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FINAL REPORT

LDEF SOLAR CELL RADIATION EFFECTS ANALYSIS

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1.0 INTRODUCTION

Because of the extended time that the Long Duration Exposure Facility (LDEF) mission stayed in space, the solar cells on the satellite experienced greater environments than originally planned. The cells showed an overall degradation in performance that is due to the combined effects of the various space environments. The purpose of this analysis is to calculate the effect of the accumulated radiation on the solar cells, thereby helping Marshall Space Flight Center (MSFC) to unravel the relative power degradation from the different environments.

2.0 ANALYSIS

2.1 BACKGROUND

Solar cell damage depends on the radiation environment and the construction of the solar cell itself. The solar cell is a bipolar junction, where the illuminated side of the junction is heavily doped, while the unexposed side is lightly doped. The heavily doped region is called the emitter, while the lightly doped side is called the base.

Incident photons excite hole electron pairs in the cell material. Because of carrier density gradients near the junction, electrons diffuse toward the junction in the p-type material, while holes diffuse to the junction in the n-type region. The high electric field in the depletion layer accelerates the carriers to the opposite side of the junction. The carriers crossing the junction result in the photon generated cell current.

The photo generated current can be modeled by using the circuit shown in Figure 1 where I_g is the photogeneration current, I_d is the diode current, R_{sh} is the cell

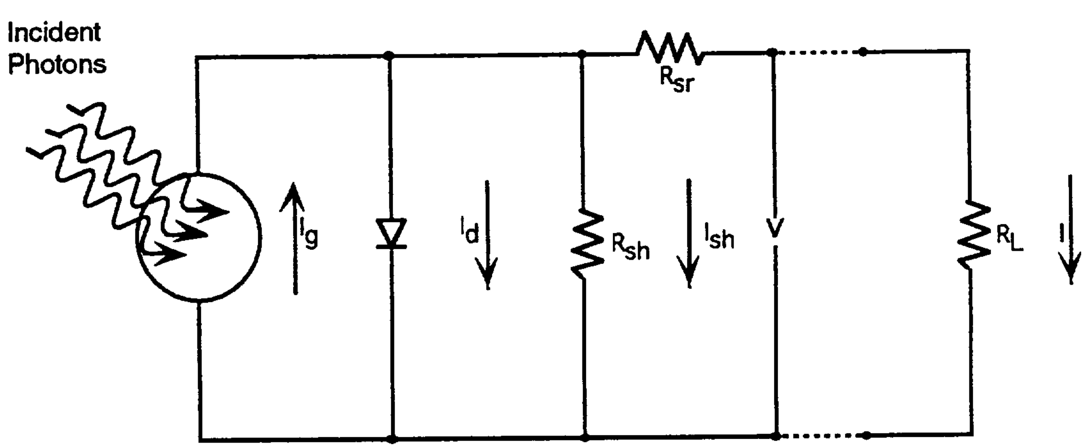


Figure 1. Circuit Model of Solar Cell

shunt resistance (usually ~10^4 ohms), R_{sr} is the series resistance (small for a high quality cell), and R_L is the load resistance. This circuit is useful to understand how radiation affects the material parameters and therefore the solar cell electrical performance. Various elements of the circuit model are described below.

2.1.1 Diode Current, I_d

The diode current, I_d, represents the ordinary diode conduction current for the p-n diode forming the solar cell. This current is given by the equation:

$$I_d = I_o\left[\exp\left(\frac{eV_o}{nKT}\right)-1\right] \quad (1)$$

where I_o is the diode saturation current, V_o is the voltage across the diode, e is the charge on an electron (1.6 x 10^{-10} coulombs), k is Boltzman's constant, T is the temperature in kelvins, and n is an idealization factor which relates to the quality of the junction (References 1, 2). The diode saturation current is related to the diode material parameters. This current is given in standard textbooks (Reference 2) as follows:

$$I_o = en_i^2 A_J\left(\frac{\sqrt{D_n/\tau_n}}{N_A} + \frac{\sqrt{D_p/\tau_n}}{N_D}\right) \quad (2)$$

where D_n, D_p are the diffusion constants, τ_n, τ_p are the carrier lifetimes, N_A, N_D are the impurity carrier concentrations in each region, and A_J is the junction area.

