

HIGH CONCENTRATING GaAs CELL OPERATION USING OPTICAL WAVEGUIDE SOLAR ENERGY SYSTEM¹

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ABSTRACT

This paper discusses the results of the concentrating photovoltaic (CPV) cell experiments conducted with the Optical Waveguide (OW) Solar Energy System. The high concentration GaAs cells developed by Research Triangle Institute (RTI) were combined with the OW system in a "fiber-on-cell" configuration. The cells' performance was tested up to a solar concentration of 327. Detailed V-I characteristics, power density and efficiency data were collected. It was shown that the CPV cells combined with the OW solar energy system will be an effective electric power generation device.

OPTICAL WAVEGUIDE (OW) SOLAR ENERGY SYSTEM

In the OW Solar Energy System, solar radiation is collected by the concentrator which transfers the concentrated solar power to the OW transmission line consisting of low-loss optical fibers. The OW transmission line transmits the high intensity solar radiation to the thermal reactor for thermochemical material processing. By making use of an efficient OW transmission line, solar energy can be utilized for material processing not possible with conventional solar power systems. In the NASA program which Physical Sciences Inc. (PSI) completed recently, a ground test model of the OW solar energy system was developed and tested for performance characterization (1). A schematic representation of the system is given in Figure 1. The ground test model consists of a concentrator array, the OW transmission line, and the solar thermal reactor. A photo of the ground test model is given in Figure 2.

OPTICAL WAVEGUIDE PHOTOVOLTAIC POWER GENERATION EXPERIMENT

One of the important capabilities of the OW System developed in this program is that it can generate electric power when it is not used for material processing. A concentrating CPV is an ideal device for the optical waveguide system because the highly concentrated solar radiation can be effectively coupled to the CPV cells as shown in Figure 3. The concentrated solar radiation is defocused at the end of the optical fiber to provide optimum radiation intensities for the CPV cell. This "fiber-on-cell" configuration allows the small scale, high concentration CPV to operate at high efficiencies. Another important advantage of this power generation concept is that the quantity of the photovoltaic (PV) cells can be reduced significantly, allowing use of more expensive and efficient PV cells for the power generation system. The purpose of this experiment is to

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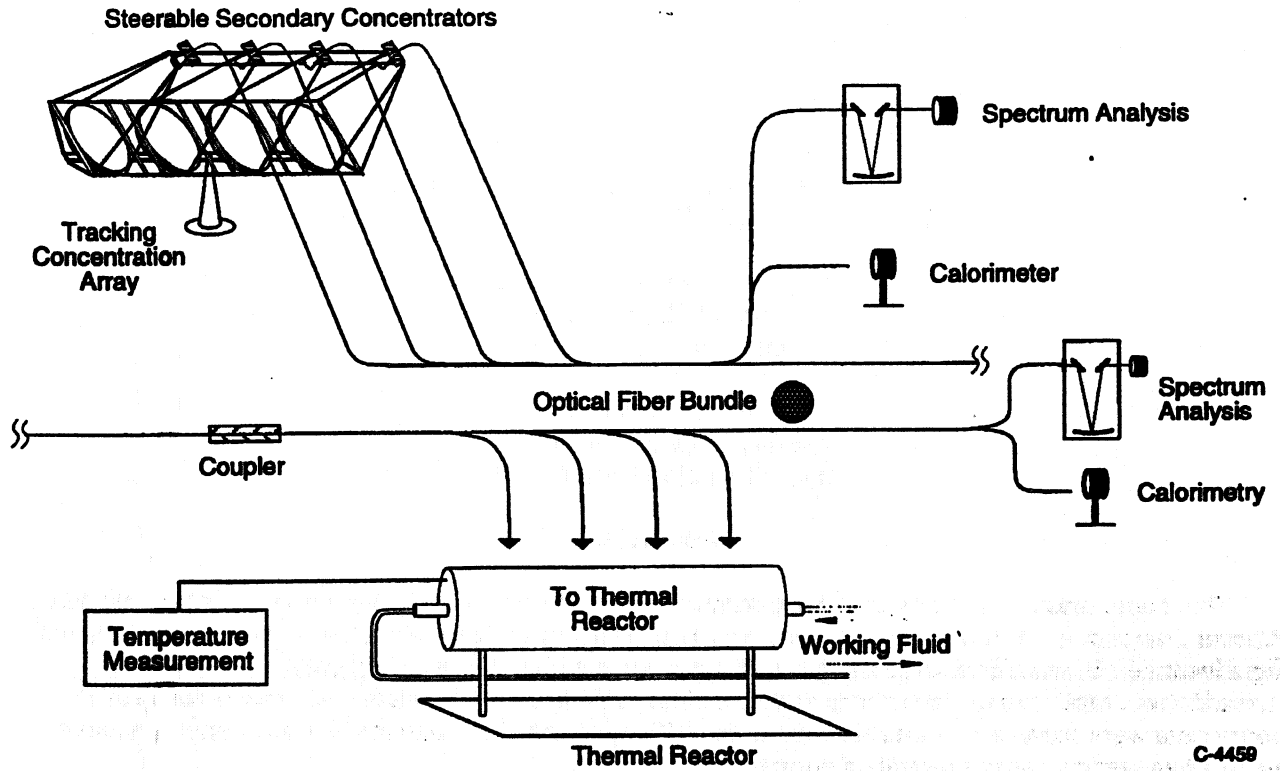


Figure 1. Schematic representation of the subscale ground test model of the OW solar energy system.

