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# ANALYSIS OF GaAs AND Si SOLAR CELL ARRAYS FOR EARTH ORBITAL AND ORBIT TRANSFER MISSIONS

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## ABSTRACT

Silicon and gallium arsenide arrays were studied and compared for LEO, GEO, and LEO to GEO electric propulsion orbit transfer missions. The study determined the sensitivities of total cost to parameters such as mission duration, array cost, cover glass thickness, and concentration ratio. The purpose was to guide technology development and to quantify cost tradeoffs between silicon and gallium arsenide arrays for selected mission classes. Results indicate that development of the technology for low cost, light weight concentrators should be increased and that cost reduction efforts for gallium arsenide cells be pursued.

## INTRODUCTION

During the last three years the NASA-Lewis Research Center has been supporting efforts to define technology needs to satisfy the projected increasing power requirements of future space missions. One of the studies carried out has been in the area of solar arrays for space power generation. Specifically, Silicon and Gallium Arsenide solar arrays were compared on the basis of their total cost as a function of various parameters (e.g., mission duration, cover glass thickness and concentration ratio).

The solar array systems were studied and compared for LEO (300 n. mi. low-Earth orbit), GEO (geosynchronous Earth orbit) and LEO to GEO electric propulsion missions. The cost analysis for the orbital missions included launch costs and purchase costs for arrays that were sized for end of life power. For the orbit transfer missions the launch and purchase costs of the propulsion system were included in the cost analysis.

The principal result of the study has been to quantify the cost tradeoffs between gallium arsenide and silicon arrays for specific classes of missions and system characteristics. The conclusions are being used to provide guidance to Lewis solar cell technology efforts.

## BASIC ASSUMPTIONS

A baseline set of input parameters was defined and assumptions made in regard to cost, efficiency, mass and other properties of the solar array systems. Some of these parameters were varied to determine the sensitivities of the costs to the inputs (e.g., mission duration, cover glass thickness and concentration ratio). The base case array purchase costs were assumed to be \$300/W for the silicon array and \$500/W for the gallium arsenide array. Transportation costs were assumed to be \$700/kg for launch to LEO and \$11,500/kg for launch to GEO (1); volume and packaging constraints were not considered in the transportation costs. The AMO efficiency of the silicon arrays was assumed to be 14% and of the gallium arsenide arrays, 17% at a temperature of 60° C. For the orbit transfer missions, the propulsion system (electric thrusters) was sized for the end of life power of the solar array.

The specific masses of the arrays were derived from the reference cell data shown on Table 1. The specific masses for the orbital cases were 31.5 g/W for silicon arrays and 28.5 g/W for gallium arsenide arrays. The orbit transfer cases assumed a 0.051 cm cover, based on results to be discussed later, resulting in specific masses of 35.4 g/W for silicon arrays and 31.7 g/W for gallium arsenide arrays.

TABLE 1. - REFERENCE CELL MASS DATA

| | |
|---|---|
| 0.2 mm silicon (silicon cell only), g | 0.186 |
| 0.2 mm GaAs (GaAs cell only), g | 0.425 |
| Two 0.11 mm adhesive layers, g | 0.097 |
| 0.15 mm cover glass (orbital cases), g | 0.1275 |
| 0.51 mm cover glass (orbit transfer), g | 0.4335 |
| Array structure per cell, g | 2.0 |
| AMO solar flux, W/cm$^2$ | 0.137 |
| Cell area, cm$^2$ | 4 |

Additional input parameters were required for analysis of the cases with concentrated arrays. A concentrator specific mass of 1 kg/m$^2$ of reflected sunlight and a concentrator specific cost of \$2000/m$^2$ of reflected sunlight were assumed. The concentrator mass and cost were normalized to the area of sunlight reflected onto the array to keep the analysis independent of concentrator configuration and efficiency. For the concentrated

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*Aerospace Engineer, Systems Concepts Branch, Space Propulsion and Power Division cases, array temperature was calculated using the Stefan-Boltzmann radiation relationship. Silicon array output was assumed to decrease by 0.5% per °C until it reached zero at 260° C (2). GaAs array output was assumed to decrease by 0.17% per °C (3).

