N93-29686

# THE EFFECT OF THE LOW EARTH ORBIT ENVIRONMENT ON SPACE SOLAR CELLS: RESULTS OF THE ADVANCED PHOTOVOLTAIC EXPERIMENT (S0014)

David J. Brinker
NASA Lewis Research Center
Cleveland, OH 44135
Phone: 216/433-2236, Fax: 216/433-6106

John R. Hickey
The Eppley Laboratory, Inc.
Newport, RI 02840

David A. Scheiman
Sverdrup Technology, Inc.
Brook Park, Ohio 44142

## SUMMARY

The results of post-flight performance testing of the solar cells flown on the Advanced Photovoltaic Experiment are reported. Comparison of post-flight current-voltage characteristics with similar pre-flight data revealed little or no change in solar cell conversion efficiency, confirming the reliability and endurance of space photovoltaic cells. This finding is in agreement with the lack of significant physical changes in the solar cells despite nearly six years in the low Earth orbit environment.

## INTRODUCTION

The Advanced Photovoltaic Experiment (APEX) is an LDEF science experiment designed to provide reference cell standards for laboratory photovoltaic performance measurements as well as to investigate the solar spectrum and the durability of space solar cells in the low Earth orbit environment. APEX, one of the first group of experiments accepted for inclusion on LDEF, was designated experiment S0014 and occupied position E9 on the leading edge of the satellite.

The accurate evaluation of the on-orbit performance of a solar cell intended for use in space power generation is crucial to ensuring sufficient electrical power over the lifetime of the satellite. If the conversion efficiency of a solar cell is overrated, as determined by laboratory-based measurements, adequate power will not be available to meet satellite mission objectives. If underrated, more cells than necessary will be used, increasing both cost and the amount of heat which must be dissipated by the spacecraft thermal management system. An accurate determination of the space, or Air Mass Zero (AM0), performance of a solar cell is complicated by the circumstance that the efficiency of a cell for collecting a photon is a function of the wavelength of the photon. This wavelength dependent efficiency is known as the spectral response and depends on the choice of the semiconductor used for the cell, the design of the electrical junction in the cell and its anti-reflection layer. Because neither a laboratory solar simulator nor terrestrial sunlight exactly matches the spectral content of extraterrestrial sunlight, reference cells with the same spectral response of the cells under test must be calibrated in true

AM0 sunlight to enable accurate measurements. This restriction creates the requirement for large numbers of reference cells, one for each unique cell design.

Over the last 35 years, the era of space photovoltaic power generation, a number of ground-based AM0 calibration techniques have been developed. These, including sounding rockets, high altitude balloons and aircraft, and mountain-top measurements, had to suffice because of limited access to space. The Long Duration Exposure Facility represented the first opportunity to expose a large number of solar cells directly to AM0 sunlight, record the pertinent data and safely return the cells for use in the laboratory. Thus the principle objective of APEX was to calibrate reference standards. The timely return of the cells and flight data would enable their use as reference standards.

A second objective was to determine the endurance of these advanced cell designs in the low Earth orbit environment. This was to be accomplished by the acquisition and recording of cell performance data during the planned eleven month flight from the 120 calibration standards, as well as another 16 cells for which the entire current-voltage characteristic was measured. The measurement of the energy distribution of the extraterrestrial solar spectrum was the third objective. Three instruments designed to measure both broadband and spectral irradiance were included: an absolute cavity radiometer, sixteen narrow bandpass filters coupled with silicon solar cell detectors, and a dichroic mirror which divided the solar spectrum into two parts. However, the unexpected increase in flight time from eleven to sixty-nine months resulted in the inability to meet some of these original objectives.

Details of the design of APEX, as well as the preliminary results, were presented at the First LDEF Post-Retrieval Symposium (Refs. 1, 2). In this paper, more detailed results concerning the endurance of the space cells included in the experiment will be discussed. Further results concerning the performance and durability of the optical components of APEX have been published elsewhere in these proceedings (Ref. 3). Data concerning some of the micrometeoroid/debris impacts and resulting features from the front plates of APEX has also been reported here (Ref. 4).

## SOLAR CELL FLIGHT SAMPLES

When the announcement of opportunity for LDEF experiments was released in 1976, a launch of about 1980 was envisioned. As a result, the solar cell samples prepared for APEX represented the state-of-the-art in space cell technology as of 1979, as well as samples of cells in use on a variety of satellites. Flight samples were solicited from the principal industrial and governmental groups who either manufactured or conducted research and development on space photovoltaic devices. These APEX solar cell investigators and the number of cells each supplied are:

| | |
|---|---|
| A.F. Wright Aeronautical Laboratory | 8 |
| Applied Solar Energy Corporation | 14 |
| COMSAT Laboratories | 7 |
| European Space Agency | 9 |
| Jet Propulsion Laboratory | 34 |
| NASA Lewis Research Center | 56 (Includes 19 sensor cells) |
| NASA Marshall Space Flight Center | 11 |
| Solarex Corporation | 7 |
| Spectrolab, Inc. | 9 |