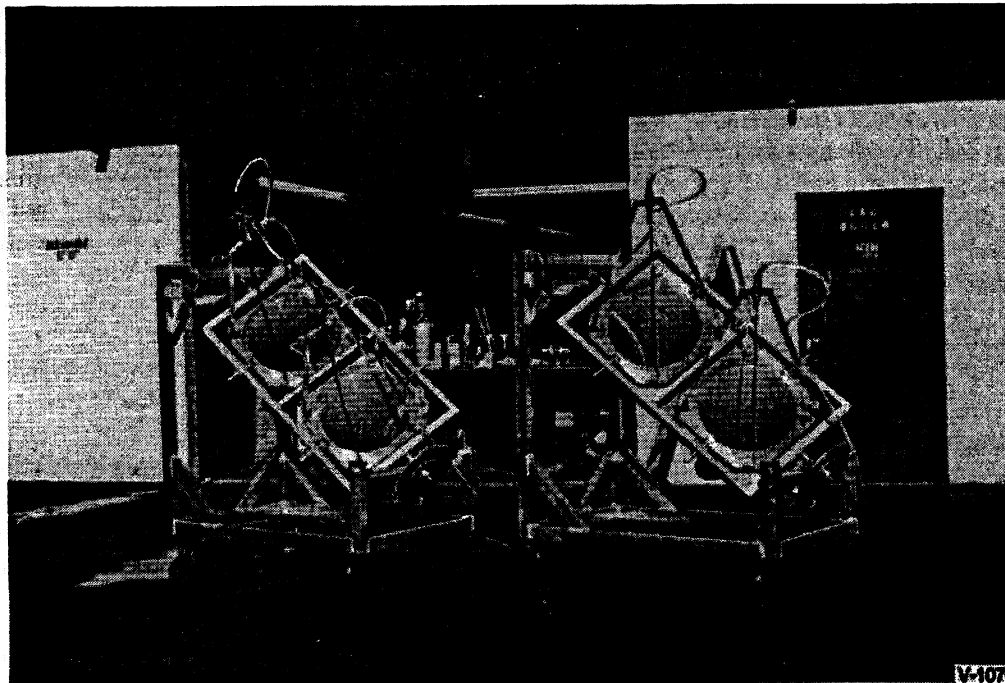
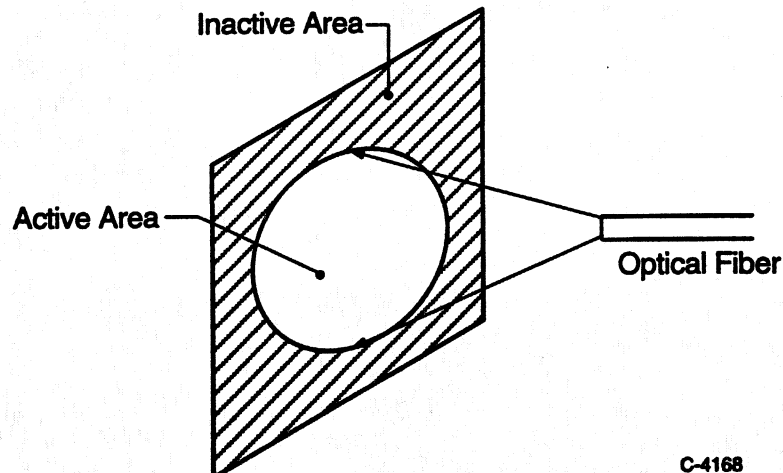


Figure 2. Photograph of the subscale ground test model of the OW solar energy system.



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Figure 3. Fiber-on-cell coupling of optical fiber and concentrating photovoltaic cell.

demonstrate the feasibility of the OW photovoltaic power generation, and to identify technology issues associated with the power generation system.

Photovoltaic Cell (PV) Characteristics

The PV cell used in the present experiment was the GaAs cell prepared by Dr. Michael L. Timmons, Semiconductor Materials Research Department, Research Triangle Institute (RTI). The GaAs cell (about 0.5×0.5 cm in size) has a circular aperture area of 0.16 cm^2 . With the electric contact grid partially blocking the front surface of the cell, the active area becomes 0.14 cm^2 . The cell has p-on-n polarity with the back side connected to the substrate acting as ground or negative potential. Positive voltage is produced at the top surface. Figure 4 shows a photograph of the cell soldered on a copper plate. This cell, when illuminated with 1-sun AM0 Xe-lamp solar simulator, produces a short circuit current of 200 mA, the open circuit voltage being 1.1 V. The fill factor for the cells are greater than 0.8. The efficiency of the cell under the 40 ~ 50 suns AM0 solar simulator light was measured to be 16% based on the aperture area (0.16 cm^2), and 18.5% based on the active area (0.14 cm^2).

We have tested a total of seven PV cells. Each cell was soldered to a copper plate ($4 \times 4 \times 3/16$ in.) which acted as a heat sink. A single or multiple optical fibers were placed at the PV cell such that the solar flux filled the aperture of the cell as shown in Figure 5. We utilized both 3-ft and 2-m cables for the power generation experiment. For each experiment, solar power from the optical fiber(s) was measured by the thermopile calorimeter (Coherent 210). The output power characteristics of the PV cell were measured by changing the load resistor. During the test the copper plate temperature was constant at room temperature. Of the seven PV cells we tested, #3 cell appeared to be defective, and #5 and #7 cells showed low open circuit voltage when tested at 1-sun. Consequently, data for these cells were not discussed in this paper.

Solar Spectral Characteristics

Figure 5 compares the solar spectra in space (2) and the solar spectra on the ground at Air Mass Two (AM2). Spectral distribution of the direct solar insolation at the test site was not measured. We believe, however, that the spectra at the test site will be somewhat higher than the AM2 spectra. As shown in the figure, the solar spectra in space (AM0) contains a higher percentage of the spectra for $\lambda < 0.87 \mu\text{m}$ than that of AM2. The wavelength $\lambda = 0.87 \mu\text{m}$ (1.43 eV) corresponds to the bandgap cut-off of the GaAs cell. We may expect from this fact that the efficiency of the GaAs cell when exposed to the terrestrial 1-sun will be lower than the value measured with the solar simulator (AM0) light.

The spectral intensity distribution of the fiber output is shown in Figure 6. These data were taken using a 10-m long fiber at 2 p.m. on May 31, 1995. The vertical axis of Figure 6 shows "relative" spectral intensity reduced from the silicon detector voltage output with appropriate corrections for: 1) higher order blocking filter transmission;

