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# SOLAR-CELL PERFORMANCE AT HIGH TEMPERATURES

*by Jacob D. Broder, Harold E. Kautz,
Joseph Mandelkorn, Lawrence Schwartz,
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# SOLAR-CELL PERFORMANCE AT HIGH TEMPERATURES*

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## SUMMARY

Open-circuit voltage, curve power factor, and maximum power output as functions of temperature were measured for 1-, 10-, 20-, and 80-ohm-centimeter silicon cells. The results were compared with those for gallium arsenide solar cells and indicated that, for temperatures to 200° C, 1-ohm-centimeter silicon solar cells performed better than any other commercially available solar cells. One- and ten-ohm-centimeter bombarded silicon solar cells were also measured and compared at high temperatures. In the temperature range to 100° C, the 10-ohm-centimeter silicon cell was superior to the 1-ohm-centimeter cell after bombardment. For temperatures beyond 200° C and under high illumination intensities, gallium phosphide solar cells may prove useful.

## INTRODUCTION

Various space missions can be envisioned that would subject the solar cells of a space vehicle to temperatures higher than 75° C. Questions arise as to what performance to expect of silicon solar cells, and what, if any, substitute cells can be used to better advantage at these high temperatures.

In this report, the temperature behavior of unbombarded and bombarded silicon cells of various resistivities and unbombarded and bombarded gallium arsenide cells will be discussed and compared. The characteristics to be discussed are open-circuit voltage, maximum power output, and curve power factor, which is defined as the maximum power output divided by the product of the short-circuit current and the open-circuit voltage.

## SOLAR-CELL CHARACTERISTICS

Table I shows typical outer-space characteristics of unbombarded cells at 25° C. These are the values that can be achieved for n-on-p silicon solar cells of various resistivities. In going from 1-, to 10-, to 50-, to 100-ohm-centimeter cells, the open-circuit voltage decreases. The small increase in short-circuit current for 10-ohm-centimeter cells occurs because of the longer diffusion lengths in 10-ohm-centimeter cells. The short-circuit current remains

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TABLE I. - EQUIVALENT OUTER-SPACE CHARACTERISTICS

OF UNBOMBARDED CELLS AT 25° C

| Cell | Open-circuit voltage, v | Contact resistance, ohms | Short-circuit current per cm², ma/cm² | Maximum power output per cm², mw/cm² | Voltage at maximum power, v | Curve power factor, percent | Outer-space efficiency, percent |
|---|---|---|---|---|---|---|---|
| Gallium arsenide | 0.9 | 0.3 | 11 | 7.2 | 0.7 | 73 | 5.1 |
| | .9 | .3 | 16 | 10.0 | .7 | 70 | [a]7.1 |
| Silicon | | | | | | | |
| 1 ohm cm | 0.57 | 0.3 | 32 | 12.6 | 0.43 | 69 | 9.0 |
| 10 ohm cm | .54 | .3 | 36 | 14.0 | .44 | 72 | 10.0 |
| 50 ohm cm | .49 | .4 | 36 | 11.5 | .42 | 65 | 8.2 |
| 100 ohm cm | .43 | .7 | 36 | 8.5 | .3 | 55 | 6.0 |

[a]Manufacturer's quoted sunlight efficiency, 10.5 percent.

at this value for the higher resistivity cells, since processing reduces the diffusion lengths to approximately equal values.

The curve power factors of the 10-ohm-centimeter cells are better than those of 1-ohm-centimeter cells because junctions with better characteristics can be made in 10-ohm-centimeter material. As the resistivity increases, however, the maximum power output decreases because of the lower open-circuit voltage and the increasing bulk parasitic resistance. Maximum efficiencies are achieved for 10-ohm-centimeter cells.

Of the two categories of gallium arsenide cells in table I, the 5.1-percent-efficient cells were procured commercially, and the 7.1-percent-efficient cells were obtained through the courtesy of the U.S. Air Force, Wright Air Development Center. The efficiencies quoted are based on airplane measurements that agree with filter-wheel simulator measurements.