2.1.2 Photogeneration Current, I_g

The photogeneration current can be found by analyzing the above circuit. Applying Kirchoff's laws, the load current J can be written as:

$$I = I_g - I_0\left[\exp\left(\frac{e\,(V + IR_{sr})}{nkT}\right)-1\right] - \frac{(V + IR_{sr})}{R_{sh}} \quad (3)$$

where all quantities are as defined above.

The photogeneration current is related to the short circuit current of the illuminated cell. The short circuit current can be found by setting the output voltage V in the circuit to zero (V = 0). The result of this calculation is

$$I_{sc} \cong I_g - I_0\left[\exp\left(\frac{eI_{sc}R_{sr}}{nkT}\right)-1\right] - \frac{I_{sc}R_{sr}}{R_{sh}} \quad (4)$$

where I_{sc} is the short circuit current.

For the usual case of well-constructed solar cells, R_{sr} is approximately 0.5 ohms, and R_{sh} is approximately 10^4 ohms (References 3 and 4). Under these conditions, I_{sc} is a good approximation of I_g.

2.1.3 Open Circuit Voltage, V_{oc}

The open circuit voltage is the output voltage as the load resistance approaches infinity. To find a usable expression for the open circuit voltage, consider Eq. (3), which describes the output current for the solar cell equivalent circuit. The open circuit voltage is found by setting the load current, I, of Eq. (3) equal to zero.

Under the condition that the shunt current, I_{sh}, is small with respect to the diode short circuit current, the form for the open circuit voltage is given as

$$V_{0c} \cong \left(\frac{nkT}{e}\right) \ln \left(\frac{I_{sc}}{I_0}\right) \quad . \tag{5}$$

2.2 DATA COLLECTION

Physitron was provided a description of the solar cells to be analyzed. Both types are silicon, n-on-p, manufactured by Applied Solar Energy Corporation. The thick type (8 mil) was tested with a variety of covers. The thin type (2 mil) was tested with a single 2 mil thick microsheet cover. The solar cell descriptions are shown in Table 1.

The LDEF environment included cosmic rays, protons, neutrons, and electrons. The principal contributors to the effects in the solar cells were electrons and protons. A tabulation of those environments is shown in Table 2. The proton fluence was on the order of 10^9 per cm^2 with energies ranging from 0.5 to 200 MeV. The electron fluence ranged from 10^8 to 10^{12} per cm^2 with energies between 0.5 to 3 MeV.

One notes from the table that the electron dose dominates at the surface, with a value of approximately 2.53×10^6 rads at the surface. The LDEF mission had one uncovered solar cell, which therefore would experience the maximum damage from the electron fluence at the surface. The surface fluence can be estimated from this equivalent 1 MeV electron dose to be approximately 5×10^{14} electrons/cm^2. This fluence can be used to estimate the solar cell degradation.

2.3 RADIATION EFFECTS

The effects of ionizing radiation on solar cells is primarily due to degradation in minority carrier lifetimes resulting from lattice damage and recombination center creation.

Table 1. Solar Cell Descriptions

I. Thick Solar Cells

Manufacturer: Applied Solar Energy Corporation
Size: 2 x 4 cm, 8 mil thick
Type: Silicon, n-on-p, 2 ohm-cm, junction depth about 0.25 micron
Contacts: Chemical vapor deposited dielectric wraparound "N" pad at back center of cell, Ti-Pd-Ag material.
Dual anti-reflectance coatings
Aluminum back surface reflector contact thickness ~6 microns minimum
No back surface field

a. No cover
b. 6 mil thick 0211 microsheet
   Manufactured by OCLI
   Anti-reflectance coating only
   DC 93-500 cover adhesive ~ 2 mils thick
c. 6 mil thick 0211 microsheet
   Manufactured by OCLI
   Anti-reflectance coating, ultraviolet filter - 350 nm
   DC 93-500 cover adhesive
d. 6 mil thick frosted (etched) fused silica cover
   Manufactured by OCLI
   Anti-reflectance coating, ultraviolet filter - 350 nm
   DC 93-500 cover adhesive
e. 6 mil thick fused silica cover
   Manufactured by OCLI
   Anti-reflectance coating, ultraviolet filter - 350 nm
   DC 93-500 cover adhesive
f. 6 mil thick microsheet (12 cell module back side exposed)
   Manufactured by OCLI
   Anti-reflectance coating, ultraviolet filter - 350 nm
   DC 93-500 cover adhesive
   Mounted with solar cell modules face down
   Exposed surface is 1 oz. rolled annealed copper printed circuit with anti-tarnish coating encapsulated between 2 sheets of 1 mil Kapton H film, 0.5 mil high temperature polyester adhesive. The solar cells are bonded to the copper interconnect using parallel gap electric resistance welding. The solar cells are bonded to the Kapton substrate using two strips of double back 3M Isotac acrylic adhesive.

