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SOLAR CELL RADIATION DAMAGE STUDIES WITH 1 MEV ELECTRONS AND 4.6 MEV PROTONS

by William R. Cherry and Luther W. Slifer

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Greenbelt, Maryland

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SUMMARY

The degradation of several types of solar cells irradiated with 1 Mev electrons in stages up to $10^{16}/cm^2$ was measured under standard tungsten illumination and also under air-mass-one sunlight illumination. The degradation of similar cells irradiated with 4.6 Mev protons in stages up to $3 \times 10^{11}/cm^2$ was measured under tungsten illumination. The solar cell types included P/N cells, N/P cells with various base resistivities from less than 1 ohm-cm to 25 ohm-cm, and drift field N/P cells.

The results showed that the N/P cells are conclusively more resistant to either type of radiation than the P/N cells and that, within the ranges of the experiments the N/P cells with higher base resistivity are more radiation resistant than those with lower base resistivity. The latter result is most pronounced with the electron-irradiated cells. The results also gave positive indication that the radiation resistance of solar cells is enhanced by the drift field construction.

CONTENTS

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(Manuscript Received June 17, 1963)

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INTRODUCTION

After the July 1962 Atomic Energy Commission Pacific tests, erratic behavior developed in several U. S. satellites in orbit. Subsequent analysis of data has revealed an enhanced radiation belt consisting primarily of high energy electrons at altitudes between 500 and 4,000 nautical miles.

The need for more radiation-resistant solar cells for NASA spacecraft frequenting the new man-made and the natural belts became apparent. A series of 1 ohm-cm N/P silicon solar cells which had been irradiated with 1 Mev electrons at doses ranging from zero to 10^{16} electrons/cm^2 was used to establish a damage rate specification (GSFC Spec 63-106).

During October and November 1962, state-of-the-art samples of N/P silicon solar cells were purchased from eight sources within the United States. A quantity of P/N silicon solar cells was also purchased for comparative purposes.

EXPERIMENT

In conjunction with personnel at the Naval Research Laboratory, an elaborate experiment was planned using 1 Mev electron and 4.6 Mev proton irradiations. A standard light source described in Appendix A was used to select 30 cells from each group with median current voltage characteristics of the lot. The initial current, voltage, spectral response, and diffusion length characteristics of each cell were measured. The cells were then irradiated to the various dosage levels shown in Table 1, taking selected current, voltage, spectral response, and diffusion length measurements.

A summary of all individual short circuit current measurements, average short circuit currents per group, percentage change in average short circuit current, and percent change in average maximum power is presented in Appendixes B and C for both electron and proton bombardments. These values were obtained using the standard tungsten light described in Appendix A.

Caution must be exercised in using this data. The cells were state-of-the-art cells; thus some were representative of production in sizable quantities while others were representative of pilot-line production. After the preliminary meeting held at Goddard on January 23, 1963, when change in I_{sc} as a function of 1 Mev electron dosage was discussed, several of the manufacturers changed

Table 1

Radiation Test Scheme for Solar Cell Degradation.

1 Mev Electrons			4.6 Mev Protons		
Dosage (e/cm^2)	Number of Cells	Number of Cells Withdrawn at Dosage Level	Dosage (p/cm^2)	Number of Cells	Number of Cells Withdrawn at Dosage Level
0	15	1	0	6	0
10^{11}	14	1	10^{10}	6	0
10^{12}	13	1	3×10^{10}	6	0
10^{13}	12	1	10^{11}	6	0
10^{14}	11	1	3×10^{11}	6	6*
10^{15}	10	1			
10^{16}	9	9			

*Except as indicated in Appendix B.

the base material used in their cells; thus, results would be quite different today. Furthermore, the cell performance was measured in tungsten light, which will emphasize the damage to a cell more than air mass one or air mass zero sunlight. From the data presented, it is not possible to select the best cell for sunlight use. The experiment was to show the relative damage of a cell to an accepted reference; and it accomplished this very well. Clearly, as seen in Figure 1, the change in I_{sc} for 1 Mev electron bombarded cells fell into four groups, which were a function of base resistivity and drift field. From the data in Appendixes B even cells with base resistivities less than 1 ohm-cm were apparent.

The cells which were irradiated with 1 Mev electrons to $10^{16}/cm^2$ were measured for percentage change in I_{sc} under tungsten light and sunlight at Table Mountain, California. Also the percentage change in I_{sc} was measured in tungsten light for the cells irradiated with 4.6 Mev protons. The results are shown in Table 2.

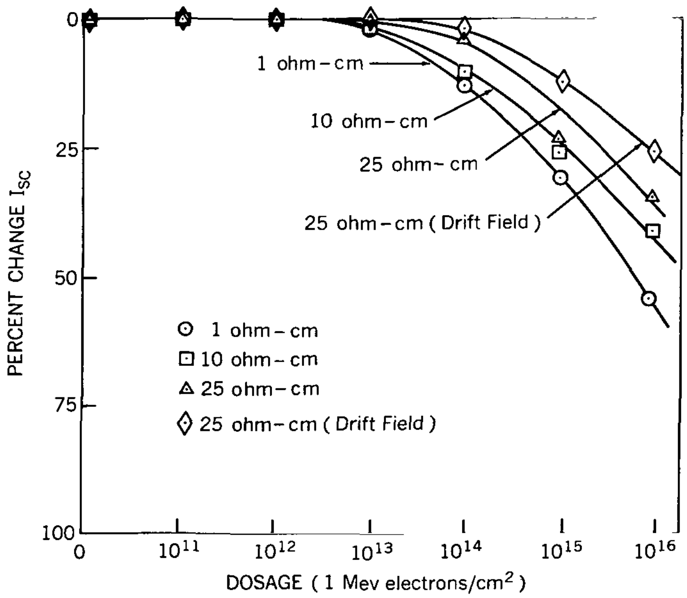

Figure 1—Comparison of base resistivity with percent change in short circuit current caused by 1 Mev electrons.

Table 2 shows that within a 1 percent change of I_{sc}, the cells maintained their same order of damage resistance in both tungsten light and sunlight. It also shows that with 4.6 Mev protons, the distinction between the various base resistivities is not as pronounced as with 1 Mev electrons, but the proton studies were not carried to the equivalent orbital dosage as the electrons.

When percentage change of maximum power caused by 10^{16} electrons/cm^2 is used as the index, the relative order is again the same as that for the short circuit current (See Table 3). The base resistivity again establishes distinct groups of less than 1 ohm-cm, 1 ohm-cm,

Table 2

Short-Circuit Current Degradation of Irradiated Cells.

