COST PERFORMANCE OF MULTI-JUNCTION, GALLIUM ARSENIDE, AND SILICON SOLAR CELLS ON SPACECRAFT

Edward M. Gaddy
Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

Spacecraft solar array engineers now have cell choices running from inexpensive and less efficient silicon (Si) cells, to gallium arsenide on germanium (GaAs/Ge) cells, to more expensive and efficient multi-junction (MJ) cells. This paper finds that the more array weight can be reduced by using more efficient cells, even when they are a very expensive option in terms of the array alone, and put into the spacecraft payload i. e. the scientific instruments or in the case of commercial spacecraft, the communications equipment, the more cost effective the spacecraft array system. This is true for a wide variety of spacecraft. This is because of the very high price of launching a spacecraft payload and supporting it with a spacecraft.

INTRODUCTION

This paper reports the cost effectiveness of using Si, GaAs/Ge and MJ solar cells on varying types of spacecraft and solar arrays. The spacecraft selected are mainly differentiated by their weight. The largest weighs approximately 4,700 Kg, the next 3,500 Kg and the lightest 240 Kg. All of the spacecraft are low earth orbiters.

In all of the cases studied, the more efficient solar cells offer substantial performance advantages to the spacecraft. Namely, more spacecraft payload can be launched and used. If any reasonable cost estimate is assigned to launching the payload and supporting it in orbit, the more efficient cells offer an enormous price advantage to less efficient cells.

LARGE SPACECRAFT

The large spacecraft studied is a typical low earth orbiting spacecraft. It will have a life of 5 years, a weight of 4,690 Kg, an altitude of 700 km, an inclination of 98 degrees and a single side whose normal is parallel to the spacecraft's velocity and another side whose normal always points to the nadir. The spacecraft will be equipped with a flexible blanket array that is sun tracking.

The cost effectiveness of .14 mm thick multi-junction, .14 mm thick gallium arsenide, .062 mm thick silicon and .20 mm thick silicon solar cells on this spacecraft is compared below. The attributes of these cells and their associated blanket arrays is shown in Table I for the spacecraft's nominal 5,600 W end of life (EOL) array. The thin silicon cells have metallization that adds significant weight to them and explains why the silicon cells' weight does not ratio with thickness and efficiency. The blanket weight in Table I includes the cell weight. If extremely lightweight blanket components are used, the thin silicon cells will have a weight advantage over the GaAs/Ge cells. However, at present this type of blanket is not yet practicable.

Table I
Blanket Array Attributes Populated With Different Cells

Attribute	*Si*	*Thin Si*	*GaAs*	*MJ*
Nominal Efficiency	14.8	14.0	18.5	24
EOL Efficiency	7	7.8	11.8	16
Array Area (m^2)	59.0	52.9	35.0	25.8
Cell Wt. (Kg)	36.7	14.5	32.3	23.8
Blanket Wt. (Kg)	102.1	73.8	72	53.6
Blkt. Hsing Wt. (Kg)	72.8	70.4	61.5	56.2
Mast Assy. Wt.(Kg)	33.6	32.1	26.8	23.6
Other Weight (Kg)	24.6	23.5	19.9	18.1
Total Weight (Kg)	233.2	199.9	180.2	151.5
Cost (M$)	28.0	29.5	38.0	33.3

The table uses cell costs per square centimeter of $1.25 for Si, $2.08 for thin Si, $20.83 for GaAs/Ge, and $26.04 for MJ cells. The price for the GaAs/Ge and MJ cells is on the high end. The price for the MJ cells is particularly uncertain because they are not yet in production. Nonetheless, the above should be a reasonable estimate in that the production cost of MJ cells is readily compared to GaAs/Ge cells. The major difference is that the MJ cells must have more active layers grown. As this can be done under automatic control without moving the cell from the reactor where the layers are grown, the cost increase is minimal. The

25th PVSC; May 13–17, 1996; Washington, D.C.

difference in price is primarily due to a necessarily lower yield and the addition of reverse bias protection.