II. Thin Solar Cells

Manufacturer: Applied Solar Energy Corporation
Size: 2 x 4 cm, 2 mil thick
Type: Silicon, n-on-p, 10 ohm-cm
Contacts: Junction wraparound, Ti-Pd-Ag materials (≈ 0.25 micron thick)
Dual anti-reflectance coatings
No back surface reflector
Back surface field
2 mil thick microsheet cover
   Manufactured by Pilkington P.E. Limited
   No coatings or filters
   DC 93-500 cover adhesive

Table 2. Dose LDEF Mission Caused by Trapped Protons and Electrons Behind an Aluminum Slab

Thickness (gm/cm^2)	Electrons (rads)	Protons (rads)	Total (rads)
0	2.53×10^6	1340	2.5×10^6
0.05	3680	560	4240
0.1	1150	488	1640
0.2	310	418	728
0.3	130	380	511
0.4	69	355	424
0.5	40.9	335	376
1.0	4.13	274	278
2.0	0.99	212	212
5.0	0.0583	130	130
10.0	0.0296	75.3	75.3
20.0		35.0	35.0
30.0		19.6	19.6
40.0		12	12

2.3.1 Short Circuit Current, I_{sc}, Radiation Degradation

First, one notes that the short circuit current for the solar cell can be approximated by a log-linear curve fit. As shown in Figure 2, the form for I_{sc} can be found experimentally to fit the equation:

$$I_{sc} = a \ln(L) + b \tag{6}$$

where L can be identified as the cell diffusion length and a, b are experimentally determined constants. One notes that the diffusion length is given by:

$$L = \sqrt{D\tau} \tag{7}$$

where D is the diffusion constant and τ is the minority carrier lifetime.

To determine the radiation response, one can use the usual lifetime degradation response given by:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + K_\tau \Phi \tag{8}$$

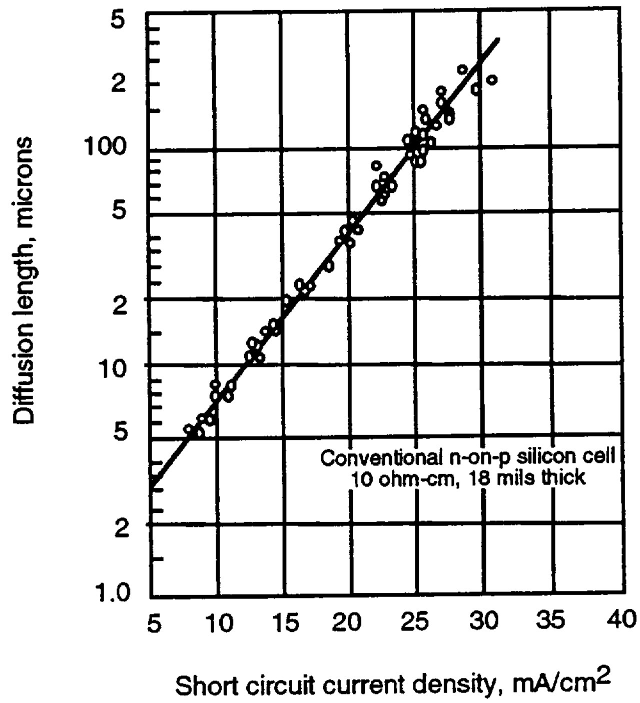


Figure 2. Minority Carrier Diffusion Length vs. Short Circuit Current Density of Conventional n-on-p Silicon Solar Cells

where K_τ is a lifetime damage constant and Φ is a fluence of particles. Φ can represent proton fluence or electron fluence.