Base Resistivity (ohm-cm)	Cell Group	10^{16} Electrons/cm^2				3×10^{11} Protons/cm^2	
		Change in I_{sc} with Tungsten Light (percent)	Order of Radiation Resistance	Change in I_{sc} at Table Mountain (percent)	Order of Radiation Resistance	Change in I_{sc} with Tungsten Light (percent)	Order of Radiation Resistance
graded	$J_{D/F}$	22.0	*	No Cells	*	No Cells	*
graded	$E_{D/F}$	24.5	*	13	*	No Cells	*
25	E	34.5	1	25	1	30.5	2
10	F	40.3	2	28	2	29.8	1
10	G	41.1	3	31	3	32.0	3
1	B	50.6	4	33	4	35.7	4
1	C	51.8	5	39	5	37.0	6
1	D	52.5	6	40	7	37.5	7
<1	K	53.6	7	39	6	36.5	5
<1	H	56.4	8	44	8	40.8	8
1	A(P/N)	77.9	9	66	9	57.1	9

*The drift field cells are not listed since they were not completely tested.

Table 3

Peak Power Degradation of Irradiated Cells.

Base Resistivity (ohm-cm)	Cell Group	10^{16} Electrons/cm^2		3×10^{11} Protons/cm^2	
		Change in P_{mp} with Tungsten Light (percent)	Order of Radiation Resistance	Change in P_{mp} with Tungsten Light (percent)	Order of Radiation Resistance
graded	$E_{D/F}$	42.6	*	No Cells	*
graded	$J_{D/F}$	43.2	*	No Cells	*
25	E	48.1	1	37.9	2
10	F	52.1	2	35.2	1
10	G	52.6	3	39.3	3
1	C	58.7	4	41.3	5
1	D	59.2	5	42.2	6
1	B	59.7	6	41.0	4
<1	K	63.1	7	45.2	7
<1	H	63.6	8	46.9	8
1	A(P/N)	85.6	9	65.7	9

*The drift field cells are not listed since they were not completely tested.

10 ohm-cm, and 25 ohm-cm, cells. The drift field cells are still superior. There is not the clear distinction between base resistivities at a 4.6 Mev proton dosage of $3 \times 10^{11}/\text{cm}^2$ as with a 1 Mev electron dosage of $10^{16}/\text{cm}^2$, but generally the higher base resistivity is more radiation-resistant.

Graphs showing the percentage degradation of maximum power as a function of proton and electron dosage are presented in Figures 2-12. These data show that with a 4.6 Mev proton dosage of $3 \times 10^{11}/\text{cm}^2$, there is at least 10 times the radiation resistance for N/P cells using a minimum of

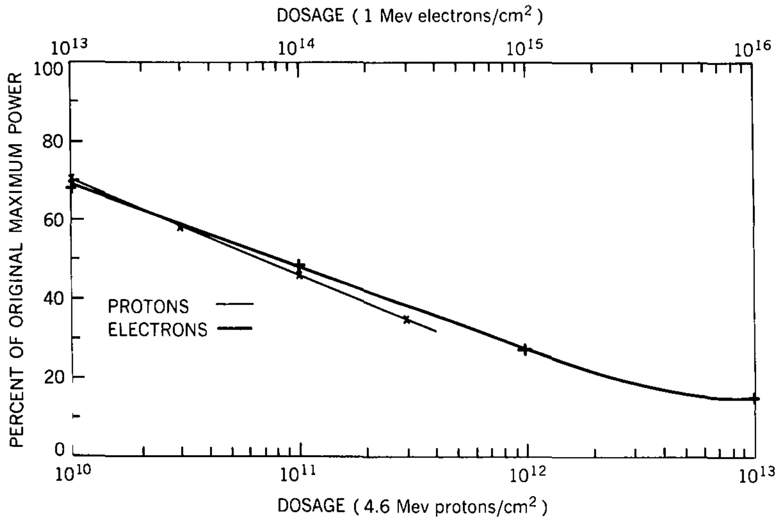

Figure 2—Maximum power versus particle dosage for Group A solar cells.

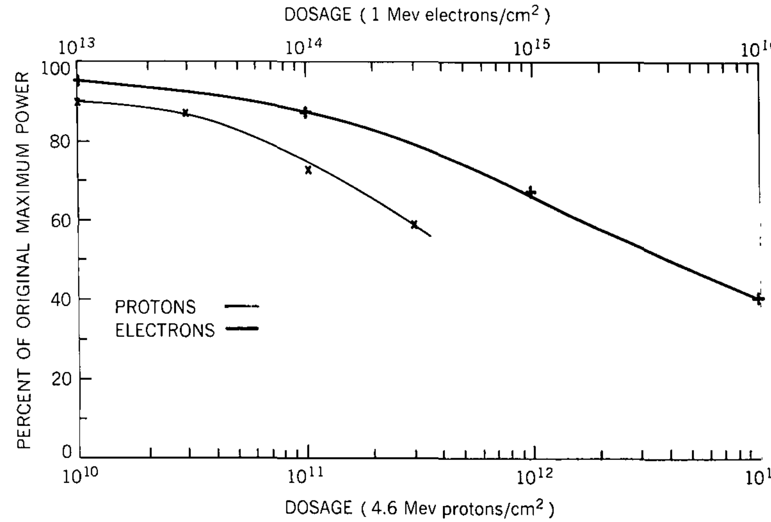

Figure 3—Maximum power versus particle dosage for Group B solar cells.

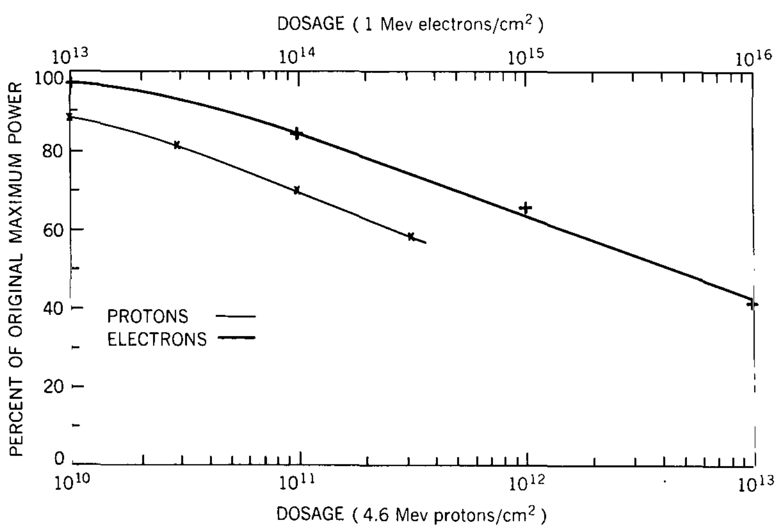

Figure 4—Maximum power versus particle dosage for Group C solar cells.

