Solar Cell Degradation under 1-Mev Electron Bombardment

By W. ROSENZWEIG, H. K. GUMMEL and F. M. SMITS

(Manuscript received July 23, 1962)

The effect of radiation damage on the important parameters of solar cells has been evaluated for groups of blue-sensitive n-on-p, normal p-on-n, and blue-sensitive p-on-n cells using 1-Mev electrons. The outer space short circuit current, maximum power, junction characteristic, and spectral response are presented quantitatively as a function of radiation flux along with the bulk minority-carrier diffusion length.

The rate of change of inverse squared diffusion length with flux is found to be 1.22×10^{-8} *for the p-on-n cells, as compared to* 1.7×10^{-10} *for the n-on-p. The degradation of the spectral response is consistent with the measured diffusion length for both types of cells if one assumes a total effective front layer of 1 μ thickness for the p-on-n cells.*

As a result of the less rapid degradation of their minority-carrier lifetime, the n-on-p cells exhibit a greater resistance to radiation than the p-on-n cells. Comparing only the two types of blue-sensitive cells, after prolonged bombardment, the flux ratios required to achieve equal values of short-circuit current and maximum power are 17 and 9.5 respectively.

I. INTRODUCTION

The high-energy electron and proton radiation in the Van Allen Belt produces defects in semiconductors which cause a reduction in solar cell power output. This raises immediately the problem of assessing the expected useful life of the power plant of a satellite that passes through this radiation belt. The life is the time for which the power plant is capable of delivering the electrical power necessary for successful operation of the satellite.

For an evaluation one has to determine the maximum power point under outer space solar illumination after various amounts of bombardment by protons of differing energies and by electrons of differing energies, with various thicknesses of shielding over the cells. Such information may then be synthesized to yield the expected performance for a given Van Allen Belt spectrum under given shielding conditions. An attempt at a direct experimental investigation of these relations has the disadvantage of being exceedingly complex and involved. However, the complexity of this problem can be significantly reduced by recognizing that the solar cell performance is strongly dependent on the minority-carrier lifetime in the bulk of the material. This minority-carrier lifetime is ordinarily the most radiation-sensitive parameter in a semiconductor, and a solar cell will, practically speaking, be useless due to minority-carrier lifetime degradation before any of the other determining parameters are significantly affected by radiation.

The performance of a given type of solar cell after irradiation is determined almost entirely by the minority-carrier lifetime remaining after the irradiation, rather than by the type of radiation responsible for the lifetime degradation. The different radiations might cause degradations that lead to differences in temperature dependence of the solar cell performance. However, such differences, if present, can be expected to be unimportant for most practical applications.

These considerations imply that relative damage rates can be established for protons and electrons of various energies, from which the radiation damage due to the complex particle spectrum in the Van Allen Belt can be related to the radiation damage under any one monoenergetic radiation.

The problem can thus be divided into two broad studies. One is the detailed study of the solar cell characteristics, i.e. short-circuit current, maximum power, etc., as a function of exposure to a conveniently available monoenergetic radiation. The other is an investigation of the relative damage rates for the various radiations, from which a monoenergetic flux can be derived which is equivalent in radiation damage to the complex Van Allen spectrum.

With the over-all solar cell performance depending on a variety of process variables, a statistical experiment is advisable for the first part so that the effects of variations in solar cell structure are averaged.

For the investigation of the relative damage rates for the various radiations it is desirable to study the degradation of the minority-carrier lifetime, or of a quantity that is directly related to the minority-carrier lifetime, such as the minority-carrier diffusion length. Since this quantity is a bulk property of the material one is concerned with only one variable. In addition, since all the solar cell parameters are smoothly varying functions of the diffusion length, and the diffusion length varies with flux in a known way [see (1) below], one can perform useful interpolations and extrapolations on the values of the parameters to extremely low and high radiation fluxes.

This paper is devoted to the first part of such an over-all evaluation, i.e. the determination of the degradation of the important cell parameters on bombardment with radiation of one kind. It describes an experiment in which solar cell performance as a function of 1-Mev electron irradiation was investigated for samples large enough to give good statistical results. For comparison blue-sensitive n-on-p solar cells, blue-sensitive p-on-n, and normal p-on-n solar cells were studied.

First the details of the electron irradiations are given, followed by a general description of the performance tests at the various stages of the bombardment. The final sections summarize the results and give the conclusions of the experiment.

II. ELECTRON IRRADIATIONS AND DIFFUSION LENGTH MEASUREMENTS

The evaluation of solar cell performance was carried out with a 1-Mev electron Van de Graaff generator with the external beam scattered by a total of 5.5 mils of aluminum and 5 inches of air. Groups of 16 or more solar cells of the following types were used:

1. Blue-sensitive n-on-p cells produced by the Western Electric Company. These cells were randomly selected from a lot of 10,000 cells having an efficiency greater than 7.5 per cent under outer space light.
2. Normal p-on-n cells secured from a commercial source and rated as 14 per cent efficient under tungsten light.
3. Blue-sensitive p-on-n cells secured from a commercial source rated as 12 per cent efficient under outer space light.

