	411	22.6

ADVANCED CELL EQUIVALENT

Characteristics of advanced cells producing the same array performance results are also shown in Tables 5 and 6. Preliminary temperatures were calculated using Equation 1 and the assembled cell efficiencies (Table 1) with respect to the reference cell operating temperature. From these an approximate operating efficiency was determined for the preliminary temperature. Iteration of the calculations using the revised efficiencies provided the final temperature, which, in turn was used to calculate cell power, etc. The significance of the iteration was negligible for small differences in efficiency but temperature differences of 5°C or more result for the high efficiency cells.

These results were then used to determine the area and mass, shown in Tables 7 through 10, for the advanced arrays. The area is determined by the number of cells required. The mass is determined from the sum of the tare mass and the cell mass for the particular array and cells under consideration.

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Table 7.
Added Values – LEO Drum

Cell Option	Area (m^2)	Length (m)	Transp. Value ($M)	Value Per Cell ($)	Prod. Value ($M)	Value Per Cell
Reference	235	8.84	–	–	–	–
Thin Silicon	189	7.11	4.28	22.66	4.04	21.36
Thin GaAs	193	7.26	3.91	20.27	3.69	19.10
High Eff. Si	145	5.45	8.39	57.89	7.90	54.47
GaAs on Si	149	5.60	8.02	53.84	7.55	50.65
GaAs	122	4.59	10.52	86.25	9.92	81.29
Multibandgap	87.6	3.30	13.72	156.59	12.94	147.67
50% Cell	50.3	1.89	17.21	342.11	16.21	322.25

Table 8
Added Values – LEO Wing

Cell Option	Area (m^2)	Tare Mass (kg)	Cell Mass (kg)	Total Mass (kg)	Transp. Value ($M)	Value Per Cell ($)	Prod. Value ($M)	Value Per Cell ($)
Reference	126	142	47	189	–	–	–	–
Thin Silicon	101	114	9	123	0.101	1.00	1.46	14.44
Thin GaAs	91.9	104	4	108	0.124	1.35	1.99	21.64
High Eff. Si	77.2	87.0	28.8	116	0.112	1.45	2.85	36.87
GaAs on Si	71.0	80.0	8.1	88.1	0.155	2.18	3.21	45.19
GaAs	57.6	64.9	49.0	114	0.115	2.00	3.99	69.27
Multibandgap	41.5	46.8	35.3	82.1	0.164	3.96	4.93	118.77
50% Cell	23.7	26.7	20.1	46.8	0.218	9.22	5.97	251.78

Table 9
Added Values – GEO Drum

Cell Option	Area (m^2)	Tare Mass (kg)	Cell Mass (kg)	Total Mass (kg)	Transp. Value ($M)	Value Per Cell ($)	Prod. Value ($M)	Value Per Cell ($)
Reference	235	617	88	705	–	–	–	–
Thin Silicon	190	499	18	517	2.26	11.87	3.95	20.79
Thin GaAs	180	473	8	481	2.69	14.93	4.83	26.82
High Eff. Si	146	384	54	438	3.20	21.95	7.81	53.50
GaAs on Si	139	365	16	381	3.89	27.97	8.42	60.61
GaAs	114	299	97	396	3.71	32.53	10.62	93.15
Multibandgap	82.1	216	70	286	5.03	61.24	13.42	163.44
50% Cell	47.4	125	40	165	6.48	136.71	16.46	347.34

Table 10
Added Value – GEO Wing

Cell Option	Area (m^2)	Tare Mass (kg)	Cell Mass (kg)	Total Mass (kg)	Transp. Value ($M)	Value Per Cell ($)	Prod. Value ($M)	Value Per Cell ($)
Reference	126	142	47	189	–	–	-	–
Thin Silicon	101	114	9	123	0.792	7.84	1.46	14.44
Thin GaAs	86.0	96.9	4	101	1.06	12.28	2.33	27.13
High Eff. Si	78.1	88.0	29.1	117	0.86	11.06	2.79	35.77
GaAs on Si	66.4	74.8	7.6	82.4	1.28	19.27	3.48	52.36
GaAs	54.0	60.9	45.9	107	0.98	18.22	4.20	77.77
Multibandgap	39.0	44.0	33.2	77.2	1.34	34.40	5.07	130.12
50% Cell	22.6	25.5	19.2	44.7	1.73	76.62	6.03	266.87