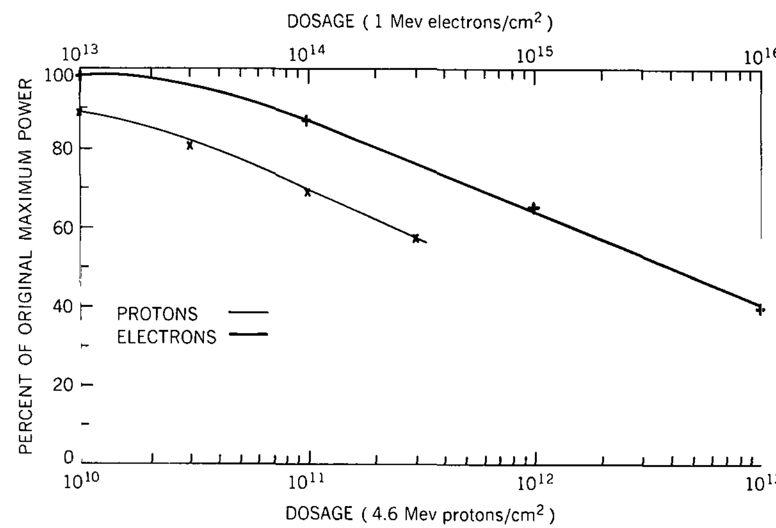

Figure 5—Maximum power versus particle dosage for Group D solar cells.

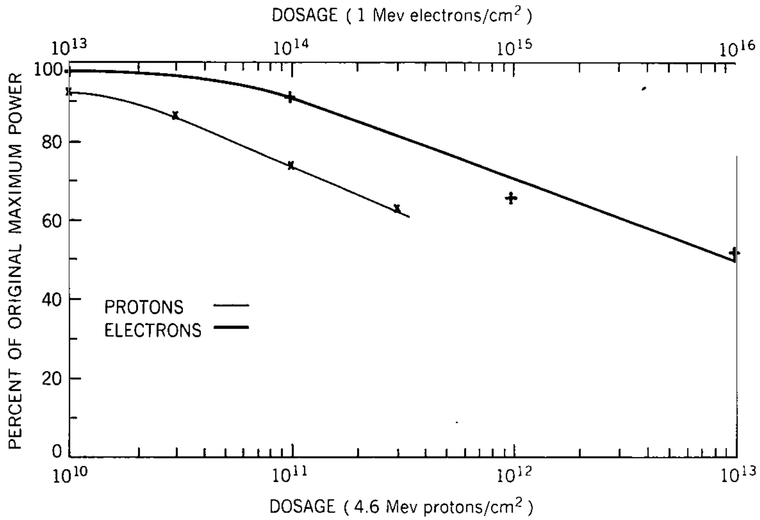

Figure 6—Maximum power versus particle dosage for Group E solar cells.

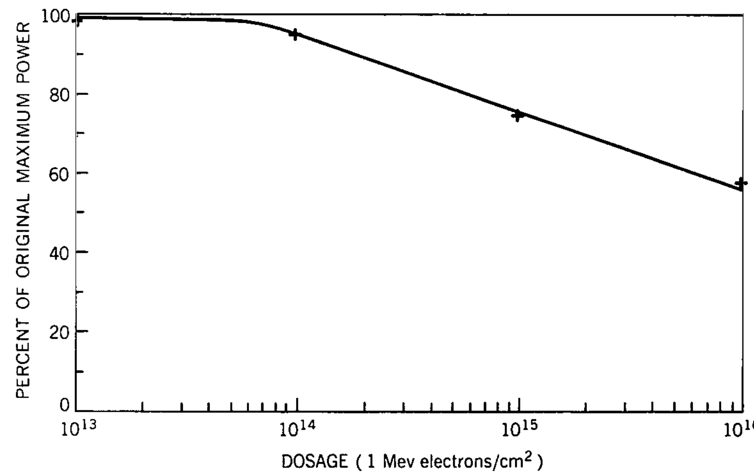

Figure 7—Maximum power versus particle dosage for Group $E_{D/F}$ solar cells.

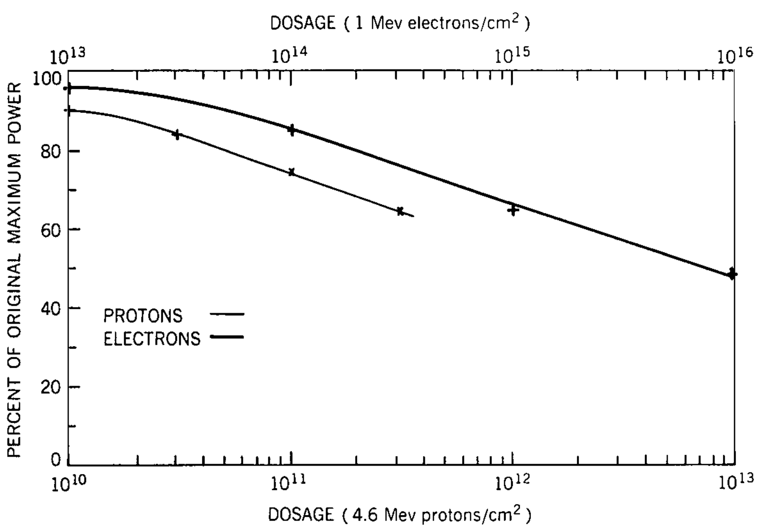

Figure 8—Maximum power versus particle dosage for Group F solar cells.

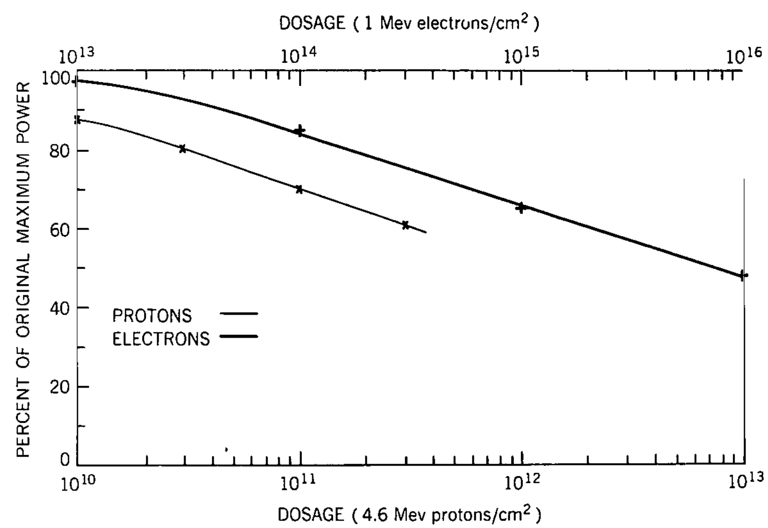

Figure 9—Maximum power versus particle dosage for Group G solar cells.