## UNBOMBARDED CELLS

Figure 1 shows the change in open-circuit voltage as a function of temperature for silicon solar cells of various resistivities. There is a 0.2 millivolt per °C difference between the temperature coefficients for open-circuit voltage for 1- and 10-ohm-centimeter cells, a negligible difference between the coefficients for 10- and 20-ohm-centimeter cells, and a significant difference of 0.6 millivolt per °C between the coefficients for 1- and 80-ohm-centimeter cells. Similar temperature coefficients of open-circuit voltage were obtained for solar cells doped to equivalent resistivities with either aluminum, gallium, indium, or gadolinium.

Another important factor in the temperature degradation of solar cells is the change in curve power factor with temperature, shown in figure 2. The curve power factor of 10-ohm-centimeter cells degrades faster than that of 1-ohm-centimeter cells, and that of 80-ohm-centimeter cells degrades most rapidly with increasing temperature. This decrease in curve power factor occurs be-

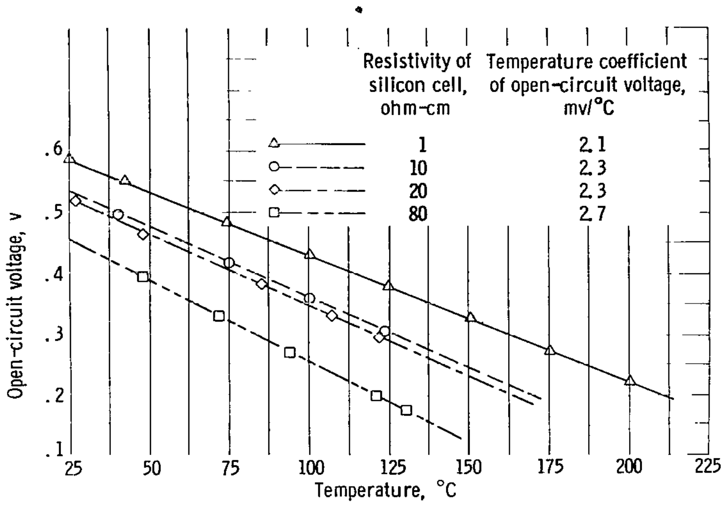


Figure 1. - Open-circuit voltage as function of temperature for silicon cells of various resistivities.

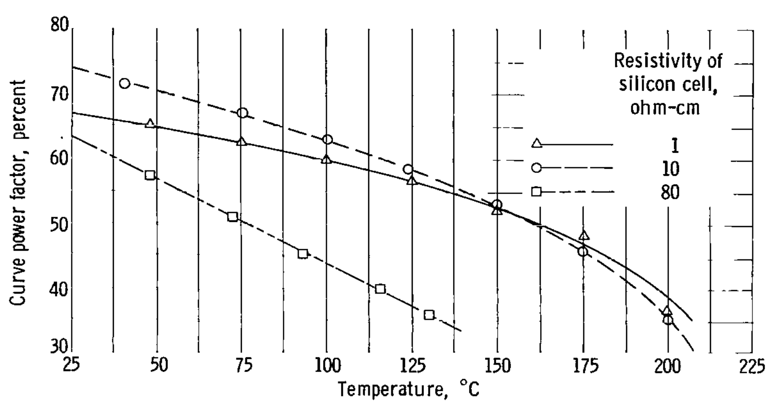


Figure 2. - Curve power factor as function of temperature for various silicon cells.

cause junction losses increase with increasing temperature.

The degradation of open-circuit voltage and of curve power factor leads to degradation of maximum power output, as shown in figure 3. For these measurements the short-circuit current is maintained constant for all temperatures at a value equivalent to the outer-space current at 25° C. A measure of the power degradation is indicated by the temperature at which the power falls to one-half that at 25° C and is given by the coefficient expressed as percent power lost per °C. As the resistivity of the base material is increased, this half-power point occurs at lower temperatures. For 1-ohm-centimeter cells, the half-power point occurs at about 135° C. For 10-ohm-centimeter cells it is about 20° C lower, and for 80-ohm-centimeter cells, it occurs below 100° C. The same values of half-power point have been found for silicon doped with materials other than boron (aluminum, gallium, indium, or gadolinium).

From these considerations it is apparent that the 1-ohm-centimeter cell would be the most usful for high-temperature applications.