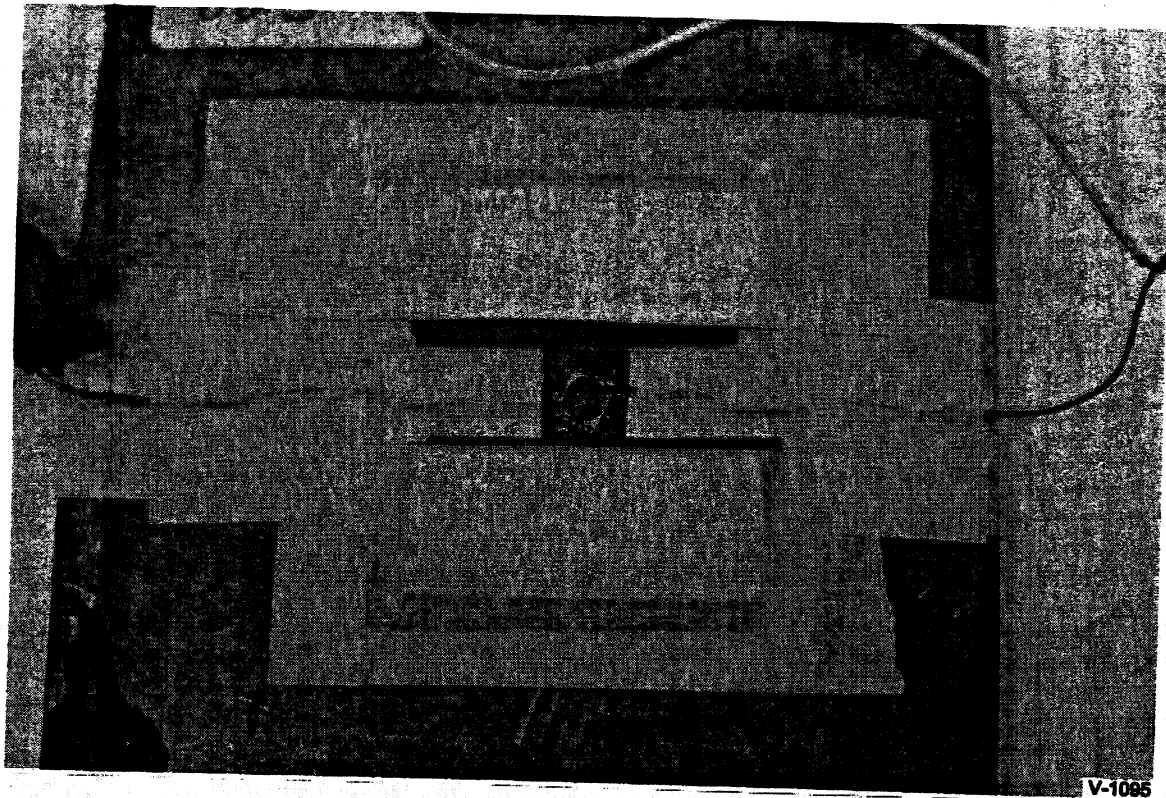


Figure 4. The RTI GaAs cell soldered on the copper substrate.

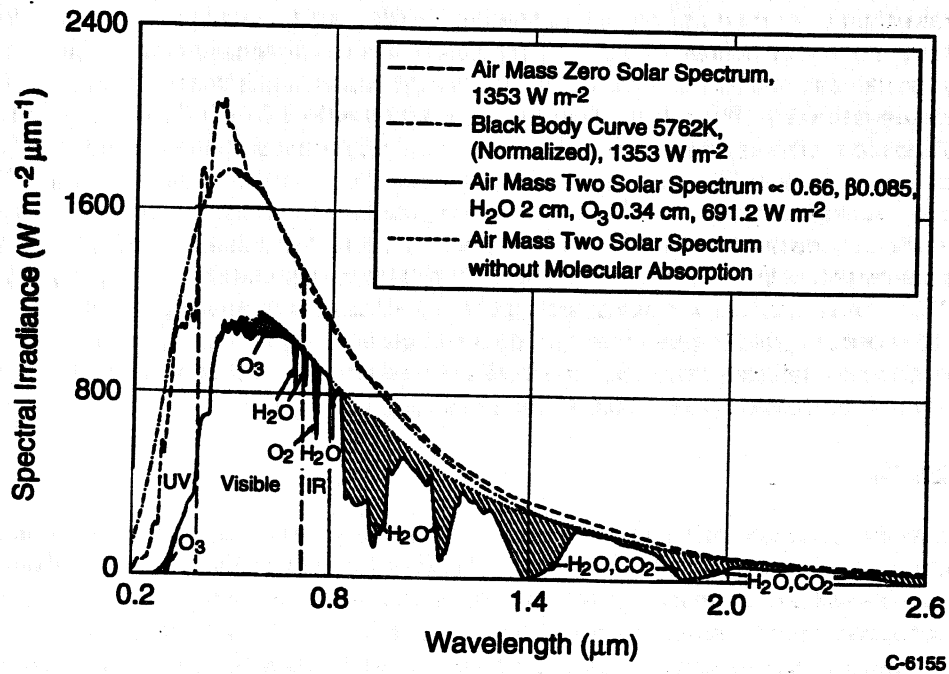


Figure 5. Comparison of AM0 and AM2 solar spectra, showing the various atmospheric absorption bands in AM2.

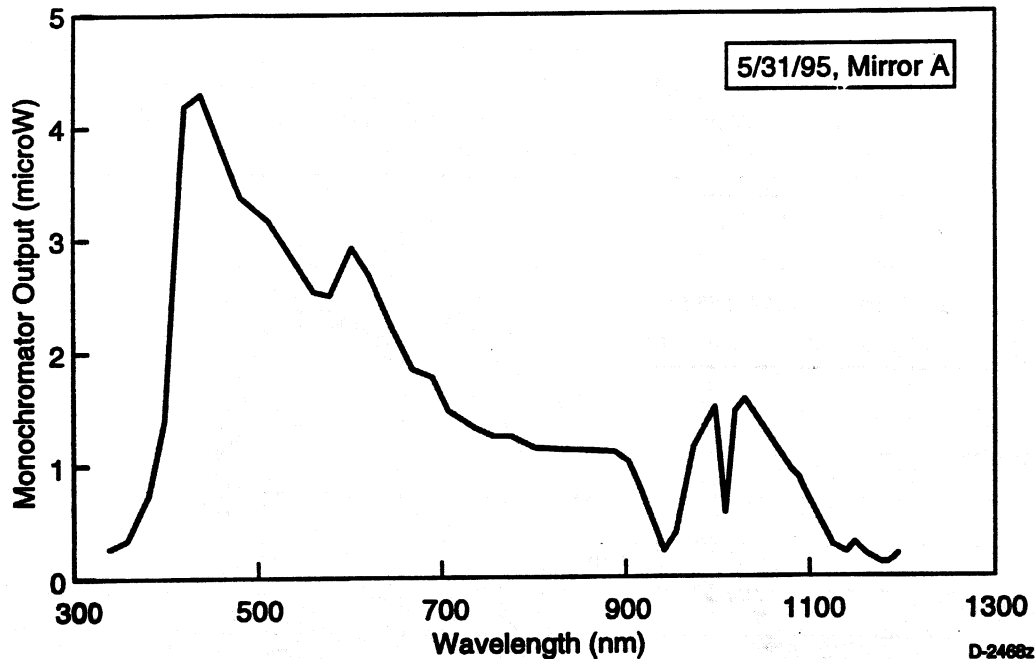


Figure 6. Spectral intensity distribution of the optical fiber output.