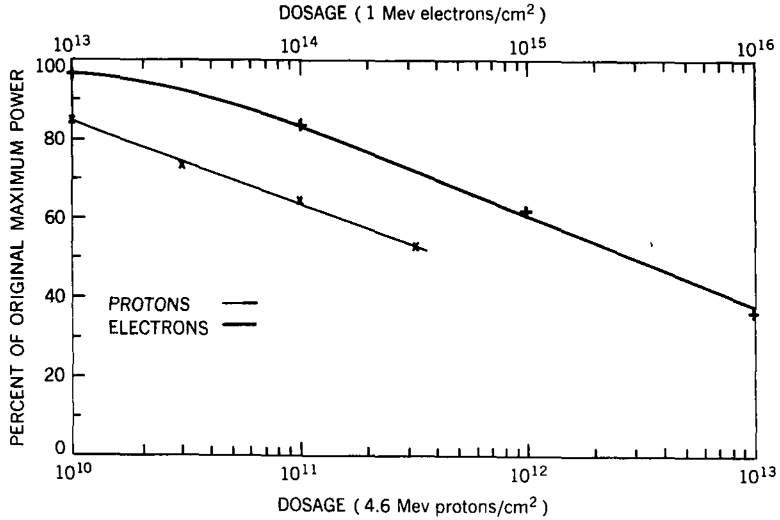

Figure 10—Maximum power versus particle dosage for Group H solar cells.

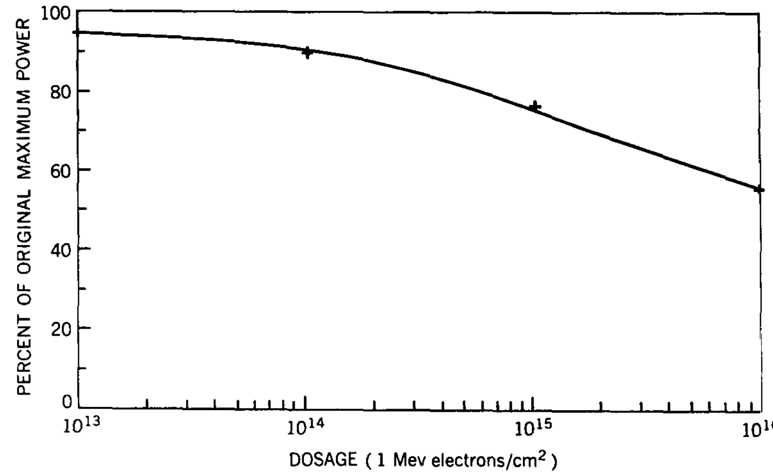

Figure 11—Maximum power versus particle dosage for Group $J_{D/F}$ solar cells.

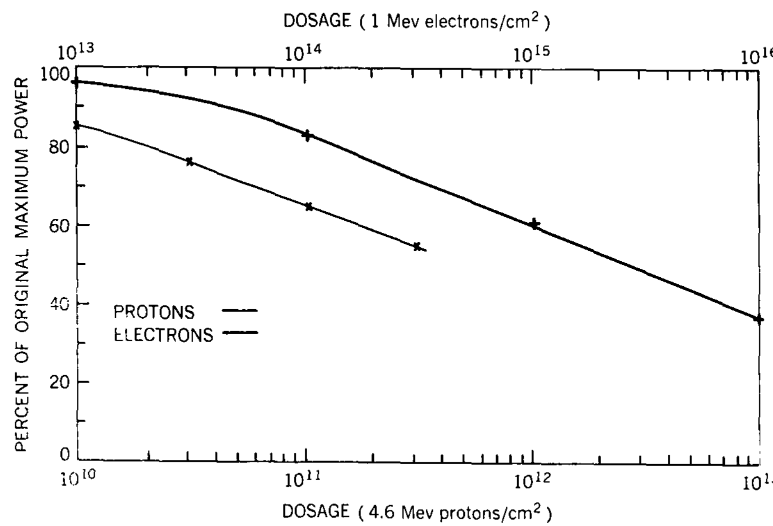

Figure 12—Maximum power versus particle dosage for Group K solar cells.

1 ohm-cm base resistivity material than for the P/N cell under the tungsten light source. Base resistivity is not as predominant a factor at 3×10^{11} protons/cm^2 as it is at 10^{16} electrons/cm^2. Perhaps an equivalent proton dosage, which would be about 10^{13}/cm^2, might show a correlation of base resistivity versus radiation damage. However, base resistivities of less than 1 ohm-cm are below the Group D reference all the way, while the 25 ohm-cm cells show less degradation of maximum power.

CONCLUSIONS

For cells at room temperature, we can conclude the following:

1. The 1 ohm-cm N/P silicon solar cell is conclusively more radiation-resistant than 1 ohm-cm P/N cells to 1 Mev electrons and/or 4.6 Mev protons in percentage change in both I_{sc} and maximum power output. This applies for both the 2800°K tungsten light and sunlight.

2. The 1 ohm-cm N/P silicon solar cell is definitely more radiation-resistant to 4.6 Mev protons than cells made of lower base-resistivity material. There is an indication that the 1 ohm-cm cells are also more radiation-resistant to 1 Mev electrons than lower base-resistivity cells.

3. As base resistivity of N/P cells is increased beyond 1 ohm-cm, the radiation resistance to 1 Mev electrons definitely improves. This trend continues to at least 25 ohm-cm material. Radiation resistance of N/P cells to 4.6 Mev protons seems to improve to at least 10 ohm-cm base resistivity, but beyond that showed little or no improvement.

4. There is a positive indication that a silicon solar cell containing a built-in drift field will have greater radiation resistance to 1 Mev electrons than a silicon cell without such a field. No drift field cells were available for the proton experiment.

ACKNOWLEDGMENTS

The experiments were performed at the Naval Research Laboratory under NASA sponsorship. In particular, the outstanding work of Messrs. E. Brancato, R. Statler, J. Weller, and R. Lambert is acknowledged.

Appendix A

Light Source Used to Determine Radiation Damage to Silicon Solar Cells

A reflector flood tungsten bulb of 300 watts, 120 volt rating is color-temperature calibrated at 2800°K. The bulb is mounted so that the light path to the cell passes through a filter consisting of 1/2" (total thickness) of plexiglas plus 3 cm of de-ionized water. The filter size is at least 1 foot in diameter in order to reduce edge effects. All air bubbles adhering to the surfaces are removed so as to avoid local distortions.

Ten silicon solar cells, typical of the batch being evaluated, are calibrated in natural sunlight under acceptable atmospheric conditions:

1. Sun in clear sky and horizontal visibility at least 5 miles;
2. Measurements made between 11 am and 1 pm Local Standard Time, March 1 to October 30;
3. Temperature 25 ± 2°C.

The light source is operated at the voltage necessary to attain a 2800°K color temperature at all times. The light intensity of 100 mw/cm^2 of equivalent natural sunlight is established by moving calibrated cells nearer or farther from the filter until I_{sc} conditions indicate the proper intensity. Measurements on all test cells will be made from this point. Precautions are taken to maintain cell temperature at 25°C ± 2°.

