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# Indium Phosphide Solar Cells—Status and Prospects for Use in Space

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# INDIUM PHOSPHIDE SOLAR CELLS - STATUS AND PROSPECTS FOR USE IN SPACE

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## ABSTRACT

The current status of indium phosphide cell research is reviewed and state of the art efficiencies compared to those of GaAs and Si. It is shown that the radiation resistance of InP cells is superior to that of either GaAs or Si under 1 MeV electron and 10 MeV proton irradiation. Using lightweight blanket technology, a SEP array structure and projected cell efficiencies, array specific powers are obtained for all three cell types. Array performance is calculated as a function of time in orbit. The results indicate that arrays using InP cells can outperform those using GaAs or Si in orbits where radiation is a significant cell degradation factor. It is concluded that InP solar cells are excellent prospects for future use in the space radiation environment.

IN THE PAST, indium phosphide solar cells have been of interest largely because of their potential for terrestrial applications. Research activity was primarily directed toward structures such as n-type indium tin oxide on p-type InP (n-ITO/p-InP) (1) and n-type CdS on p-type InP (n-CdS/p-InP) (2). Recently, however, it has been demonstrated that monolithic indium phosphide homojunction cells have properties which make them candidates for use in the space radiation environments (3,4). For example, it has been shown that InP cells have significantly more radiation resistance than either GaAs or silicon cells under 1 MeV electron and 10 MeV proton irradations (3,4). In addition it has been observed that exposure to light tends to partially remove radiation induced degradation in InP (5). Furthermore the degradation can be removed by annealing at the relatively low temperature of 115 °C. Also since the energy gap of InP (1.35 eV) at room temperature lies between that of GaAs and Si it has the potential of achieving AMO efficiencies greater than silicon and just below that of gallium arsenide. Thus, the excellent radiation resistance and annealibility coupled with potential for high efficiency introduce the possibility that InP can supply significantly more end of life array output power than either GaAs or Si in the space radiation environment. In this paper, we review the status of InP solar cell research and address their potential advantages for use in space.

## BACKGROUND

Historically, the first InP cell, reported in 1959 was an n/p homojunction whose efficiency was approximately 2 percent (8). This result is not surprising, considering the state of the art at that time. Since then, there has been a modest amount of research, much of it concerned with heteroface structures such as ITO/InP and CdS/InP. The choice of CdS follows from its lattice constant (5.850 Å) which is close to that of InP (5.869 Å). Furthermore, since CdS has a band gap of 2.41 eV, a major portion of the solar spectrum is transmitted to the InP. Active area efficiencies as high as 15 percent at air mass 2 have been reported for the n-CdS/p-InP heteroface cell (9). With respect to ITO/InP, the highest efficiency cells have been produced by Coutts and his coworkers (10). Total area efficiencies of 16.2 percent have been reported at AM 1.5 and light intensities of 100 mW/cm$^2$. These latter cells were produced by RF sputter deposition of ITO onto a p-type substrate (10). Rather than being a heteroface ITO/InP cell, it is believed that the cell is an n/p buried homojunction resulting from diffusion of tin into the zinc doped p-type substrate during the sputter deposition process (10). Prior to this, a monolithic InP homojunction cell with reasonable efficiencies was produced by Turner and Fan (11). These latter cells were $n^+pp^+$ and were produced by liquid phase epitaxy with total area AM1 efficiencies as high as 15 percent. In addition to the preceding, MIS Schottky barrier cells have been fabricated on p-type InP with AM2 efficiencies of 14.5 percent (12).

No air mass zero efficiencies or radiation damage data were reported for the preceding cells. This follows from a primary interest in terrestrial applications. Recently, however, radiation damage data were reported for n/p homojunction cells with excellent results (3,4). These latter cells have achieved AM 1.5 efficiencies of 18.5 percent (13), and have exhibited radiation resistance superior to both GaAs and silicon under both electron and proton irradiations (3,4). The AMO efficiencies of these n/p homojunction cells have been determined at NASA Lewis (Table 1). Figures 1 and 2 show the I-V curve and spectral response of the highest efficiency cell. Measurements for the various cell types, from other sources, are summarized in Table 2.