Each group provided cells representative of technologies which were either in development or production. The experiment was designed to accommodate a total of 155 such cells, including the silicon cells which were employed as sensors for the spectral radiometer portion of the experiment. All cells were permanently mounted on aluminum plates with a thermistor in contact with the rear of the cell. Because the short-circuit current (Isc) of a solar cell is directly proportional to the intensity of the incident light and is strongly dependent upon the spectral content of that incident light, it was therefore the principal parameter of interest. 139 cells were designated as Isc cells, 120 to be calibrated as reference standards and returned to the investigators, eighteen for use as spectral radiometer sensors and one as a night sensor to signal the data acquisition system that conditions were correct for the requisite periodic calibration of the cavity radiometer. For these cells, the short-circuit current was converted to a voltage through the use of a precision load resistor. In most cases a 0.1 Ω value was used. The remaining sixteen cells were designated IV cells, that is the entire current (I) - voltage (V) characteristic curve was measured through the loading of the cell by a series of appropriately sized resistors.

The delay in the launch of LDEF by several years provided both the opportunity and necessity for updating the sample set, to one including the most recent advances. The cell investigators were invited in mid-1982 to submit new cells. Of the 136 calibration cells (120 Isc and 16 IV cells), 69 were replaced. Many of those which were not replaced were either standards previously calibrated by other techniques or representative of cells in use on a variety of satellites.

At that time, cells made of silicon were the only type in production, with the development of gallium arsenide in its early stages and years from production and utilization in space. This is reflected in the distribution of these semiconductor types in the APEX complement, which is summarized by cell type and size below:

| | | | | | |
|---|---|---|---|---|---|
| Silicon: | 105 | 2 x 2 cm | Gallium Arsenide: | 10 | 2 x 2 cm |
| | 21 | 2 x 4 cm | | 1 | 1.3 x 1.6 cm |
| | 2 | 5 x 5 cm | | 11 | |
| | 15 | 5.9 x 5.9 cm | | | |
| | 1 | 6 x 6 cm (module) | | | |
| | 144 | | | | |

The cells were mounted on 127 aluminum plates of twelve different sizes and configurations. 28 of the mounts each held two 2 x 2 cm cells. Each mount was equipped with a Yellow Springs Instruments Type 16429 thermistor (10,000 Ω @ 25 °C). An additional thermistor monitored the Eppley absolute cavity radiometer.

## POST-FLIGHT CELL EXAMINATIONS

After deintegration of the Advance Photovoltaic Experiment from LDEF it was returned to the Lewis Research Center and the flight Magnetic Tape Memory was removed for processing. Functional testing of the data acquisition system was conducted prior to removal of the various sensors for post-flight testing and recalibration. The results of these tests have been previously reported (Refs. 1,2). The solar cells were then removed from APEX. The leads from the data acquisition system to both the thermistor and cells contacts were cut near their attachment points at the back side of the mounting plate feedthrough. The leads were cut rather than unsoldered to avoid any possible contaminating fumes from molten solder. All cells were then visually inspected and individually photographed.

The overall condition of the cell sample set was excellent. The contaminating film seen over much of LDEF was present to a varying degree on APEX, the thickness of the layer dependent upon location. No loss of cell coverglass nor significant changes in color or appearance was observed. Several of the cells were cratered from micrometeoroid and/or debris impacts, with the range of damage spanning from microscopic craters in the coverglass surface to penetration of the coverglass and cell and cratering of the underlying aluminum mounting plate. However, even the few cells in which the cratering extended into the solar cell itself, or caused a crack in the coverglass and cell, electrical continuity was maintained. Loss in current proportional to the damage area and increase in fill factor due to cell cracking was observed. The electrical leads from the mounting plate feedthrough to the cell front and rear contacts were found to open in six cells. A silver ribbon of about 3 mil thickness was used for these cells. Where the flat portion of the ribbon faced the ram direction, the ribbon was severely eroded, creating an open circuit. In most cases the ribbon twisted through 90° at the feedthrough so that the narrow (3 mil) edge faced the ram direction; here the silver ribbon remained intact. Examination of the flight data indicates that the erosion did not occur to any extent that would affect cell performance during the data recording portion of the flight, the first eleven months. Post-flight performance testing of these cells was accomplished by direct probing of the cell contacts, no significant change from pre-flight performance was seen.