To achieve uniform exposure for all cells, the solar cells were mounted near the perimeter of an aluminum disc which was continuously rotated during the irradiations in such a way that the cells passed through the center of the beam. The electron beam intensity was calibrated with a vacuum Faraday cup located on the beam axis at the same distance from the beam exit window as that at which the cells were irradiated. The irradiation duty cycle on the rotating wheel was measured by using a prebombarded solar cell as radiation intensity monitor[1] measuring the integrated exposure per turn referred to the center of the beam. The purpose of the prebombardment was to keep the cell diffusion length from changing during the measurement. The exposures were monitored with the Faraday cup positioned near the edge of the wheel off the beam axis.

The cells were irradiated in five steps to integrated fluxes of 1.8×10^{13},

9.0×10^{13}, 5.4×10^{14}, 2.7×10^{15}, and 1.8×10^{16} electrons/cm². Before the first and after each successive bombardment the cells were subjected to optical and electrical measurements by methods described in the next section. In addition to these measurements the minority-carrier diffusion length was also determined for each cell by measuring the short-circuit current response of the solar cells under a low intensity 1-Mev electron beam filtered by 12 mils of aluminum placed directly over the cell.[2] Under this condition excess carriers are generated uniformly throughout the bulk of the cell at a rate of 225 pairs/μ per incident electron. Except at very short diffusion lengths as discussed below, the short-circuit current thus obtained is proportional to the diffusion length.

These diffusion length measurements permit a correlation between the results reported here and the radiation damage effects of other radiations.

III. MEASUREMENT OF SOLAR CELL PARAMETERS AND OUTER SPACE CALCULATIONS

The ultimate criterion for the performance of a solar power plant is the power it can deliver after a substantial exposure to radiation, regardless of the initial performance. This requires that the absolute performance of the solar cells under outer space illumination be studied. To permit the performance of such tests in the laboratory a solar cell test facility has been developed which is described in detail elsewhere.[3]

Prior to bombardments and after each bombardment step, all cells were tested in this facility. A set of control cells was kept with the cells under study and received the same handling except for the bombardments. These control cells were tested, interspersed among sample cells, each time the sample cells were tested. In this way, the stability of the test facility was monitored and corrections for small drifts could be applied. The largest corrections necessary amounted to about 1 per cent.

In the test facility the quantum efficiency, defined as electrons delivered into a short circuit per incident photon, is measured at eight wavelengths between 0.4 and 0.95 μ. Also, under a "white light" source of intensity approximately equal to outer space sunlight, short-circuit current, open-circuit voltage, and voltage across a 10-ohm load are measured. These quantities define the forward current-voltage characteristic of the diode. Some additional tests, such as a reverse leakage measurement, and the cell voltage for a 50-ma injected forward current in the dark are also performed.

The results of these measurements are automatically recorded on IBM cards and processed on an IBM 7090 computer.

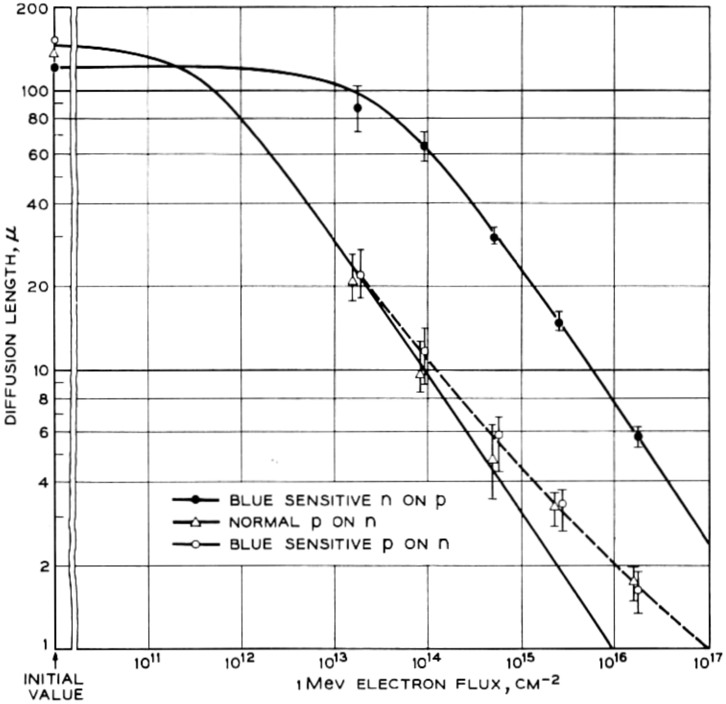

Fig. 1 — Diffusion length versus 1-Mev electron flux.

