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X-765-73-87
PREPRINT

NASA TM X- 66231

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C. NICOLETTA

MARCH 1973

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

1 Ω-cm and 10 Ω-cm Silicon solar cells, manufactured by AEG-Telefunken, were exposed to 1.0 MeV electrons at a fixed flux of 10^{11} e/cm^2-sec and fluences of 10^{13}, 10^{14} and 10^{15} e/cm^2. I-$\overline{V}$ curves of the cells were made at room temperature, -63° C and +143° C after each irradiation. A value of 139.5 mw/cm^2 was used as AMO incident energy rate per unit area. The 10 Ω-cm cells appear more efficient than 1 Ω-cm cells after exposure to a fluence greater than 10^{14} e/cm^2. The 1.0 MeV electron damage coefficients for both 1 Ω-cm and 10 Ω-cm cells are somewhat less than those for previously irradiated cells at room temperature. The values of the damage coefficients increase as the cell temperatures decrease. Efficiencies as pertaining to maximum power output, are about the same as those of n on p silicon cells evaluated previously.

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EFFECTS OF ELECTRON IRRADIATION AND TEMPERATURE ON 1Ω-cm AND 10Ω-cm SILICON SOLAR CELLS

GENERAL INTRODUCTION

1Ω-cm and 10Ω-cm solar cells, manufactured by AEG-Telefunken, West Germany, were irradiated with 1.0 MeV electrons. These cells were of the same type reported on earlier for proton irradiation, (Ref. 1).

From an engineering point of view, the effect of radiation on minority carrier lifetimes is of prime importance in determining the response of the cell. Electrons with energies >1.0 MeV cause damage to the base region of the cell affecting carrier lifetimes.

The damage is due to the energy given up by the incident particle in passing through the material. For solar cells, this energy forms damage centers, which shorten the minority carrier lifetimes and reduce the short circuit current. Since generally electron penetration is much greater than for protons, a 1.0 MeV electron will pass through a 300μ thick silicon solar cell, (Fig. 1). In doing so it gives up equal increments of energy along its path, and therefore produces damage centers at a uniform rate. Thus, a linear dependence between short circuit current and minority carrier diffusion length can be assumed. This is not the case for 1.0 MeV protons striking 300μ thick cells, since they are absorbed within the cell, (Ref. 1). From the expression for carrier lifetime with particle fluence, (Ref. 2)

$$\frac{1}{\tau} = \frac{1}{\tau_o} + K\Phi \qquad (1)$$

one obtains the electron damage coefficient, K.

Since the diffusion length is related to the lifetime by

$$L = \sqrt{D\tau} \qquad (2)$$

where D is the diffusion constant, we have

$$\frac{1}{L^2} = \frac{1}{L_o^2} + K\Phi \qquad (3)$$

where L_0 is the initial diffusion length and Φ the fluence.

The damage coefficient is a measure of cell degradation at a particular energy and temperature for incident particles.

As in the previous work with proton irradiation, these cells were exposed to electrons at room temperature and the I-$\overline{V}$ curves were made approximately at room temperature, -65^{o}C, and +145^{o}C. Fluence levels were selected to fit in with previous tests and were in the range of from 10^{13} e/cm^2 to 10^{15} e/cm^2.

Solar cell efficiencies are obtained directly from the I-$\overline{V}$ curves, and, as in the case of protons, represent the single most important quantity for power conversion in space. The solar cell efficiency η is defined as $\frac{\text{maximum power input}}{\text{power input}}$ and is expressed by the equation, (Ref. 2)

$$\eta = \frac{I_{sc} \frac{q}{kT} V_{mp}^{2} \left(1 + \frac{I_o}{I_{sc}}\right)}{\left(1 + \frac{q}{kT} V_{mp}\right) A \, (\text{AMOS.C.})} \tag{4}$$

where I_{sc} - short circuit current

q - electron charge

k - Boltzmann's constant

T - absolute temperature of cell

V_{mp} - value of voltage at max. power

I_o - saturation current

A - solar cell area

(AMOS.C.) - air mass zero solar constant

From eq. (4) it is apparent that efficiency increases with decreasing temperature and decreases with decreasing short circuit current. Short circuit current in turn decreases with increasing fluence.