In addition, the price of the MJ cells for the first several missions on which they are used will undoubtedly be significantly higher than that given in the table. This is, of course, for contingency to cover unanticipated costs for the first few uses of the advanced cells. The Table I price for the GaAs/Ge cell and the MJ cell are both significantly higher than used in a similar study by Ralph,[1] but the results of this paper are close to his results. Namely, the higher efficiency cells offer substantial cost benefits for a typical blanket type array.

The next to last row of the table shows a progressively decreasing array weight with more efficient cells. As the array weight goes down the weight of the spacecraft payload may be increased. If the payload weight increases some of the spacecraft systems that support the payload must also increase. To compute this system weight increase, the payload needs are assumed to be proportional to its weight, the subsystem capabilities that support the payload are assumed proportional to the payload's needs, and the weight of the subsystem is assumed to be in proportion to the subsystem's capability. For example, if the payload weight increases ten percent, its ability to produce data is assumed to increase ten percent and the weight of the command and data handling system is assumed to increase ten percent after taking into account the amount of data generated by the spacecraft. With these assumptions, a series of equations can be used to compute the increase in spacecraft payload weight. For the case of the array changing from GaAs to MJ cells the following equations are applicable:

$$\mathrm{INSTR} = 1163.3 \tag{1}$$

$$\mathrm{DATA} = 369.7 \tag{2}$$

$$\mathrm{COMM} = 204.1 \tag{3}$$

$$\mathrm{ELEC} = 294.8 \tag{4}$$

$$\mathrm{PWR} = 427.6 \tag{5}$$

$$\mathrm{SA} = 151.5 \tag{6}$$

In the above INSTR, DATA, COMM, ELEC, PWR, and SA are respectively the weight in kilograms of the payload, the command and data handling system, the communications system, the electrical system, the power system less the solar array and the solar array.

The simultaneous equations that compute the weight change of the these subsystems are:

$$\mathrm{CF{*}DATA}\ (28.7-\Delta\mathrm{DATA}-\Delta\mathrm{COMM}-\Delta\mathrm{ELEC}-\Delta\mathrm{PWR}-\Delta\mathrm{SA})/\mathrm{INSTR} = \Delta\mathrm{DATA} \tag{7}$$

$$\mathrm{CF{*}COMM}\ (28.7-\Delta\mathrm{DATA}-\Delta\mathrm{COMM}-\Delta\mathrm{ELEC}-\Delta\mathrm{PWR}-\Delta\mathrm{SA})/\mathrm{INSTR} = \Delta\mathrm{COMM} \tag{8}$$

$$\mathrm{PF{*}ELEC}\ (28.7-\Delta\mathrm{DATA}-\Delta\mathrm{COMM}-\Delta\mathrm{ELEC}-\Delta\mathrm{PWR}-\Delta\mathrm{SA})/\mathrm{INSTR} = \Delta\mathrm{ELEC} \tag{9}$$

$$\mathrm{PF{*}PWR}\ (28.7-\Delta\mathrm{DATA}-\Delta\mathrm{COMM}-\Delta\mathrm{ELEC}-\Delta\mathrm{PWR}-\Delta\mathrm{SA})/\mathrm{INSTR} = \Delta\mathrm{PWR} \tag{10}$$

$$\mathrm{SF{*}PF{*}SA}\ (28.7-\Delta\mathrm{DATA}-\Delta\mathrm{COMM}-\Delta\mathrm{ELEC}-\Delta\mathrm{PWR}-\Delta\mathrm{SA})/\mathrm{INSTR} = \Delta\mathrm{SA} \tag{11}$$

$$\mathrm{CF} = .9 \tag{12}$$

$$\mathrm{PF} = .457 \tag{13}$$

$$\mathrm{SF} = .863 \tag{14}$$

where CF is the fraction of the command and data handling system that is used to support science, PF is the fraction of power that is used by the instrument in nominal operation, and SF is the fraction of weight that the solar array changes when there is a change in the array's power capability. The number 28.7 is the difference in weight in kilograms between the GaAs and the MJ arrays, given in Table I.