Appendix B

A Comparative Study of 1 Mev Electron-Bombarded Silicon Solar Cells

Introduction

At the request of Goddard Space Flight Center, the Naval Research Laboratory conducted an experiment to determine the effects of 1 Mev electron radiation on the photon conversion properties of N/P silicon solar cells. The solar cells tested were from 10 different groups of recent production by undisclosed sources, which were purchased by GSFC and given to NRL without manufacturer identification. The radiation damage was studied after each radiation with 1 Mev electrons at doses of 10^{11}, 10^{12}, 10^{13}, 10^{14}, 10^{15}, and 10^{16} electrons/cm^2. Among the parameters examined were the minority carrier diffusion length, spectral response, output power, and short circuit current, although only the latter measurements will be reported herein.

Instrumentation

To assure uniformity of integrated electron flux to all cells, they were placed on an aluminum wheel rotating at 10 rpm under the beam tube of the Van de Graaff generator. The circular path of every cell was the same and passed through the axis of the beam tube about 6 inches below the exit window. Irradiation was done at different flux densities, and the time to reach each decade of dose varied from 2 minutes at 10^{11} e/cm^2 to 14 hours at 10^{16} e/cm^2. The deviation in uniformity of integrated flux from one cell to another was no greater than 0.25 percent at 10^{13}/cm^2 and was much less at the larger doses. The flux was calibrated by measuring the output of a radiation-damaged solar cell relative to a Faraday cup, and throughout the radiation the flux was monitored by a Faraday cup positioned near the wheel. Air was blown across the surface of the wheel for cooling the cells. The wheel temperature did not go above 30°C at any time during the irradiation.

The short circuit current of the solar cells was determined by measuring the voltage drop across a 1-ohm precision resistor loading the cell when it was illuminated. The light source was a 300-watt reflector flood bulb with a calibrated color temperature of 2800°K with a heat-absorbing filter consisting of 3 cm of distilled water contained in a plexiglas holder. The light intensity was adjusted by placing the cell holder at a distance from the lamp which corresponded to a 100 mw/cm^2 intensity as determined by a set of 10 Standard N/P solar cells which had been calibrated by GSFC and supplied to NRL for this purpose. The voltage across the 1-ohm loading resistor was measured by a voltage-to-frequency converter and displayed on a frequency counter. The accuracy of the short circuit current measurement is ± 0.1 ma for all cells except Group B, in which some contact resistance was evident. For these cells the accuracy is probably ± 0.3 ma.

Results

Tables B1-B5 list all the measured values of short circuit current following the indicated electron dose. The average value of short circuit current for each group of cells at the indicated dose is shown

Table B1

Groups A and B Solar Cell Short-Circuit Current After 1 Mev Electron Radiation.

Cell Number	Initial Current (ma)	Current After Dosage (ma)					
		10^{11} (electrons/cm^2)	10^{12} (electrons/cm^2)	10^{13} (electrons/cm^2)	10^{14} (electrons/cm^2)	10^{15} (electrons/cm^2)	10^{16} (electrons/cm^2)
A-1-1	48.1						
A-1-2	47.3	47.3					
A-1-3	47.2		44.6				
A-1-4	48.6		45.4	37.0			
A-1-5	48.4		44.0	34.7	24.8		
A-1-6	47.4			34.3	24.1	15.0	
A-1-7	48.1			35.8	26.2	16.6	10.3
A-1-8	47.5			34.7	24.8	15.3	9.4
A-1-9	47.7			38.1	28.5	18.7	11.7
A-1-10	47.9			36.8	26.9	17.3	11.0
A-1-11	48.0			36.5	26.9	17.4	11.0
A-1-12	47.9			35.0	25.1	15.8	9.8
A-1-13	47.8			36.0	26.2	16.7	10.2
A-1-14	48.6			37.3	27.5	18.0	11.1
A-1-15	47.8			37.6	27.4	17.9	11.1
B-1-1	70.4						
B-1-2	78.6	78.9					
B-1-3	79.5		78.5				
B-1-4	76.4		76.4	74.6			
B-1-5	75.2		75.1	74.2	70.1		
B-1-6	81.6			79.9	74.5	60.4	
B-1-7	76.4			75.7	71.1	57.5	38.5
B-1-8	77.2			76.6	71.0	57.5	38.2
B-1-9	85.0			81.9	75.9	60.2	39.8
B-1-10	78.2			77.6	72.1	58.8	39.6
B-1-11	80.1			79.0	73.1	59.1	41.5
B-1-12	78.3			77.3	70.4	55.2	35.6
B-1-13	80.5			79.9	74.2	60.2	41.0
B-1-14	83.0			81.7	76.0	61.6	42.9
B-1-15	82.1			79.9	73.5	58.2	39.1

Table B2

Groups C and D Solar Cell Short-Circuit Current After 1 Mev Electron Radiation.

Cell Number	Initial Current (ma)	Current After Dosage (ma)					
		10^{11} (electrons/cm^2)	10^{12} (electrons/cm^2)	10^{13} (electrons/cm^2)	10^{14} (electrons/cm^2)	10^{15} (electrons/cm^2)	10^{16} (electrons/cm^2)
C-1-1	51.5						
C-1-2	51.4	51.3					
C-1-3	51.4		50.9				
C-1-4	52.0		51.2	50.8			
C-1-5	50.5		50.3	49.4	43.9		
C-1-6	51.6			51.0	45.5	36.4	
C-1-7	51.9			51.1	45.3	36.1	24.8
C-1-8	52.2			51.3	45.2	36.0	24.9 ·
C-1-9	51.4			50.7	45.2	36.1	25.1
C-1-10	51.2			50.3	44.9	35.7	24.6
C-1-11	52.0			50.5	45.0	35.9	25.1
C-1-12	50.7			50.0	44.8	35.8	24.8
C-1-13	51.1			50.4	44.9	35.8	24.4
C-1-14	51.0			49.6	44.6	35.3	25.0
C-1-15	51.2			50.1	44.6	35.6	25.0
D-1-1	45.1						
D-1-2	45.6	45.4					
D-1-3	45.0		45.0				
D-1-4	45.0		44.9	44.5			
D-1-5	44.4		44.5	44.1	39.6		
D-1-6	45.1			44.4	40.8	32.4	
D-1-7	44.4			44.0	39.6	31.3	21.0
D-1-8	45.4			45.2	40.9	32.5	22.0
D-1-9	45.6			45.2	40.4	32.0	21.3
D-1-10	45.1			44.5	40.8	32.6	22.2
D-1-11	45.1			44.9	40.4	32.1	21.6
D-1-12	45.2			44.7	40.1	31.9	21.3
D-1-13	45.1			44.4	40.0	31.5	21.2
D-1-14	44.4			43.9	39.7	31.2	20.9
D-1-15	45.2			44.8	40.5	31.9	21.5

Table B3

Groups E, $E_{D/F}$, and $J_{D/F}$ Solar Cell Short-Circuit Current After 1 Mev Electron Radiation.