The wide variety of solar simulators used and the propensity of some investigators to use active rather than total areas sometimes makes it difficult to compare cell performance. We have found, for example that in converting air mass 1.5 data to air mass zero, cell efficiencies are reduced by 25 percent. Since, for space applications, our interest lies in air mass zero, total area measurements, all of the cell parameters quoted in the remainder of this report will adhere to these conditions.

## COMPARISON WITH OTHER CELLS

As mentioned previously, the band gap of InP lies between that of Si and GaAs, hence its theoretical efficiency should lie between the efficiencies of these two cells. This can be seen in Fig. 3 where we have used Loferski's calculation of efficiency as a function of band gap (7). The figure also includes the highest efficiencies achieved to date for cells shown, i.e., 21 percent for GaAs (14), and 13.6 percent for InP from Table 1. The two values shown for silicon are 18 percent for the low resistivity

(0.2 Ω-cm) thick cell (15) and 14.1 percent for a 10 Ω-cm, 2 mil silicon cell (16). Because of its thickness and low resistivity, the higher efficiency silicon cell exhibits poor radiation resistance compared to the 2 mil, 10 Ω-cm cell. This makes the higher efficiency cell a doubtful candidate for use in orbits where radiation induced degradation is a significant loss factor. Thus, in considering performance in the space radiation environment, the 2 mil silicon cell is preferred because of its inherently greater radiation resistance.

The fact that InP has the lowest achieved efficiency to date should not discourage continued R&D on this cell. Silicon cells have reached their present state after 30 yr of R&D while the present GaAs cells have been under development for 16 yr. On the other hand, the homojunction n/p cell has been the object of 6 yr of extremely low keyed R&D. With increased effort, it is believed that InP cells will achieve efficiencies in the vicinity of 20 percent.

## RADIATION EFFECTS

The performance of InP, GaAs and Si under 1 MeV electron irradiation is shown in Fig. 4, where the comparison is made on the basis of normalized cell maximum power. In this figure, the InP data is obtained from Ref. 3, GaAs from Ref. 17, and 2 mil silicon from the radiation handbook (18). The figure clearly shows the superior radiation resistance of InP over the remaining cells. Similar data for 10 MeV proton irradiations are shown in Fig. 5 where the InP data is obtained from Ref. 4, the GaAs data from Ref. 19 and the 2 mil silicon date from previously unreported data obtained at NASA Lewis. From the figure, under 10 MeV proton irraditions, the InP cells exhibit radiation resistance which is superior to the remaining cell types.

The data of Fig. 4, for InP, includes the effects of incident light on cell performance, an effect which is illustrated in Fig. 6 (5). The increased output under illumination follows from the cell recovery, due to minority carrier injection, which has been observed under forward bias conditions (20). Since the effect increases with light intensity one would expect greater recovery at air mass zero than was observed in Ref. 5.

The recovery noted under minority carrier injection is one form of annealing. Additional recovery, by heating is also observed at a conveniently low temperature (Fig. 7) (6). In this case, complete recovery at 115 °C is observed after a radiation dose which has reduced cell output essentially to zero. This temperature is low enough so that no irreversible damage to array components would occur if thermal annealing in space were attempted. If thermal annealing in space is impractical, annealing could be accomplished by passing current through the cell under forward bias conditions. On the other hand, thermal annealing becomes practical in space if the cell were used under concentration, an application where the increased light intensity results in cell heating. In this case, the heating could be used to advantage in keeping the cell at a temperature where complete recovery is obtained. Thus, thermal annealing combined with the additional shielding afforded by the concentrator structure could conceivably result in a cell showing no degradation in the space radiation environment.