The outer space short-circuit current is computed from the quantum efficiencies. The remainder of the measurements are used to obtain the output characteristics of the cell corresponding to the outer space illumination and the maximum power point. Averages of the results are formed for each group. Generally, only these averages are quoted in the following section.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The results of the various measurements are presented in Figs. 1–11. A plot of the mean diffusion length in microns as a function of the integrated electron flux is given in Fig. 1. The limits placed around each point indicate not the experimental error but the rms deviation from the mean of the measured quantity for the given sample. It is to be noted that the deviation for the n-on-p cells becomes smaller as the flux is increased, indicating that the damage rates are quite similar for the cells in the entire sample.

The diffusion length is expected to decrease according to the equation

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

in which Φ is the bombardment flux in cm^{-2}, L is the diffusion length in cm for that flux, and L_0 is the initial diffusion length. Equation (1) is an expression of the fact that the recombination rate of the excess minority carriers at any point in the bombardment is proportional to the initial number of recombination centers present plus the number introduced during the bombardment, the latter being proportional to the flux. The solid curve passing through the points for the n-on-p cells was computed using (1) with $L_0 = 119\ \mu$ and $K = 1.7 \times 10^{-10}$.

The experimental points for the p-on-n cells can be fitted, as shown in the dashed curve, by assuming a sensitive thickness consisting of the bulk diffusion length, as given by the solid line, and a one-micron

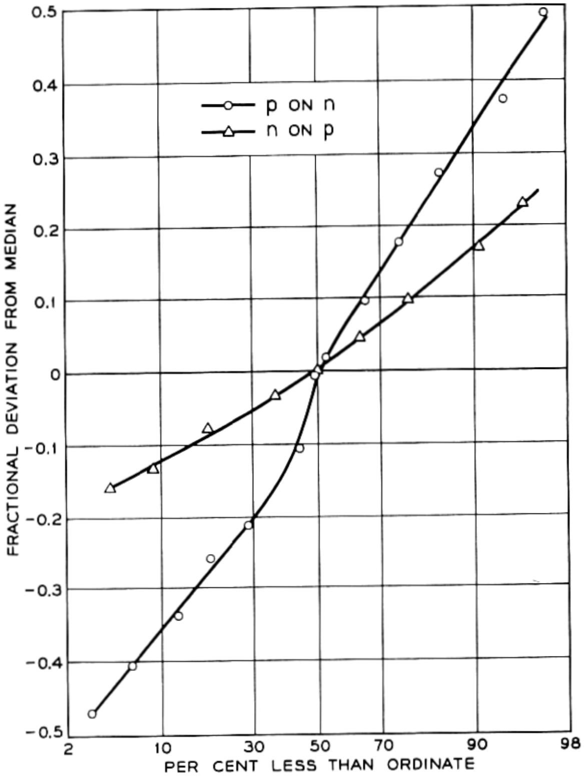

Fig. 2 — Statistical distribution of the degradation constant K.

thickness which represents the sum of the depletion layer and the sensitive region of the front layer. The solid curve was computed from (1) with $L_0 = 146\ \mu$ and $K = 1.22 \times 10^{-8}$. Capacitance measurements indicate a depletion layer thickness of 0.5 μ, leaving 0.5 μ for the front layer, which appears reasonable.

It is instructive to plot the deviation of the degradation constants K for the individual cells as compared to the median value. Such a plot is shown in Fig. 2. It can be seen that the n-on-p cells show a tighter distribution than the p-on-n cells. This suggests that there may be an uncontrolled variable in the bulk n-type material which affects the

