NASA-TP-1811 19810011645

NASA Technical Paper 1811

Analysis of Costs of Gallium Arsenide and Silicon Solar Arrays for Space Power Applications

Kent S. Jefferies

MARCH 1981

NASA

NASA Technical Paper 1811

Analysis of Costs of Gallium Arsenide and Silicon Solar Arrays for Space Power Applications

Kent S. Jefferies
*Lewis Research Center
Cleveland, Ohio*

National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

1981

Summary

Costs of silicon and gallium arsenide solar arrays were compared for low-Earth-orbit (LEO) and geosynchronous-Earth-orbit (GEO) missions and for LEO-to-GEO orbit transfer missions using electric propulsion. The analysis included solar array purchase costs and launch costs and took into account the additional cost to provide a larger beginning-of-life (BOL) array to compensate for radiation degradation. Radiation flux for each mission and degradation characteristics for each type of cell were used to compute the degradation. For the orbit transfer mission the purchase and launch costs of the propulsion system were added to the array costs in order to determine total mission costs. Sensitivities of cost to a variety of parameters such as mission duration, cover glass thickness, and array specific mass were analyzed. Costs of concentrated solar power systems were compared with costs of planar solar arrays.

It was concluded that for the reference values of the input parameters the cost of solar power from silicon planar arrays is less than that from gallium arsenide (GaAs) arrays. However, solar power cost is sensitive to array purchase cost, solar cell efficiency, and array specific mass. For certain values of these parameters GaAs arrays can cost less than silicon arrays.

Analysis of concentration without active cooling showed concentrated GaAs arrays to be more cost effective than planar or concentrated silicon arrays on the basis of the cost parameters assumed for this study. With active cooling the computed costs of concentrated silicon arrays were slightly less than those of concentrated GaAs arrays.

Results of this study indicate that solar cell development should give a high priority to reducing array costs and that the development of low-cost, lightweight solar concentrators should be pursued.

Introduction

During the last three years the NASA Lewis Research Center has been supporting efforts to define technology needs that will 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 (GaAs) solar arrays were compared on the basis of their total cost as a function of various mission and technical parameters (e.g., mission duration, cover glass thickness, and concentration ratio). Rockwell International, Lockheed, and TRW have conducted similar studies under contract to the NASA Marshall Space Flight Center (refs. 1 to 3).

Solar cells, specifically silicon cells, are presently the principal source for electric power production in space. Solar cell technology today is advancing rapidly. The conventional silicon solar cell is being made lighter, higher in efficiency, lower in cost, and more resistant to radiation damage. Gallium arsenide solar cells are now being developed and are under consideration as the next-generation solar cell for space applications. Their primary advantages over silicon cells are higher efficiency, higher allowable operating temperature, and potentially higher radiation resistance. Another photovoltaic technology advancement being considered by NASA is low-cost, lightweight solar concentrators. They may have a significant effect on solar array size and cost for future missions.

This report presents the results of an analytical study undertaken to guide the NASA Lewis Research Center in the development of GaAs technology. Comparisons between silicon and GaAs solar array mission costs are based on specific reference values of the input parameters. As part of this study the sensitivities of costs to the input parameters have been evaluated. The reader may use these sensitivities to determine the effects of parameter changes on solar array mission costs and on cost comparisons.

Approach

A digital computer program was developed to evaluate solar array costs for three mission classes: (1) low Earth orbit (LEO), (2) geosynchronous Earth orbit (GEO), and (3) LEO-to-GEO electric propulsion orbit transfer missions. Solar array size and cost were based on end-of-life (EOL) power requirements for each case. The word "cost" (or "total cost") within this report generally refers to array purchase cost plus array launch cost per EOL watt but does not include development costs. Other costs are distinguished by an adjective (e.g., launch cost or total mission cost).

Radiation dosage was calculated and then applied to the specific solar cell degradation characteristics to determine the array power degradation. Beginning-of-life (BOL) power requirements to achieve the EOL power were then computed. Array purchase costs and launch costs were calculated from the BOL power requirement. In general, except for orbit transfer mission total costs, all costs were normalized for ease of comparison (e.g., \$/W EOL).

A mission and technology parametric analysis was performed to determine the effect of the parameters on total cost. Sensitivities of cost to variations of mission duration, array mass, array cost, cover glass thickness, and solar cell efficiency were determined. Solar concentration with and without cooling was considered, and the sensitivities of cost to concentration ratio, concentrator cost, and concentrator specific mass were evaluated. The results were then used to make recommendations on areas for technology development.

Assumptions

A baseline set of assumptions was used to define cost, efficiency, mass, and other properties of the solar array systems. Reference values of these parameters were chosen to correspond to technologies and costs that could be expected within the next few years. The reference values used in this study are listed in tables I and II.

TABLE I.—SOLAR CELL REFERENCE VALUES

Specific mass factors:	
Area per cell, cm^2	4.0
Mass of 0.2-mm-thick silicon, g	0.186
Mass of 0.2-mm-thick GaAs, g	0.425
Mass of two 0.11-mm-thick layers of adhesive, g	0.097
Mass of 0.1-mm-thick cover glass, g	0.085
Cover glass thickness (orbital), cm	0.015
Cover glass thickness (orbit transfer), cm	0.051
AM0 efficiency of silicon cell at 60° C	0.14
AM0 efficiency of GaAs cell at 60° C	0.17
AM0 solar flux, W/cm^2	0.137
Array structure mass per cell	2.0
Array specific mass, g/W:	
Silicon array specific mass (orbital)	31.5
GaAs array specific mass (orbital)	28.5
Silicon array specific mass (orbit transfer)	35.4
GaAs array specific mass (orbit transfer)	31.7
Other cell parameters:	
Cost of silicon array, \$/W	300.0
Cost of GaAs array, \$/W	500.0
Temperature coefficient of silicon cell performance, $°C^{-1}$	−0.005
Temperature coefficient of GaAs cell performance, $°C^{-1}$	−0.001

TABLE II.—MISSION REFERENCE VALUES

Mission duration (orbital), yr	10
Mission duration (orbital transfer), yr	1
Cost of launch to low Earth orbit, \$/kg	700
Cost of launch to geosynchronous Earth orbit, \$/kg	11 500
Cost of launch for orbit transfer mission, \$/kg	700
Orbit transfer mission payload mass, kg	1000

Array purchase costs.—The purchase cost of the silicon array was assumed to be \$300/W (ref. 4), that is, \$100/W for the bare cell and \$200/W to assemble an array and install cover glass. Gallium arsenide cells are in the experimental stage, and costs are expected to fall rapidly if the cells are produced in large quantities. Prices in the range of \$5000/W for the bare cell are currently being charged, but prices as low as \$100/W have been projected (private communication from D. Flood of Lewis). This study assumes a GaAs cell cost of \$300/W. Gallium arsenide arrays for space were therefore assumed to cost \$500/W, that is, \$300/W for the bare cell and \$200/W to assemble an array and install cover glass.

Transportation costs.—Transportation costs were based on a Space Shuttle launch to LEO. For GEO missions this would be followed by a Space Shuttle/Interim Upper Stage (IUS) transfer from LEO to GEO. Launch costs were assumed to be \$700/kg for launch to LEO and \$11 500/kg for launch to GEO (ref. 5). The orbit transfer mission assumes launch to LEO and electric propulsion to GEO. Therefore the orbit transfer launch cost was assumed to be the LEO cost of \$700/kg with the costs for the electric propulsion considered separately. Launch costs were calculated on a per-unit-mass basis and therefore volume and packaging constraints, dedicated missions, or multiple Shuttle requirements were not considered.