The first post-flight electrical test performed was measurement of the short-circuit current utilizing the precision load resistor mounted on each cell for the flight. The resistors were soldered to the cell mounting plate electrical feedthroughs on the underside of the cell mounting plates. These measurements, as well as subsequent current-voltage (I-V) tests, were carried out in the Solar Cell Evaluation Laboratory at Lewis Research Center using a Spectrolab X-25L solar simulator. This simulator employs a short-arc xenon lamp as the light source and provides uniform, collimated illumination. The intensity of the simulator was set using an aircraft calibrated silicon standard which is identical to the standard used at Eppley Laboratory for pre-flight testing, where a xenon arc lamp simulator was also utilized. Cell temperature was monitored using the flight thermistors. One thermistor was found to be open. An examination of the flight data showed abnormal readings from it, indicating that the failure occurred before launch. With this sole exception, all of the thermistors functioned properly, providing values in close agreement with a temperature sensor used in controlling the laboratory test fixture. The short-circuit current values obtained in these tests are useful in comparison with both pre-flight performance and flight data. The values obtained were in most cases in excellent agreement with pre-flight values, with the exception of those cells without coverglass.

Upon completion of the measurement of the short-circuit current, the load resistor was removed from the circuit by cutting one of its two leads. If LDEF had been retrieved on schedule and the value of the cells as calibration standards was retained, the load resistors could not have been removed. However, the absence of data from the last five years on-orbit negates their usefulness as standards. The complete I-V characteristic of all cells were then measured at 25 °C and recorded. A representative sampling of the silicon cells flown on APEX is shown in Table 1. All of these cells are n-p type, as were most of the silicon cells flown, the standard configuration for silicon space cells due to its superior radiation tolerance. The post-flight illuminated current-voltage characteristic of each of the six cells of Table 1 is shown in Figures 1 through 6. Also included for comparison in the figures are the pre-flight values (measured at Eppley Laboratory) of short-circuit current (Isc), open circuit voltage (Voc) and fill factor (F.F.).

Cell IV#7 (Mount B-1L) was manufactured by Spectrolab for the Solar Maximum Mission satellite. The base resistivity of the cell was 10 Ω-cm with an anti-reflection coating of $Ta_2O_5$. A similar cell, but 2 x 4 cm in size, was also flown as sample ISC#32. As can be seen in Figure 1, little change in cell performance due to time on-orbit has occurred. The small differences in Isc and Voc are within experimental accuracy. The results from ISC#32 are nearly identical to that of IV#7.

The cell of Figure 2, ISC#95, is a large area (5.9 x 5.9 cm) cell in which the front contact wraps around the edge of the cell enabling all leads to be attached from the rear. This cell is the predecessor to the Space Station Freedom cell. Seven such cells were flown. Little change in Isc or Voc was noticed, however the drop in fill factor of about 2 percentage points was typical of this set of cells. A set of four cells with the same design but with conventional top/bottom contacts also showed little change in Isc or Voc. The drop in fill factor was larger, ranging from 6 to 18 percentage points.

Cell ISC#112 (Figure 3) has a base resistivity of 1 Ω-cm and an anti-reflection coating of $Ta_2O_5$. Its 30 mil coverglass is the thickest on APEX and the only grooved design. The grooves are situated above the cell collection fingers and serve to reflect light to those areas where it can be collected. No decrease in performance was seen with an identical cell, IV#9, having similar results.

The cell of Figure 4, ISC#114, and a companion cell, IV#11, employed a texturized surface to optimize photon absorption and thus increase short-circuit current. The cells have a base resistivity of 10 Ω-cm and also use a $Ta_2O_5$ anti-reflection coating. The post-flight currents of the cells, in excess of 189 ma, are the largest current densities of the APEX cell complement.

The last two cells of Table 1 were two of fifteen silicon cells which did not have coverglasses. The purpose of a coverglass is to prevent energetic protons from damaging the semiconductor material and degrading its electronic transport properties, which, in turn, reduces cell conversion efficiency. The choice of coverglass material and its thickness are determined by the energy and flux of the protons, which varies with orbital inclination and altitude. Proton damage is evidenced by the drop in Isc as well as the substantial loss of Voc. Similar drops in performance were seen in the entire set of unglassed cells. Cell ISC#83 has a base resistivity of 10 Ω-cm and is consequently more radiation tolerant than the 1 Ω-cm material of cell ISC#63. This is confirmed by the data of Figures 5 and 6.

Table 2 is a summary of the gallium arsenide solar cells contained in the APEX sample set. Ten of the eleven cells were fabricated by Hughes Research Laboratory using the liquid phase epitaxy techniques. Post-flight simulator calibration for the gallium arsenide cells was accomplished using a gallium arsenide aircraft standard of the same design and vintage of these Hughes cells. The remaining cell, ISC#111 (Figure 7), is a metal-oxide-semiconductor structure made at JPL and primarily of interest as a terrestrial cell. The cell is covered with a coverglass of unknown material. At this time the source of the increase in current from pre-flight to post-flight is not known. A change in the junction structure (formed by the metal and oxide layers) is unlikely as the open-circuit voltage is unchanged. The contaminating film covering the cell may have served to improve the anti-reflection properties of the front surface of the coverglass.