The reference orbit transfer mission transported a 1000 kg payload from LEO to GEO in 1 year using electric propulsion. Total mission costs are defined as the sum of the propulsion system cost including propellant, the array purchase cost and transportation costs to LEO. The propulsion system mass was calculated based on a modular approach described in Ref. 4 and was assumed to be 200 kg plus 17 kg/kW of input power. Using the rocket equations and the baseline study assumptions, it can be calculated that 4.4 W are required to transport 1 kg from LEO to GEO in 1 year. This was based on propulsion system assumptions of 3000 sec specific impulse, 6000 m/sec velocity increment, and propulsion system efficiency of 70%. The electric propulsion system was assumed to cost $300/W. The propellant mass was calculated to be 0.05 kg/W/yr and assumed to cost $50/kg.

## SOLAR CELL DEGRADATION

Gallium arsenide solar cells have a recognized advantage over silicon solar cells in terms of radiation tolerance. Figure 1 represents the normalized curves of power versus radiation dose used in the study. The silicon curve represents a 10 ohm-cm textured cell with back surface field (5) while the gallium arsenide curve is based on data from experimental cells (3). Comparison of the curves of Fig. 1 shows that gallium arsenide has 5% to 10% less degradation for orbital missions of 10 years and 2% to 3% less degradation that silicon for orbit transfer missions of 1 year. There is a crossover in radiation tolerance corresponding to orbit transfer missions of 1.5 years duration.

GaAs and silicon array costs versus LEO and GEO mission durations are shown on Fig. 2. The GEO costs are higher than the LEO costs because the launch cost is much greater for the GEO mission. Since the costs are calculated on a per end-of-life watt basis, the costs increase due to degradation as mission duration increases. This cost increase due to degradation is only a small part of the total cost.

As an example, the GaAs purchase cost is 60% of the BOL cost for a GEO mission, the remainder being transportation cost. However, degradation for a ten-year mission only adds 25% to the BOL cost.

Comparison of the curves on Fig. 2 shows silicon costs to be lower than GaAs costs for LEO and GEO orbital missions. This is principally caused by the array purchase cost differential of $200/W. However, for the GEO case, the overall GaAs system cost (including launch cost) is only $100/W more than the silicon cost. This is because the GaAs array mass per watt of output is less than for silicon, resulting in lower launch costs for GaAs.

Purchase cost is the dominant factor in LEO array cost and also one of the two major factors in GEO array cost, the other being launch costs. Technology efforts in GaAs and silicon should be to reduce cell production costs per watt of output in addition to weight reduction and radiation tolerance.

The total mission cost, as defined previously, for an electric propulsion LEO to GEO mission with a 1000 kg payload is shown on Fig. 3 versus mission duration. As mission time increases, the power and propulsion requirements decrease, and cost therefore decreases. There are, however, penalties such as cost of capital investment which would penalize a long duration orbit transfer mission which have not been included in the analysis. As in the orbital cases, the orbit transfer mission cost is higher using GaAs solar arrays than using silicon solar arrays for all mission durations shown. This is again primarily due to the $200/W array purchase cost advantage of silicon. Cost rises rapidly as mission duration is reduced below 1 year. The array and propulsion system assumptions used in this study produce a power to mass ratio that limits the minimum trip time to about 1/3 year.

## CONCENTRATED ARRAYS

A performance advantage of gallium arsenide solar arrays over silicon solar arrays is their greater operational temperature range. Gallium arsenide arrays will produce about two-thirds as much power at 260° C as at 60° C, whereas silicon solar arrays decline to zero output at 260° C. A potential bonus, although not considered in this study, is that gallium arsenide solar arrays may begin to self anneal the radiation damage at 200° C (6).