2) grating efficiency; and 3) silicon detector responsivity. There is a distinct "dip" in intensity between 900 and 1000 nm which is due to absorption by atmospheric water vapor and by the -OH ions in the fiber material. The intensity distribution curve in Figure 6 shows that the solar spectra of the optical fiber output contains a sufficient amount of photon intensity of interest to photovoltaic power generation ($\lambda < 0.87 \mu\text{m}$).

EXPERIMENTAL RESULTS

Power Generation With the Direct 1-Sun

Prior to the high concentration experiment we conducted the direct 1-sun exposure experiments. For these measurements, the cells were exposed to the direct sun without using the optical fibers. The voltage-current (V-I) characteristics of the cells for the direct 1-sun exposure were taken. The solar flux intensities at the test site were 847 to 885 W/m^2 . The solar powers which fell on the cell based on the cell aperture area (0.16 cm^2) were 0.0135 to 0.0141 W. The open circuit voltage for some cells was anomalously low. This is likely due to the leakage path somewhere in the cell circuit. However, when the solar intensity is increased, the open circuit voltage improves towards 1.1 V as will be shown later.

In Figure 7, the efficiency of the cell is plotted as a function of the cell potential. Except for cell #1, the peak efficiency takes place at the cell voltage of 0.7 - 0.8 V. The peak efficiency ranges from 11 to 13%. The efficiency values shown here are based on the cell aperture area (0.16 cm^2). As discussed before, the RTI cells were tested with AM0 solar simulator lighting to yield an efficiency of 16%. This 3 to 5% difference may be attributed to difference in spectral distribution between the AM0 flux and the flux on the ground, or to the non-ideal cell preparation process for this particular experiment.

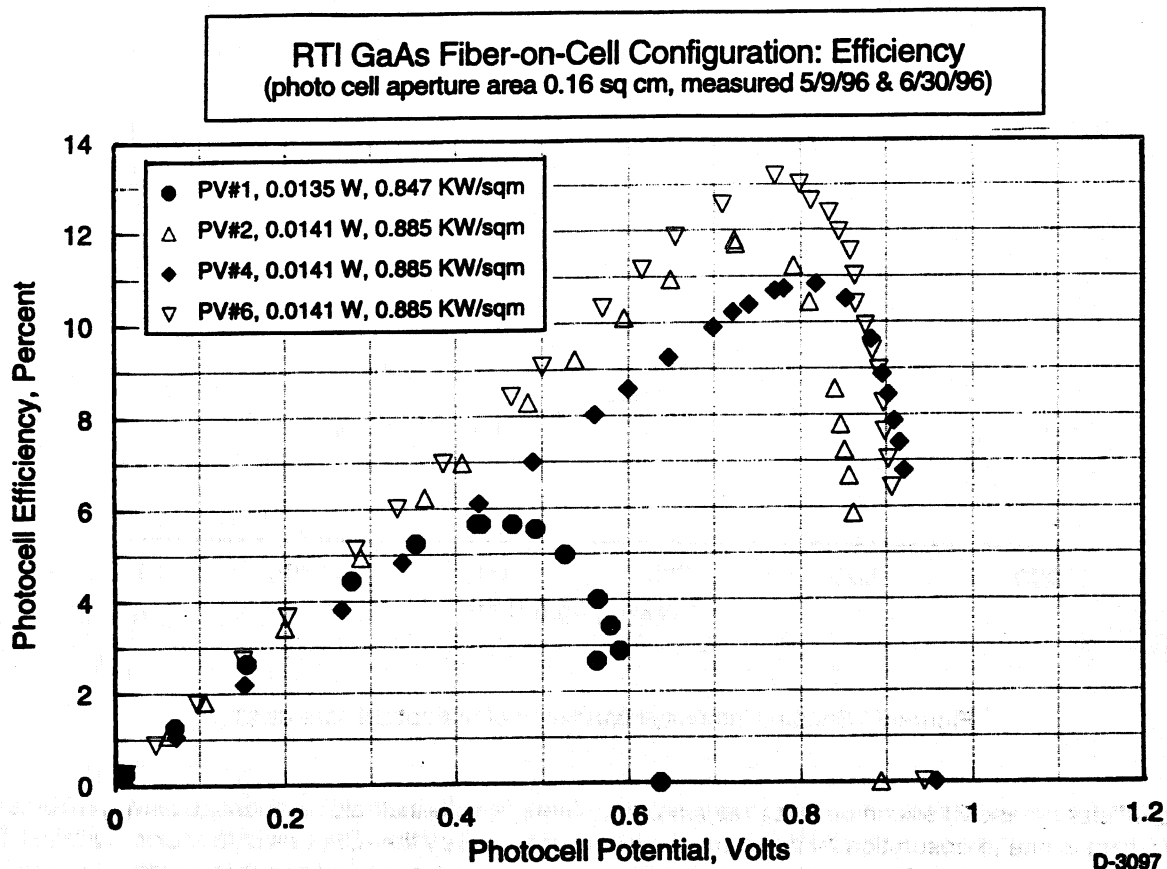


Figure 7. The efficiency-voltage characteristics of the four RTI GaAs cells at the direct 1-sun.

Power Generation With High Concentration Solar Flux from the Optical Waveguide

Figure 8 shows the V-I characteristics of the cell #1 as they were illuminated with the high intensity solar flux from the optical fiber. The solar power input to the cell, listed on the figure legend in the middle column at the right of the cell number, was measured by a thermopile calorimeter. The intensity of the solar flux, listed on the right column of the legend, was calculated using the optical fiber power output, and the solar cell aperture area (0.16 cm^2). The open circuit voltage (V_{op}) is constant at 1.1 V regardless of the solar flux intensity, while the cell current increases with solar flux intensity.

The power output of cell #1 as the function of cell voltage is given in Figure 9. The solar flux intensity to cell #1 is 288 kW/m^2 , or 320 suns based on 880 W/m^2 on the ground. The corresponding cell output is 0.53 W. This is a remarkable high power capability for this small GaAs cell.