The remaining three cells of Table 2 (Figures 8 through 10) are similar in design with the exception of the junction depth (Dj). Each cell, ISC#71, ISC#76 and ISC#77, represents a set of three flown on APEX. The effect of the fused silica coverglass on ISC#71 is most apparent in the open-circuit voltage, with that of the uncovered cells sustaining significant losses. As in the case of the silicon cells, this is due to the energetic protons found in LEO. The decrease in Voc and Isc of cell ISC#77 is greater than that of ISC#76 due to the shallower depth of its junction (0.35 μm versus 0.50 μm).

## CONCLUSIONS

Post-flight examination and performance testing of the complete cell complement of APEX has been conducted. The overall condition of the sample set is excellent with no loss of coverglasses nor significant changes in color or appearance. Several of the cells sustained micrometeoroid/debris impacts with varying degrees of subsequent damage. However, in no case was the electrical functioning of the cells totally impaired. With the exception of one pre-flight failure, all 128 thermistors functioned perfectly in post-flight testing, as did the cell load resistors. Very little degradation in cell conversion efficiency was demonstrated by post-flight performance measurements. The open-circuit voltage and short-circuit current of those cells that did not have a coverglass did decrease, as expected.

## REFERENCES

1. Brinker, D.J., Hickey, J.R. and Scheiman, D.A.: Advanced Photovoltaic Experiment, S0014: Preliminary Flight Results and Post-Flight Findings. Proc. First LDEF Post-Retrieval Symposium, p. 1395, NASA CP-3134, 1991.

2. Hickey, J.R.: Passive Exposure of Earth Radiation Budget Experiment Components LDEF Experiment AO147: Post-Flight Examinations and Tests. Proc. First LDEF Post-Retrieval Symposium, p. 13493, NASA CP-3134, 1991.

3. Hickey, J.R., Brinker, D.J. and Jenkins, P.P.: Studies of Effects on Optical Components and Sensors: LDEF Experiments AO-147 (ERB Components) and S-0014 (APEX). Proc. Second LDEF Post-Retrieval Symposium, 1992.

4. Coombs, C.R., Atkinson, D.R., Allbrooks, M. and Wagner, J.D.: Damage Areas Due to Craters on LDEF Aluminum Panels. Proc. Second LDEF Post-Retrieval Symposium, 1992.

Table 1 - SILICON CELLS

| Cell Number | | Description | Coverglass | Remarks |
|---|---|---|---|---|
| IV#7 | B-1L | Spectrolab, Solar Maximum Mission | 12 mil Crng. 7940 | Little pre- to post-flight change |
| ISC#95 | M-5 | ASEC, Large Area, Wrap Around Contact | 6 mil Fused Silica | SSF predecessor |
| ISC#112 | B-2R | COMSAT Very High Blue Sensitivity | 30 mil 7070 | V-grooved cover |
| ISC#114 | B-4R | COMSAT Non-Reflecting | 12 mil Fused Silica | Textured surface High current |
| ISC#63 | NA-10 | Solarex, Back Surface Field/Reflector | No cover | $\Delta$Voc = 65 mV $\Delta$Isc = 13.1 mA |
| ISC#83 | B-21R | LeRC A/C Standard | No cover | $\Delta$Voc = 46 mV $\Delta$Isc = 4.7 mA |

Table 2 - GALLIUM ARSENIDE CELLS

| Cell Number | | Description | Coverglass | Remarks |
|---|---|---|---|---|
| ISC#111 | A-2 | JPL, AMOS | Unknown material | Only heterostructure cell on APEX |
| ISC#71 | NB-15L | Hughes, Dj = 0.5 µm | 12 mil F.S. | $\Delta$Voc = -10 mV $\Delta$Isc = 14.5 mA |
| ISC#76 | NB-29R | Hughes, Dj = 0.5 µm | No Cover | $\Delta$Voc = 65 mV $\Delta$Isc = 21.7 mA |
| ISC#77 | NB-29L | Hughes, Dj = 0.35 µm | No Cover | $\Delta$Voc = 85 mV $\Delta$Isc = 23.7 mA |