The greater operational temperature range of GaAs enables it to benefit from solar concentration more than silicon in an uncooled concentrator system. Costs versus concentration ratio for silicon and GaAs arrays for ten-year LEO and GEO orbital missions are shown on Fig. 4. The GEO curves are similar to the LEO curves, differing mainly because the launch cost to GEO is higher. Costs for silicon arrays as shown in Fig. 4 increase rapidly at concentration ratios greater than four. This is caused by the decrease in efficiency of the silicon array with increasing temperature overcoming the benefits of solar concentration. Silicon arrays could be used at higher concentration ratios if cooling were supplied, but without cooling, the optimum concentration ratio appears to be about two. The GaAs curves show continuing cost reduction as the concentration ratio was increased to ten. GaAs costs at a concentration ratio of ten are about half the minimum silicon costs. These curves illustrate the potential savings in solar array costs through the use of concentration. However, to realize this cost savings it is necessary to develop low cost, low mass solar concentrators similar to those baselined in this study. Additional savings for both GaAs and Si would be possible if low cost, low mass cooling concepts are developed.

Figure 5 shows the costs for concentrated arrays for the orbit transfer mission. As in the orbital cases, there is a significant savings (about 30% to 40% of the total mission cost) achievable by using GaAs solar cells with solar concentration.

## VARIATION OF COVER GLASS THICKNESS

Cover glass thickness was varied from 0 - 0.15 cm (0-60 mils) to evaluate the tradeoff between the cost associated with increased cover glass mass and the increased radiation protection of a thicker cover glass. It was assumed that cover glass thickness could be modified without changing the array cost assumptions or array structure weight. Figure 6 shows array cost versus cover glass thickness for a 10 year mission for the LEO and GEO orbital cases. The no coverglass point on the GEO curve was omitted because bare cells would not survive in GEO. There is a slight cost reduction shown for increasing cover glass thickness to 0.05 cm, but the cost savings does not appear sufficient to warrant changing from the conventional thicknesses of about 0.01 cm.

The orbit transfer mission spirals out from LEO to GEO and passes through the Van Allen radiation belts. The radiation flux is therefore two to three orders of magnitude greater in the orbit transfer mission than in the orbital missions. To protect the solar cells from this high radiation environment, a thick cover glass is required. Figure 7 shows that total mission cost for the orbit transfer mission rises rapidly if the cover glass thickness is reduced below 0.05 cm. For the orbit transfer mission and for other missions with a very high radiation exposure thick cover glass $\approx$0.05 cm (20 mils) is recommended. Although the costs shown on Fig. 7 continue to decrease for cover thicknesses greater than 0.05 cm, there are factors not included in this analysis, such as increased structure weight and handling problems which would tend to increase the costs for thicker cover glass.

## CONCLUSIONS

An economic analysis has been performed on silicon and gallium arsenide array (planar and concentrated) systems for the generation of power in space on orbital, LEO and GEO, and orbit transfer missions using electric propulsion. A baseline set of solar array and mission parameters was defined and the sensitivity of cost to mission duration, cover glass thickness and concentration ratio was determined. It was found that for the missions considered, the assumed purchase cost advantage of silicon arrays was not overcome by the greater radiation resistance of gallium arsenide arrays.

The use of reflectors for concentration may significantly reduce the power system cost. However, gallium arsenide arrays benefit considerably more from solar concentration than silicon arrays in terms of mission cost because of their higher allowable temperature.

In the case of orbit transfer missions a cover glass thickness of at least 0.05 cm (20 mils) is recommended to reduce total mission cost. The orbital missions are less sensitive to cover glass thickness.

Results indicate that solar cell development should give a high priority to reducing cell costs, and that the development of low cost, light weight solar concentrators should be pursued.