Radiation degradation.—Figures 1 and 2 were used to determine the radiation dose and the fraction of power remaining at any time in the mission for each of the mission classes. Figure 1 (derived from data in ref. 6) shows the total radiation flux (protons and electrons) as a function of cover glass thickness. The flux shown in figure 1 is normalized to equivalent 1-MeV electrons based on the relative proton and electron damage to silicon cells. The curves in figure 1 represent the equivalent flux for the three assumed missions: (1) a 300-nautical-mile LEO orbit with a 30° inclination, (2) a GEO orbit with a 0° inclination, and (3) a LEO-to-GEO orbit transfer mission. The flux for the orbit transfer mission, which passes through the Van Allen radiation belts, was calculated by integrating the flux at each altitude. The flux for a given cover glass thickness was determined from the appropriate mission curve

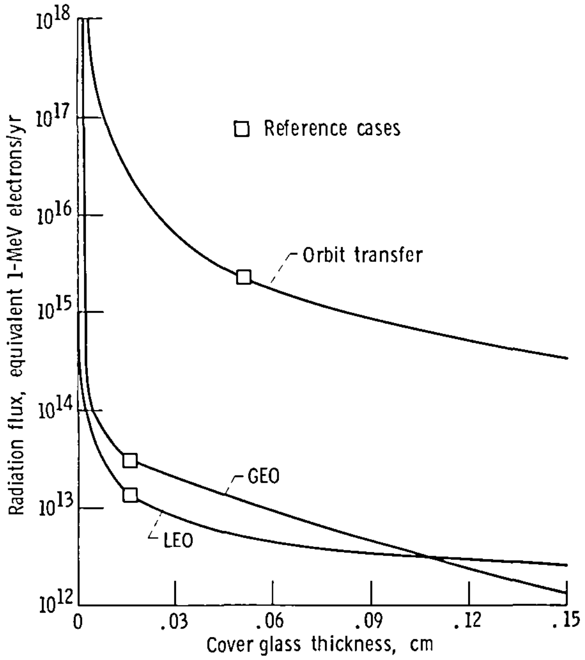


Figure 1. - Total radiation flux for low-Earth-orbit (LEO), geosynchronous-Earth-orbit (GEO), and orbit transfer missions.

in figure 1. Flux through the back surface of the cell was also determined from figure 1 by assuming that the array structure would provide back shielding equivalent to 0.15 centimeter of cover glass. The total flux through the front and back surfaces was multiplied by the mission duration to calculate the total radiation dose.

Figure 2 is a plot of the ratio of solar cell (EOL) power to BOL power as a function of total radiation dose. These data are based on short-duration tests at high flux. Some of this degradation may be annealed during a longer duration mission at lower flux (ref. 7). The three curves in figure 2 represent degradation of silicon solar cells, GaAs cells, and an advanced, more-radiation-resistant GaAs cell. The silicon curve represents a typical space cell (10-ohm-cm textured cell with back surface field, ref. 6). The GaAs curve is based on data from experimental cells (ref. 8). The advanced GaAs cell curve is based on a hypothetical shallow-junction cell that would have about one-fifth the radiation degradation of the reference GaAs cell. This is an optimistic projection of the potential reduction of radiation degradation of GaAs cells. The total radiation dose determined from figure 1 is used to find the power ratio in figure 2, which is then used to compute the BOL power requirement. Beginning-of-life power is multiplied by array cost per watt to determine array purchase cost.

Array mass.—The input values used to determine array mass per BOL watt for the reference cases are the specific mass factors listed in table I. Array specific mass was calculated by adding the masses of the solar cell, the cover glass, and the array structure and then dividing by the power per cell. The reference case for the orbital missions assuming a 0.015-centimeter cover thickness were 31.5 g/W for silicon arrays and 28.5 g/W for GaAs arrays. The orbit transfer mission assumption of a 0.015-centimeter cover thickness, which was based on the results discussed in the section Effects of Cover Glass Thickness, resulted in specific masses of 35.4 g/W for silicon arrays and 31.7 g/W for GaAs arrays.

Concentrator.—For analysis of the cases with concentrated arrays a concentrator specific mass of 1 kilogram per square meter of reflected sunlight and a concentrator specific cost of $2000 per square meter 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 reflector configuration and efficiency. Array temperature was assumed to increase proportionally with the fourth root of the concentration ratio. Silicon array output was assumed to decrease by 0.5 percent per degree C until it reached zero at 260° C (ref. 9). Gallium arsenide array output was assumed to decrease by 0.17 percent per degree C (ref. 8).

Electric propulsion.—The reference orbit transfer mission transported a 1000-kilogram payload from

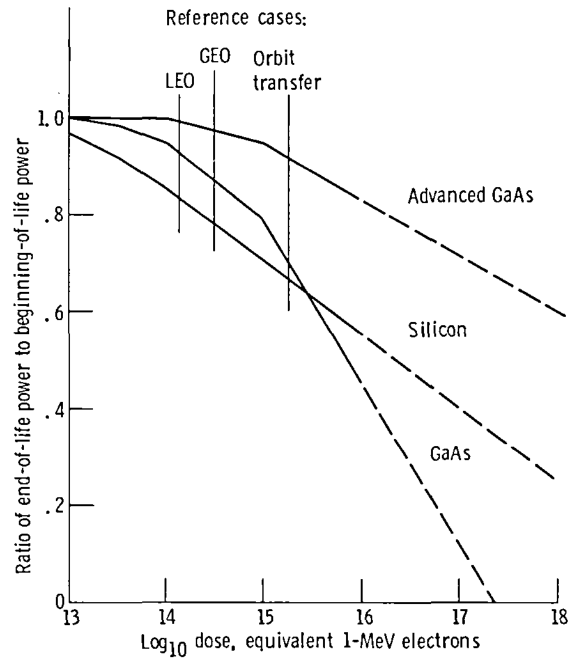


Figure 2. - Solar cell degradation curves for various doses.

LEO to GEO in 1 year by electric propulsion. Costs for the propulsion system including propellant and transportation to LEO were added to the array purchase and launch costs to determine total mission costs. The propulsion system mass was calculated by using the modular approach described in reference 10 and was assumed to be 200 kilograms for the core unit plus 17 kilograms per kilowatt of input power for the propulsion modules. It was calculated that 5.5 watts of peak power (EOL) was required to transport each kilogram from LEO to GEO in 1 year. This was based on assumptions of a 3000-second specific impulse, a 6000-meter-per-second velocity increment, and a 70-percent propulsion system efficiency. Cost for the electric propulsion system was assumed to be \$300/W. The propellant mass requirement was assumed to be 0.05 kg/W yr at a cost of \$50/kg.

Input Parameters

Array and mission parameters were varied to determine the sensitivity of space power cost to those parameters. Each parameter was varied independently while the reference values were maintained for the other parameters. The input variables are listed in table III along with their reference values and the ranges over which they were varied. In general, the ranges were chosen to include the near-term possibilities for each parameter. The concentrator parameter ranges were chosen to include the ranges where concentrated arrays are competitive with planar arrays.

TABLE III.—INPUT PARAMETERS

Parameter	Reference value		Range
	Silicon	GaAs	
Orbital mission duration, yr	10	10	0.25–32.0
Orbit transfer mission duration, yr	1	1	0.5–8.0
Efficiency	0.14	0.17	0.13–0.22
Orbital mission array specific mass, g/W	31.5	28.5	0–100.0
Orbit transfer mission array specific mass, g/W	35.4	31.7	0–100.0
Orbital mission cover slide thickness, cm	0.015	0.015	0–0.152
Orbit transfer mission cover slide thickness, cm	0.051	0.051	0–0.152
Array cost, \$/W	300	500	0–2000
Concentration ratio	1	1	1–10
Concentrator effective mass, kg/m^2	1	1	1–60
Concentrator effective cost, $\$/m^2$	2000	2000	2000–60 000

Results and Discussion—Planar Arrays

The effects of varying each of the parameters in table III are discussed for the three mission classes: LEO, GEO, and orbit transfer. For each class the costs of using a silicon array are compared with the costs of using a GaAs array.

Effect of Mission Duration on Silicon Launch and Array Costs

Since radiation dose increases with mission duration, solar cell degradation causes output power to decrease with time. Therefore as mission duration increases, more array is required to produce the same end-of-life power capability. For the orbital missions duration was varied from 0.25 to 32 years; for the orbit transfer missions duration was varied from 0.5 to 8 years. Figure 3 shows silicon array cost, launch cost, and total (array plus launch) cost for the three mission classes (LEO, GEO, and orbit transfer) as a function of mission duration.

For a silicon array in LEO the total cost increases from \$325/W (EOL) for a 0.25-year mission to \$425/W (EOL) for a 32-year mission (fig. 3(a)). This cost increase is due to the increase of array degradation from 3 percent to 25 percent. Array purchase cost is 90 percent of the total cost for the LEO mission. Since launch cost is only 10 percent of the total cost, reduction of mass only has a small effect on total cost for LEO missions.

For the GEO mission the launch cost exceeds the array purchase cost (fig. 3(b)). Launch cost and array purchase cost (per EOL watt) each increase by the same proportion as mission time increases. Total cost increases from \$630/W (EOL) for a 0.5-year mission to \$860/W (EOL) for a 32-year mission. This cost increase is due to the increase of array degradation from 4 percent to 29 percent.

The major difference between the LEO and GEO costs is the higher launch cost for the GEO mission. Cost of launch to LEO is less than 10 percent of the total LEO cost; cost of launch to GEO is more than 50 percent of the total GEO cost. Launch cost and hence array mass are therefore important cost factors for GEO missions.