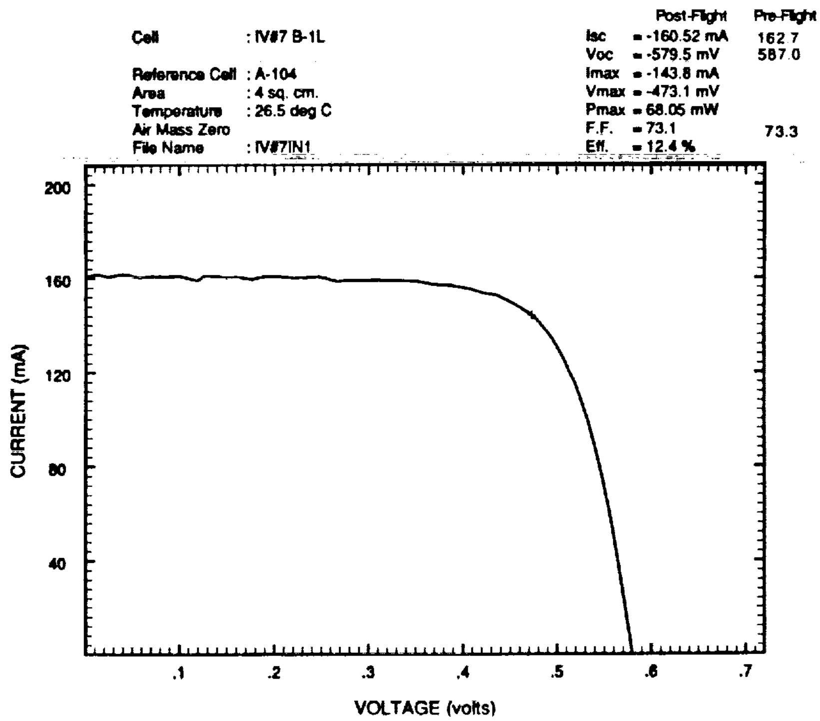


Figure 1 - Illuminated Performance of Silicon Cell IV#7, B-1L

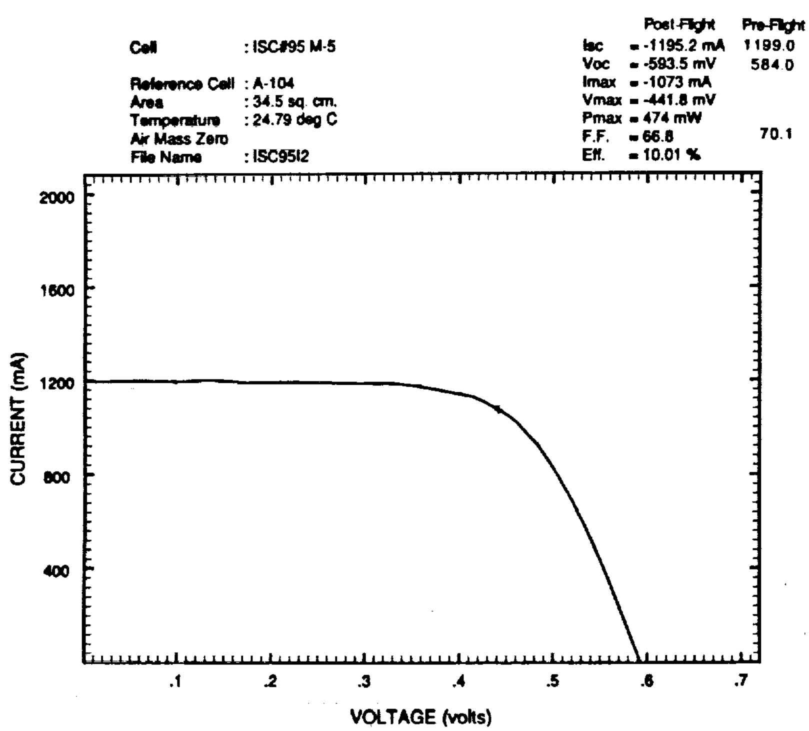


Figure 2 - Illuminated Performance of Silicon Cell ISC#95, M-5

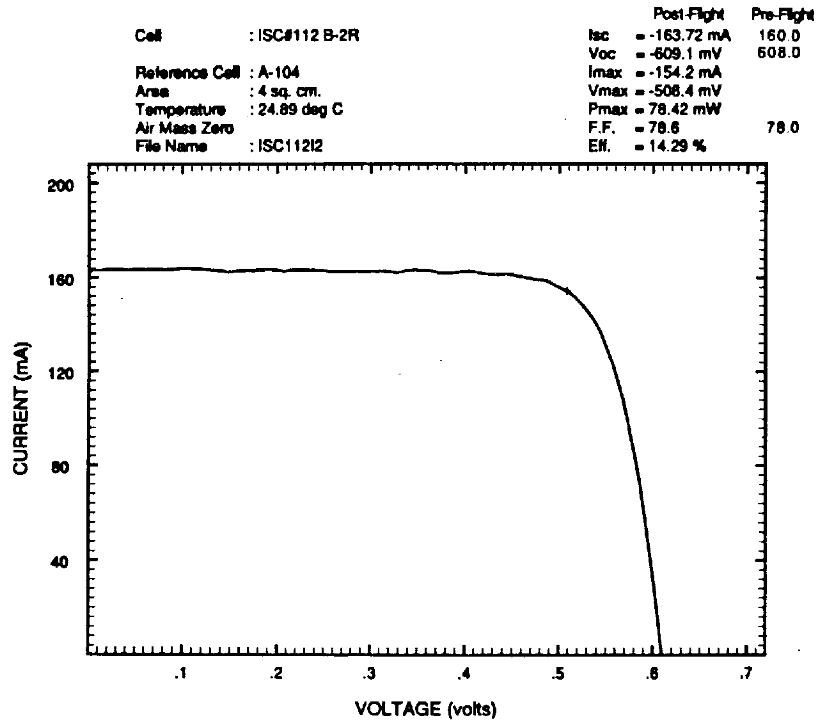