The efficiency-voltage characteristics of cell #1 for various flux intensities is given in Figure 10. The open circuit voltage (V_{op}) of cell #1 recovers from its anomalous value of 0.63 to 1.1 V as the flux intensity is increased. The maximum efficiency for cell #1 is 12% at high flux intensities.

RTI GaAs Fiber-on-Cell Configuration: V-1 Characteristics
 (photo cell aperture area 0.16 sq cm, measured 5/7/96)

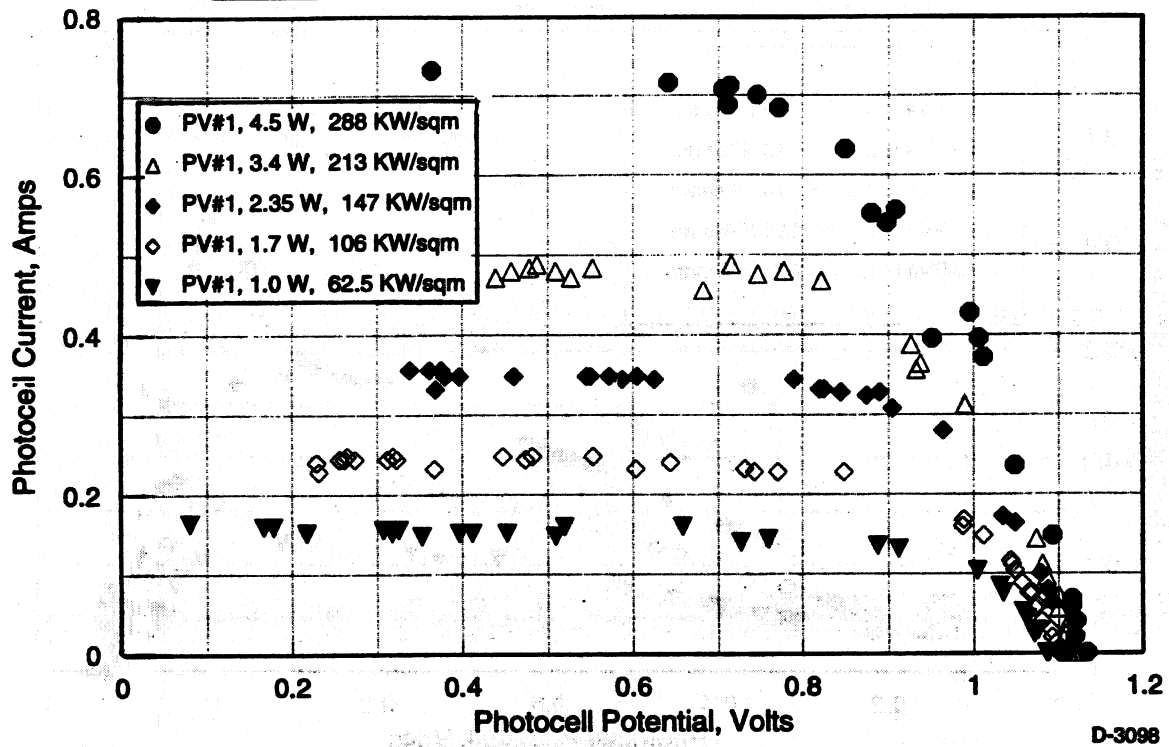


Figure 8. The voltage-current characteristics of the RTI GaAs cell #1 for high intensity solar flux.

RTI GaAs Fiber-on-Cell Configuration: Power Output
 (photo cell aperture area 0.16 sq cm, measured 5/7/96)

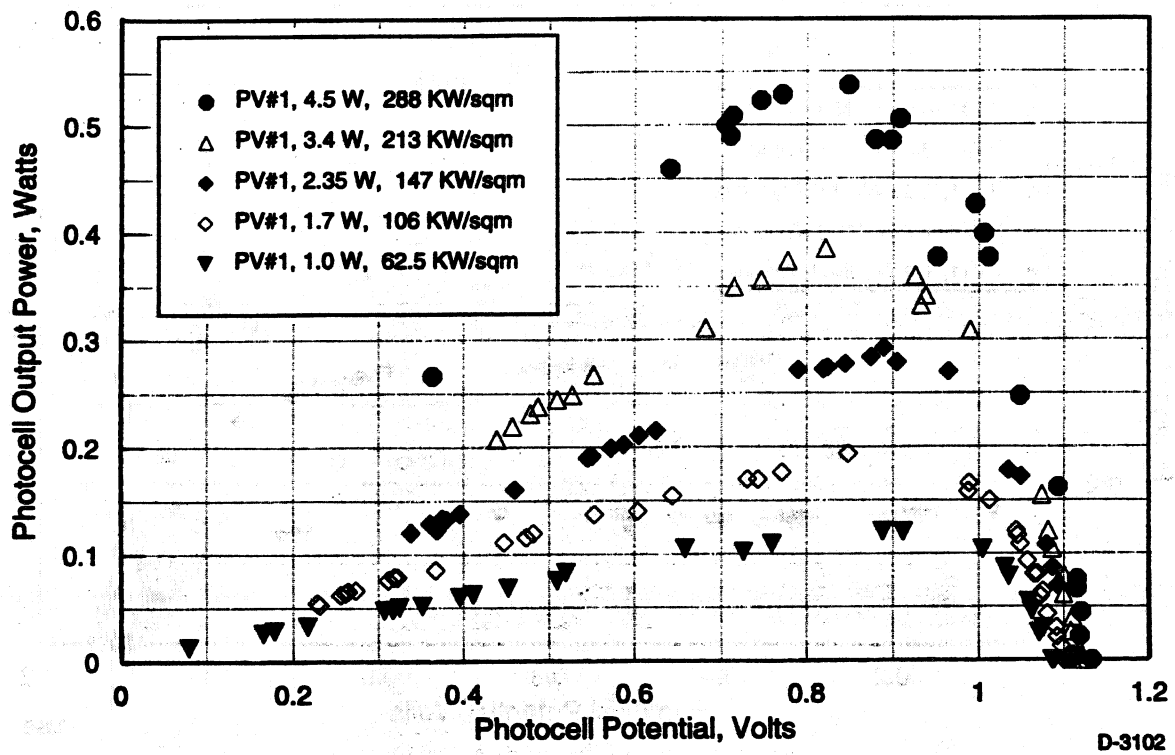


Figure 9. The cell power output versus cell voltage for the RTI GaAs cell #1.