The third case is an orbit transfer mission in which the array was launched to LEO on the Shuttle. Electric propulsion (powered by the array) was used to take the array to GEO. Figure 3(c) shows the cost of an array and the cost of launching the array to LEO per watt (EOL) for orbit transfer missions of various durations. The cost of the electric propulsion system is not included in this curve but is included in

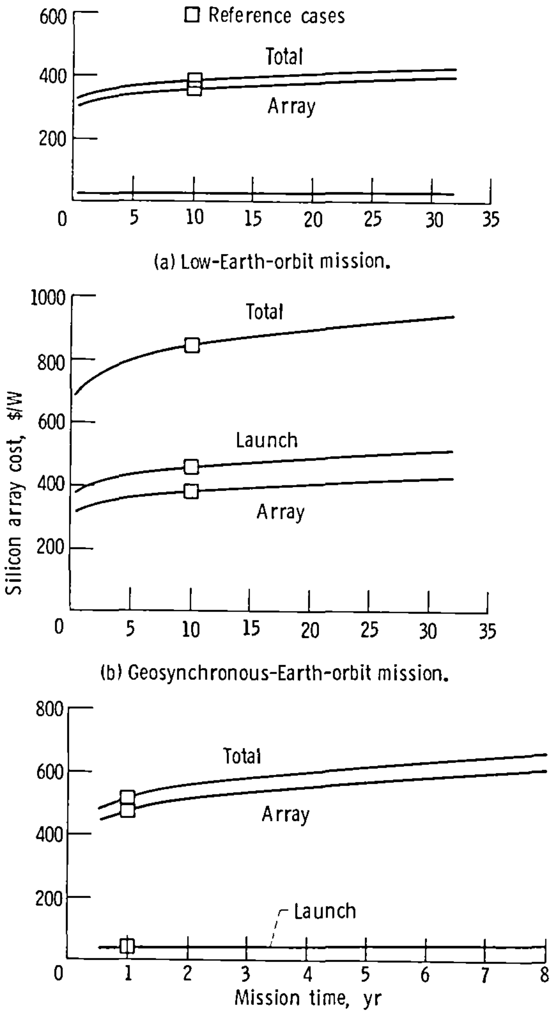


Figure 3. - Effect of mission time on silicon solar array costs.

sections of the report.

Radiation flux was shown in figure 1 to be 100 to 1000 times greater for the orbit transfer mission than for the orbital missions. However, the cover glass thickness was increased as shown in table I from 0.015 centimeter for the orbital missions to 0.051 centimeter for the orbit transfer missions. The effect of cover glass thickness on mission costs is shown in the section Effect of Cover Glass Thickness. Figure 3(c) shows that the cost increases from $475/W (EOL) for a 0.5-year orbit transfer mission to $650/W (EOL) for an 8-year orbit transfer mission. The cost increase is due to the increase of array degradation from 33 percent to 50 percent. The launch cost is only a small part of the total cost in figure 3(c). However, it is shown in the section Effects of Array Mass that increasing array mass decreases payload capability and therefore significantly affects total orbit transfer mission cost.

The ratio of launch costs to total costs for each of the mission classes is approximately the same for GaAs arrays as for silicon arrays. The discussion of launch cost, array purchase costs, and total cost is therefore not repeated for GaAs.

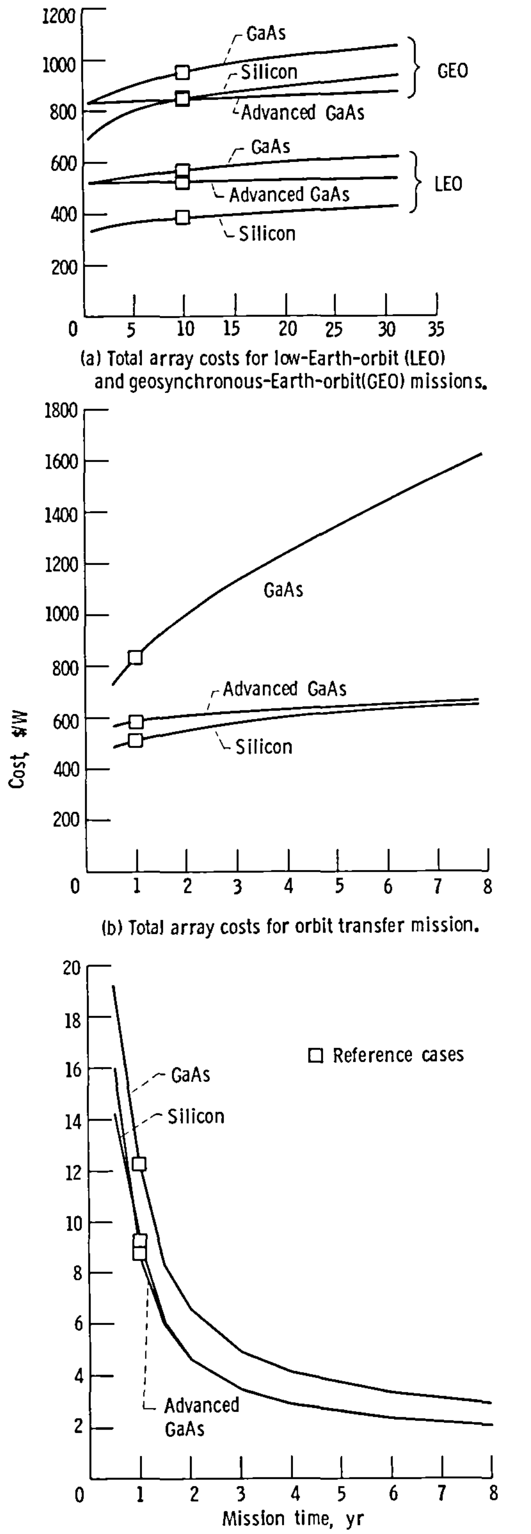
Comparison of Planar Gallium Arsenide and Silicon Array Costs

The curves for total GaAs costs as a function of mission duration are superimposed in figure 4 on the total cost curves presented previously for silicon.

Total array costs for LEO and GEO missions.—The costs of GaAs and silicon arrays per watt for LEO and GEO missions are shown in figure 4(a). Two types of GaAs arrays are represented, a baseline array and an advanced, more-radiation-tolerant array. Comparison of the LEO curves in figure 4(a) shows that the total EOL cost of the base GaAs array is about $200/W more than the total EOL cost of a silicon array for all mission durations shown. The advanced GaAs array, by virtue of its lower radiation degradation, is only $100/W more expensive than silicon arrays for the long-duration LEO missions. The cost differential for the LEO missions is primarily due to the initial $200/W difference in the array purchase cost between silicon and GaAs arrays assumed for the study.

Comparison of the GEO curves in figure 4(a) shows that the total costs for the baseline GaAs array are only about $100/W more than those for the silicon array for the range of mission durations studied. The advanced GaAs array is also $100/W more expensive than the silicon array for short-duration missions. However, the advanced GaAs array, because of its greater radiation tolerance, is less expensive than silicon arrays for long-duration missions.

Total array costs for orbit transfer mission.—The cost of planar GaAs arrays is compared with that of silicon arrays in figure 4(b) for various orbit transfer mission durations. The orbit transfer mission involves a spiral-out trajectory from LEO to GEO in which the solar array passes through the Van Allen radiation belts. Radiation flux is 100 to 1000 times greater for the orbit transfer mission than for the orbital missions. It was expected that the superior radiation resistance of GaAs arrays would show them to be lower in cost for the orbit transfer mission than silicon arrays. However, the radiation resistance superiority of the baseline GaAs cell does not exist at the high radiation dosages encountered in long-



(c) Total orbit transfer mission costs.

Figure 4. - Effect of mission time on total array and orbit transfer mission costs for gallium arsenide, silicon, and advanced gallium arsenide arrays.

duration orbit transfer missions. The radiation degradation curves shown in figure 2 for the silicon and the baseline GaAs cells cross at a dosage corresponding to a 1.5-year orbit transfer mission. And for higher dosages silicon arrays have more radiation resistance than GaAs arrays. Therefore in figure 4(b) the GaAs array cost is initially higher than the silicon cost because of the purchase cost differential, and the difference increases with mission duration because of the increasing degradation of GaAs.

The advanced GaAs curve shown in figure 4(b) assumes greatly reduced radiation degradation. This hypothetical advance on radiation tolerance for GaAs arrays would make them competitive with silicon arrays for orbit transfer missions.

Total mission cost for orbit transfer mission.—The reference orbit transfer mission transported a 1000-kilogram payload from LEO to GEO in 1 year. Total mission costs are defined as the sum of the propulsion system costs, the array purchase cost, and transportation costs to LEO. Figure 4(c) shows the total mission cost for the planar silicon, GaAs, and advanced GaAs arrays as a function of orbit transfer time. As mission duration increases, the power required for propulsion decreases. This reduces the required array and propulsion system size. There is a compounding effect because reducing the array and propulsion system size reduces the total mass being propelled from LEO to GEO and thus enables an additional decrease in power. There are, however, penalties that have not been included in the analysis such as cost of capital investment, which would penalize a long-duration orbit transfer mission. At the other extreme, short-duration missions become very expensive. There is a minimum duration, approximately 1/3 year, below which the specific power of the array and propulsion system are not sufficient to carry a payload from LEO to GEO. Below this minimum-duration point the mission cannot be accomplished with the assumptions used in this study.