Figure 3 - Illuminated Performance of Silicon Cell ISC#112, B-2R

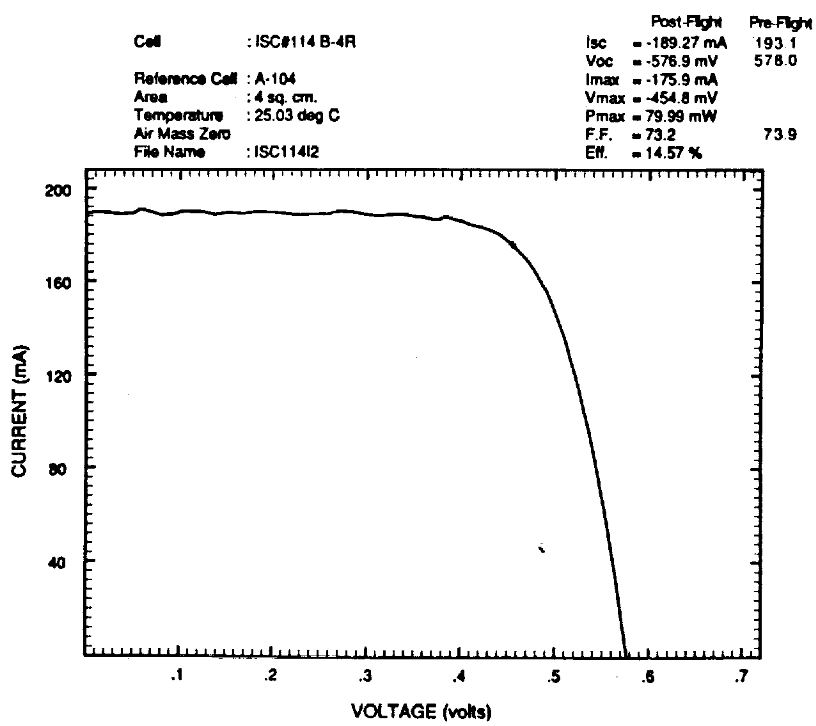


Figure 4 - Illuminated Performance of Silicon Cell ISC#114, B-4R

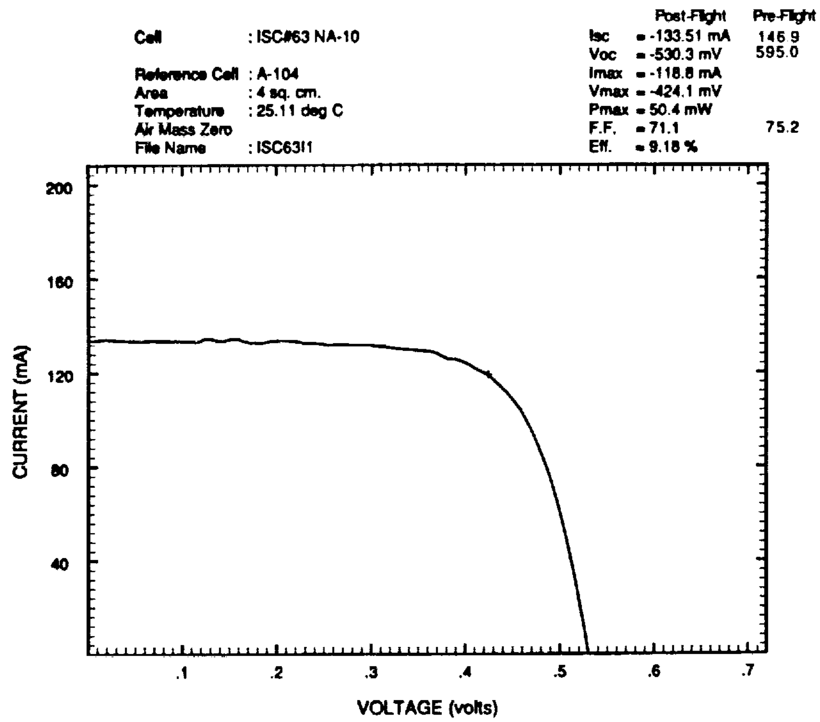


Figure 5 - Illuminated Performance of Silicon Cell ISC#63, NA-10