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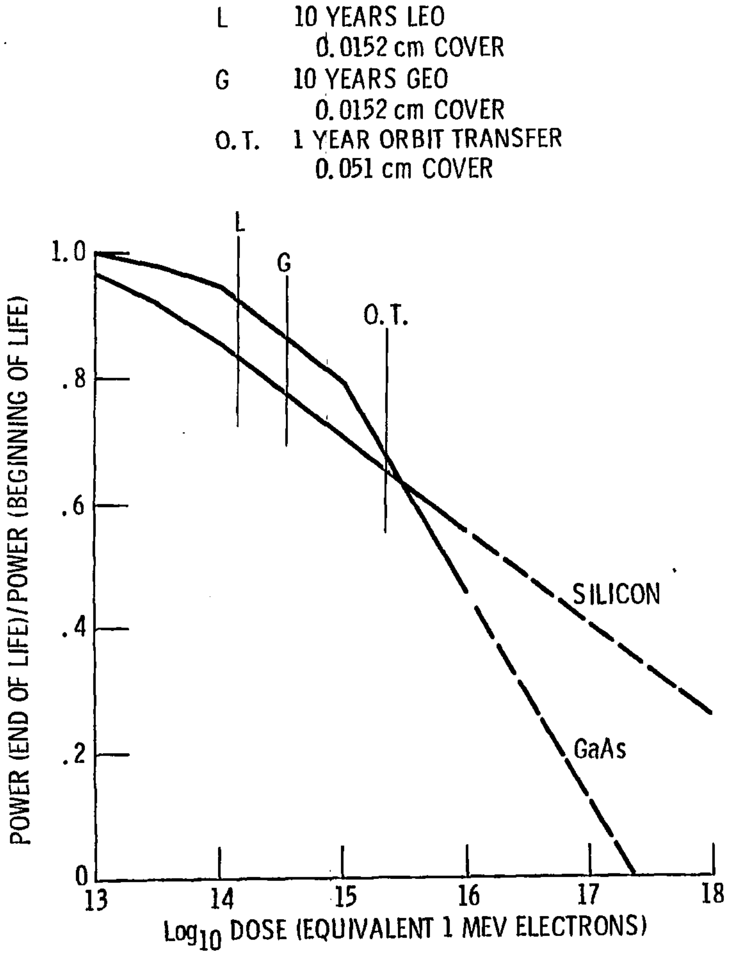

Figure 1. - Solar cell degradation curves for various doses.

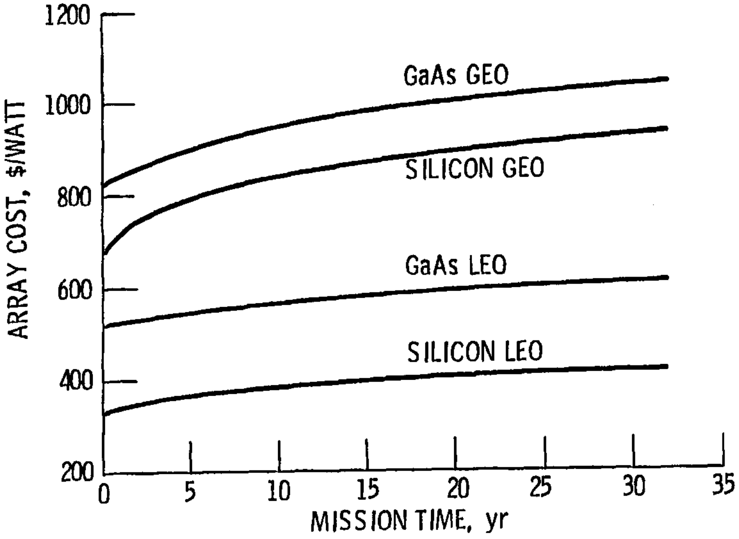

Figure 2. - Array cost versus orbital mission duration.