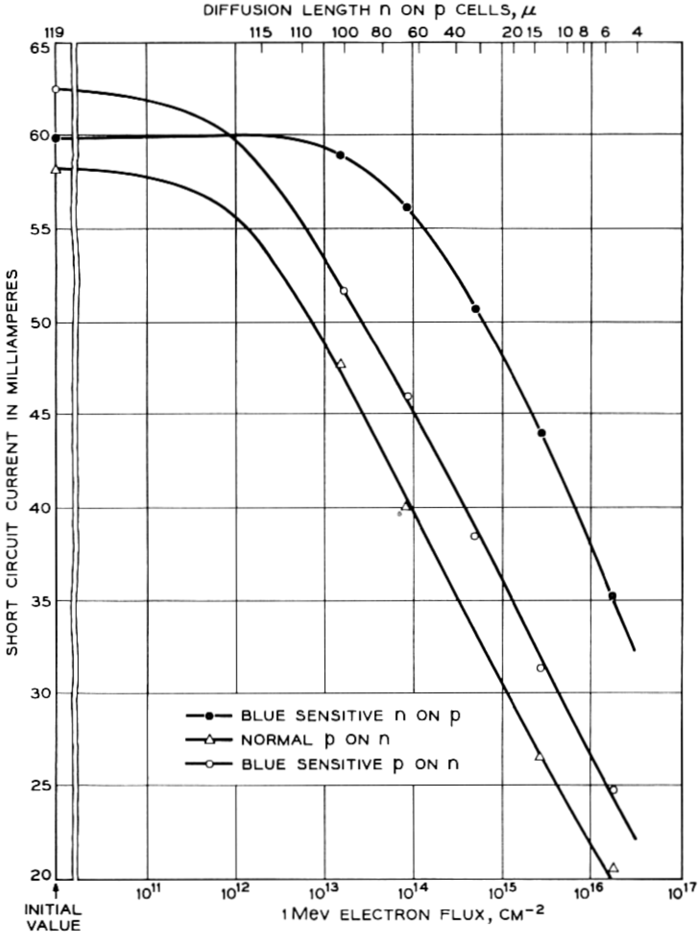

Fig. 3 — Outer space short circuit current versus 1-Mev electron flux.

sensitivity to particle radiation. This variable could possibly be the oxygen content of the material.

For the three types of solar cells the predicted mean outer space short-circuit current as a function of electron flux is given in Fig. 3. The results show that the radiation resistance of n-on-p cells is higher than that of p-on-n cells. The two types of cells reach the same short-circuit current for more than a factor of fifteen in electron exposure, which holds in spite of the fact that the n-on-p has initially a lower short-circuit current. This may be understood, qualitatively, by noting the greater rapidity with which the quantum efficiency, Figs. 4–6, degrades at the red end of the spectrum for the p-on-n cells as compared to the n-on-p. These curves also point out the significance of the spec-

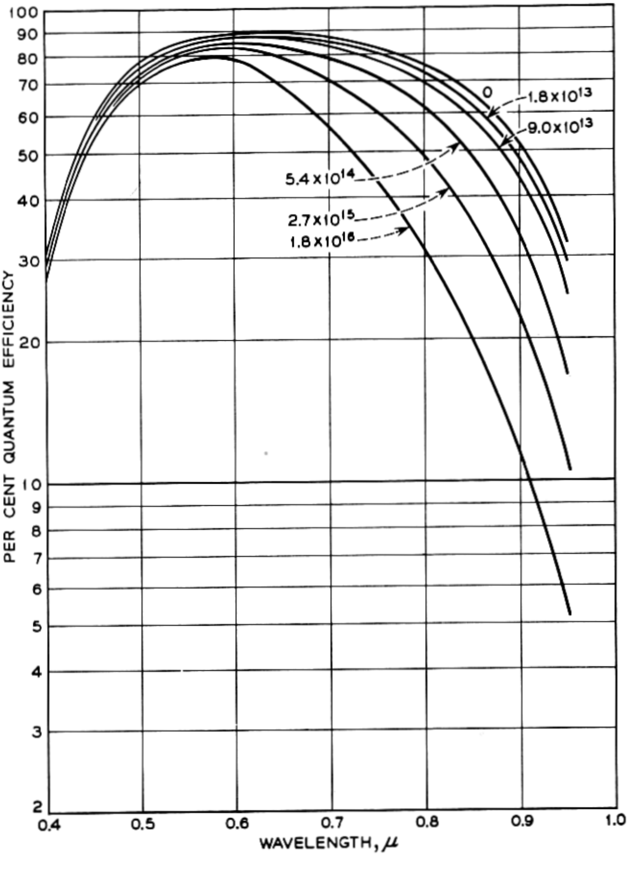

Fig. 4 — Per cent quantum efficiency versus wavelength after various levels of bombardment for blue-sensitive n-on-p cells.

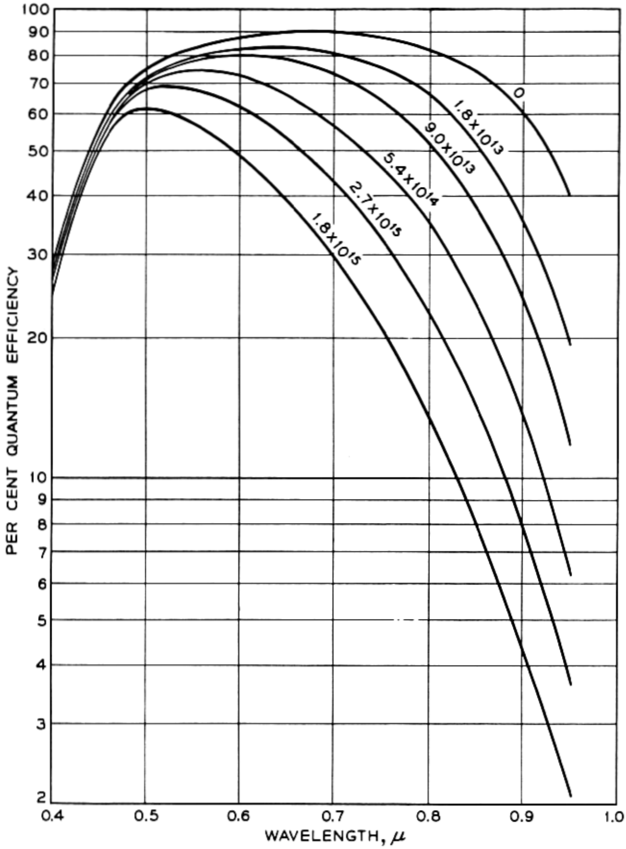

Fig. 5 — Per cent quantum efficiency versus wavelength after various levels of bombardment for normal p-on-n cells.

trum of the light source used to evaluate short circuit current degradation.