The solution to these equations is:

$$\Delta\mathrm{DATA} = 4.61 \tag{15}$$

$$\Delta\mathrm{COMM} = 2.55 \tag{16}$$

$$\Delta\mathrm{ELEC} = 1.87 \tag{17}$$

$$\Delta\mathrm{PWR} = 2.71 \tag{18}$$

$$\Delta\mathrm{SA} = 0.83 \tag{19}$$

$$\mathrm{Total} = 12.57 \tag{20}$$

Not all of the 28.7 Kg can go into the payload because as the payload increases in weight so must the spacecraft subsystem weight to support it. From equation (20), the spacecraft subsystem weight increase is 12.6 Kg. Therefore, keeping the spacecraft weight constant, the net instrument weight increase is 16.1 Kg.

The price estimate for such a spacecraft equipped with a GaAs/Ge array is $580 million dollars and the launch vehicle is $120 million. The weight of such a spacecraft is 4,690 Kg and it will have a payload of 1163 Kg. On this basis it takes $602,000/Kg to launch and support the payload. The launched 16.1 Kg is therefore worth $9.62 million dollars. The price of "buying" the additional 16.1 Kg with a more efficient solar array is obtained by the following. From Table I, the MJ array is priced $4.7 million dollars less than the GaAs/Ge array. However, the prices in Table I do not account for the increase in array power capability required by the increased instrument capability. This is obtained from equations (6) and (19) that show that the MJ array increases in weight by .83 Kg/151.7 Kg or .0055 percent. Assuming the array price is proportional to the array weight leads to an array price of $33.5 million. Thus the MJ array is priced at $4.5 million less than the GaAs/Ge array. This is still not the complete picture in that the other subsystems of the spacecraft must also be increased in capability and price to accommodate the larger instrument. If this increase in capability and price is proportional to the weight of the subsystem the spacecraft increases in price $1.3 million, using data not in this paper. Thus the cost to launch and service the additional 16.1 Kg is

$3.2 million. This data, as well as data for the silicon, and thin silicon arrays is summarized in Table II.

Table II
Cost Effectiveness of Solar Cells by Type
For a Large Spacecraft with a Blanket Array

Item	*Si*	*Thin Si*	*GaAs*	*MJ*
Cost Per Unit Wt. to Launch & Support Science (K$/Kg)	605	598	602	591
Instrument Weight	1134	1152	1163	1179
Additional Instrument Wt. Over Si Array (Kg)	0	18	29	45
Cost Per Unit Weight to "Buy" Science with High Perf. Cells ($/Kg)	N/A	216	500	253

The above computations are not exact as there are many uncertainties and inefficiencies that factor into the fabrication of spacecraft, particularly a one of a kind spacecraft. Many subsystems are not the optimum weight because they are based on earlier subsystems to obtain heritage. The weight uncertainty for certain new equipment or instruments may be high and this will cause the spacecraft to carry a large weight contingency for a while. When this contingency is resolved, the spacecraft may then have the ability to carry additional weight that can be traded for dollars by using a less expensive array. But, on the average, the computations should be valid.

To use Table I to obtain the $3.2 million dollar advantage computed another way above, the "Additional Instrument" weight row in GaAs is multiplied by the "Cost Per Unit Weight" for GaAs and the corresponding product is computed for the MJ array. The two products are subtracted. The Table value is $3.1 million, the difference from the $3.2 million being due to rounding.

MEDIUM SPACECRAFT

Computations similar to the above have been performed and published for medium and small size spacecraft.[2,3] The medium size spacecraft will have a life of 3.5 years, a weight of 3,512 Kg, an altitude of 350 km, an inclination of 35 degrees and a single side whose normal is parallel to the spacecraft's velocity and another side whose normal always points to the nadir. The spacecraft will be equipped with a sun tracking array with an aluminum face sheet and honeycomb core substrate. The small spacecraft will have a life of 2 years, a weight of 241 Kg, an altitude of 700 km, an inclination of 98 degrees and a single side whose normal points at the sun. The spacecraft will be equipped with a fixed array with an aluminum face sheet and honeycomb core substrate.