Cell Number	Initial Current (ma)	Current After Dosage (ma)					
		10^{11} (electrons/cm^2)	10^{12} (electrons/cm^2)	10^{13} (electrons/cm^2)	10^{14} (electrons/cm^2)	10^{15} (electrons/cm^2)	10^{16} (electrons/cm^2)
E-1-1	22.0						
E-1-4	22.6	22.7					
E-1-5	22.0		22.2				
E-1-8	21.5		21.6	21.7			
E-1-10	21.9		22.0	22.0	21.0		
E-1-11	21.8			21.9	21.0	17.0	
E-1-13	21.9			21.8	20.8	16.9	14.3
E-1-15	22.4			22.5	21.4	17.4	14.8
E-1-18	21.3			21.3	20.4	16.5	13.9
E-1-19	22.1			22.2	21.1	17.1	14.5
$E_{D/F}$-1-2	20.2						
$E_{D/F}$-1-3	19.2	19.2					
$E_{D/F}$-1-6	21.7		21.8				
$E_{D/F}$-1-7	20.5		20.7	20.7			
$E_{D/F}$-1-9	19.4		19.5	19.7	19.2		
$E_{D/F}$-1-12	19.8			19.9	19.6	17.9	
$E_{D/F}$-1-14	21.0			21.1	20.7	18.8	15.7
$E_{D/F}$-1-16	21.5			21.6	21.3	18.9	16.2
$E_{D/F}$-1-17	20.5			20.7	20.3	18.4	15.3
$E_{D/F}$-1-20	19.8			19.8	19.4	17.6	14.4
$J_{D/F}$-1-1	43.9						
$J_{D/F}$-1-2	44.0		44.1				
$J_{D/F}$-1-3	44.5		44.6	44.5			
$J_{D/F}$-1-4	46.1		46.2	45.9	45.8		
$J_{D/F}$-1-5	42.7		42.9	42.7	42.3	37.5	
$J_{D/F}$-1-6	45.5			45.8	45.0	40.9	34.7

Table B4

Groups F and G Solar Cell Short-Circuit Current After 1 Mev Electron Radiation.

Cell Number	Initial Current (ma)	Current After Dosage (ma) 10^{11} (electrons/cm^2)	10^{12} (electrons/cm^2)	10^{13} (electrons/cm^2)	10^{14} (electrons/cm^2)	10^{15} (electrons/cm^2)	10^{16} (electrons/cm^2)
F-1-1	52.5						
F-1-2	50.7	50.8					
F-1-3	52.1		52.0				
F-1-4	52.3		52.1	51.4			
F-1-5	52.2		52.1	51.2	47.3		
F-1-6	52.0			51.2	47.1	38.8	
F-1-7	51.5			50.1	45.9	37.1	28.0
F-1-8	51.9			50.7	46.9	39.0	31.7
F-1-9	51.5			50.5	47.1	39.0	31.8
F-1-10	52.4			51.7	47.9	39.4	32.2
F-1-11	51.8			51.0	47.3	38.7	31.2
F-1-12	52.7			51.8	48.0	39.6	31.9
F-1-13	52.4			51.8	47.8	40.1	32.3
F-1-14	51.6			50.8	46.8	39.5	31.7
F-1-15	50.0			48.9	44.5	36.7	27.7
G-1-1	50.3						
G-1-2	50.2	50.4					
G-1-3	49.7		49.7				
G-1-4	47.7		47.5	46.6			
G-1-5	46.8		46.6	45.8	41.5		
G-1-6	50.6			49.6	44.9	37.1	
G-1-7	48.5			47.4	43.2	35.8	28.7
G-1-8	49.1			48.0	44.1	36.4	29.2
G-1-9	48.2			47.2	43.1	35.8	28.1
G-1-10	49.5			48.5	44.2	36.4	29.0
G-1-11	49.5			48.5	44.1	36.6	29.7
G-1-12	50.0			49.0	44.3	37.0	29.7
G-1-13	48.5			47.4	42.9	35.7	27.8
G-1-14	50.1			49.4	44.5	37.2	30.0
G-1-15	49.4			48.3	44.3	36.4	28.5

Table B5

Groups H and K Solar Cell Short-Circuit Current After 1 Mev Electron Radiation.

Cell Number	Initial Current (ma)	Current After Dosage (ma)					
		10^{11} (electrons/cm^2)	10^{12} (electrons/cm^2)	10^{13} (electrons/cm^2)	10^{14} (electrons/cm^2)	10^{15} (electrons/cm^2)	10^{16} (electrons/cm^2)
H-1-1	50.1						
H-1-2	46.8	47.0					
H-1-3	48.5		48.0				
H-1-4	50.3		50.1	48.5			
H-1-5	48.0		47.5	46.0	41.3		
H-1-6	48.3			47.0	42.1	32.9	
H-1-7	50.0			48.5	42.8	33.5	21.7
H-1-8	49.2			48.1	42.4	33.0	21.3
H-1-9	49.5			48.3	42.7	33.3	21.7
H-1-10	49.0			47.6	42.3	32.8	21.3
H-1-11	47.5			46.3	40.8	31.7	21.0
H-1-12	48.0			47.0	42.0	32.8	21.5
H-1-13	50.1			48.5	42.8	33.0	21.6
H-1-14	48.8			47.4	42.1	32.6	21.4
H-1-15	49.9			48.1	42.4	32.8	21.2
K-1-1	47.9						
K-1-2	49.3	49.7					
K-1-3	47.6		47.4				
K-1-4	47.7		47.6	46.5			
K-1-5	47.4		47.4	46.5	41.3		
K-1-6	48.0			46.8	41.2	32.4	
K-1-7	49.1			47.7	42.3	33.2	22.6
K-1-8	48.7			47.4	41.7	32.5	22.1
K-1-9	45.6			44.2	38.8	30.0	19.6
K-1-10	49.3			47.7	41.9	32.8	22.2
K-1-11	48.1			46.8	41.4	32.6	22.4
K-1-12	47.7			46.3	41.0	32.4	22.1
K-1-13	49.4			48.8	43.9	35.7	27.1
K-1-14	46.6			45.5	40.2	30.9	20.3
K-1-15	48.4			47.1	41.4	32.4	22.0

in Table B6. It should be noted that not all cells were measured at every dose, so that the average current at each dose is for a different set of cells of the group. The precentage change in average short-circuit current is shown in Table B7. This change is computed from the average change in current for the cells measured at a given dose level relative to the initial average current of that same set of cells.

A more complete report describing this and other phases of the experiment in more detail is in preparation.

Table B6

Group Average Short-Circuit Current of Solar Cells After 1 Mev Electron Radiation.