EXPERIMENTAL TECHNIQUES

In order to assure electron beam stability, homogeneity, and size, these experiments were conducted using a small portable chamber under low vacuum. The electron beam passed in a straight horizontal line into the chamber from the accelerator and was vertically swept at ~400 Hz. The effective beam size at the target was about 38 cm by 7 cm. The solar cells were attached to a temperature controlled brass sample holder by silver epoxy cement. In the first exposure batch, nine cells were mounted on the holder with Faraday cups centrally located and at one end of the holder. In the second batch, twelve cells were similarly exposed. The sample chamber was attached to the horn assembly at the end of the accelerator drift tube. The electron beam passes through a 50μ thick titanium window before impinging on the cells. Using energy loss data for Aluminum from Berger & Seltger's tables (Ref. 3) and correcting for titanium, we found that for 1 MeV electrons, approximately 35 KeV or about 3% of the energy is lost in the window.

Cold gaseous nitrogen was circulated through the brass sample holder for the low temperature measurements which were made first. Heaters (350 watt) were used on the input gas lines to the holder to obtain the high temperatures. A Cu-Constantan thermocouple was mounted on the sample holder to monitor solar cell temperature. Due to thermal limitations, it was only possible to heat the samples to $+145^\circ$C.

After particle irradiation, the vacuum chamber was removed from the horn assembly of the accelerator and brought to ambient atmosphere. A 1.6 cm thick glass plate was then placed over the chamber opening in order to irradiate the cells for I-$\overline{V}$ measurements. The variation in the electron beam energy supplied by the Van de Graaff accelerator was about ±1.0%. The flux used in all irradiations was 10^{11} e/cm^2-sec, and was far more uniform (<±10% variation) over the target area than the proton flux in the previous experiments (Ref. 1).

An X-25 solar simulator using a 3000 watt Xenon lamp was used in making the I-$\overline{V}$ measurements. A value of 139.5 mw/cm^2 was maintained as AMO (Air Mass Zero) during all measurements. The variation of the light beam over the samples was about ±2.0%. A Spectrolab D550 electronic load coupled to an x-y platter provided the I-$\overline{V}$ curves.

The solar cells are (2 x 2) cm N/P silicon 300μ and 200μ thick. They included partially and fully covered cells with about 150μ of fused silica. Each cell has four leads to reduce resistance losses, two on the buss bar and two on the Ti(Pd)Ag layer on the back of the cell.

The first batch of 9 cells irradiated, consisted of:

three 10Ω-cm (300μ) uncovered

three 10Ω-cm (300μ) covered

three 10Ω-cm (200μ) uncovered.

These were irradiated to fluences of $4.2 \cdot 10^{13}$, 10^{14}, 10^{15} e/cm^2.

The second batch of 12 cells consisted of:

three 1Ω-cm (300μ) covered

three 1Ω-cm (300μ) 50% covered

three 10Ω-cm (300μ) 50% covered

three 1Ω-cm (300μ) uncovered

irradiated to fluences of 10^{13}, 10^{14}, and 10^{15} e/cm^2.

After each of the above fluences was reached, I-$\overline{V}$ curves of each sample were made at room temperature, ~-63°C, and ~145°C, immediately after irradiation to minimize annealing effects.

The energy loss by the 1.0 MeV electrons in passing through the 150μ fused silica coverslides is about 65 keV, (Ref. 4), which is negligible. That is to say, damage for both covered and uncovered cells should be similar.

RESULTS

Characteristic I-$\overline{V}$ curves, showing solar cell power output in watts, were made for each measurement. Figures 2-15 show typical I-$\overline{V}$ curves for the seven different types of solar cells before irradiation and again after 10^{15} e/cm^2. The I-$\overline{V}$ curves for intermediate fluences of $4.2 \cdot 10^{13}$ e/cm^2 and 10^{14} e/cm^2 have been omitted in this report.

As in the case of the cells used for proton irradiation, these cells exhibited the same room temperature efficiency before irradiation to within 0.6%.

Table 1 gives the values of the open circuit voltage and short circuit current with electron fluence and sample measurement temperature. The efficiencies of the cells are found to increase with lower cell measurement temperature, and to decrease with higher cell measurement temperatures. Note the efficiencies of both 1Ω-cm and 10Ω-cm covered and uncovered cells are about the same, ~7.0% after 10^{15} e/cm^2 at 25°C, see figures 16-19. The 10Ω-cm cells appear slightly more efficient above 10^{14} e/cm^2 than the 1Ω-cm cells. Luft and Rauschenback observed similar results on Texas Instruments I/P cells, (Ref. 5), as did Cherry and Slifer (Ref. 6).