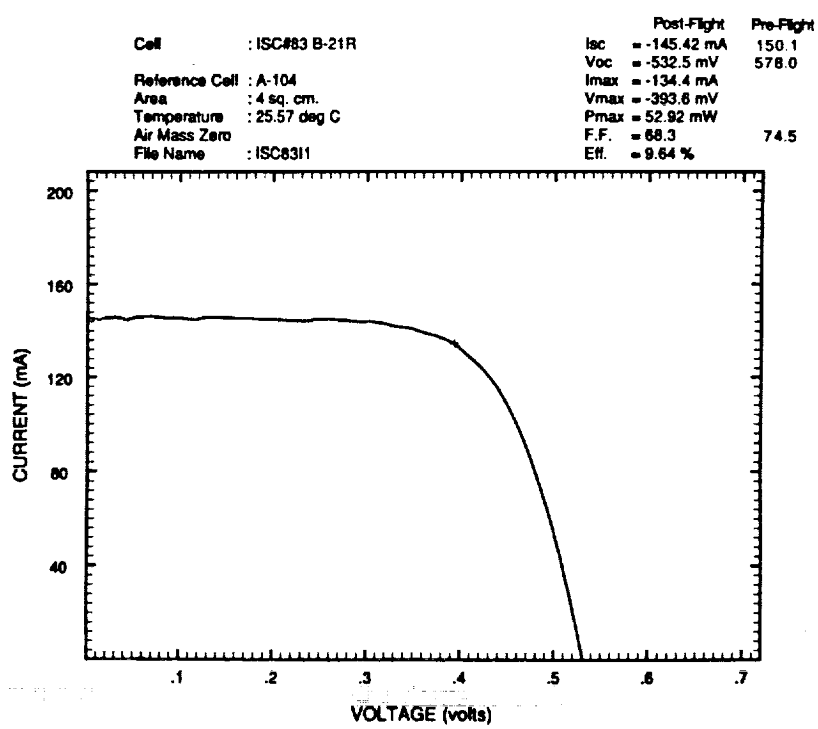


Figure 6 - Illuminated Performance of Silicon Cell ISC#83, B-21R

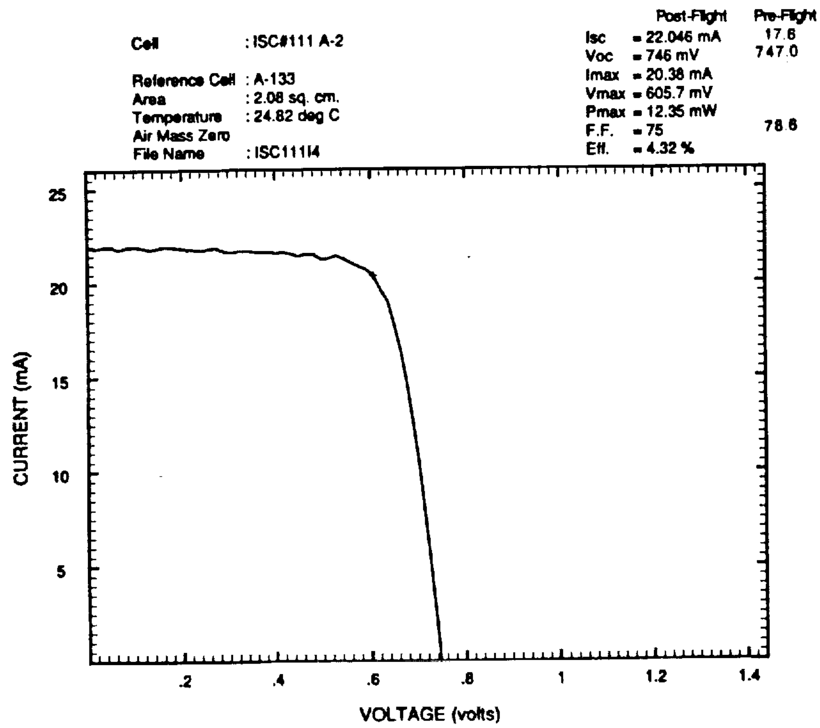


Figure 7 - Illuminated Performance of Gallium Arsenide Cell ISC#111, A-2

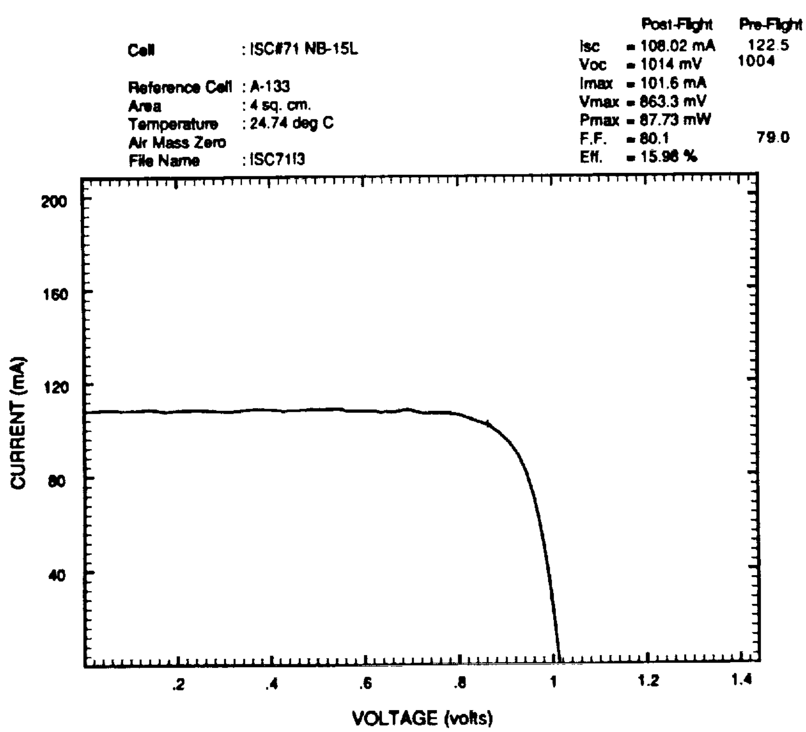