Comparing the curves in figure 4(c) shows that the total mission costs with the silicon and advanced GaAs arrays are about the same for mission durations from 0.5 to 8 years and that the mission using the baseline GaAs array is about 30 percent more expensive. Again, this is primarily due to the $200/W array purchase cost advantage of silicon.

Since the superior radiation tolerance of the advanced GaAs array has not yet been achieved, the curves in the remainder of this report compare the silicon array with the baseline GaAs array but do not include the advanced, more-radiation-tolerant GaAs cell.

Total mission cost for baseline orbit transfer mission.—The mass breakdown for the reference

1-year orbit transfer mission for silicon and GaAs arrays is shown in figure 5. The payload is about 40 percent of the total mass; the thrusters, the propellant, and the array are each about 20 percent of the total mass. There is little difference between the mass distribution with the silicon array and that with the GaAs array.

The cost of each element for the reference 1-year orbit transfer mission for the silicon and GaAs arrays is shown in figure 6. The only substantial difference is in the array cost. Array cost in each is more than half of the total cost (57 percent for Si; 69 percent for GaAs). The actual GaAs array cost is about 60 percent more than the silicon array cost. This reflects the difference between the array purchase cost assumption of $500/W for GaAs and $300/W for silicon.

Effects of Array Mass

To evaluate the effect of the reference-cell assumptions, solar array mass was parameterized.

Array mass for LEO and GEO missions.—The influence of array mass on total array cost for 10-year LEO and GEO missions is shown in figure 7(a). The cost at zero mass represents the total array cost if launch costs are excluded. The nearly horizontal slope of the LEO curves indicates that array mass is not a major cost driver for LEO missions. The steep increase of the GEO curves indicates that cost is sensitive to array mass for the GEO missions. If array mass could be reduced by 50 percent from the reference values for the GEO missions, there would be a savings of 25 percent of the total cost.

Array mass for orbit transfer mission.—The

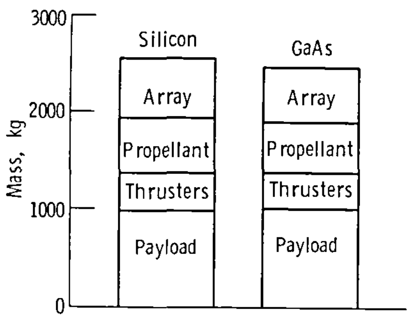


Figure 5. - Reference orbit transfer mission masses for silicon and gallium arsenide solar arrays.

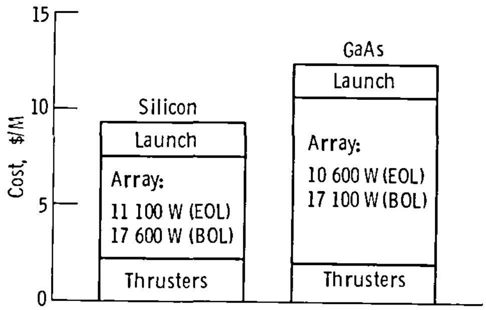
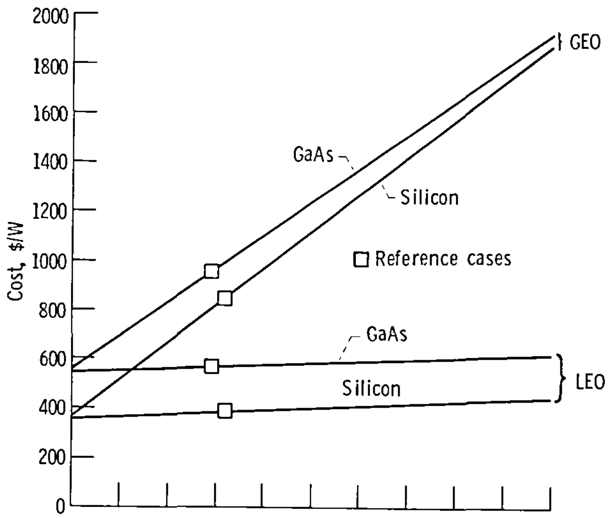
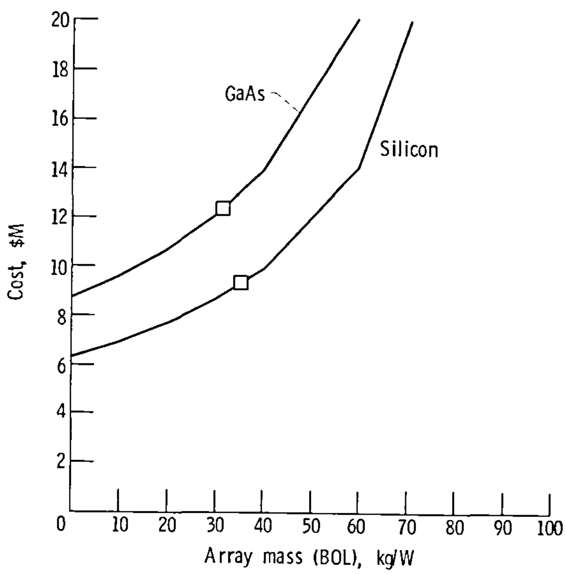


Figure 6. - Reference total orbit transfer mission costs for silicon and gallium arsenide solar arrays.



(a) Array costs for low-Earth-orbit (LEO) and geosynchronous-Earth-orbit (GEO) missions.



(b) Total orbit transfer mission costs.

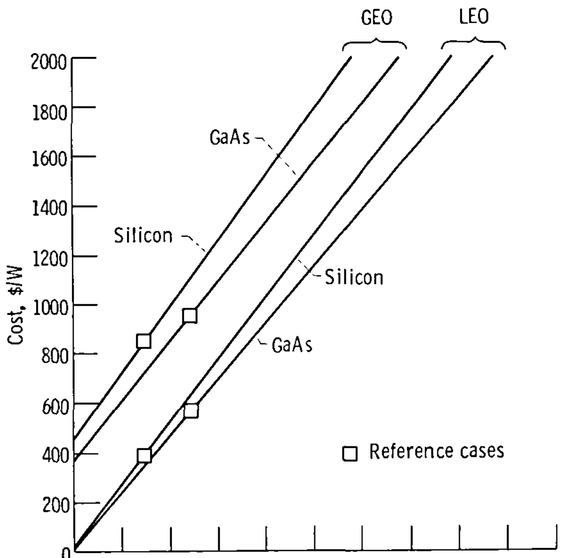
Figure 7. - Effect of array mass on array and total mission costs for gallium arsenide and silicon solar arrays.

sensitivity of total mission cost to array mass is shown in figure 7(b) for the orbit transfer mission. Even though launch costs per kilogram are the same for the orbit transfer and LEO missions, the orbit transfer mission total costs are much more sensitive to array mass than are the LEO mission array costs. Since the array and the electric propulsion system are sized to propel the total mass of the array, propulsion system, and payload, any increase in array specific mass necessitates a larger power and propulsion system to meet the mission requirements. Figure 7(b) shows an approximately exponential dependence of total mission cost on array specific mass. If array mass could be reduced by 50 percent from the reference values for the 1-year orbit transfer mission, there would be a savings of 15 to 20 percent of the total mission cost.

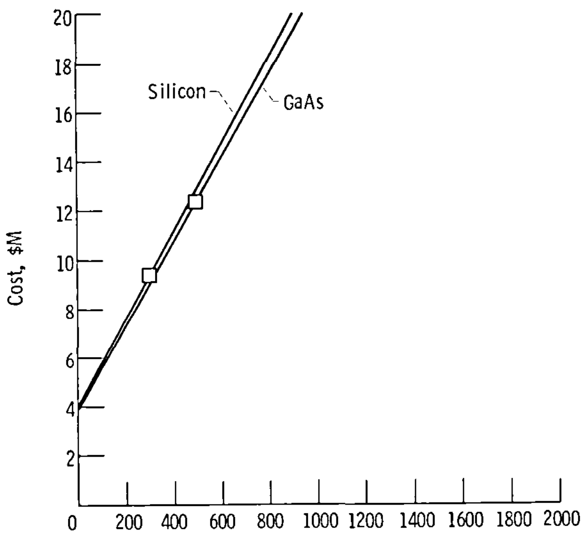
Effects of Array Purchase Cost

Another assumption parameterized was the array purchase cost. Figure 8(a) shows the variation of total cost as a function of BOL array purchase cost for the LEO and GEO missions; figure 8(b) displays the results for the orbit transfer missions. In each case total cost is strongly dependent on, and is a linear function of, array purchase cost. The silicon curves have a steeper slope (more cost dependence) that the GaAs curves because of the greater silicon BOL array power required.