Cell Group	Initial Current (ma)	Current After Dosage (ma)			
		10^{13} (electrons/cm^2)	10^{14} (electrons/cm^2)	10^{15} (electrons/cm^2)	10^{16} (electrons/cm^2)
A	47.9	36.2	26.2	16.9	10.6
B	78.8	78.2	72.9	58.9	39.6
C	51.4	50.4	44.9	35.9	24.8
D	45.0	44.6	40.3	31.9	21.4
E*	22.0	21.9	21.0	17.0	14.4
$E_{D/F}$*	20.4	20.5	20.1	18.3	15.4
F	51.8	50.9	47.0	38.8	30.9
G	49.2	48.0	43.7	36.4	29.0
H	48.9	47.6	42.2	32.8	21.4
$J_{D/F}$*	44.5	44.7	44.4	39.2	34.7
K	48.1	46.8	41.4	32.5	22.3

*The E, $E_{D/F}$ and $J_{D/F}$ group averages are based on a smaller number of cells, the number of which decreases with increasing radiation dose (see Table B3).

Table B7

Percentage Change in Average Short-Circuit Current of Solar Cells After 1 Mev Electron Radiation.

Cell Group	Change After Dosage (percent)			
	10^{13} (electrons/cm^2)	10^{14} (electrons/cm^2)	10^{15} (electrons/cm^2)	10^{16} (electrons/cm^2)
A	24.6	45.3	64.7	77.9
B	1.6	8.6	26.6	50.6
C	1.9	12.5	30.2	51.8
D	0.9	10.4	29.3	52.5
E*	0.5	4.5	22.6	34.5
$E_{D/F}$*	0.0	1.5	10.3	24.5
F	1.9	9.3	25.1	40.3
G	2.0	11.0	26.2	41.1
H	3.1	13.7	33.1	56.4
$J_{D/F}$*	0.0	0.2	12.0	22.0
K	2.5	13.7	32.4	53.6

*The E, $E_{D/F}$ and $J_{D/F}$ group averages are based on a smaller number of cells, the number of which decreases with increasing radiation dose (see Table B3).

Table B8

Percentage Change in Average Maximum Power of Solar Cells After 1 Mev Electron Radiation.

Cell Group	Change After Dosage (percent)			
	10^{13} (electrons/cm^2)	10^{14} (electrons/cm^2)	10^{15} (electrons/cm^2)	10^{16} (electrons/cm^2)
A	29.7	52.3	72.4	85.6
B	5.2	12.4	33.1	59.7
C	3.0	15.2	35.4	58.7
D	1.4	12.9	34.8	59.2
E*	1.8	8.6	34.2	48.1
$E_{D/F}$*	0.4	4.1	25.0	42.6
F	3.3	14.1	34.2	52.1
G	2.0	15.1	35.2	52.6
H	3.4	16.5	38.6	63.6
$J_{D/F}$*	5.0	9.4	23.2	43.2
K	3.5	17.3	39.3	63.1

*The E, $E_{D/F}$ and $J_{D/F}$ group averages are based on a smaller number of cells, the number of which decreases with increasing radiation dose (see Table B3).

Appendix C

A Comparative Study of 4.6 Mev Proton-Bombarded Silicon Solar Cells

Introduction

A comparative study was made of the radiation damage rates of silicon solar cells from 4.6 Mev protons as a companion experiment to a 1 Mev electron damage study recently done at the Naval Research Laboratory.* The solar cells used in both experiments were supplied by Goddard Space Flight Center from lots of experimental cells and typical production quality cells of late 1962, which had been procured for this purpose. The proton energy of 4.6 Mev was low enough to produce a high damage rate throughout the bulk material of the cell to a depth exceeding the minority carrier diffusion length before irradiation. The radiation damage was measured after each proton bombardment at doses of 10^{10}, 3×10^{10}, 10^{11}, and 3×10^{11} protons/cm^2. Included in the measured characteristics were the minority carrier diffusion length, the spectral response, and the voltage-current characteristics of the cells under filtered tungsten light. Only the results of the short circuit current and maximum power measurements will be reported herein.

Radiation

The NRL 5 Mev Van de Graaff accelerator was used for the source of protons. The beam was scattered by a .0004-inch gold foil placed about 18 feet from the end of the drift tube where the solar cells were placed. The foil served the dual purpose of reducing the beam intensity and providing a uniform flux distribution at the cells. The proton energy incident on the foil was measured as 5.127 Mev, while the energy incident on the solar cells was calculated to be 4.657 Mev, because of energy absorption by the foil. The flux was measured by collecting all of the beam current passing through a defining aperture into the insulated end section of the tube, which acted as a Faraday cup. The flux density was about 1.4×10^8 protons/cm^2. The flux variation over the end of the beam tube where the solar cells were placed was ±1 percent. The variation in integrated flux from one radiation to another was within ±1.3 percent. There were 9 groups of 6 cells each which were irradiated 4 at a time by permuting the cell types and positions for each exposure. The pressure in the tube was about 5×10^{-5} mm-Hg.

Measurements

The voltage-current characteristics of the cells were measured under the same light source used for the electron damage study.* This was a 300-watt reflector flood bulb calibrated to a color temperature of 2800°K with a heat absorbing filter consisting of 3 cm of deionized water in a plexiglas

*Radiation Damage Symposium, Goddard Space Flight Center, January 23, 1963.

holder interposed before the sample cells. The light intensity was adjusted by moving the cell holder to a position from the lamp which gave a short-circuit current from a standard cell equivalent to 100 mw/cm^2 solar intensity at air mass one. This was determined by a set of 10 Standard N/P solar cells which had been calibrated by the Goddard Space Flight Center for this purpose. The short-circuit current was measured by precision resistors and voltage-to-frequency conversion with an overall accuracy of ±0.1 ma for all cells except in Group B, where the accuracy is probably ±0.3 ma (see Appendix B).

Results and Conclusions

Tables C1-C3 present all the measured values of short-circuit current following the indicated proton dose. The average value of short-circuit current for each group of cells at the indicated dose is shown in Table C4. The percentage change in the average short-circuit current is given in Table C5. Table C6 gives the percentage change in maximum power output of each group as a function of proton dose.

The radiation damage rates, indicated by the percentage change in short-circuit current, follow the same trend as shown in the 1 Mev electron damage study; the higher bulk-resistivity cells have the lowest damage rate, and the P/N cells have the highest rate. There are two variations in the order of damage rates from electrons compared to protons. Group E, which has a significantly

Table C1

Groups A, B, C Solar Cell Short-Circuit Current After 4.6 Mev Proton Radiation.

Cell Number	Initial Current (ma)	Current After Dosage (ma)			
		10^{10} (protons/cm^2)	3×10^{10} (protons/cm^2)	10^{11} (protons/cm^2)	3×10^{11} (protons/cm^2)
A-1-16	47.5	36.9	31.8	26.0	20.9
A-1-18	49.1	36.9	32.1	26.0	20.9
A-1-20	48.1	35.1	30.6	24.5	19.6
A-1-22	48.6	37.0	32.6	27.0	21.4
A-1-23	47.6	35.7	31.1	25.4	20.0
A-1-24	47.3	36.2	31.7	25.9	20.4
B-1-16	81.7	77.5	70.4	61.6	51.7
B-1-17	82.8	78.8	72.0	63.7	54.2
B-1-18	81.6	76.9	71.6	62.6	53.5
B-1-19	78.6	74.5	69.0	59.4	
B-1-20	83.4	78.4	71.9	62.3	52.7
B-1-21	79.6	75.4	70.0	61.0	51.7
C-1-16	50.7	45.5	41.6	36.7	31.9
C-1-19	51.5	45.2	41.7	36.6	31.5
C-1-20	49.2	43.3	39.8	35.1	30.2
C-1-21	50.0	44.6	41.2	36.8	31.5
C-1-22	47.2	42.9	40.0	35.6	30.5
C-1-24	49.0	44.8	42.0	37.3	31.8

Table C2

Groups D, E, F Solar Cell Short-Circuit Current after 4.6 Mev Proton Radiation.