## PROJECTED PERFORMANCE IN SPACE

Considering the present state of the art, GaAs cells would outperform InP in the space radiation environment. However, with an increased R&D effort, InP solar cells can reasonably be expected to achieve efficiencies well above those exhibited by the present day cells. By analogy with the progress attained for GaAs, we assume a projected efficiency of 20 percent for InP under research conditions in the laboratory. Under these conditions, GaAs cells have already achieved AMO efficiencies of 21 percent (14). Noting that these efficiencies are 2 percent below the theoretical values shown in Fig. 3, we assume a projected efficiency of 17 percent for the 2 mil silicon cell. Since these are the projected efficiencies of the best laboratory cells, one anticipates that lower efficiencies will be achieved in production. It is our intent to compare the cells in a solar array where the cells are fabricated on a production rather than a laboratory basis. Hence, in comparing the cells in the space radiation environment we assume projected production efficiencies of 19 percent for GaAs, 18 percent for InP and 15 percent for Si.

As a basis for comparison, we use array specific power, where

$$P_a = \frac{(\eta_T \times I \times D)}{M_{sa}} \qquad (1)$$

where $P_a$ is array specific power in W/kg, $\eta_T$ is cell efficiency at the temperature T, I is solar intensity at AMO in W/M$^2$, D is a derating factor which accounts for losses due to packing factor, cell mismatch, diode losses etc. and $M_{sa}$ is array specific mass in kg/M$^2$. Using a lightweight solar cell blanket and a SEP structure (21), we obtain the BOL array specific powers shown in Table 3. In computing these results, we used in all cases, 2 mil cell thickness, 10 mil cover glass, a packing factor of 0.9, a derating factor of 0.8 and 1372 W/m$^2$ for the AMO solar intensity. Cell efficiencies at 60 °C were computed using the temperature dependency factors $-9.1\times10^{-2}$ for Si, $-4.4\times10^{-2}$ for GaAs and $-6.3\times10^{-2}$ mW/cm$^2$ °C for InP.

For silicon, estimates of expected performance in space environments are obtained in the usual manner, using the 1 MeV electron damage equivalent fluences from the radiation handbook (18). Although a beginning has been made in obtaining similar 1 MeV damage equivalences for GaAs, the data is incomplete inasmuch as only proton irradiation effects have been considered (22). In the case of InP there is no damage equivalence data available. In view of this, in estimating the effects of radiation on InP and GaAs, for specific space orbits, we use the silicon 1 MeV damage equivalent fluences. This is admittedly an approximation. However, considering the results shown in Figs. 4 and 5, we assume that this procedure yields an upper limit for the 1 MeV electron damage equivalent fluences of these latter two cell types. The results of these calculations, at temperatures of 60 °C for geosynchronous orbit, a mid altitude orbit at 0 °C inclination and an altitude of 6000 NM and a polar orbit at 800 NM are shown in Figs. 8 to 10, respectively. These orbits were chosen using the criterion that radiation induced degradation is a significant loss mechanism. In each case, the projected GaAs array specific power is highest at BOL. However with increasing time in orbit, the projected InP array specific power becomes significantly greater than the arrays containing either GaAs or Si.

## DISCUSSION

The preceding approximate calculations indicate the advantage inherent in using fully developed indium phosphide solar cells in space environments where radiation induced degradation is a significant loss factor. This is dependent on attaining higher efficiencies than those presently attained. This can only be accomplished through an increased R D effort such as the one initiated by NASA Lewis. Initial results from this program are encouraging. For example; consider the initial results, from the RPI group, shown in Table 1 (23). Experimental evidence indicates that InP cell efficiencies increase with decreasing base dopant concentrations reaching a maximum at about $5x10^{15}/cm^3$ (24). Hence, judging solely by base dopant concentration, the cell in Table 1 with concentration of $4.6x10^{16}$ should have an efficiency less than that for the cell with $10^{16}/cm^3$ concentration. However, the reverse is true. In this respect, it is noted that the Ibaraki cells are fabricated by a closed tube diffusion process while the RPI cells are fabricated by open tube diffusion (23). It is anticipated that cells processed in the latter program using base dopant concentrations close to the optimum will yield efficiencies exceeding those shown in Table 1.