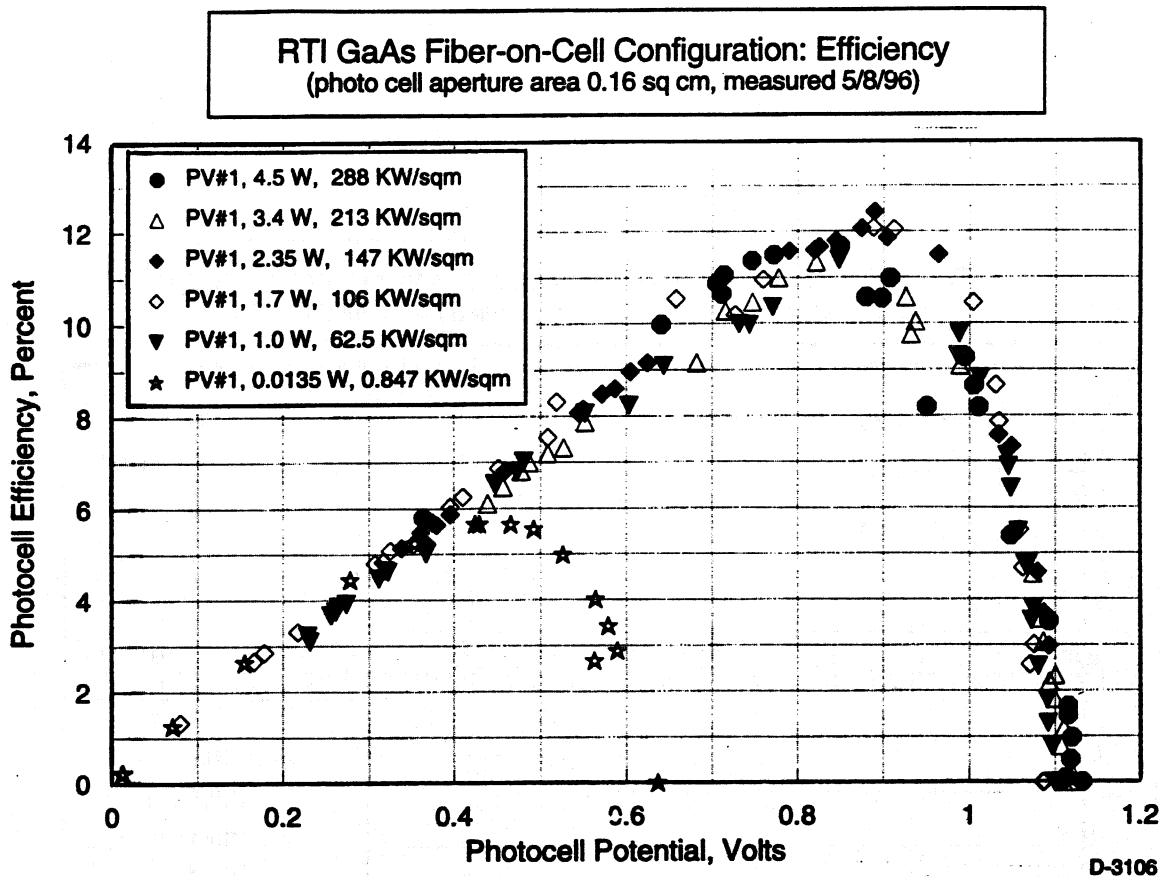


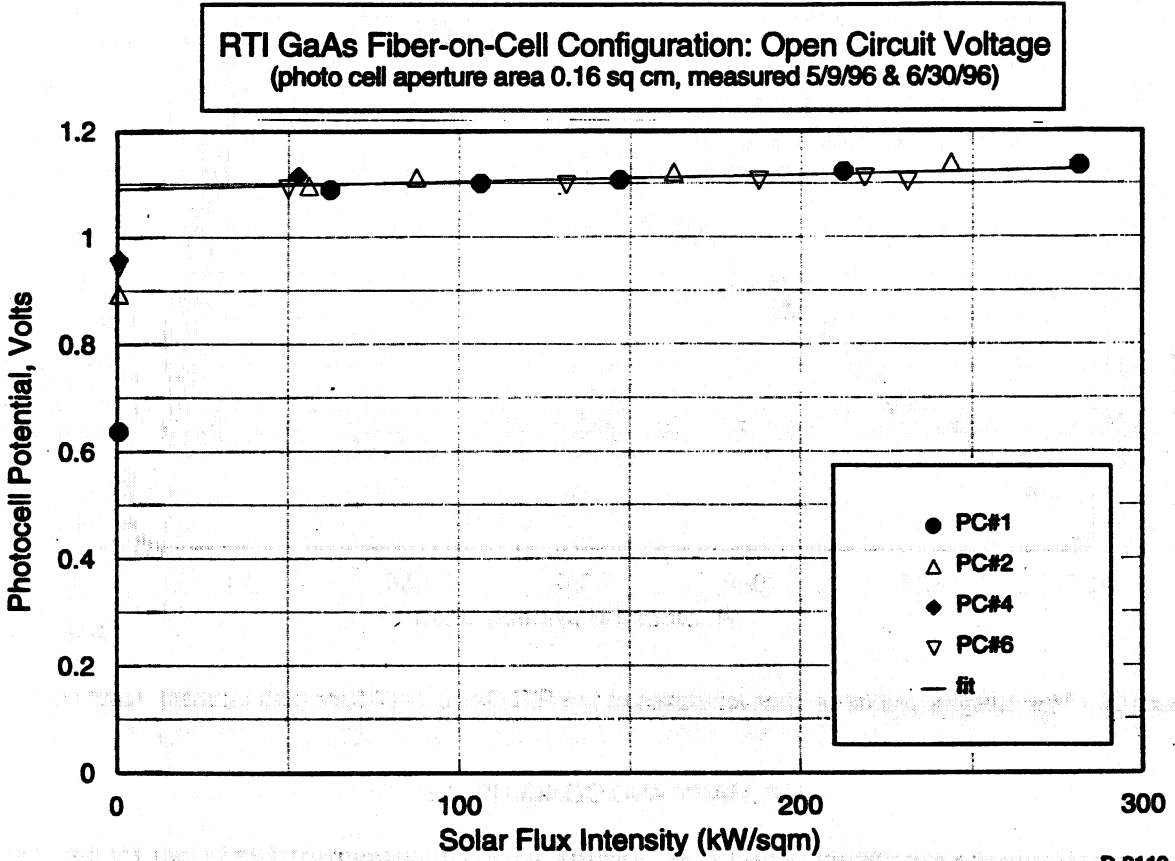
Figure 10. The efficiency-voltage characteristics of the RTI GaAs cell #1 for high intensity solar flux.