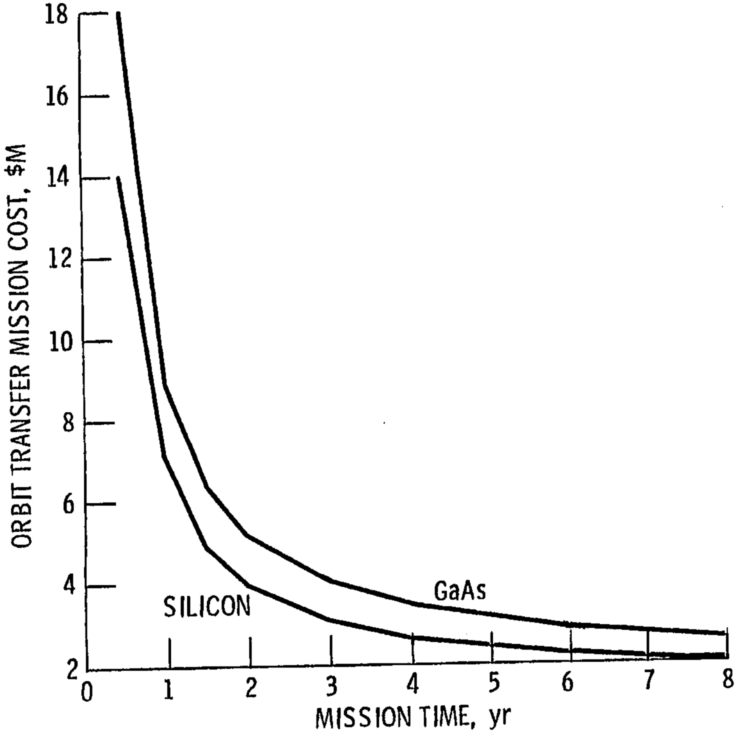

Figure 3. - Array cost versus orbit transfer mission duration.

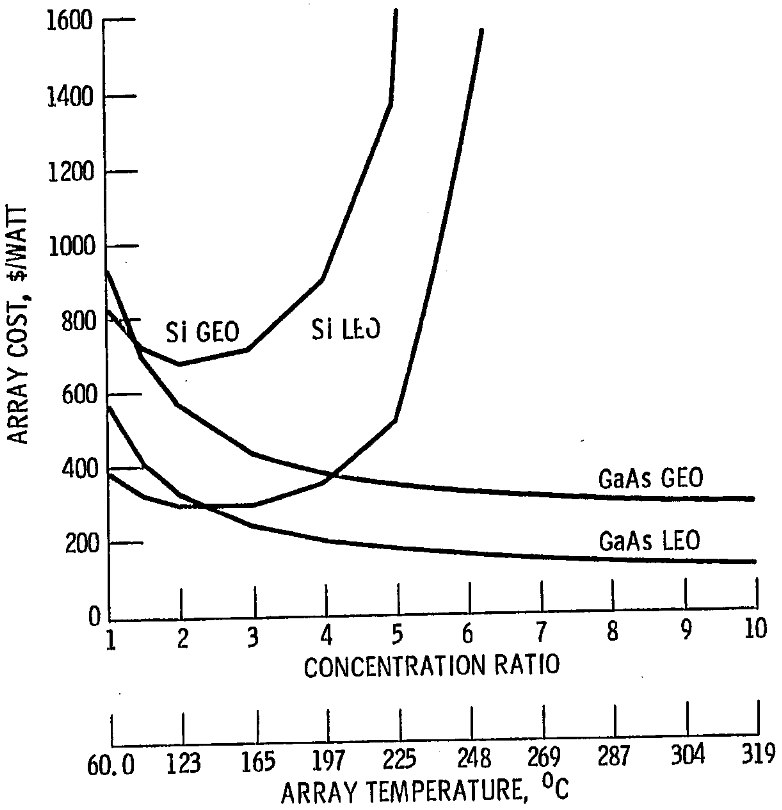

Figure 4. - Concentrated array cost versus concentration ratio for a 10-year orbital mission.