A better insight into the short-circuit current degradation may be obtained from the plots in Figs. 7–9. These show the measured contributions to the total short-circuit current for outer space sunlight falling into the indicated wavelength intervals as a function of bombardment flux. Since these contributions were measured by means of narrow-band filters centered in the indicated intervals one can compare the results with theoretical computations for monochromatic light.[4] The solid curves are the results of such computations carried out by means of (2) normalized to the initial experimental short circuit current contribution.

$$I_i = I_{Ni}\left[(1 - e^{-\alpha_i x_F}) + \frac{e^{-\alpha_i x_J}}{1 + \frac{1}{\alpha_i}\sqrt{\frac{1}{L_0^2} + K\Phi}}\right] \tag{2}$$

I_i = short-circuit current contribution for the *i*th wavelength.
α_i = absorption coefficient for the *i*th wavelength.
x_F = the effective front layer thickness for the collection of carriers produced by penetrating radiation.
x_J = junction depth.
I_{Ni} = normalization factor for the *i*th wavelength.

In (2), the first term within the large brackets represents the contribution due to carriers collected from the total front layer, and the second

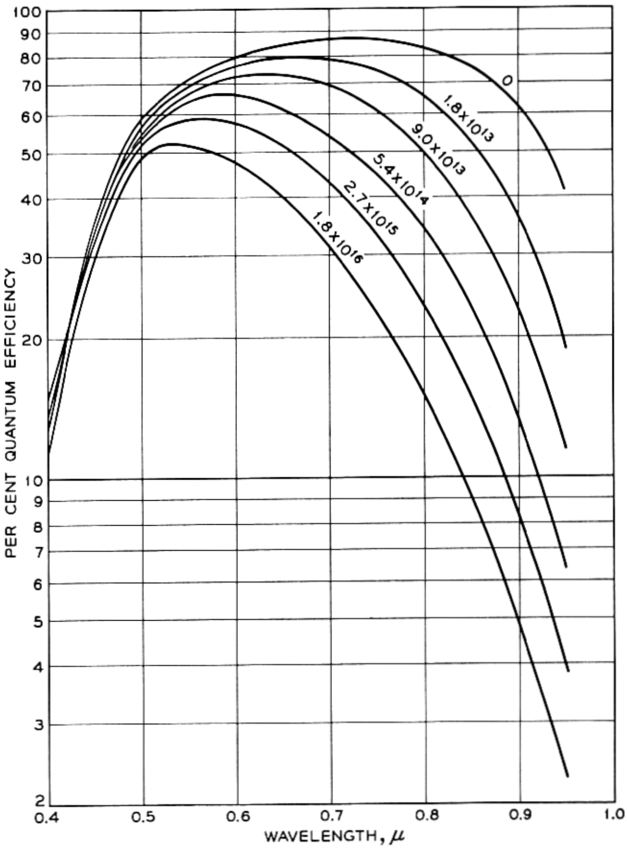

Fig. 6 — Per cent quantum efficiency versus wavelength after various levels of bombardment for blue-sensitive p-on-n cells.