To interpret this in terms of solar cell response, we combine the lifetime damage equation with the definition of diffusion length. The resulting equation,

$$\frac{1}{L^2} = \frac{1}{L_0^2} + K\Phi \tag{9}$$

provides an expression for the degradation of the diffusion length. The factor, K, is the diffusion length damage constant. Values for the damage coefficients can be determined from the literature. Table 3 gives some typical values (Reference 2).

Table 3. Lifetime Damage Constants for Neutrons, Electrons and Protons (References 2 and 5)

Substrate Resistivity (ohm-cm)	1 MeV Neutron Damage Constants K_τ (cm^2/s)	
	Injection Level	
	1×10^{-3}	1×10^{-1}
n-type		
1	5×10^{-6}	2×10^{-6}
10	3×10^{-6}	5×10^{-7}
p-type		
1	2×10^{-6}	5×10^{-7}
10	2×10^{-6}	5×10^{-7}
	20 MeV Proton Damage Constants K_τ (cm^2/s)	
n-type		
1	$\sim 5 \times 10^{-6}$	$\sim 2 \times 10^{-6}$
10		$\sim 5 \times 10^{-6}$
p-type		
1	$\sim 2 \times 10^{-6}$	$\sim 1 \times 10^{-6}$
10		$\sim 5 \times 10^{-6}$
	3 MeV Electron Damage Constants K_τ (cm^2/s)	
n-type		
1	$\sim 2 \times 10^{-7}$	$\sim 5 \times 10^{-8}$
10	$\sim 5 \times 10^{-8}$	$\sim 1 \times 10^{-8}$
p-type		
1	$\sim 3 \times 10^{-8}$	$\sim 5 \times 10^{-9}$
10	$\sim 1 \times 10^{-8}$	$\sim 3 \times 10^{-9}$

A typical constant for 1 MeV electron on an n-on-p solar cell structure is 1.7×10^{-10}. Using a typical starting diffusion length for electrons in p material of 100 µm gives the curve shown in Figure 3.

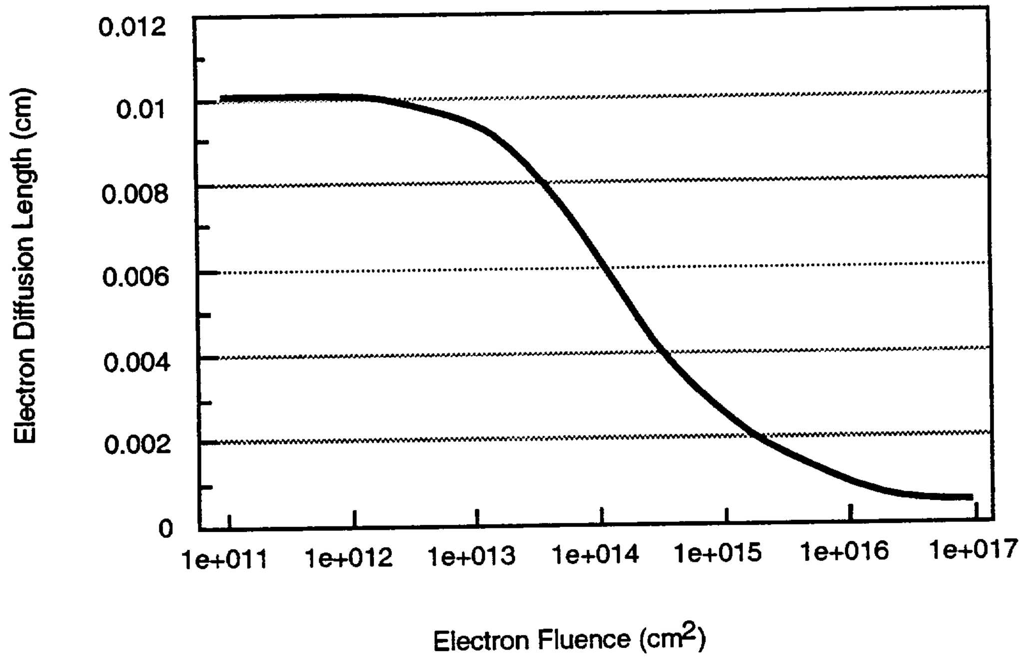


Figure 3. Minority Diffusion Length in p Material

2.4 ANALYSIS

At low photon energies (wavelengths longer than the junction depth of the solar cell), most of the solar cell current originates from diffusion charge collection from the back-side material. For an n-on-p solar cell, the device of study here, this collection will be electrons (minority carriers) diffusing from the p-type substrate material to the junction region. For these devices, the junction depth is approximately 0.25 μm.