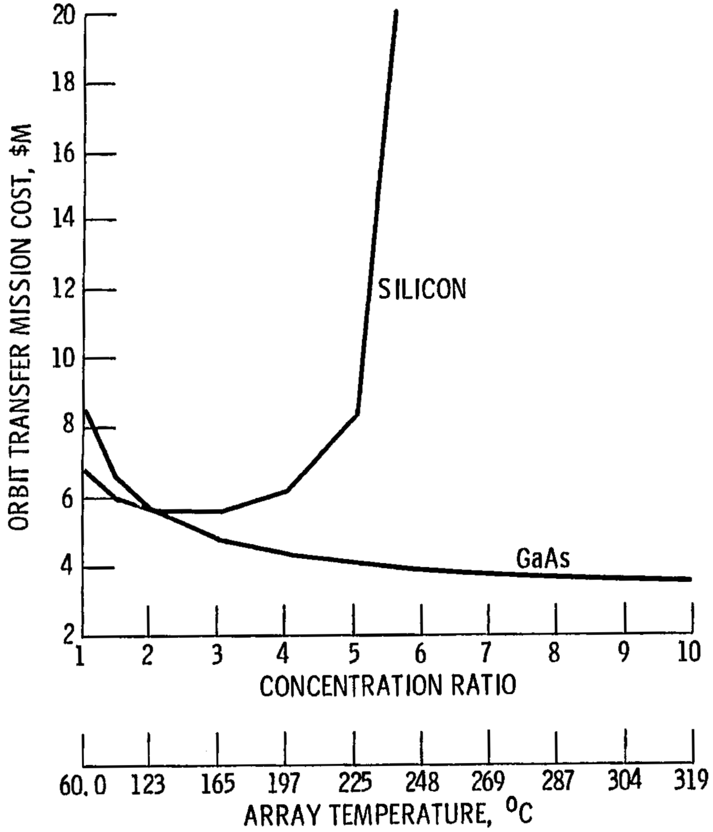

Figure 5. - Orbit transfer mission cost versus concentration ratio.

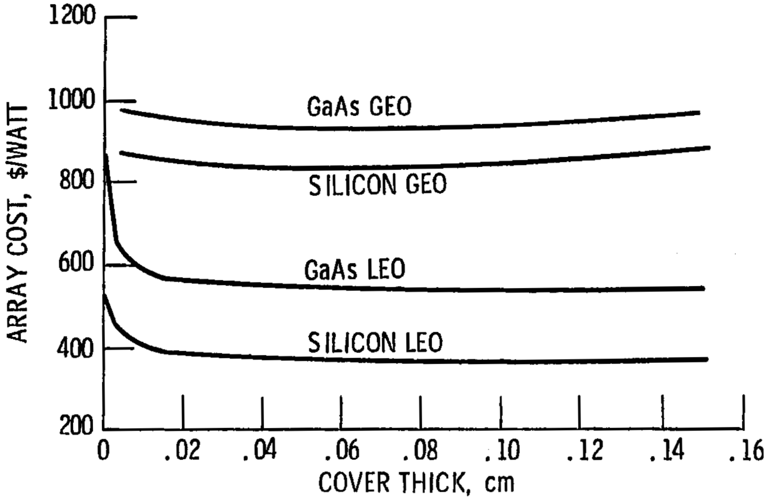

Figure 6. - Array cost versus coverglass thickness for 10-year orbital mission.

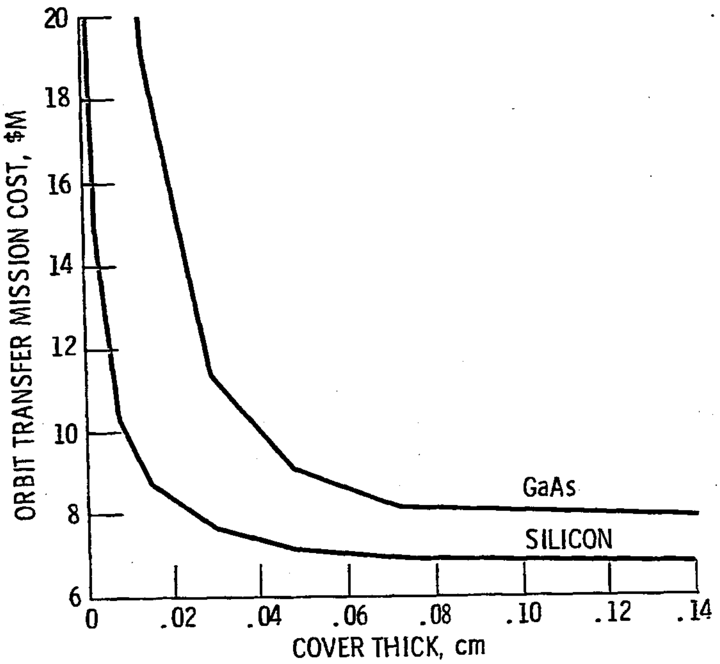

Figure 7. - Orbit transfer mission cost versus cover thickness.

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