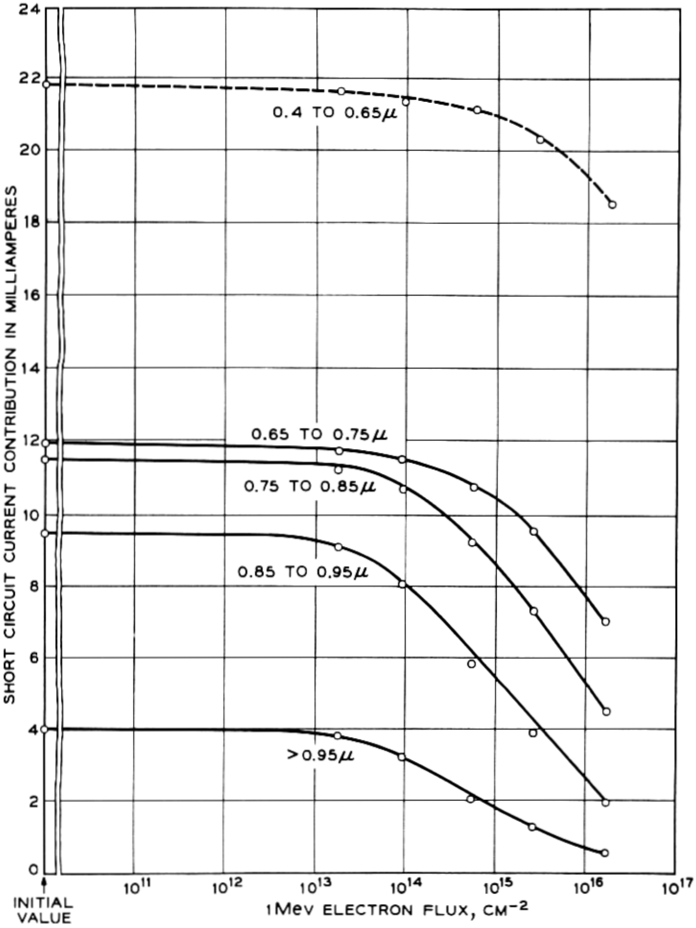

Fig. 7 — Contribution to outer space short-circuit current by sunlight in various wavelength intervals for n-on-p cells as a function of 1-Mev electron flux.

the contribution from the bulk. The effective thickness x_F is expected to be independent of wavelength only as long as $\alpha_i x_F \ll 1$. Thus, a comparison of the experimental points with (2) was made only for wavelengths greater than 0.65 μ. This wavelength region is the one in which the greatest changes are produced by radiation. The agreement between the theoretical model and the experimental points is noted to be good.

The predicted maximum power for outer space sunlight as a function of flux is given in Fig. 10. The decrease in maximum power with bom-

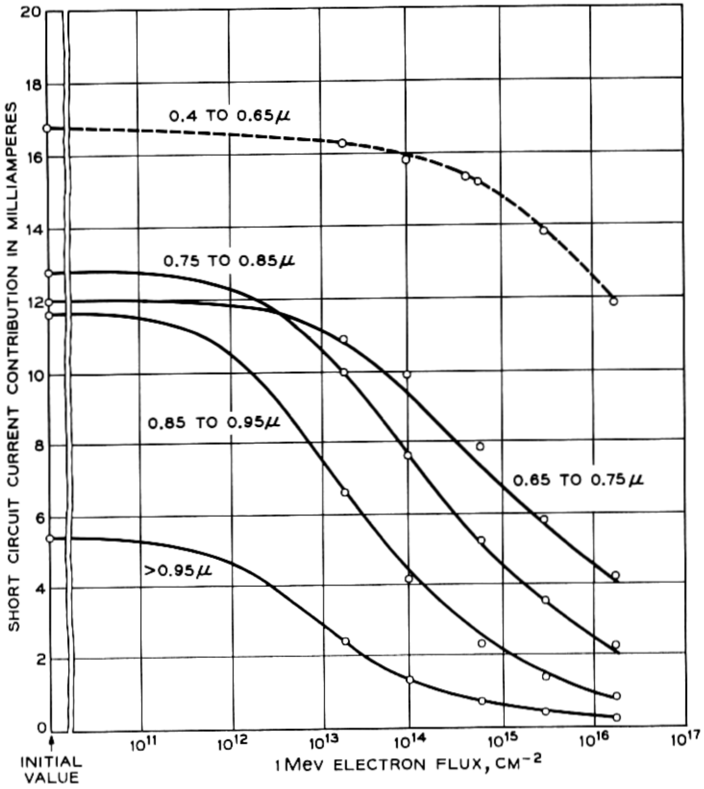

Fig. 8 — Contribution to outer space short-circuit current by sunlight in various wavelength intervals for normal p-on-n cells as a function of 1-Mev electron flux.

bardment is caused not only by the decrease in short-circuit current, but also by the degradation of the junction. A measure of the amount of this degradation is the decrease in the open-circuit voltage corresponding to a fixed short-circuit current. Fig. 11 is a plot of the open-circuit voltage corresponding to a short-circuit current of 50 ma as a function of 1-Mev electron flux.

These results may be analyzed by noting that over a limited range, the voltage-current relationship for the cell can be expressed by the formula

$$I = I_0 e^{(qV/nkT)} - I_{sc} \tag{3}$$

where I_{sc} is the short-circuit current, n is some number equal to or greater than one, and I_0 is a saturation current. I_0 increases as the minority-carrier lifetime decreases, causing the maximum power to decrease even for a fixed short-circuit current. I_0 varies as τ^{-m} with $m = \frac{1}{2}$ or $m = 1$ depending on whether the saturation current is diffusion limited or due to space charge recombination, respectively.