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COST DIFFERENTIAL AND BREAK-EVEN VALUE

To determine the cost differential for the advanced solar array, the differences between the advanced array area and mass and those of the reference array were first calculated. These were then used in conjunction with the specific reference production cost (Table 3) and the appropriate specific transportation cost (Table 4) to determine the cost differentials shown in the value columns of Tables 7 through 10.

From these, the break-even value per cell was calculated. It is the sum of the reference cell cost, the value added to the cell from transportation charge savings and the value added to the cell from production cost savings. These final results are shown in Table 11.

Table 11
First Order Comparative Break-Even Values
($/Cell – June 1982)

	LEO		GEO	
CELL OPTION	DRUM	WING	DRUM	WING
Reference	16	20	16	20
Thin Silicon	60	35	49	42
Thin GaAs	55	43	58	59
High Eff. Si	128	58	91	67
GaAs on Si	120	67	105	92
GaAs	184	91	142	116
Multibandgap	320	143	241	185
50% Cell	680	281	500	363

DISCUSSION

The results in Tables 7 through 11 point up several significant factors. Table 7 shows that significant bay-length-dependent transportation charges are associated with drum arrays. As a result

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cell efficiency has a major impact on cost. Improved packing factor and packaging would have similar effects in reducing these costs. In addition it is noted that for arrays operating below 25°C (production measurement temperature) there are slight advantages for cells with higher temperature coefficients. Simultaneously, efficiency effects are equally important to area-dependent production costs. Finally, cost savings for high efficiency cells are about equally divided between production and transportation cost savings.

In Table 8 it can be seen that for a well packaged array, savings by reduction of cell mass (thickness, density) are very small. This results first from the low cost for mass dependent shuttle transportation, and secondly, because the cell mass is a relatively small fraction of the array mass. Gains through mass reduction in the remainder of the array (tare mass reduction), though small, could be more effective in reducing transportation costs. Finally, because of the more efficient use of cells in the oriented wing configuration than in the drum configuration, production savings are proportionately less, but still significant.

Because of the high cost of transportation to GEO, both efficiency improvements and mass reduction for both wing and drum arrays are significant (Tables 9 and 10). However, the mass reduction is primarily a result of improved efficiency and the related reduction in array tare mass rather than the reduction in cell mass. It is recognized that any array mass reduction would most likely be counterbalanced by an increase in payload (instruments). The result, then, would not be in transportation cost reduction but in increased payload capability.

For the GEO wing array, the benefits of low temperature coefficients and high radiation resistance have significant value because of their impact on operating efficiency. These benefits are almost as significant as the direct benefit of BOL efficiency.

CONCLUSIONS

1. A methodology has been developed by which comparative break-even values for advanced solar cells can be obtained to a first order of approximation.

2. The methodology, applied to a variety of advanced solar cells currently under development, shows the relative values of the anticipated developments. The relative values for each advanced cell type show the dependence of value on the application.

3. When viewed in conjunction with the performance targets and design configurations of the various cells considered, the process provides insight as to the significance of the various design and performance variables, such as efficiency, thickness, density, radiation resistance, temperature coefficient, etc.

4. BOL cell efficiency is shown to be the factor of major impact on cost, with radiation resistance and temperature coefficient, because of their impact on operating efficiency, becoming significant for radiation damaged or high temperature operational requirements. Array tare mass, packaging and packing factor are also significant factors. Cell mass itself is relatively insignificant.

5. The methodology, modified by suitable definition of the pertinent scenario elements to accommodate the salient design features, can be applied to additional cell designs, such as large area cells and low absorptivity cells, and to other solar array components such as coverglasses, assemblies, substrates, etc.

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