These cost parametric curves can be used to determine what the GaAs purchase costs would have to be in order for their total cost to equal the total cost of the silicon arrays. For example (fig. 8(a)), if the silicon purchase cost is \$300/W (BOL) for a GEO mission, the total cost is about \$850/W. An \$850/W total cost would correspond to a \$420/W (BOL) GaAs array purchase cost.



(a) Array costs for low-Earth-orbit (LEO) and geosynchronous-Earth-orbit (GEO) missions.



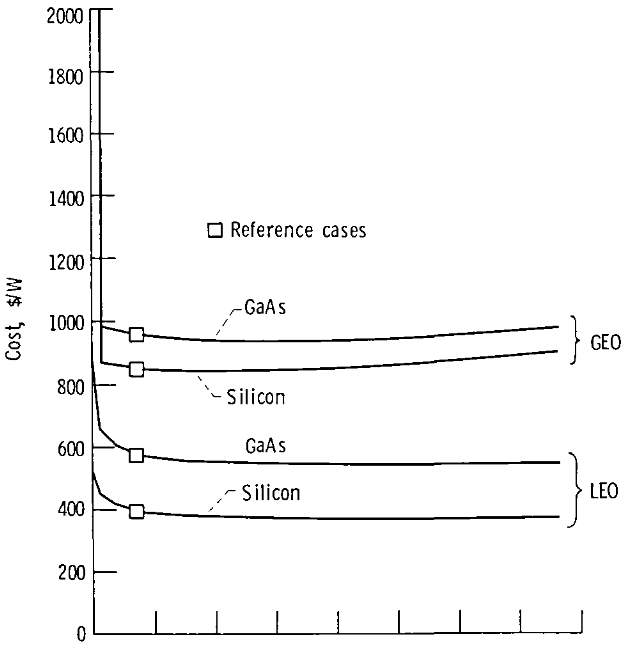
(b) Total orbit transfer-mission costs.

Figure 8. - Effect of array purchase cost on array and total mission costs for gallium arsenide and silicon solar arrays.

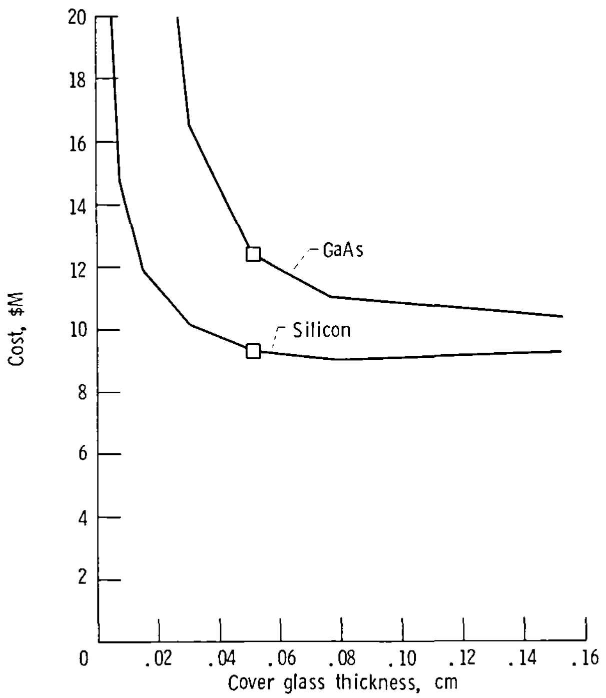
Effects of Cover Glass Thickness

Cover glass is used on a solar cell to attenuate the radiation flux and thereby reduce the damage. Increasing the cover glass thickness increases the radiation protection, but it also adds to the array weight. For a particular cell and a specific mission, there is an optimum cover glass thickness in terms of total cost. A thinner-than-optimum cover glass increases cost because more cells are required to produce the same end-of-life power. The greater mass of a thicker-than-optimum cover glass increases launch cost more than the enhanced radiation protection decreases array purchase cost.

LEO and GEO missions.—Cost as a function of cover glass thickness is shown in figure 9(a) for the reference 10-year LEO and GEO missions. Cost for the LEO mission decreases rapidly as cover glass thickness increases from 0 (a bare cell) to the reference value of 0.015 centimeter. Cost continues to decrease for cover glass thicknesses greater than 0.015 centimeter but so slightly that for LEO missions the most practical cover glass thickness for ease of manufacturing and handling is recommended. However, the cost will eventually increase for very thick covers when the launch cost becomes dominant.



(a) Array costs for low-Earth-orbit (LEO) and geosynchronous-Earth-orbit (GEO) missions.



(b) Total orbit transfer mission costs.

Figure 9. - Effect of cover glass thickness on array and total mission costs for gallium arsenide and silicon solar arrays.

A bare cell will not perform the GEO mission because of radiation damage. This results in the computed cost going to infinity. A minimum thickness of cover glass (0.002 cm), however, can provide protection from the low-energy protons that are abundant at GEO. Cost decreases slightly as the cover glass thickness is increased beyond the reference value (0.015 cm) and up to 0.05 centimeter. Above 0.05 centimeter the increasing transportation charges have a greater effect on cost than does the decreasing radiation damage. The reference value of cover glass thickness was chosen to be 0.015 centimeter on the basis of current space solar cell designs. Although the analysis shows a slight reduction of cost above 0.015 centimeter, cost may increase in this range as a result of two factors not included in the analysis: (1) Array costs (assumed to be constant) are likely to increase with cover glass thickness; and (2) array structure mass (assumed to be constant at 2 g/cell) may increase with cover glass thickness.

Orbit transfer mission.—Total mission cost is shown as a function of cover glass thickness in figure 9(b) for the orbit transfer mission. There is a greater percentage reduction in cost as cover glass thickness increases for the orbit transfer mission than for the orbital missions because of the greater benefit of radiation protection at the higher radiation exposures. Again, as in GEO, the bare cell cannot complete the mission. The optimum thickness of cover glass is greater for the orbit transfer mission than for the orbital missions. This is due to the payoff in cost for radiation protection at the greater radiation dosages encountered in the orbit transfer trajectory exceeding the penalty of additional mass.

As the cover glass thickness increases, the mass of the array increases and this causes the required power for the mission to also increase. The effect of greater array mass eventually overcomes the benefit of radiation protection. A cover glass thickness of 0.05 centimeter was chosen for the reference case. Although there is a slight decrease in cost for cover glass thicker than this reference value, the increases in array cost ($/W BOL) and in array structure mass may nullify this decrease.

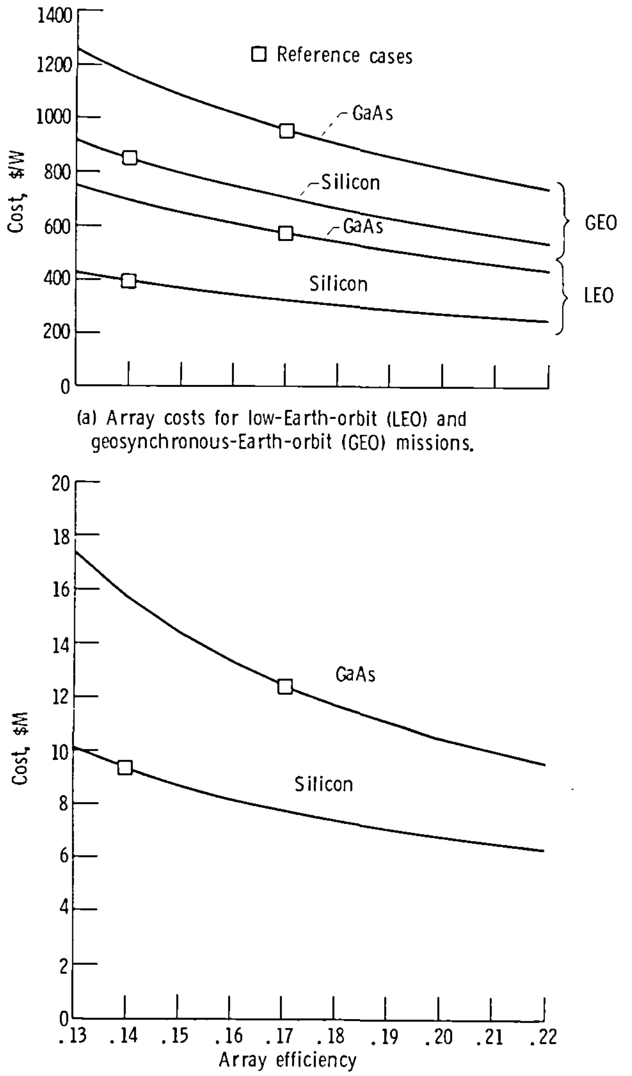
Unlike the orbital cases, where the GaAs and silicon curves were approximately parallel for the full range of cover glass thicknesses, the GaAs curve rises much more sharply than the silicon curve as the cover glass thickness is decreased below 0.05 centimeter. This effect is primarily due to the sharper dropoff in GaAs power than in silicon power for radiation doses greater than 10^{15} 1-MeV electrons, as shown in figure 2. The increase of equivalent radiation flux with decreasing cover glass thickness is shown in figure 1.