At sufficiently high fluxes the inverse lifetime is proportional to the flux, so that the slopes in Fig. 11 yield the values 2.3 $mnkT$. The slope for the n-on-p cells is 27 mv/decade and for the p-on-n 30 mv/decade. Both of these values are consistent with the pair of values $m \cong \frac{1}{2}$, $n \cong 1$. One can thus conclude that as far as the variation of diode

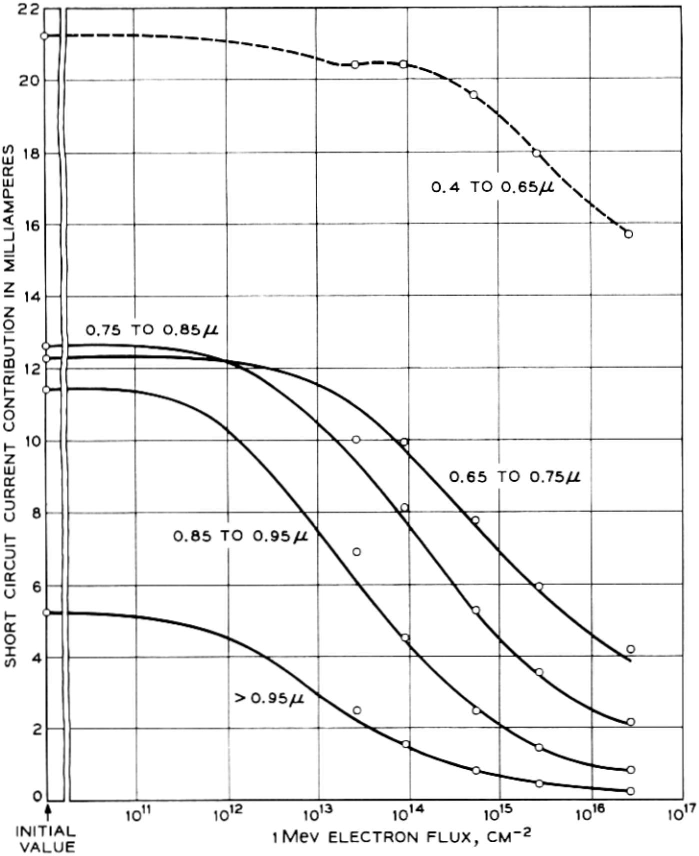

Fig. 9 — Contribution to outer space short-circuit current by sunlight in various wavelength intervals for blue-sensitive p-on-n cells as a function of 1-Mev electron flux.

characteristics with radiation damage is concerned, the solar cells behave as ideal diodes with diffusion-limited saturation currents (at current densities comparable to outer space short circuit currents).

Since the diffusion length variation with radiation follows a simple functional relation, its study is very suitable for finding relative radiation damage rates among different radiations. In essence, one needs to measure the K-values, as defined above, for protons as a function of

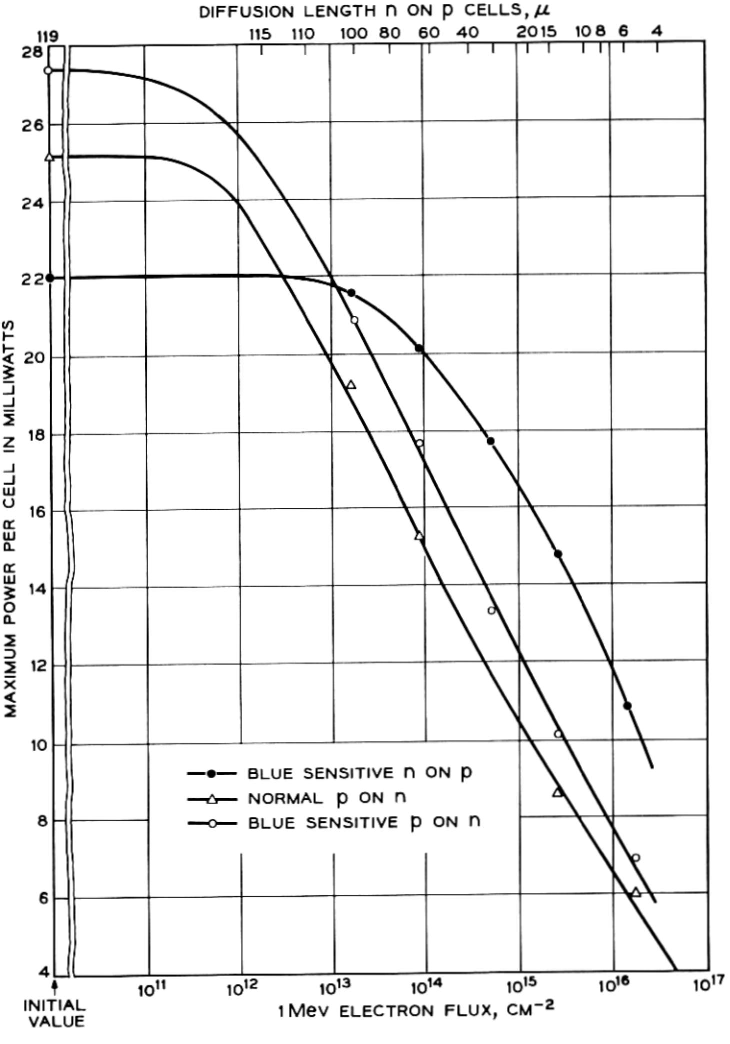

Fig. 10 — Maximum power versus 1-Mev electron flux.