Relative efficiencies with fluence are plotted in figure 23 for 10Ω-cm Heliotek cells (Wilsey, Ref. 7) and for 10Ω-cm cells (Reynard, Ref. 8). The relative efficiencies of the 1Ω-cm cells are seen to be less than the 10Ω-cm Heliotek and AEG cells.

Efficiencies before irradiation, for the 250μ thick N/P cells measured at 145°C, were found to be ~5.0%, and compare closely with Lewis and Kirkpatrick's results, (Ref. 9).

The values of the electron damage coefficients are given in table 2. Values of initial diffusion lengths for N/P blue sensitive silicon solar cells are taken from Rosenzweig, (Ref. 10). In all cases, note that the damage coefficients increase with decreasing temperature. The values of the present AEG-Telefunken cells appear to be less than values for cells irradiated previously by 1 MeV electrons at room temperature, (Ref. 11).

Comparison of efficiencies of these electron irradiated cells with previously irradiated cells is about the same. After 10^{15} e/cm^2, the present AEG cells are about 0.5% lower in efficiency than n on p (150 to 280) in thick cells, (Ref. 12).

Although damage coefficients vary somewhat between covered and bare cells of the same type, this difference is considerably less than the difference between 1Ω-cm and 10Ω-cm cells.

CONCLUSIONS

(1) Above a fluence of 10^{14} e/cm^2, the 10Ω-cm cells appear more efficient than 1Ω-cm cells.

(2) Damage coefficients for both the 1Ω-cm and 10Ω-cm cells, measured at room temperature, are less than values evaluated for earlier cells.

(3) Damage coefficients increase with decreasing measurement temperature.

(4) Efficiencies of the AEG cells are about the same, or slightly less, than those of earlier irradiated N/P cells.

ACKNOWLEDGEMENTS

Thanks go to Mr. Arthur DuFault of the Facilities Management Section for irradiation of the cells and to Mr. William Gdula of STACO for assembling the apparatus and running the I-V curves.

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Table 1

	80-7 (1Ω-cm bare)									81-10 (1Ω-cm cov)								
fluence P/cm^2	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C
0	590	132	25	730	127	-62	330	140	146	590	128	25	715	124	-66	370	136	145
10^{14}	565	119	25	750	110	-63	315	130	143	555	120	25	650	114	-63	335	130	143
10^{15}	530	98	24	705	83	-64	260	110	148	515	102	24	615	91	-62	280	111	148
	152-3 (10Ω-cm 50%)									81-4 (1Ω-cm 50%)								
fluence P/cm^2	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C
0	550	139	25	625	134	-63	270	146	146	595	132	25	725	126	-62	330	139	144
10^{14}	525	130	25	665	118	-64	270	142	143	570	123	25	755	112	-63	330	135	145
10^{15}	495	116	25	670	96	-67	215	125	148	530	101	25	735	85	-67	260	114	148

Table 1 (Continued)

	152-18 (10Ω-cm cov)									151-16 (10Ω-cm bare)								
fluence P/cm^2	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C
0	545	146	25	630	142	-60	270	155	140	550	142	25	625	136	-60	270	147	140
4.2 10^{13}	545	138	25	655	126	-67	270	147	143	540	134	25	660	124	-62	265	139	143
10^{15}	495	119	26	665	104	-64	225	133	144	490	119	26	640	103	-64	220	130	144
	150-5 (10Ω-cm 200)																	
fluence P/cm^2	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C	V_{oc} mv	I_{sc} ma	T °C
0	520	129	25	605	125	-60	250	137	140									
4.2 10^{13}	530	125	25	605	120	-65	250	131	143	No Cell Tested								
10^{15}	495	110	26	540	106	-66	215	124	144									

Table 2

Damage Coefficients (1.0 MeV Electrons)