Effects of Array Efficiency

The BOL efficiencies of the silicon and GaAs solar arrays were varied from 0.13 to 0.22. Array mass per cell and the array cost per cell were maintained constant as the efficiencies were varied from their reference values of 0.14 for silicon and 0.17 for GaAs.

LEO and GEO missions.—GaAs and silicon costs as functions of efficiency are shown in figure 10(a) for the LEO and GEO orbital missions. The curves show that array total cost is strongly dependent on cell efficiency. If the GaAs cell efficiency could be increased to 0.20 while maintaining the cost per cell and the mass per cell, GaAs would become more cost effective than silicon for the GEO mission. However, for the LEO mission increasing GaAs efficiency even to 0.22 would not overcome the cost advantage of silicon. Increasing the efficiency of silicon cells would of course increase their cost advantage for both the LEO and GEO missions.

Orbit transfer mission.—As in LEO and GEO, increasing array efficiency without increasing array mass or cost per cell reduces cost for the orbit transfer mission. Figure 10(b) shows that increasing GaAs efficiency to 0.22 without increasing mass or cost per cell would make it competitive with the 0.14-efficient silicon cell. Increasing the efficiency of silicon cells would further increase the orbit transfer mission cost difference between silicon and GaAs.



(a) Array costs for low-Earth-orbit (LEO) and geosynchronous-Earth-orbit (GEO) missions.

(b) Total orbit transfer mission costs.

Figure 10. - Effect of array efficiency on array and total mission costs for gallium arsenide and silicon solar arrays.

Results and Discussion—Concentrated Arrays

The effects of varying the concentration ratio (with and without array cooling) are discussed for the three mission classes: LEO, GEO, and orbit transfer. Also discussed are the effects of varying the concentrator mass and cost assumptions.

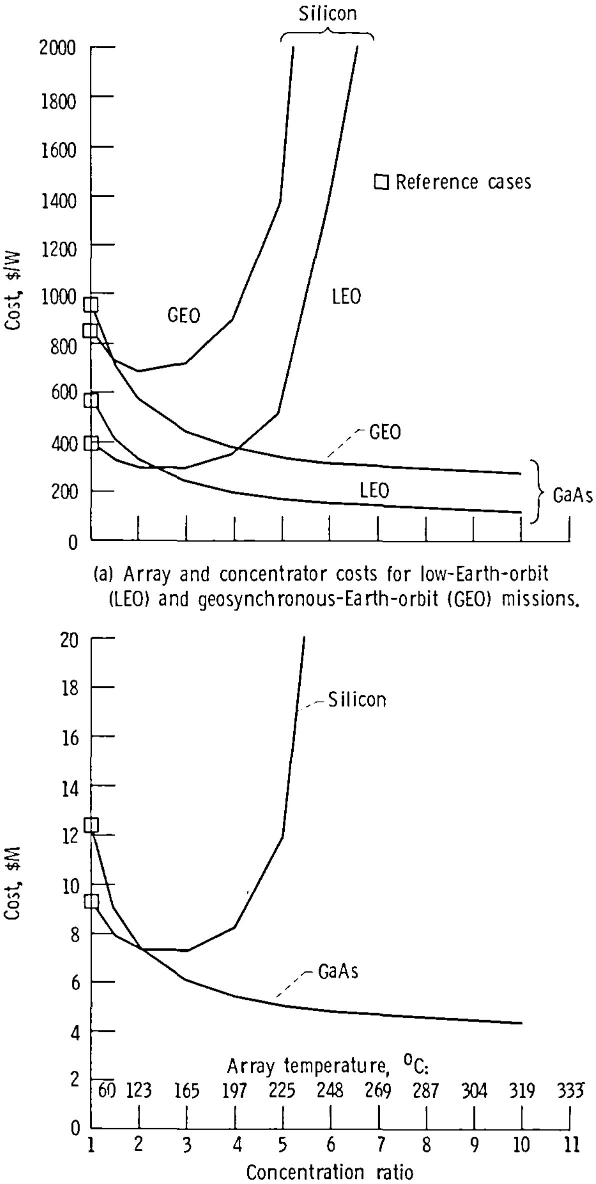
Effects of Concentration

A performance advantage of gallium arsenide 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. Temperature coefficients of performance for silicon and GaAs arrays are listed in table I. A potential bonus, although not considered in this study, is that GaAs solar arrays may begin to self-anneal radiation damage at 200° C (ref. 11). The greater operational temperature range of GaAs enables these arrays to benefit from solar concentration more than do silicon arrays in an uncooled concentrator system.

LEO and GEO missions.—Costs as a function of concentration ratio for silicon and GaAs arrays in 10-year LEO and GEO orbital missions are shown in figure 11(a). The temperatures computed by assuming no active cooling are shown on a parallel axis. The GEO curves are similar to the LEO curves, differing mainly because of launch costs. In both, costs for silicon arrays increase rapidly at concentration ratios greater than 4. This is caused by the decrease in efficiency of the silicon array with increasing temperature overcoming the benefit of increased illumination at the higher concentration. Silicon arrays could be used with higher concentration ratios if cooling were supplied, but without cooling the optimum concentration ratio appears to be approximately 2. The GaAs curves show continuing cost reduction as the concentration ratio is increased to 10. At that concentration ratio GaAs costs are about half the minimum silicon costs. These curves illustrate the potentially significant savings in solar power system costs if the technology of concentrator systems is developed.

Orbit transfer mission.—The orbit transfer mission cost for concentration ratios of 1 to 10 is shown in figure 11(b). As in the orbital cases a significant cost savings (about 50 percent of the total mission cost with planar silicon arrays) can be achieved using GaAs solar arrays with concentration.

To realize the cost savings of concentration, it is necessary to develop low-cost, low-mass solar concentrators. Additional savings for both GaAs and silicon arrays would be possible if low-cost, low-mass cooling concepts were developed. The following sections of this report quantify the potential cost reduction of incorporating cooling and show the sensitivity of concentrated GaAs costs to concentrator mass and cost.



(a) Array and concentrator costs for low-Earth-orbit (LEO) and geosynchronous-Earth-orbit (GEO) missions.

(b) Total orbit transfer mission costs.

Figure 11. - Effect of concentration ratio on array and total mission costs for gallium arsenide and silicon solar arrays.

Effects of Concentration with Cooling

An analysis of the costs and masses associated with an array cooling system would require a detailed design study and is beyond the scope of this effort. It was therefore assumed that concentration and cooling could both be accomplished for the reference mass and cost of 1 kg/m^2 and \$2000/m^2 used previously for the concentrator alone. These values are optimistic, so the sensitivities of total cost to concentrator mass and cost were evaluated and are shown in the next section.

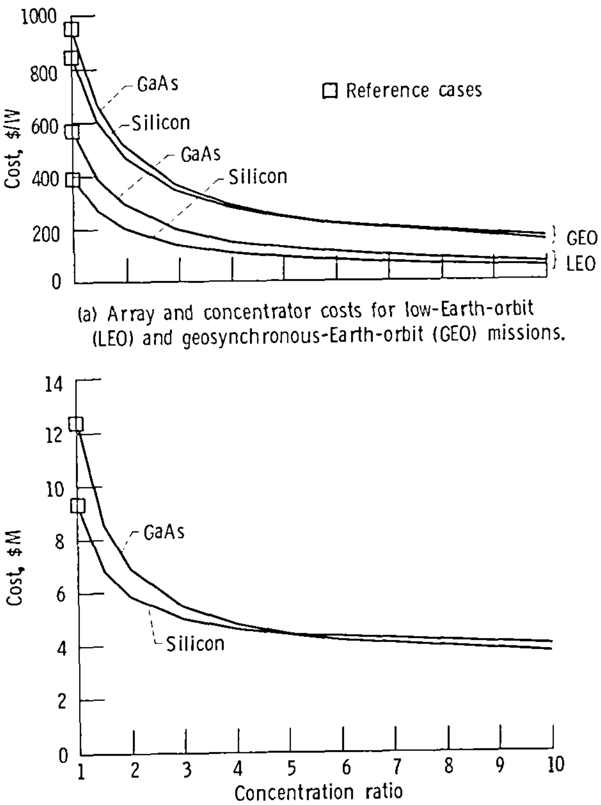
LEO and GEO missions.—Array and concentrator total costs are shown in figure 12(a) as a function of concentration ratio with the silicon or GaAs array cooled to 60° C for the orbital missions. The GEO costs are higher than the LEO costs because of the higher transportation cost. Cooling to 60° C decreases the costs for both the silicon and GaAs cases as compared with the cases shown in figure 11(a). It must be noted, however, that the cost and mass used for the concentrators alone are now being considered for both the concentrator and the cooling system. The cost reduction for silicon is dramatic. Without cooling, concentrated silicon offers little cost advantage over planar silicon. But with cooling, concentrated silicon is less expensive even than concentrated GaAs. This study did not explore variations in operational temperature. These would significantly affect the mass and costs of the cooling system.