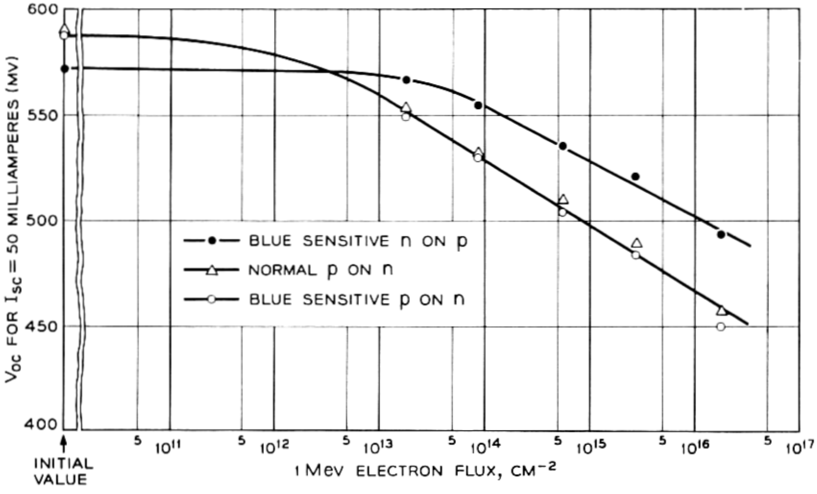

Fig. 11 — Open-circuit voltage corresponding to 50 ma short-circuit current versus 1-Mev electron flux.

energy, and for electrons as a function of energy and shielding thickness. The irradiation flux for each particle energy and shielding condition can then be converted to an equivalent 1-Mev electron flux by multiplying by the ratio of the K-values. This ratio can be termed as the "relative effectiveness" of the radiation with respect to the reference radiation, 1-Mev electrons in this instance. Thus, for example, if $R(E)$ is the ratio of K for n-on-p cells as a function of proton energy to K for 1-Mev electrons, and $\Phi(E)$ is the Van Allen Belt proton spectrum, averaged over some satellite orbit and shielding condition, in protons/(cm^{2}sec Mev), then

$$\Phi_e = \int_0^\infty R(E)\Phi(E)\,dE \tag{3}$$

where Φ_e is the equivalent 1-Mev electron flux density in electrons/(cm^2 sec). All the figures contained in this report may then have their flux scales converted to time scales. It is to be noted, however, that such a conversion is not the same for n-on-p and p-on-n cells, because the ratio of proton to electron damage is different for n-type and p-type material.

V. CONCLUSION

The effect of radiation on the important parameters governing the performance of solar cells has been evaluated for three classes of cells using 1-Mev electrons. The outer space short-circuit current, maximum power, junction characteristics, and spectral response have been presented quantitatively as a function of radiation flux along with the bulk minority-carrier diffusion length. The importance of the latter quantity is stressed as the unifying parameter which allows one to reduce fluxes of other types of radiation to equivalent fluxes of 1-Mev electrons.

In addition to supplying detailed engineering information, the results allow one to conclude the following:

The degradation in quantum efficiency at the longer wavelengths is quantitatively explained by the decrease in bulk minority-carrier diffusion length. The relatively small change in quantum efficiency at the short wavelengths suggests that surface recombination velocity and minority-carrier diffusion length in the front layer are not changed significantly by the radiation. The decrease in maximum power output is mainly due to the decrease in collection efficiency but to a smaller degree also to a degradation of the junction. The latter varies under forward bias with lifetime as an ideal diode with diffusion limited saturation current at current densities comparable to outer space conditions. The average relative fluxes required to achieve equal values for some of the parameters after prolonged bombardment, comparing only blue-sensitive cells, are shown in Table I.

TABLE I

Parameter	Flux Ratio (n-on-p relative to p-on-n)
Maximum power	9.5
Short circuit current	17
Diffusion length	72

VI. ACKNOWLEDGMENTS

The authors are very grateful to J. A. O'Sullivan, A. W. Norris, and K. R. Hill for their invaluable assistance in this work.

REFERENCES

1. Rosenzweig, W., Rev. Sci. Inst. **33,** 1962, p. 379.
2. Rosenzweig, W., Diffusion Length Measurement by Means of Ionizing Radiation, B.S.T.J., **41,** Sept. 1962, p. 1573.
3. Gummel, H. K., and Smits, F. M., to be submitted for publication in the B.S.T.J.
4. Kleinman, D. A., Considerations on the Solar Cell, B.S.T.J., **40,** January 1961, p. 85.