In addition to the need for increased efficiencies, cost reduction is an important factor. At this stage, it is difficult, if not impossible to estimate ultimate cell costs. However, past experience indicates that, with increased volume, costs will decrease. However, when used in concentrators, cell cost is a secondary factor. As mentioned previously, this could result in a cell which maintains its BOL efficiency in the space radiation environment.

In conclusion, it may be stated that the prospects for use of InP, in the space radiation environment, are excellent. At present there appears to be no fundamental barrier to the attainment of efficiencies significantly higher than those currently attained.

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Table 1 - Air Mass Zero InP Cell Parameters-n/p Homojunction Cells[a]

| Base dopant concentrations, cm$^{-3}$ | Efficiency,[d] percent | Voc, mV | Jsc, ma/cm$^2$ | FF, percent |
|---|---|---|---|---|
| [b]4x$10^5$ | 13.6 | 826 | 25.8 | 81.7 |
| [b]$10^{16}$ | 11.4 | 818 | 24.5 | 78 |
| [b]$10^{17}$ | 10.1 | 812 | 22.6 | 78 |
| [c]4.6x1016 | 12.9 | 815 | 26.3 | 82.6 |

[a] Measurements performed at NASA Lewis.
[b] Cells obtained from Ibaraki, ECL-Japan.
[c] Cells obtained from S. Ghandi (RPI), Ref. 23.
[d] Efficiencies based on total cell area.

Table 2 - InP Cell Parameters Measured at Other Than Air Mass Zero

| Cell type | Source | Air mass | Efficiency,[a] percent | Voc, mV | Jsc[a] ma/cm$^2$ | FF, percent |
|---|---|---|---|---|---|---|
| n/p homojunction | Ibaraki ECL | 1.5 | [b]18.6 | 833 | 27.7 | 81 |
| ITO/InP (n/p) | Ref. 10 | 1 | 15.8 | 768 | 26.9 | 76.7 |
|  |  | 1.5 | [b]16.2 |  |  |  |
| n-CdS/p-InP | Ref. 9 | 2 | [c]15 | 780 | 18.7 | 73.5 |
| $n^+/p/p^+$ | Ref. 11 | 1 | 15 | 780 | 26.5 | 71.5 |
| MIS | Ref. 12 | 2 | 14.5 | 739 | 17.8 | 79 |

[a] Efficiencies and short circuit currents based on total cell area except when otherwise noted.
[b] Light intensity = 100 mW/cm$^2$.
[c] Based on active area.

Table 3 - Projected Array Specific Powers at BOL

| Cell | Projected BOL cell efficiencies |  | Projected BOL array spec power,[a] W/kg |  |
|---|---|---|---|---|
|  | 25 °C | 60 °C | 25 °C | 60 °C |
| InP | 18 | 16.4 | 126 | 115 |
| Gas | 19 | 17.9 | 131 | 123 |
| Si | 15 | 12.7 | 113 | 96 |

[a] 2 mil cell, 10 mil cover glass.