		25°C		-63°C		145°C	
	e/cm^2	$I_{sc(amp)}$	$K_{(e^{-1})}$	$I_{sc(amp)}$	$K_{(e^{-1})}$	$I_{sc(amp)}$	$K_{(e^{-1})}$
10Ω-cm bare	$4.2\ 10^{13}$ 10^{15}	.034 .030	$4.9\ 10^{-11}$	.031 .026	$8.6\ 10^{-11}$	.035 .033	$2.2\ 10^{-11}$
10Ω-cm cov.	$4.2\ 10^{13}$ 10^{15}	.035 .030	$5.9\ 10^{-11}$	.032 .026	$9.0\ 10^{-11}$	.037 .033	$3.3\ 10^{-11}$
10Ω-cm 200μ	$4.2\ 10^{13}$ 10^{15}	.032 .022	$6.1\ 10^{-11}$	.030 .027	$6.3\ 10^{-11}$	.033 .031	$2.2\ 10^{-11}$
10Ω-cm 50% cov	10^{14} 10^{15}	.033 .029	$5.0\ 10^{-11}$	.030 .024	$1.2\ 10^{-10}$	.036 .031	$4.8\ 10^{-11}$
1Ω-cm bare	10^{14} 10^{15}	.030 .025	$1.0\ 10^{-10}$	.028 .021	$2.0\ 10^{-10}$	.033 .028	$7.7\ 10^{-11}$
1Ω-cm covered	10^{14} 10^{15}	.030 .026	$8.8\ 10^{-11}$	.029 .023	$1.4\ 10^{-10}$	.033 .028	$7.2\ 10^{-11}$
1Ω-cm 50% cov	10^{14} 10^{15}	.031 .025	$1.0\ 10^{-10}$	.028 .021	$1.9\ 10^{-10}$	.034 .029	$6.4\ 10^{-11}$