Orbit transfer mission.—Orbit transfer mission costs are shown in figure 12(b) for concentrated GaAs and silicon arrays cooled to 60° C. Again the costs with GaAs or silicon arrays decline with increasing concentration ratio. At a concentration ratio of 10 the cost with either GaAs or silicon is less than half the cost of the planar silicon array.

Effects of Concentrator Mass and Cost

These results are dependent on the assumptions of \$2000/m^2 for array cost and 1 kg/m^2 for array mass. In this analysis the costs and mass are based on the effective area of the concentrator. This effective area, which is the sunlight energy reflected onto the array divided by the air-mass-zero (AM0) solar flux, is less than the actual reflector area. Concentrator systems have not yet been used in a space application and have had only limited use in terrestrial systems. And there is considerable uncertainty about the cost and mass of space concentrator systems. The emphasis of this analysis was therefore to determine what values of concentrator mass and cost would enable concentrator systems to be more cost effective than planar arrays.

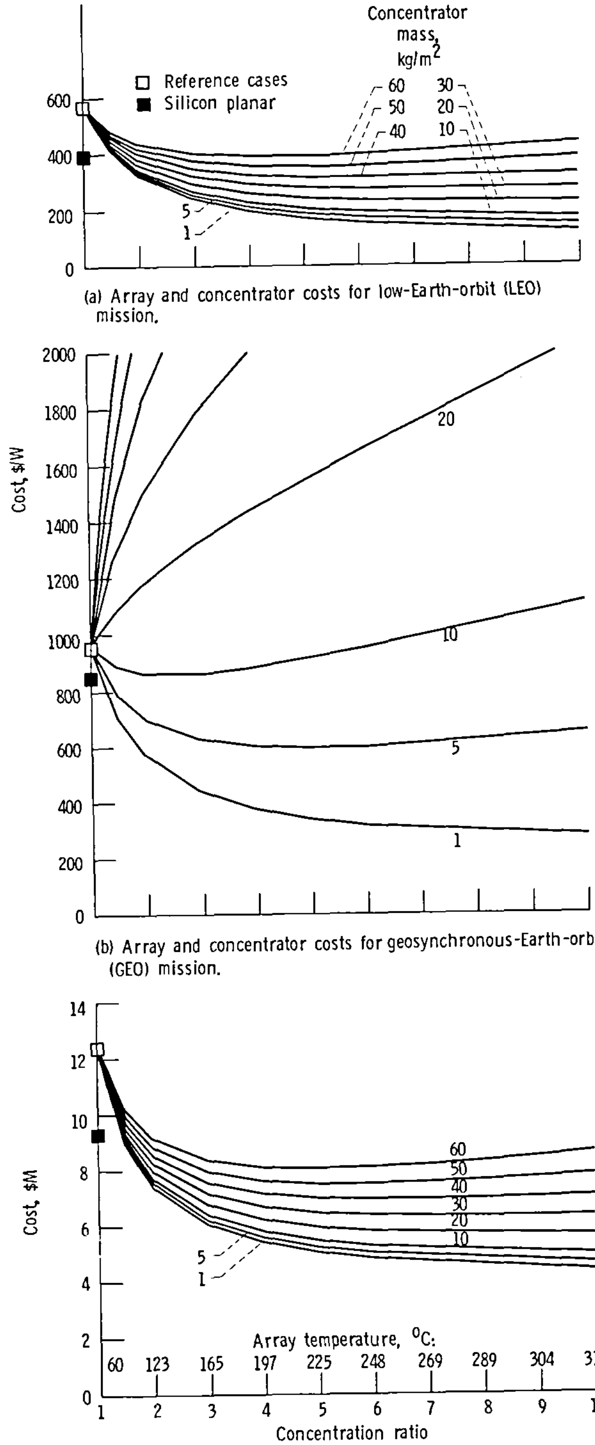
Concentrator mass.—The effect of concentrator mass on cost for GaAs arrays in the LEO, GEO, and orbit transfer missions is shown in figure 13. For these cases it was assumed that there was no active array cooling. For the LEO mission (fig. 13(a)) the cost advantage due to concentration diminishes linearly as concentrator specific mass is increased until at 60 kg/m^2 the concentrated GaAs is more expensive than planar silicon. As mentioned previously GEO mission costs are very sensitive to



(a) Array and concentrator costs for low-Earth-orbit (LEO) and geosynchronous-Earth-orbit (GEO) missions.

(b) Total orbit transfer mission costs.

Figure 12. - Effect of concentration ratio on array and total mission costs for gallium arsenide and silicon solar arrays with array cooled to 60° C.

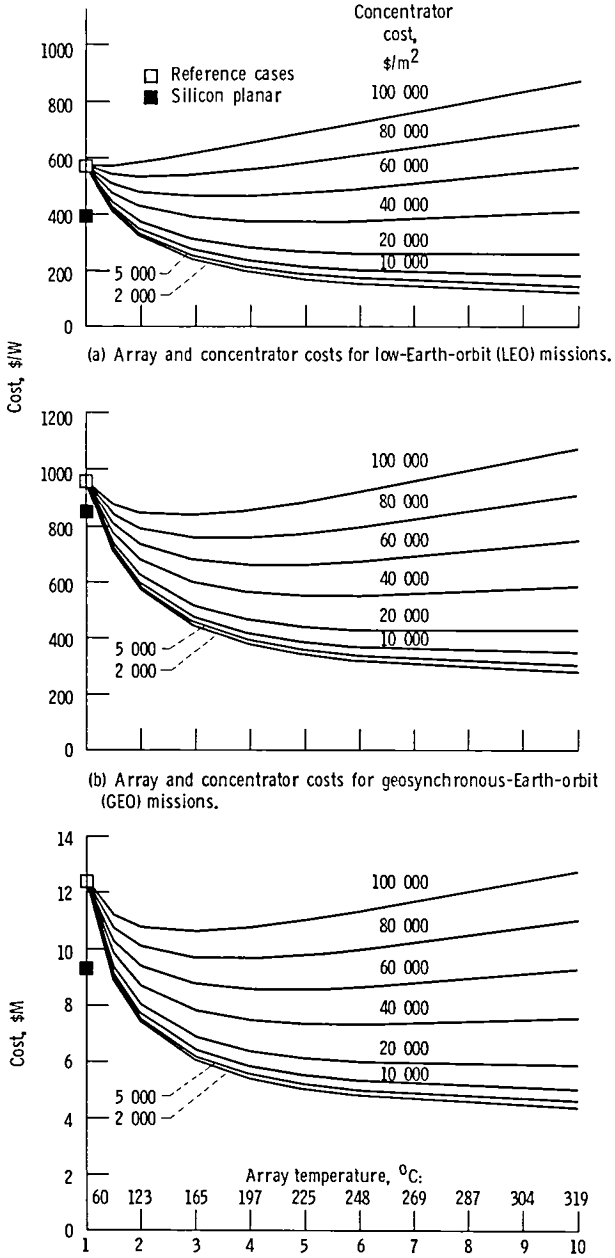


(a) Array and concentrator costs for low-Earth-orbit (LEO) mission.

(b) Array and concentrator costs for geosynchronous-Earth-orbit (GEO) mission.

(c) Total orbit transfer mission costs.

Figure 13. - Effects of concentration ratio and concentrator mass on array and total mission costs for gallium arsenide solar array.



(a) Array and concentrator costs for low-Earth-orbit (LEO) missions.

(b) Array and concentrator costs for geosynchronous-Earth-orbit (GEO) missions.

(c) Total orbit transfer mission costs.

Figure 14. - Effects of concentration ratio and concentrator cost on array and total mission costs for gallium arsenide and silicon solar arrays.

mass because of the high launch cost. For the GEO mission (fig. 13(b)) concentrated GaAs is more expensive than planar silicon if the concentrator specific mass is greater than 10 kg/m^2. The orbit transfer mission (fig. 13(c)) is similar to the LEO mission although even at 60 kg/m^2 the concentrated GaAs has some cost advantage over planar silicon.

These concentrator mass limits, 10 kg/m^2 for GEO missions and about 60 kg/m^2 for LEO and orbit transfer missions, are the approximate breakeven points between silicon planar arrays and concentrated GaAs arrays at the reference concentrator cost of $2000/$m^2$.