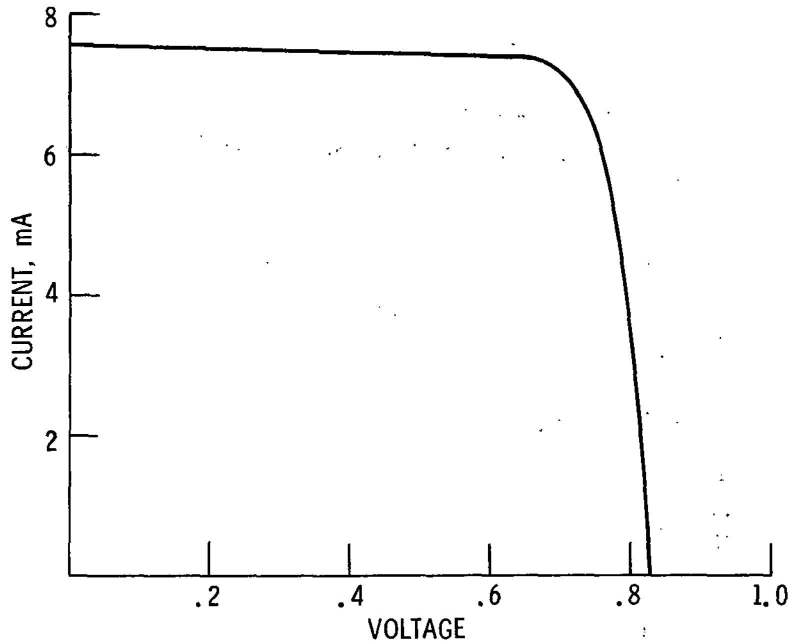

Figure 1. - I-V curve of InP cell.

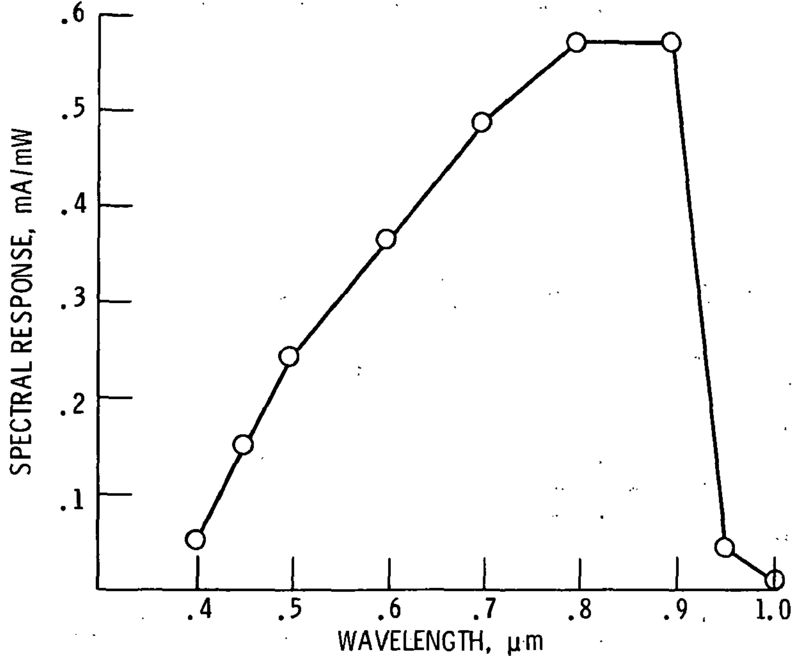

Figure 2. - Spectral response of InP cell.

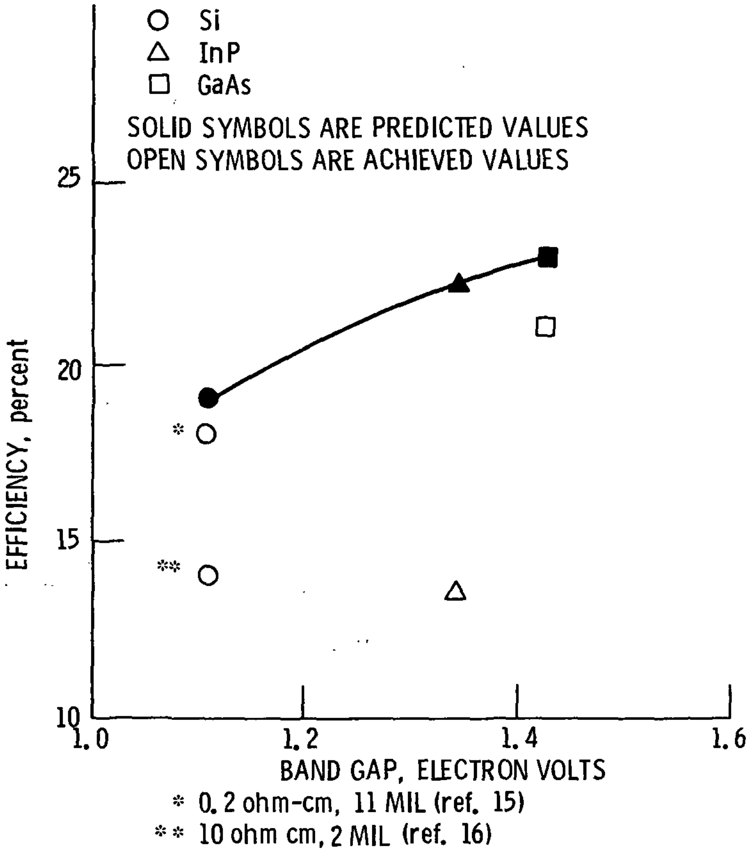

Figure 3. - Predicted and achieved AM0 efficiencies.