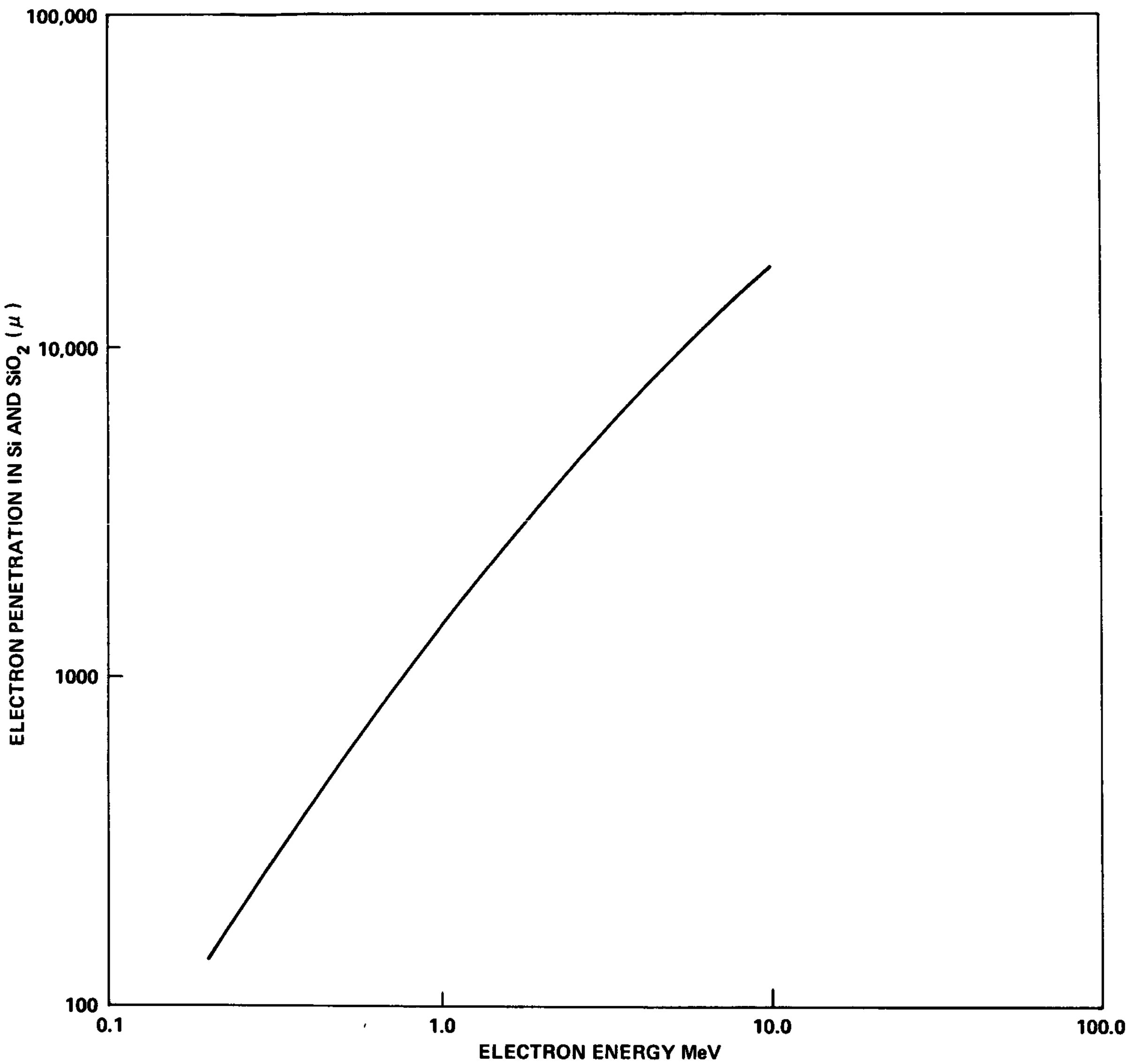

100,000
10,000
1000
100
ELECTRON PENETRATION IN Si AND SiO_2 (μ)
0.1
1.0
10.0
100.0
ELECTRON ENERGY MeV

Figure 1