## BOMBARDED CELLS

One- and ten-ohm-centimeter silicon cells were subjected to an electron bombardment of $1.5\times10^{16}$ 1-Mev electrons per square centimeter. The open-circuit voltages were measured at various temperatures below 100° C with the illumination level such that the short-circuit currents were equivalent to those the cells would have in outer space. There was no observable change in the temperature coefficient of open-circuit voltage after this level of bombardment. The same was true for proton-bombarded cells bombarded with a dose of $3.9\times10^{12}$ 10-Mev protons per square centimter, which is equivalent in damage production to approximately $1\times10^{16}$ 1-Mev electrons per square centimeter.

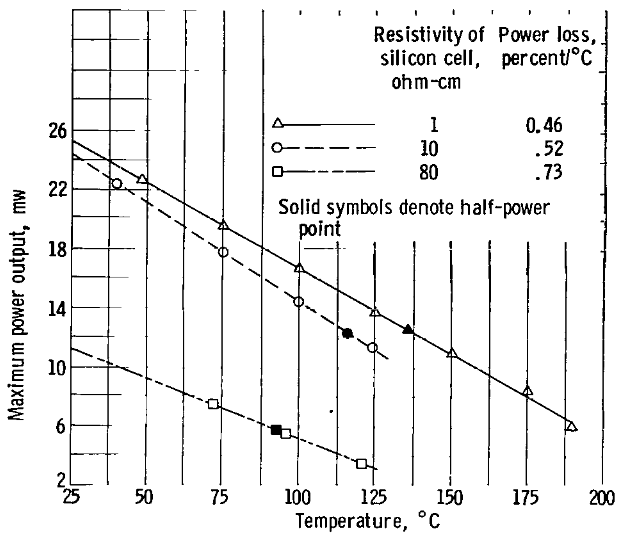


Figure 3. - Maximum power output as function of temperature for silicon cells. Illumination equivalent to that of outer-space.

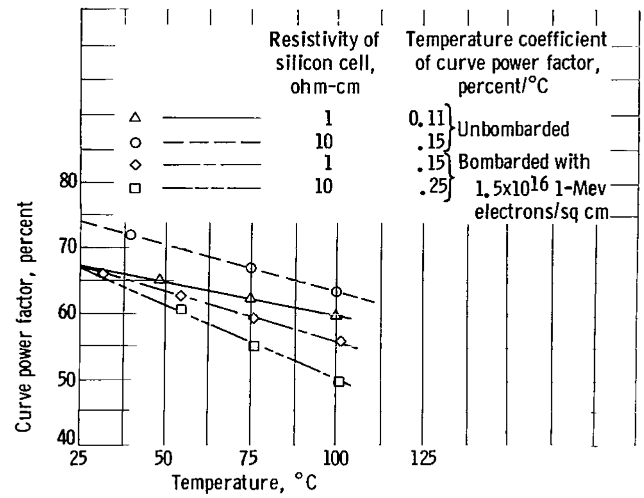


Figure 4. - Curve power factor as function of temperature for unbombarded and bombarded silicon cells.

Figure 4 is a plot of curve power factor as a function of temperature for 1- and 10-ohm-centimeter unbombarded and bombarded cells. Since the plots are straight lines in the temperature range of figure 4, a temperature coefficient of curve power factor can be determined. There is a significant change in the rate of decrease of the curve power factor with temperature for these electron-bombarded cells. The same behavior is also found for proton-bombarded cells.

Changes in the maximum power output of bombarded cells also depend on the variation of short-circuit current with temperature. The short-circuit current increases with temperature at a rate of 0.2 percent per $^{\circ}$C for heavily bombarded cells (data from H. K. Gummel of Bell Telephone Laboratories). Based on Lewis measurements and calculations, the half-power point and temperature coefficient of power output for bombarded cells will be similar to those for unbombarded cells.

The power supplies of satellites are usually designed for constant-voltage operation. Therefore, maximum power output of bombarded solar cells was studied as a function of temperature for various constant-voltage conditions. Figure 5 shows the power output for 1- and 10-ohm-centimeter electron-bombarded cells. For maximum power output at 55$^{\circ}$ C, the voltage for constant-voltage operation should be 0.3 volt for 1-ohm-centimeter cells, and 0.25 volt for 10-ohm-centimeter cells. For operation at 75$^{\circ}$ C, the voltages are 0.25 volt for 1-ohm-centimeter cells and 0.2 volt for 10-ohm-centimeter cells. Between 75$^{\circ}$ and 100$^{\circ}$ C maximum power output under constant-voltage operating conditions is attained by operating 10-ohm-centimeter cells at 0.15 volt. The power output of 10-ohm-centimeter cells at this voltage is still higher than that available from 1-ohm-centimeter cells operated at 0.2 volt in this temperature range. The optimum voltages for maximizing power output in the constant-voltage condition depend on the operating temperature and the bombardment dose. In all cases, 10-ohm-centimeter cells maintain considerably higher power output than do 1-ohm-centimeter cells, as shown in figure 5.