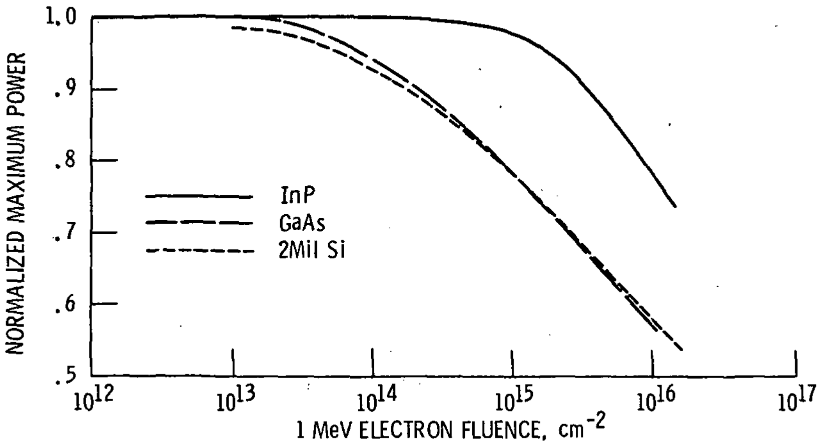

Figure 4. - Normalized maximum power versus 1 MeV Electron Fluence.

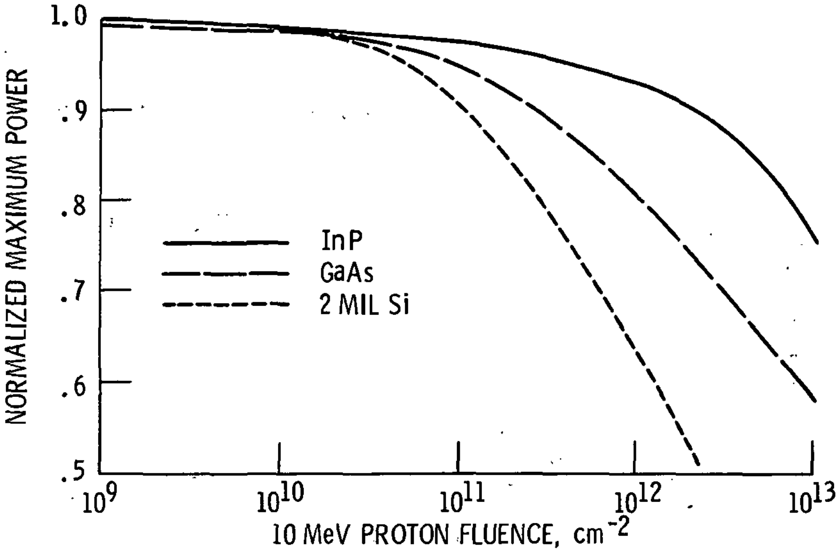

Figure 5. - Normalized maximum power versus 10 MeV Proton Fluence.