The peak of the natural solar energy spectrum occurs in the blue light region, i.e., wavelengths around 0.5 μm. Since this is where most of the solar cell energy originates, we will use 0.5 μm as the wavelength of interest here. Since this wavelength is longer than the 0.25 μm junction depth, we assume long wavelength conditions apply. The generated photocurrent density due to the electron diffusion in the p-type region is given by (Reference 5):

$$J_n = \frac{qF\,(1-R)\,\alpha L_n}{\alpha^2 L_n^2 - 1} \exp\left[-\alpha(X_j + W)\right]$$

$$\left\{ \alpha L_n - \frac{\frac{S_n L_n}{D_n}\left[\cosh\left(\frac{H}{L_n}\right) - \exp(-\alpha H)\right] + \sinh\left(\frac{H}{L_n}\right) + \alpha L_n \exp(-\alpha H)}{\left(\frac{S_n L_n}{D_n}\right)\sinh\left(\frac{H}{L_n}\right) + \cosh\left(\frac{H}{L_n}\right)} \right\} \quad (10)$$

where

α = the optical absorption coefficient which can range from 10^3 to 10^4 cm^{-1} for wavelengths of 0.9 to 0.5 μm. Since we are most concerned with the blue solar energy peak at a wavelength of 0.5 μm, we will use 10^4 cm^{-1} for α, but this report presents results for this value as well as 5 x 10^3 and 10^3 cm^{-1} for comparison;

F = the photon flux striking the solar cell. At the one solar constant level of radiation at the earth (1353 W/m^2) with an air mass factor of zero (no atmospheric attenuation), the solar flux can be approximated as 2.5 x 10^{17} photons/cm^2/sec in the blue light region;

R = the fraction of photons reflected from the surface, we will arbitrarily assume about 20% reflection;

q = the electronic charge;

L_n = the diffusion length of electrons in the p material;

X_j = the n-p junction depth in cm;

W = the depletion region width in cm;

S_n = the surface recombination velocity at the back surface, usually a large number approaching infinity. Here we used a value of 1 x 10^8 with good results. The results shown below do not depend heavily on this number;

D_n = the diffusion constant of electrons in the p region; and

H = the p region depth.

In order to gain best estimate approximations for some of these parameters, we used the solar cell information provided for the thick cells. Based on the resistivity of 2 ohm-cm, we can approximate the acceptor doping level of the p region as 6 x 10^{15} cm^{-3}. Using this doping level and assuming an abrupt junction at the n-p interface, the depletion region width will be 0.4 μm. Also, the diffusion coefficient will be approximately 1,500 cm^2/sec. The 8 mil thick layer corresponds to 203.2 μm. The junction depth is 0.25 μm. These numbers give us a starting point for rough photocurrent calculations using Eq. (10).

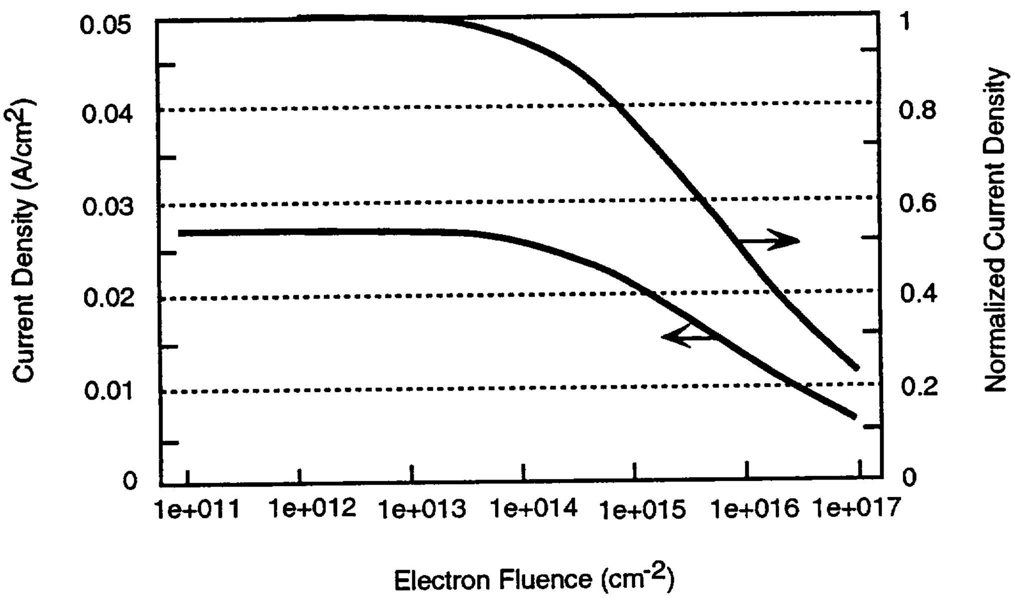
Note the {exp(-αH)} terms in Eq. (10). For the values given above, these terms are approximately 1.5 x 10^{-9}. Compared to the other terms in the equation, these terms are negligibly small and can be ignored. Thus, Eq. (10) can be reduced to:

$$J_n \cong \frac{qF(1-R)\,\alpha L_n}{\alpha^2 L_n^2 - 1} \exp\left[-\alpha(X_j + W)\right] \left\{ \alpha L_n - \frac{\frac{S_n L_n}{D_n}\cosh\left(\frac{H}{L_n}\right) + \sinh\frac{H}{L_n}}{\left(\frac{S_n L_n}{D_n}\right)\sinh\left(\frac{H}{L_n}\right) + \cosh\left(\frac{H}{L_n}\right)} \right\} \quad (11)$$

Using the values given above, the results of Figure 3 and Eq. (11), we can plot the short-circuit current density for the solar cell as a function of electron fluence for several α values. Since the solar cells are exposed to an entire spectrum of radiation, a single value of α is probably not an ideal model for the exposure. However, the α value of 104 cm-1 approximates the blue light peak of the spectrum and can be used as a good comparative parameter in the investigation of degradation with electron exposure. These plots for α values of 10^3, 5 x 10^3, and 10^4 are shown in Figures 4 through 6.

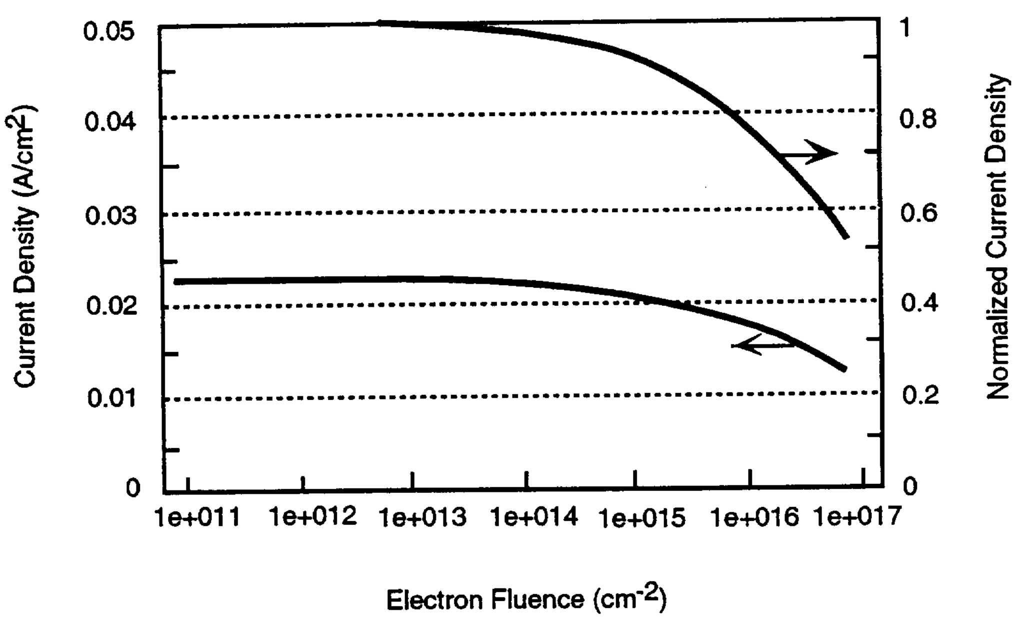
The photon flux impinging on the solar cell (F) and the reflection ratio (R) in Eq. (11) are highly variable and dependent on the orbit altitude, energy spectrum reaching the cell, as well as the physical construction of the solar cell itself. However, the degradation of the cell output with electron exposure can be determined without relying on these parameters by defining a relative (or normalized) short-circuit current density. If Eq. (11) at the electron exposure level of interest is normalized by the current density at zero electron exposure, the parameter F, R, and q are normalized out. The resulting equation is given by:

$$\frac{J_X}{J_0} = \frac{L_{nX}}{L_{n0}} \cdot \frac{\alpha^2 L_{n0}^2 - 1}{\alpha^2 L_{nX}^2 - 1} \cdot \left[\frac{\alpha L_{nX} - \dfrac{\frac{S_n L_{nX}}{D_n}\cosh\left(\frac{H}{L_{nX}}\right) + \sinh\left(\frac{H}{L_{nX}}\right)}{\frac{S_n L_{nX}}{D_n}\sinh\left(\frac{H}{L_{nX}}\right) + \cosh\left(\frac{H}{L_{nX}}\right)}}{\alpha L_{n0} - \dfrac{\frac{S_n L_{n0}}{D_n}\cosh\left(\frac{H}{L_{n0}}\right) + \sinh\left(\frac{H}{L_{n0}}\right)}{\frac{S_n L_{n0}}{D_n}\sinh\left(\frac{H}{L_{n0}}\right) + \cosh\left(\frac{H}{L_{n0}}\right)}} \right] \quad (12)$$



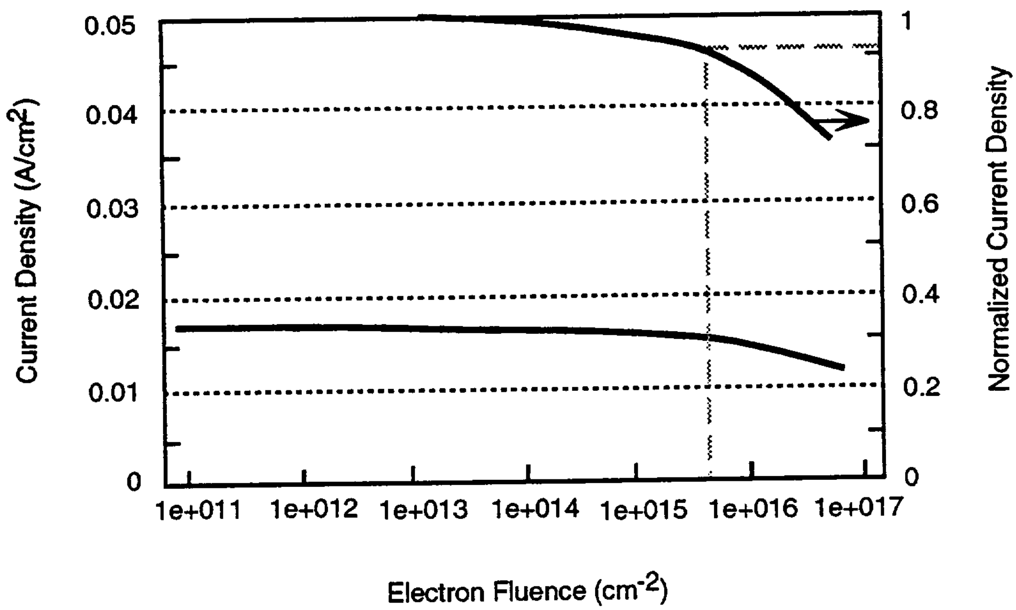
($\lambda \approx 0.9\ \mu m$)

Figure 4. Short-circuit Current Density (Absolute and Relative)



($\lambda \approx 0.6\ \mu m$)

Figure 5. Short-circuit Current Density (Absolute and Relative)



(λ ≈ 0.5 μm)

Figure 6. Short-circuit Current Density (Absolute and Relative)

where

J_X = the current density at the electron exposure level of interest,

J_0 = the current density at zero radiation exposure,

L_{n0} = the diffusion length at zero electron exposure, and

L_{nX} = the diffusion length at the electron fluence of interest, as given in Figure 3.