The computations for the cost effectiveness of the solar cells for these spacecraft were updated to the cell prices directly under Table I. Results are provided in Tables III and IV below. The updated GaAs/Ge and MJ cells are much more expensive than in the references. Even so, these cells retain a very large price advantage over silicon cells.

Table III
Cost Effectiveness of Solar Cells by Type
For a Medium Spacecraft with a Rigid Array

Item	*Si*	*GaAs*	*MJ*
Cost Per Unit Wt. to Launch & Support Science (K$/Kg)	552	531	519
Instrument Weight	633	664	678
Additional Instrument Wt. Over Si Array (Kg)	0	31	45
Cost Per Unit Weight to "Buy" Science with High Perf. Cells ($/Kg)	N/A	152	127

Table IV
Cost Effectiveness of Solar Cells by Type
For a Small Spacecraft with a Rigid Array

Item	*Si*	*GaAs*	*MJ*
Cost Per Unit Wt. to Launch & Support Science (K$/Kg)	680	641	617
Instrument Weight	58.2	62.4	64.9
Additional Instrument Wt. Over Si Array (Kg)	0	4.2	6.7
Cost Per Unit Weight to "Buy" Science with High Perf. Cells ($/Kg)	N/A	189	164

For the small and medium spacecraft, the computation for the thin silicon cells was not performed. This is because the weight of these spacecraft's rigid substrate arrays swamps the weight of the cell stack. As a result, the use of thin solar cells has only a very slight effect on the weight of the array.

CONCLUSIONS

In all cases studied, the MJ solar cells are effective in increasing the payload weight of the spacecraft. This is, of course, cost effective. It is particularly so in the case of the small and medium size spacecraft. In these cases, the MJ cells "buy" additional payload at a cost from $127,000 per kilogram to $164,000 per kilogram. This compares to launch and support costs that range from $552,000 for a medium spacecraft with a silicon array to $680,000 for a small spacecraft with a silicon array. In short, the more efficient cells are effectively a significant method of getting more out of a spacecraft. If MJ cell costs are estimated at the same price as in references [2] and [3], the cells are even a bigger bargain. They "buy" additional payload at a cost of $57,000 per kilogram to $74,000 per kilogram. At this time, it is difficult to predict which price is the most realistic.

The multi-junction cells are also very effective for large spacecraft with a blanket array, but not nearly so much as for the spacecraft with rigid arrays. For blanket arrays, the MJ cells purchase additional spacecraft payload at a cost of about $250,000 per kilogram. The reduced effectiveness of the cells is primarily because the weight of blanket arrays is less sensitive to size and more sensitive to the heavier cell weight of the GaAs/Ge and MJ cells. For the same reason, the GaAs/Ge cells show almost no advantage relative to the silicon cells and a disadvantage relative to thin silicon cells.

This paper uses a methodology that is different than that used by Ralph. His estimates are based primarily on the cost to launch the array into orbit and this cost is reported by him to be about $11K/Kg for a low earth orbit. He does not include the cost of the spacecraft support to the payload. This paper does include that cost. As a result, the price advantage of the more efficient cells is significantly greater as computed in this paper. Nonetheless the qualitative ranking of the cost effectiveness of the cells is the same.

---

[1] Gene Ralph, "High Efficiency Solar Cell Arrays System Tradeoffs," *IEEE First World Conference on Photovoltaic Energy Conversion,"* Hawaii, Figure 1, p.1998.

[2] Edward M. Gaddy, "Cost Trade Between Multi-Junction, Gallium Arsenide, and Silicon Solar Cells," *Proceedings of the 14th Space Photovoltaic Research and Technology Conference*, Cleveland, OH, Oct., 1995.

[3] Edward M. Gaddy and Hsiao L. Smith, "Relative Cost Effectiveness of Multi-Junction, Gallium Arsenide, and Silicon Solar Cells," *Proceedings of the 34th Aerospace Sciences Meeting and Exhibit*, Reno, NV, Jan., 1996.