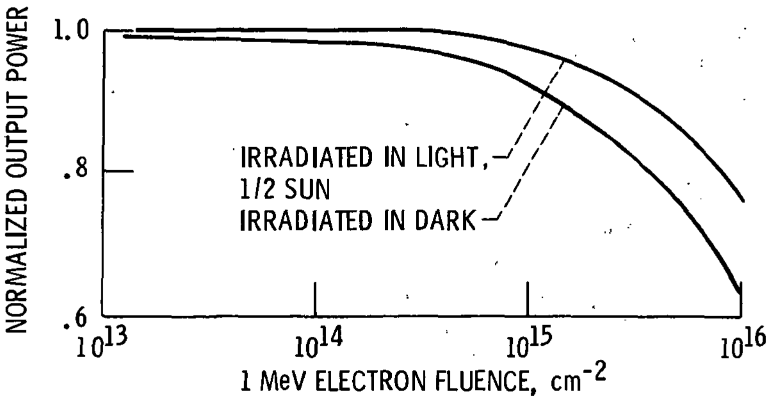

Figure 6. - Radiation damage removal in InP by incident light.

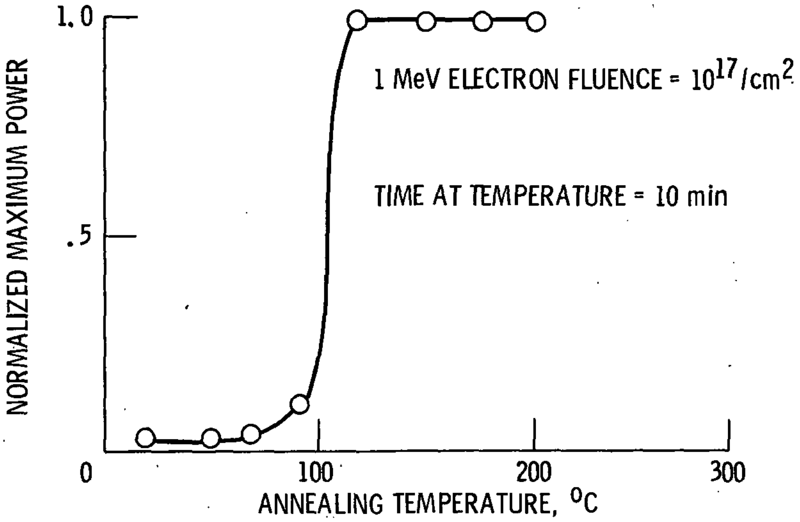

Figure 7. - Radiation damage removal in InP by low temperature heating.

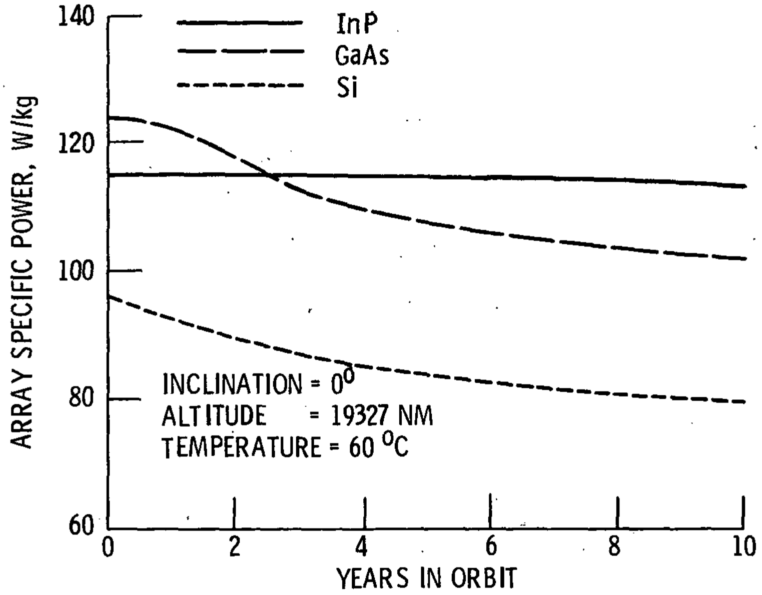

Figure 8. - Array specific power versus time in orbit.