## SILICON CELLS COMPARED WITH GALLIUM ARSENIDE CELLS

For temperatures above 150° C, the 1-ohm-centimeter cell is preferable to the 10-ohm-centimeter cell. Gallium arsenide solar cells have also been proposed for operation between 150° to 200° C. Figure 6 compares the open-circuit voltage degradation with temperature for gallium arsenide cells and 1-ohm-centimeter silicon solar cells. Gallium arsenide cells have a temperature coefficient of open-circuit voltage of 2.5 millivolt per °C as compared with 2.1 millivolt per °C for 1-ohm-centimeter silicon cells. Because of the initially higher open-circuit voltage of the gallium arsenide cell, however, its open-circuit voltage at 200° C is 0.43 volt as compared with 0.22 volt for the silicon cell. It should be realized that the ultimate limitation in the use of cells made from high-energy-gap simiconductor materials is the temperature at which the open-circuit voltage approaches zero. If the curve for gallium arsenide cells is extrapolated, the voltage will fall to zero at a temperature of about 375° C. This should be contrasted with reported open-circuit voltages of 0.4 volt for gallium phosphide experimental cells at 350° C (ref. 1).

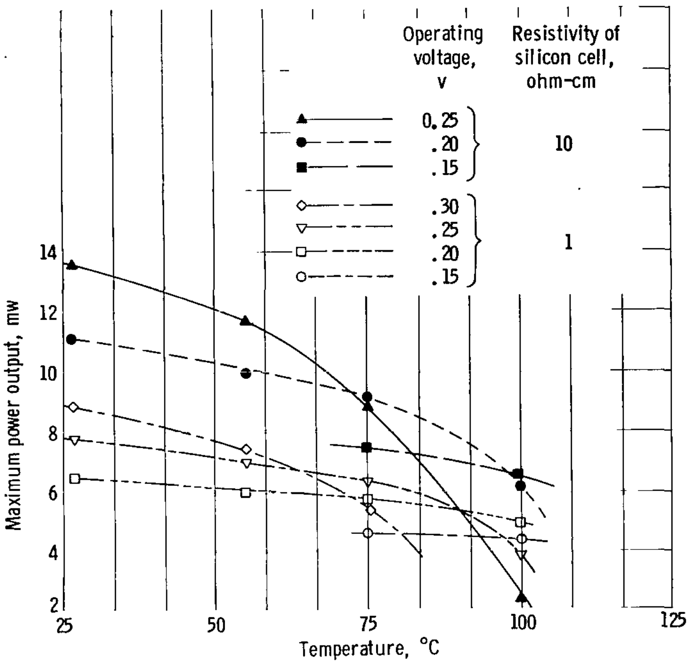


Figure 5. - Maximum power output for constant-voltage operation as function of temperature. Cells bombarded with $1.5\times10^{16}$ 1-Mev electrons per square centimeter; illumination equivalent to that of outer space.

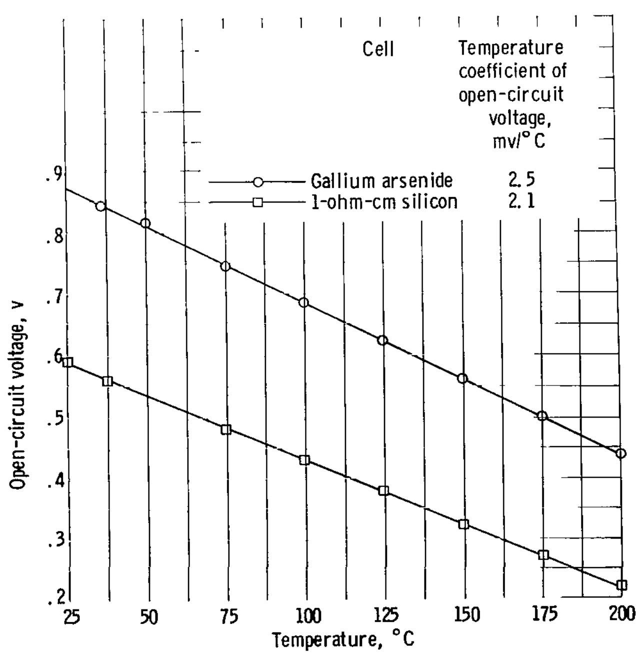


Figure 6. - Open-circuit voltage as function of temperature.