Using Eq. (12), a percentage degradation in the output short-circuit current density can be estimated without relying on the highly unpredictable parameters of F and R. These results are shown in Figures 4 through 6 by the right-hand axis.

3.0 RESULTS

Using the approximation of a blue-light peak ($\alpha = 10^4$), it can be seen from Figure 6 that electron degradation does not begin until an approximate fluence of 10^{14} cm^{-2}. At the fluence of interest here, i.e., 5×10^{14} cm^{-2}, it can be seen from Figure 6 that a degradation of approximately 10% is expected in the short-circuit density output of the solar cell of this study. That is, the generated photocurrent is reduced to 0.9 of its original, pre-radiation value. In terms of power output, this would be expected to roughly correspond to a power output of $(0.9)^2$, or 0.81, with respect to the original power output. Thus, these rough calculations predict an approximate 19% degradation in power output for this cell at an electron fluence of 5×10^{14} cm^{-2}. The results show that at higher electron fluences, degradation is expected to increase exponentially. For example, at an electron fluence of 1×10^{17} cm^{-2}, the relative current density given by Figure 6 is approximately 0.7. This would correspond to a power degradation of approximately 50%. Even worse degradations are evident in the curves for lower absorption parameters, i.e., longer wavelengths.

This analysis has been based on the 1 MeV electron equivalency environment. Variations in the solar cell base resistivity and thickness can cause variations in response to the radiation. In addition, protons with energies less than 5 MeV may deposit entirely in the solar cell (especially the thicker ones) and cause significant damage. The good news is that cover glasses can, and usually do, stop a significant portion of the particles with energies that are the most damaging.

In general, for maximum radiation hardness, solar cells with low base resistivity should be used. In addition, a large initial diffusion length minimizes the degradation in overall performance due to a radiation-induced decrease in that diffusion length.

4.0 CONCLUSIONS

The solar cells on LDEF were exposed to much higher fluences than originally planned, providing a unique opportunity to study long-term environmental effects on their operability. In order to bound the effects due to the radiation environment (electrons and protons), Physitron has predicted the degradation in a typical thick solar cell from Applied Solar Energy Corporation due to the radiation on an uncovered cell. The analysis shows that a power degradation on the order of 20% is what would be expected from the environment of 5×10^{14} cm^2. Although no explicit calculation was performed for the thin cell, one might predict a somewhat greater degradation due to their higher base resistivity and the back surface field, which can be very sensitive to radiation effects. All cells with cover sheets should experience minimal radiation degradation due to the filtering effect. The same would be true of the cells that had their back surface exposed.

In conclusion, this analysis does not reveal any unexpected effects in the solar cell performance due to the radiation exposure. By using cover glass and selecting cells with low base resistivity and large diffusion lengths, any long-term degradation effects due to the radiation environment should be minimized.

5.0 RECOMMENDATIONS

The foregoing analysis is useful from the perspective of drawing a direct comparison between theoretical and empirical behavior. The fairly close agreement between the observed and predicted behavior of the LDEF solar cells enhances confidence with which such calculations can be made in the future. Clearly, highly reliable behavior models and predictive techniques enable greater precision during the parts selection process. Ultimately, this is important when making trade-off decisions between cost, system requirements, and performance margin.

Three recommendations are made relative to this effort and possible follow-on activities.

(1) Similar calculations can be run for a broader range of technologies for the purpose of developing enhancements to the model provided in this report.

(2) An evaluation can be performed on currently available solar cell technologies and designs with respect to ionizing dose response. As appropriate, predicted behavior could be supported with existing mission data and laboratory testing. Physitron has the capability of conducting low dose-rate laboratory testing of this type. Findings from this effort would be provided to NASA in the form of an automated database and/or in written form.

(3) A first-principles, automated predictive model could be developed for use by NASA scientists and engineers. Such a model could be in a desktop (PC/Macintosh) environment and would enable the user to perform "quick-look" predictions for specific technologies of interest.

Physitron is pleased to provide this report and looks forward to supporting NASA in the future as may be warranted.

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An analysis to determine the effects of the LDEF ionizing radiation environment on solar cell performance was done. For unprotected cells, power loss of approximately 20% is estimated. Cells with cover glass are expected to see much smaller degradation.

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