Concentrator cost.—The concentrator cost was varied while maintaining the concentrator specific mass constant at 2 kg/m^2. Figure 14 shows the effect of varying the concentrator cost from $2000/$m^2$ to $100 000/$m^2$ for the LEO, GEO, and orbit transfer missions with no active cooling of the GaAs array. Total cost is seen to vary linearly with concentrator cost. For the LEO mission (fig. 14(a)) the concentrated GaAs system is less expensive than planar silicon for concentrator costs less than $40 000/$m^2$. For the GEO mission (fig. 14(b)) the concentrated GaAs system is less expensive than planar silicon for concentrator costs to $100 000/$m^2$. For the orbit transfer mission (fig. 14(c)) the concentrated GaAs system is less expensive than planar silicon for concentrator costs to $70 000/$m^2$.

Conclusions

An economic analysis of silicon and gallium arsenide solar arrays for space power has been performed. This analysis considered planar and concentrated systems for generation of electric power for low-Earth-orbit (LEO) and geosynchronous-Earth-orbit (GEO) orbital missions and for orbit transfer missions using electric propulsion. A baseline set of solar array and mission parameters was defined. Sensitivity of cost to mission duration, array mass, array cost, cover glass thickness, array efficiency, concentration ratio (with and without cooling), concentrator specific mass, and concentrator specific cost was determined.

Variation of mission duration showed that, for the reference values of the input parameters, the greater radiation resistance of the GaAs arrays did not overcome the assumed array purchase cost advantage of silicon arrays even for the longest mission durations considered.

Launch cost was seen to be a major factor for GEO missions but not for LEO or orbit transfer missions. Array mass is therefore a major cost driver in GEO, but reduction of mass has only a small effect on total cost for LEO missions. Although launch cost is not a major factor in orbit transfer mission cost, array mass is a major cost driver. An increase in array mass increases the electric propulsion power requirement and has a compounding effect on total mission costs.

Array purchase cost is a major factor in total array cost for the orbital missions and in total mission cost for the orbit transfer missions. In each case, total cost is strongly dependent on, and is a linear function of, array purchase cost.

Cover glass attenuates the radiation flux and thereby improves end-of-life cell performance. For orbit tranfer missions a cover glass thickness of at least 0.051 centimeter is recommended to reduce total mission cost. The orbital mission costs are less sensitive to cover glass thickness, and a conventional 0.015-centimeter cover thickness provides adequate protection. A thicker cover glass may be slightly more cost effective particularly for the LEO mission.

Increasing array efficiency without increasing the mass or cost per cell reduces cost for all the missions. However, increasing GaAs efficiency to 0.22 does not overcome the cost advantage of 0.14-efficient silicon cells for the LEO mission. For the GEO and orbit transfer missions total array cost would be slightly less with a 0.22-efficient GaAs cell than with the reference 0.14-efficient silicon cell. Any improvement of silicon cell efficiency would increase the cost advantage of silicon arrays.

The use of reflectors for concentration has the potential for significantly reducing power system costs. Gallium arsenide arrays benefit considerably more from concentration (without active cooling) than silicon arrays because of their higher allowable operating temperature. If cooling could be provide at a nominal cost, concentrated systems (either Si or GaAs) would have significant cost advantages over planar systems. However, the advantages of concentrator systems diminish with increasing concentrator specific cost or increasing concentrator specific mass. The cost advantage of uncooled, concentrated GaAs compared with planar silicon holds to a concentrator specific cost of \$40 000/m^2 for the LEO mission, \$100 000/m^2 for the GEO mission, or \$70 000/m^2 for the orbit transfer mission for low concentrator specific mass. At low specific concentrator cost the concentrated GaAs cost advantage holds to a concentrator specific mass of 10 kg/m^2 for GEO missions and about 60 kg/m^2 for LEO and orbit transfer missions.

Results of this study indicate that solar cell development should give a high priority to reducing array costs and that the development of low-cost, lightweight solar concentrators should be pursued.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 25, 1980

References

1. Study of Multi-kW Solar Arrays for Earth Orbit Applications. (LMSC-D715841, Lockheed Missiles and Space Co.; NASA Contract NAS8-32981.) NASA CR-161453, 1980.
2. Study of Multi-kW Solar Arrays for Earth Orbit Applications. (Rockwell International Corp.; NASA Contract NAS8-32988.) SSD 80-0064, 1980.
3. Study of Multi-kW Solar Arrays for Earth Orbit Applications. (TRW Defense and Space Systems Group; NASA Contract NAS8-32986.) TRW 33295-6001-UT-00, 1980.
4. Bernatowicz, D.T.: Cost Study of Solar Cell Space Power Systems. NASA TM X-68054, 1972.
5. Slifer, L.W., Jr.: Geosynchronous Advanced Power Systems (GAPS). Presentation to the Ad Hoc Advisory Subcommittee on Power Technology for Future Synchronous Satellites and Platforms of the Space Systems and Technology Advisory Committee, NASA Goddard Space Flight Center, 1978.
6. Tado. H.Y.; and Carter, J.R., Jr.: Solar Cell Radiation Handbook. (JPL-Pub-77-56, Jet Propulsion Lab.; NASA Contract NAS7-100.) NASA CR-155554, 1977.
7. Heinbockel, J.H.; Conway, E.J.; and Walker, G.H.: Simultaneous Radiation Damage and Annealing of GaAs Solar Cells. Fourteenth IEEE Photovoltaic Specialists Conference, Conference Record. Institute of Electrical and Electronics Engineers, 1980, pp. 1085-1089.
8. Kamath, S.; et al.: GaAs Concentrator Photovoltaic Power Systems Feasibility Investigation. SCG-70392P, Hughes Aircraft Co., 1977. (AFAPL-TR-77-80, AD-A051851.)
9. Hovel, H.J.: Solar Cells, Vol. II. Semiconductors and Semimetal, R.W. Willardson and A.C. Beer, eds., Academic Press, 1975, pp. 172-173.
10. Sharp, G.R.; et al.: Mass Study for Modular Approaches to a Solar Electric Propulsion Module. NASA TM X-3473, 1977.
11. Conway, E.J.; and Walker, G.H.: Radiation Damage in GaAs Solar Cells. Solar Cell High Efficiency and Radiation Damage, 1979. NASA CP-2097, 1979, pp. 201-207.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TP-1811		

4. Title and Subtitle
ANALYSIS OF COSTS OF GALLIUM ARSENIDE AND SILICON SOLAR ARRAYS FOR SPACE POWER APPLICATIONS

5. Report Date
March 1981

6. Performing Organization Code
506-55-72

7. Author(s)
Kent S. Jefferies

8. Performing Organization Report No.
E-536

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

10. Work Unit No.

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Technical Paper

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

A parametric analysis was performed to compare the costs of silicon and gallium arsenide arrays for Earth orbital missions. The missions included electric power in low Earth orbit (LEO), electric power in geosynchronous Earth orbit (GEO), and power for electric propulsion of a LEO-to-GEO orbit transfer mission. Inputs to the analysis for all missions included launch and purchase costs of the array. For the orbit transfer mission the launch and purchase costs of the electric propulsion system were added. Radiation flux as a function of altitude and radiation tolerance as a function of cell type were used to determine power degradation for each mission. Curves were generated that show the sensitivity of launch-array cost and total mission cost to a variety of input parameters for each mission. These parameters included mission duration, cover glass thickness, array specific cost, array specific mass, and solar cell efficiency. Solar concentration was considered, and the sensitivities of cost to concentration ratio, concentrator costs, and concentrator mass were also evaluated. Results of this study indicate that solar cell development should give a high priority to reducing array costs and that the development of low-cost, lightweight, solar concentrators should be pursued.

17. Key Words (Suggested by Author(s))
Gallium arsenides
Concentrators
Solar cells
Cost analysis
Silicon

18. Distribution Statement
Unclassified - unlimited
STAR Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	16	A02

* For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA-Langley, 1981

LIBRARY MATERIAL REQUEST

INSTRUCTIONS:

- *List only one Library Item on a form – PLEASE.*
- *For purchasing books or theses use Langley Form 125, "Purchase Request/Purchase Order."*
- *Obtain approval of Section Head or higher official for classified material.*

TO BE FILLED IN BY REQUESTER *(As appropriate)*

Document or Book Call Number *(If available)*

Title and Author/Editor

"Laminar flow airfoils" – SUBJECT

Report No. NASA TP 1811	Contract No.

Source

DDC No.	NTIS No.

Journal-Title

Article Title and Author, If Known

LIBRARY INTERNAL USE ONLY

- Order
- On Order
- L has hardcopy
- No Folder
- No Film
- Borrow
- Call In
- Reference
- Other:

LIBRARY ACTION