Figure 7 is a plot of curve power factor for 1-ohm-centimeter silicon cells and gallium arsenide cells. In general, the curve power factor of silicon cells decreases more rapidly than that of gallium arsenide cells, the decrease becoming more rapid at temperatures above 125° C.

The variation of maximum power output with temperature is shown in figure 8 for both high- and low-efficiency gallium arsenide cells

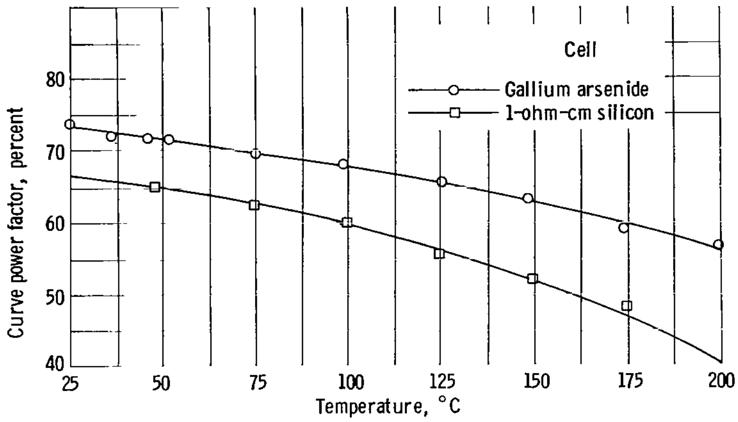

Figure 7. - Curve power factor as function of temperature for gallium arsenide and 1-ohm-centimeter silicon cells.

and for a 10-percent-efficient, 1-ohm-centimeter silicon cell. The half-power point occurs at about 165° C for gallium arsenide cells as compared with 135° C for silicon cells. This is reflected in the lower percent power lost for gallium arsenide, 0.35 percent per °C, as compared with 0.46 percent per °C for silicon. Since the short-circuit current of the silicon cell under outer-space illumination is twice that of the high-efficiency gallium arsenide cell, both cells have the same power output at 175° C. At 200° C there is a 2-milliwatt difference in power output. The power output of the 1-ohm-centimeter silicon cell, however, equals that of the commercially available, lower efficiency gallium arsenide cell at 200° C. The choice of either silicon or gallium arsenide cells for 200° C operation depends on the factors of reliability, availability, cost, and minimum power output requirement. Based on these considerations, the commercial 1-ohm-centimeter silicon cells are not surpassed for operation at 200° C by any other type of commercial cell available.

Figure 9 is a plot of the product of open-circuit voltage and short-circuit current as a function of temperature for high-efficiency gallium arsenide cells and 1-ohm-centimeter silicon cells. The significance of this plot is that, if the curve power factor of the 1-ohm-centimeter silicon cell can be raised sufficiently at room temperature, its power output will be greater than that of the high-efficiency gallium arsenide cell for all temperatures up to and including 200° C. Recent information on the effects of impurities indicates that this improvement may now be possible.