SUMMARY AND CONCLUSION

Having reviewed the experimental results, we will organize the measurement data to look for the answers to the following questions: (1) will the cell output increase with the solar flux intensity, and (2) what will be the power generation efficiency as solar flux intensity increases?

The answer to the first question is given in Figures 11 through 13. The open circuit voltage (V_{op}) of the RTI GaAs cells is plotted against the solar flux intensity in Figure 11. The V_{op} for the direct 1-sun exposure is much lower than 1.1 V. However, as the solar flux density is increased, V_{op} goes up to 1.1 V and increases steadily as the solar flux intensity increases. The data shows this tendency very clearly. The short circuit current (I_{sc}) of the RTI GaAs cell is plotted against the solar flux density in Figure 12. This is another very clear data plot: all data points line up neatly. The plot shows that the short circuit current increases linearly with the solar flux intensity.

In Figure 13, the cell electric power output is plotted against the solar flux intensity over the cell aperture area (0.16 cm²). The plotted data show that the slope is linear with no indication of saturation. The highest solar flux intensity is 288 kW/m² which corresponds to 213 suns in space (1.35 kW/m²) or 327 suns on the ground (880 W/m² at the test site). The maximum solar power input to the cell was 4.5 W. At this power range we did not observe any thermal or electrical problems. We expect that the cell will perform properly for higher solar power input, possibly up to 10 W per cell (470-suns in space).



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Figure 11. The open-circuit voltage of the RTI GaAs cells versus solar flux intensity.

RTI GaAs Fiber-on-Cell Configuration: Short Circuit Current
 (photo cell aperture area 0.16 sq cm, measured 5/9/96 & 6/30/96)

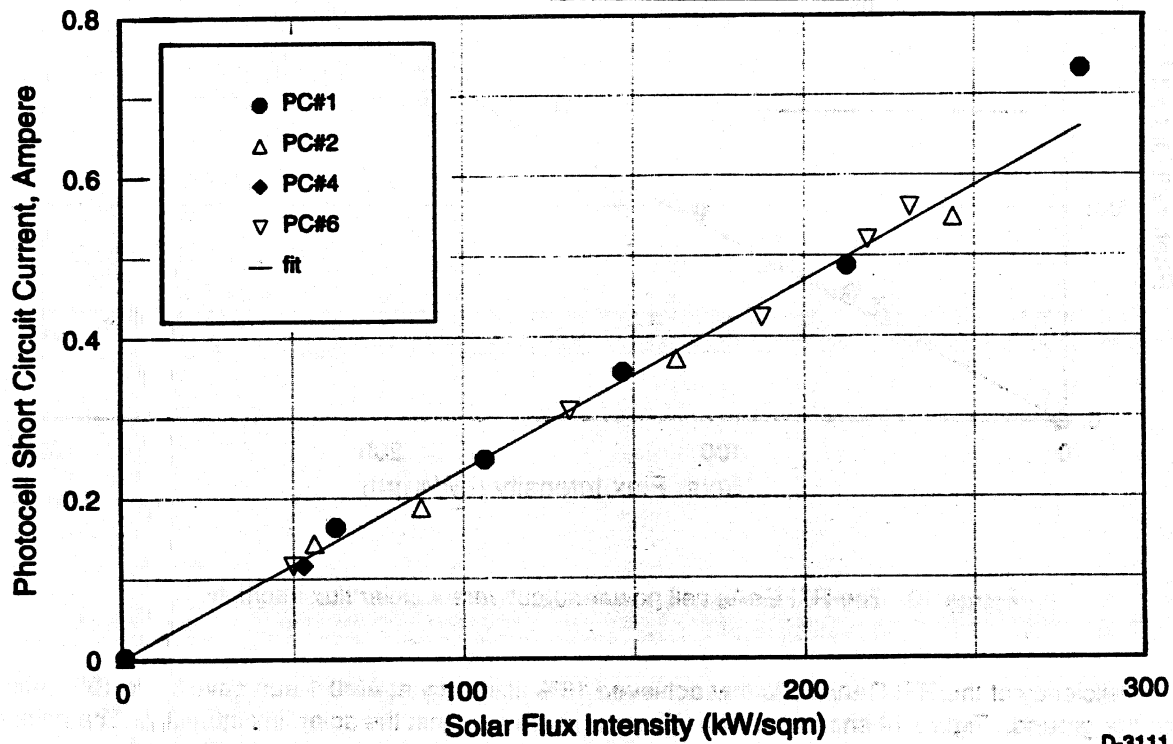


Figure 12. The short-circuit current of the RTI GaAs cells versus solar flux intensity.