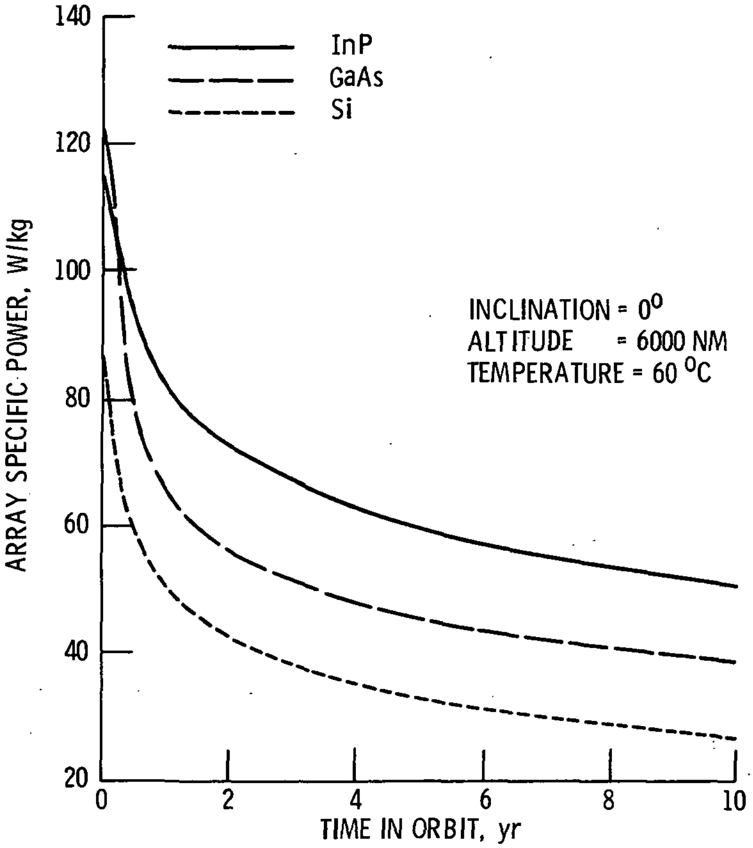

Figure 9. - Array specific power versus time in orbit.

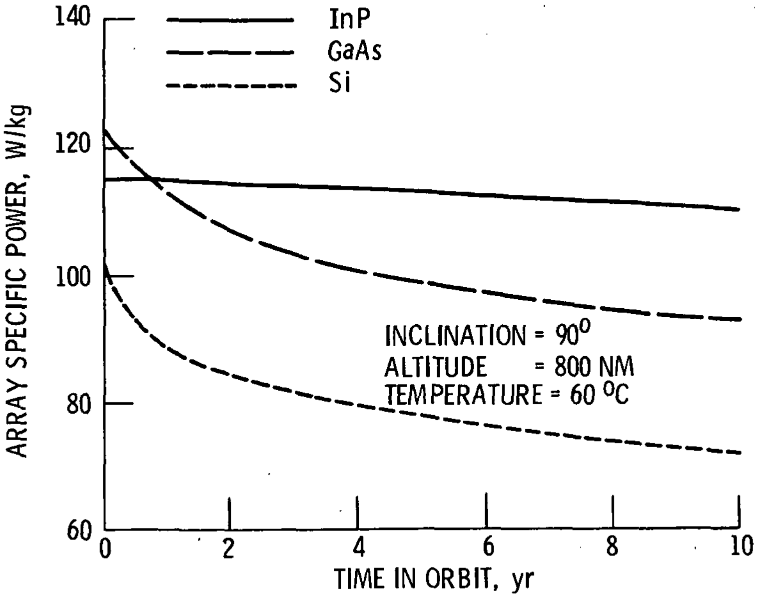

Figure 10. - Array specific power versus time in orbit.

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The current status of indium phosphide cell research is reviewed and state of the art efficiencies compared to those of GaAs and Si. It is shown that the radiation resistance of InP cells is superior to that of either GaAs or Si under 1 MeV electron and 10 MeV proton irradiation. Using lightweight blanket technology, a SEP array structure and projected cell efficiencies, array specific powers are obtained for all three cell types. Array performance is calculated as a function of time in orbit. The results indicate that arrays using InP cells can outperform those using GaAs or Si in orbits where radiation is a significant cell degradation factor. It is concluded that InP solar cells are excellent prospects for future use in the space radiation environment.

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