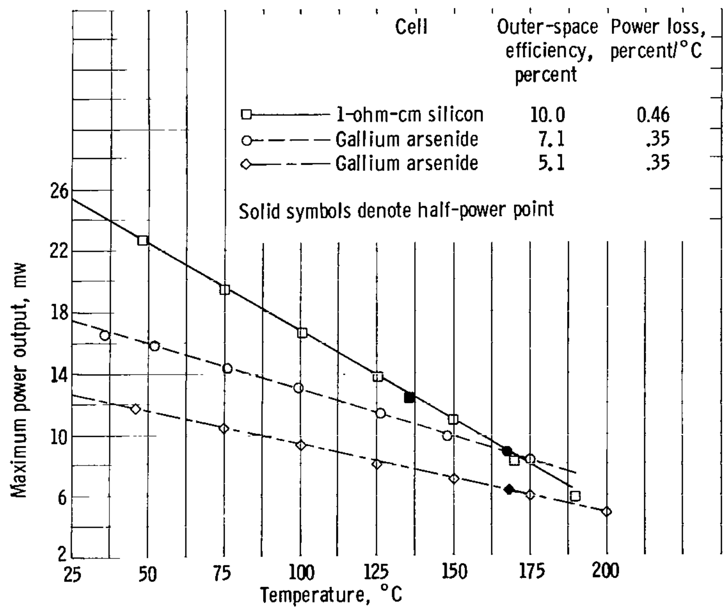

Figure 8. - Comparison of maximum power output as function of temperature for gallium arsenide cells and 1-ohm-centimeter silicon cells. Illumination equivalent to that of outer-space.

Just as for silicon solar cells, gallium arsenide cells bombarded to a dose of $3.9\times10^{12}$ 10-Mev protons per square centimeter show no change in the temperature coefficient of open-circuit voltage. Curve power factor degradation increases after bombardment in a manner similar to that for silicon. A temperature coefficient of curve

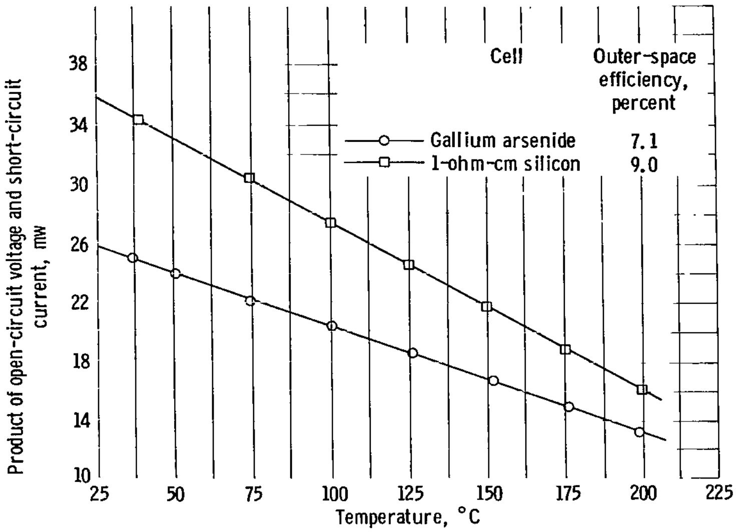


Figure 9. - Product of open-circuit voltage and short-circuit current as function of temperature. Illumination equivalent to that of outer space; cell area, 1 by 2 centimeters.

power factor of 0.12 percent per °C in the temperature range from 50° to 100° C is found for bombarded cells as compared with 0.10 percent per °C in the same temperature range for unbombarded cells.

## GALLIUM PHOSPHIDE CELLS

The performance of any available solar cell is marginal at 200° C. The gallium phosphide cell is therefore being considered for use in the range above 200° C.

The current status of gallium phosphide solar cells has been mentioned in a previous paper (ref. 1); however, it should be pointed out that, if the anticipated open-circuit voltage of 1.5 volts can be achieved, operation of these cells to temperatures of 500° C would be possible. The low short-circuit currents of gallium phosphide cells would not necessarily eliminate them from consideration, since these cells would be expected to operate where solar intensities are many times those on Earth.

## CONCLUDING REMARKS

The results of this report indicate that 1-ohm-centimeter silicon solar cells are preferred to any commercially available gallium arsenide solar cells for use at temperatures to 200° C. By proper doping, 1-ohm-centimeter silicon cells can also outperform the higher efficiency, but limited-in-production, gallium arsenide cells. For maximum power output under radiation damage conditions at temperatures to 100° C, the radiation damage resistant 10-ohm-centimeter silicon solar cell is preferred over the 1-ohm-centimeter cell. For applications at temperatures above 200° C and under high light intensities, gallium phosphide solar cells may be useful.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 22, 1964

## REFERENCE

1. Groves, W. O., and Epstein, Arnold S.: Single Crystal Gallium Phosphide Solar Cells. Proc. Fourth Annual Photovoltaic Specialist's Conf., Inter. Agency Advanced Power Group, IEEE, AIAA, and NASA Lewis, Cleveland (Ohio), June 2-3, 1964.

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