Figure 8 - Illuminated Performance of Gallium Arsenide Cell ISC#71, NB-15L

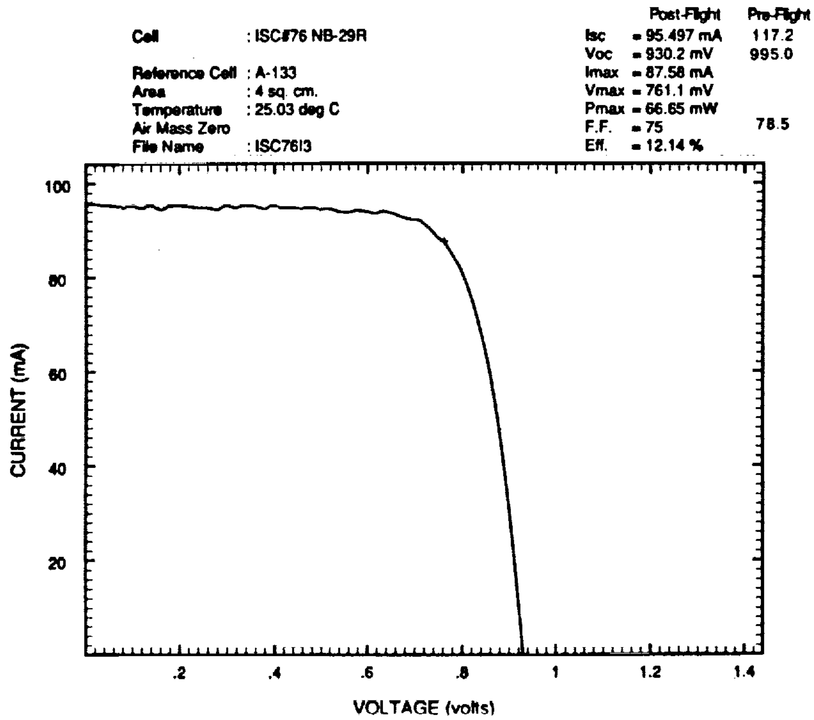


Figure 9 - Illuminated Performance of Gallium Arsenide Cell ISC#76, NB-29R

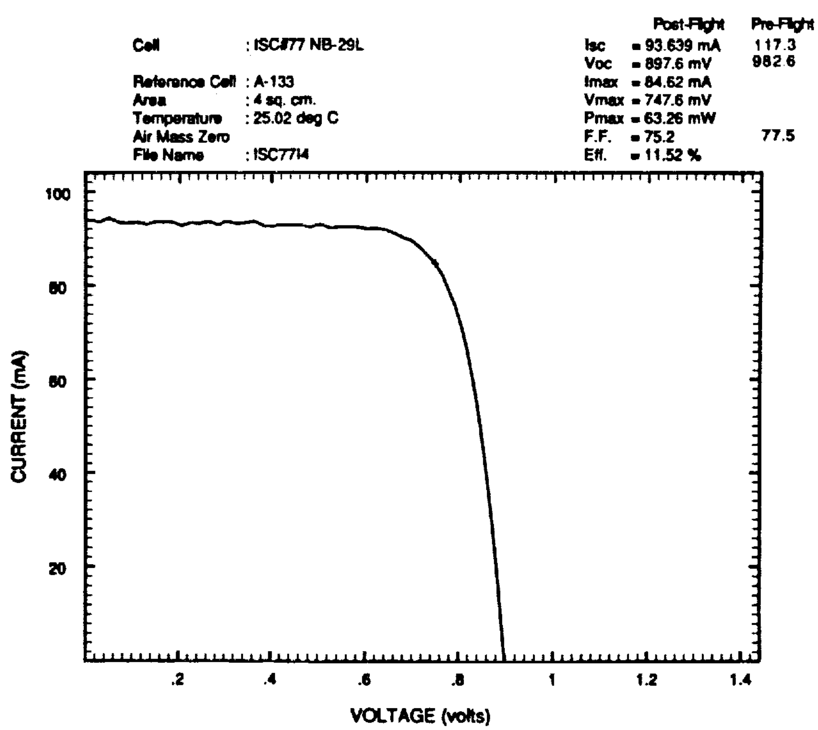


Figure 10 - Illuminated Performance of Gallium Arsenide Cell ISC#77, NB-29L