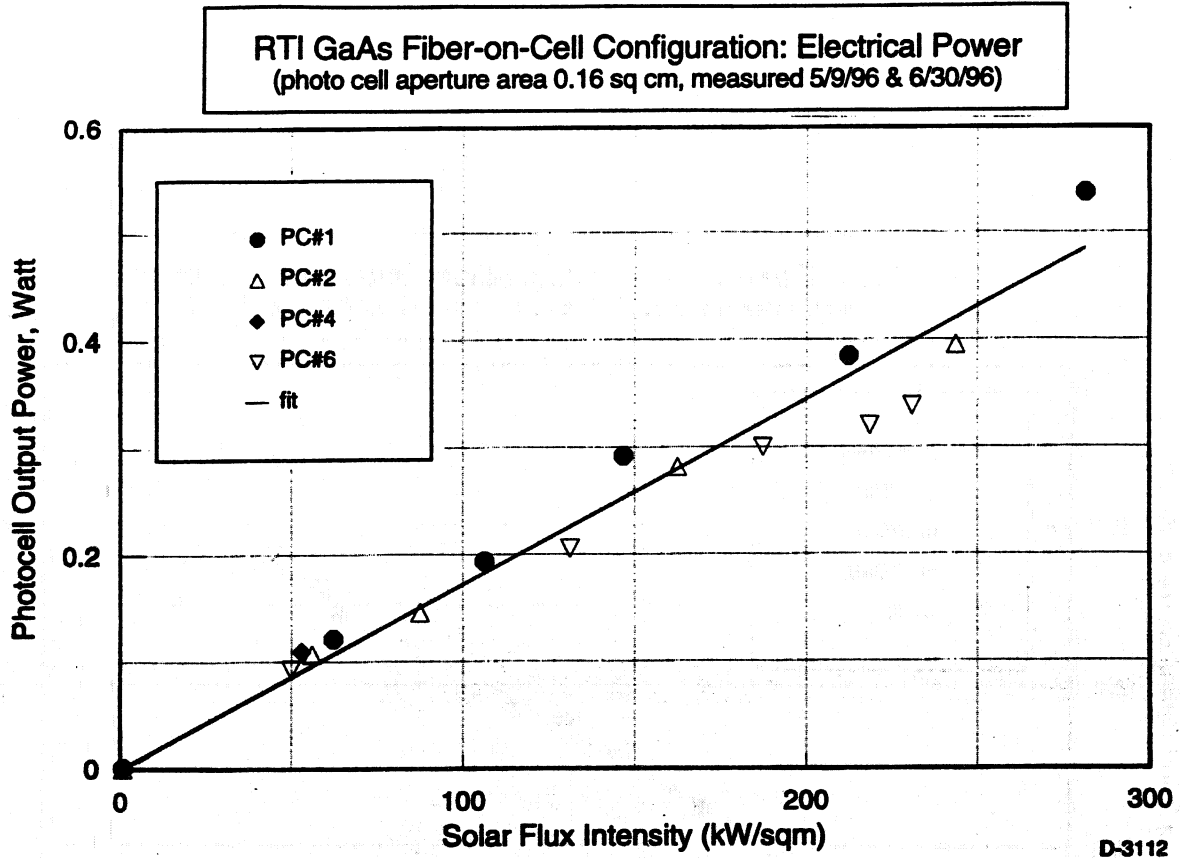


Figure 13. The RTI GaAs cell power output versus solar flux intensity.

The efficiency of the RTI GaAs cells that achieved 16% efficiency at AM0 1-sun gave 11 to 13% efficiency at 1-sun on the ground. Figure 14 shows the cell efficiency plotted against the solar flux intensity. The efficiency decreases slowly as the solar flux intensity is increased. We believe that the decrease in efficiency is due to imperfect coupling between the fiber and the cell, not to fundamental limitations of the semiconductor performance. We noticed that as the optical fiber end is fixed over the cell aperture, part of the solar flux "spilled" over the aperture area. With a proper coupling method such as with a reflective collimator, flux spill-over will be minimized. In this case, we expect that the cell efficiency will be constant. We must take note that, contrary to commonly accepted theory, the present experimental results do not show an increase in cell efficiency as solar input flux increases. We do not have an explanation for this at present.

The foregoing discussions lead us to the following conclusions. The high concentration GaAs cells when combined with the OW system will be an effective power generation device. The high power density implies a small size PV cell array which is attractive from cost and weight aspects. Furthermore, as the OW system can switch the solar power from the material processing plant to the electric power generation facility and vice versa, the PV power generation device can become an integral part of the lunar material processing plant.

The OW system can take advantage of the advanced PV cell which can operate at higher efficiency. The current experiment was conducted only for one type of GaAs cell with a moderate efficiency value. Power generation at a higher efficiency is possible and is desirable from a system engineering point of view.

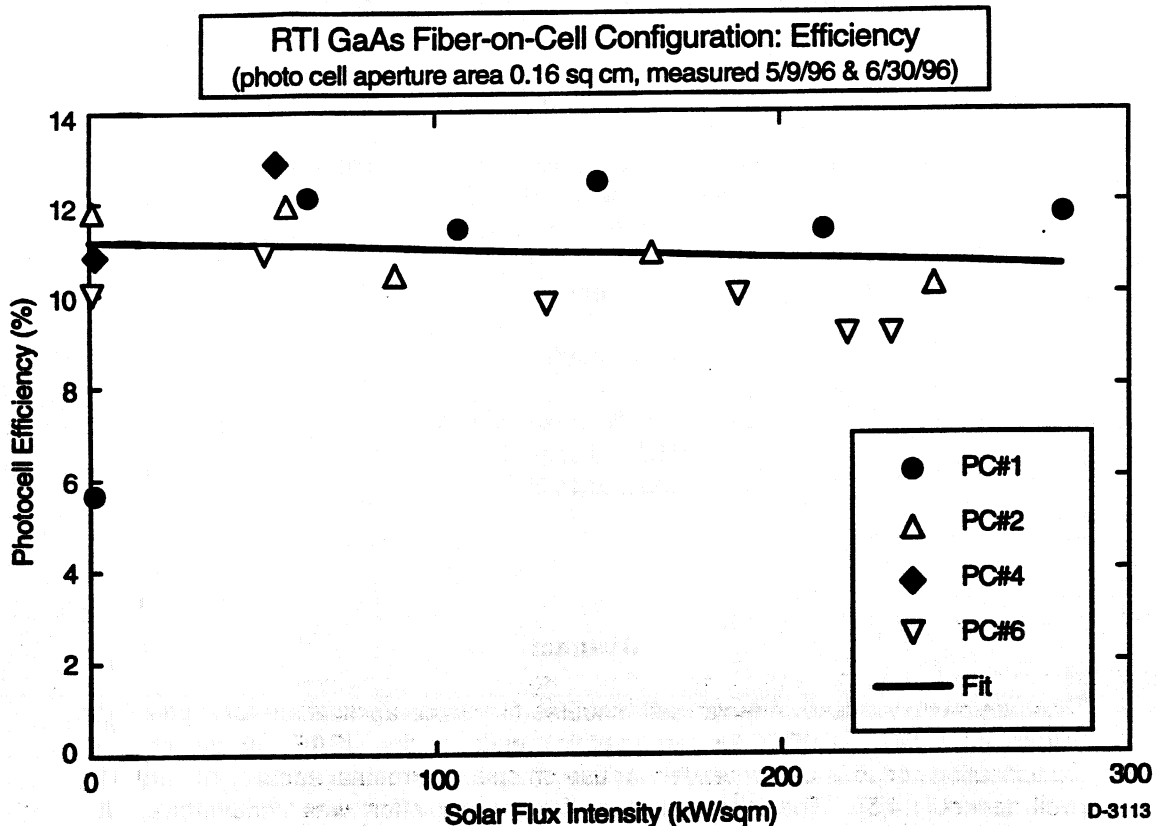


Figure 14. The efficiency of the RTI GaAs cell versus solar flux intensity.

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