Cell Number	Initial Current (ma)	Current After Dosage (ma)			
		10^{10} (protons/cm^2)	3×10^{10} (protons/cm^2)	10^{11} (protons/cm^2)	3×10^{11} (protons/cm^2)
D-1-16	44.7	40.0	36.4	31.9	27.3
D-1-17	45.9	41.1	38.1	33.4	28.8
D-1-20	44.5	39.9	36.7	32.2	27.7
D-1-21	44.7	40.2	37.2	32.7	27.8
D-1-24	46.0	40.9	37.9	33.4	28.4
D-1-25	44.7	40.4	38.1	33.9	29.2
E-1-21	21.6	20.7	19.2	17.0	15.1
E-1-22	21.7	20.5	19.4	17.1	15.3
E-1-23	21.7	20.4	19.3	17.0	15.1
E-1-24	22.4	21.0	*	17.3	15.3
E-1-25	22.1	20.1	*	17.2	15.3
E-1-26	21.8	20.0	*	17.2	15.1
F-1-16	52.7	48.4	44.7	40.3	36.2
F-1-19	52.1	48.0	45.1	40.7	36.6
F-1-22	52.2	48.0	45.1	41.2	37.3
F-1-23	51.6	46.6	44.0	39.8	35.6
F-1-24	51.8	47.7	45.2	41.4	37.2
F-1-30	52.0	46.7	†	†	†

*Measurements were inadvertently omitted.
†Cell was broken.

Table C3

Groups G, H, K Solar Cell Short-Circuit Current after 4.6 Mev Proton Radiation.

Cell Number	Initial Current (ma)	Current After Dosage (ma)			
		10^{10} (protons/cm^2)	3×10^{10} (protons/cm^2)	10^{11} (protons/cm^2)	3×10^{11} (protons/cm^2)
G-1-18	46.2	41.3	37.7	34.4	30.5
G-1-20	49.1	44.5	41.8	38.0	34.3
G-1-21	50.5	45.7	42.6	38.7	34.6
G-1-22	49.6	45.1	42.3	38.5	34.3
G-1-25	46.9	42.1	39.6	35.8	31.7
G-1-26	48.0	43.2	40.5	36.5	32.3
H-1-16	49.9	43.1	38.5	34.0	28.8
H-1-17	52.6	45.1	41.4	36.0	30.7
H-1-18	47.3	41.7	38.3	33.7	28.6
H-1-19	49.2	43.2	39.9	34.7	29.5
H-1-21	49.5	43.6	40.3	35.2	30.0
H-1-22	49.3	42.8	39.4	34.0	28.8
K-1-16	47.1	42.0	38.2	33.9	29.5
K-1-17	49.9	45.1	41.9	37.6	33.2
K-1-18	49.5	44.6	41.5	37.4	32.9
K-1-20	49.7	44.5	41.6	37.2	32.6
K-1-24	48.2	41.5	38.4	33.6	28.7
K-1-26	47.8	41.9	38.8	34.0	29.0

Table C4
Average Short-Circuit Current of Solar Cells After 4.6 Mev Proton Radiation.

Cell Group	Initial Current (ma)	Current After Dosage (ma)			
		10^{10} (protons/cm^2)	3×10^{10} (protons/cm^2)	10^{11} (protons/cm^2)	3×10^{11} (protons/cm^2)
A	48.0	36.3	31.7	25.8	20.5
B	81.3	76.9	70.8	61.8	52.8*
C	49.6	44.4	41.0	36.4	31.2
D	45.1	40.4	37.4	32.9	28.2
E	21.9	20.5	19.3*	17.1	15.2
F	52.1	47.6	44.8*	40.7*	36.6*
G	48.4	43.7	40.8	37.0	33.0
H	49.6	43.3	39.6	34.6	29.4
K	48.7	43.3	40.1	35.6	31.0

*Less than 6 cells averaged for this value.

Table C5
Percentage Change in Average Short-Circuit Current of Solar Cells After 4.6 Mev Proton Radiation.

Cell Group	Change After Dosage (percent)			
	10^{10} (protons/cm^2)	3×10^{10} (protons/cm^2)	10^{11} (protons/cm^2)	3×10^{11} (protons/cm^2)
A	24.4	34.1	46.0	57.1
B	5.4	12.9	24.0	35.7
C	10.5	17.2	26.7	37.0
D	10.4	17.1	27.0	37.5
E	6.5	10.9	21.6	30.5
F	8.7	13.9	21.7	29.8
G	9.8	15.8	23.6	32.0
H	12.8	20.1	30.3	40.8
K	11.2	17.8	26.9	36.5

Table C6
Percentage Change in Average Maximum Power of Solar Cells After 4.6 Mev Proton Radiation.

Cell Group	Change After Dosage (percent)			
	10^{10} (protons/cm^2)	3×10^{10} (protons/cm^2)	10^{11} (protons/cm^2)	3×10^{11} (protons/cm^2)
A	29.3	41.4	53.9	65.7
B	4.9	12.9	27.2	41.0
C	11.7	18.5	30.2	41.3
D	10.9	19.2	30.3	42.2
E	7.4	13.4	26.5	37.9
F	9.5	15.6	25.7	35.2
G	11.5	19.7	30.1	39.3
H	15.6	23.8	36.2	46.9
K	14.7	23.9	35.0	45.2

lower damage rate under electron radiation, had the same rate as the 10 ohm-cm cells under protons. Group K has a lower damage rate from protons than groups C and D. However, this amounts to only one percentage point difference and could be attributed to small variations in the average initial properties of the cell group. It is conceivable, for example, that one group of 6 cells from a particular lot may show a difference of 1 percent in radiation resistance compared to another group of 6 from the same lot. The data were analyzed by applying the "Students-t-Test", and difference between means was found to be significant to better than .01 level; which means that there is less than 1 chance out of 100 that the differences are due to random errors. The validity of using the filtered tungsten light for measuring I_{sc} was established by measuring the electron-damaged cells at Table Mountain and under a solar simulator. The relative order of radiation damage rate was unchanged when measuring under these three sources, except for Group K at Table Mountain.*

*"One Mev Electron Damage in Silicon Solar Cells," by R. L. Statler, Photovoltaic Specialists Conference of IEEE, Washington, D. C., April 10, 1963.

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