SOLAR CELL I-V CURVE

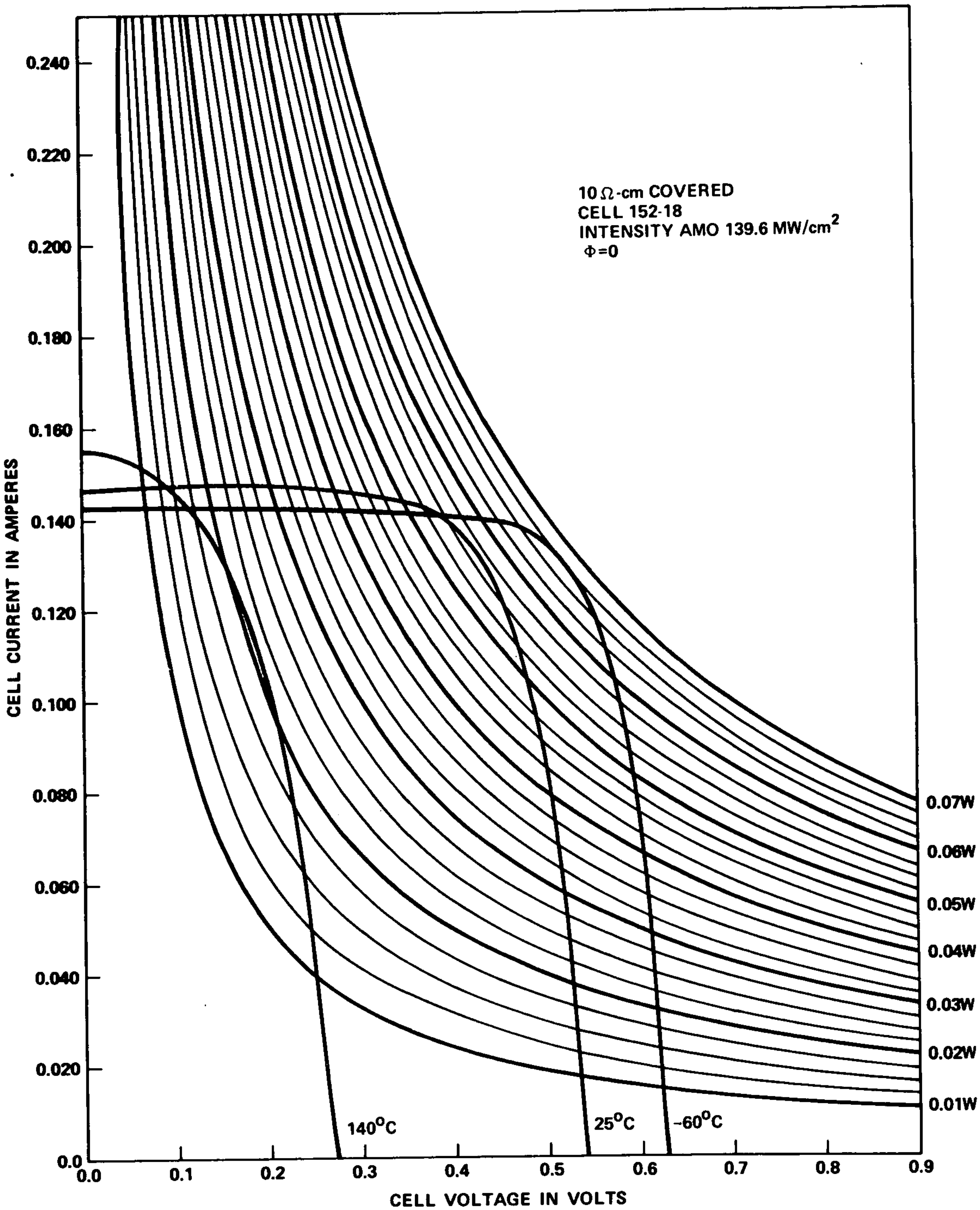


Figure 2

SOLAR CELL I-V CURVE

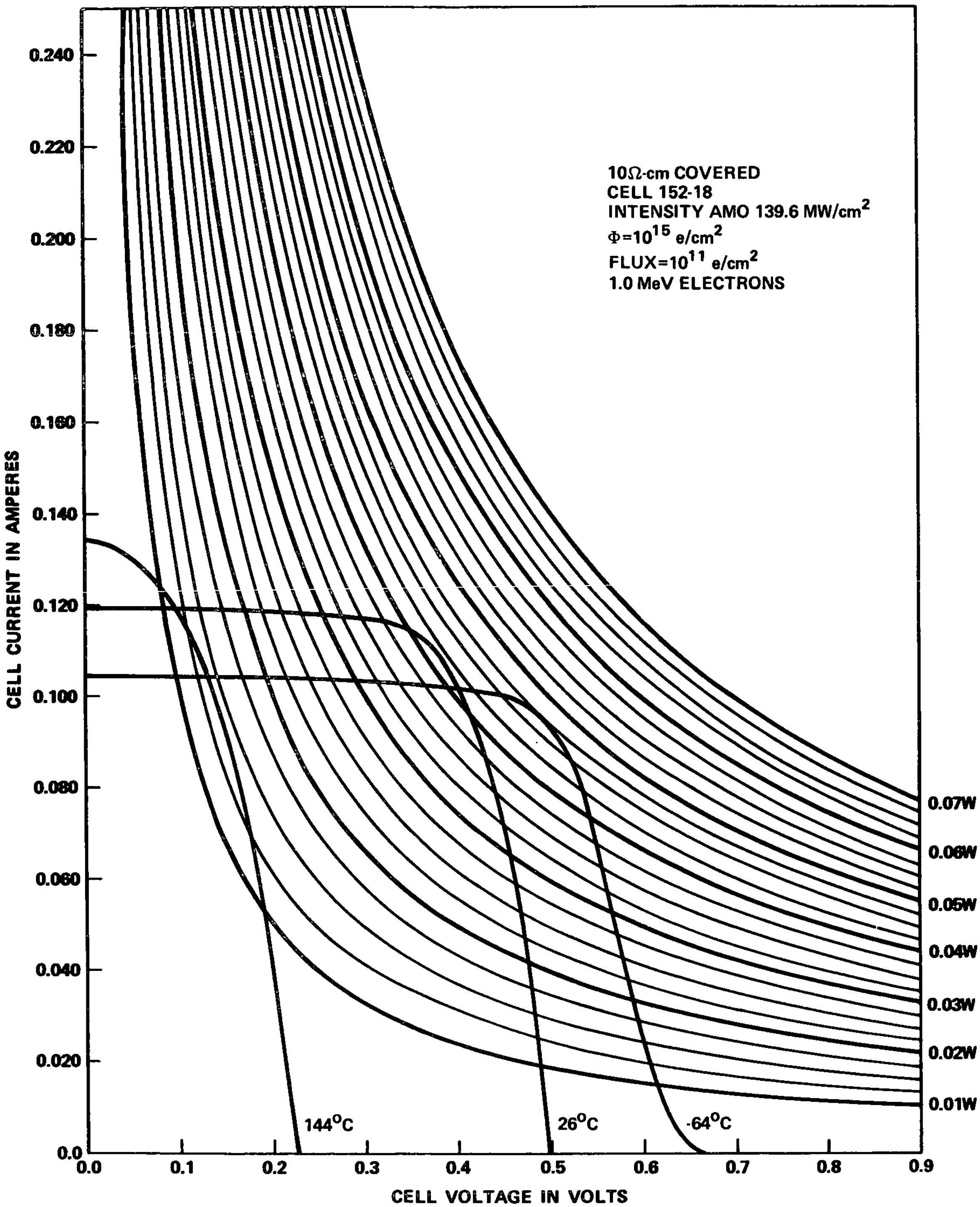


Figure 3

SOLAR CELL I-V CURVE

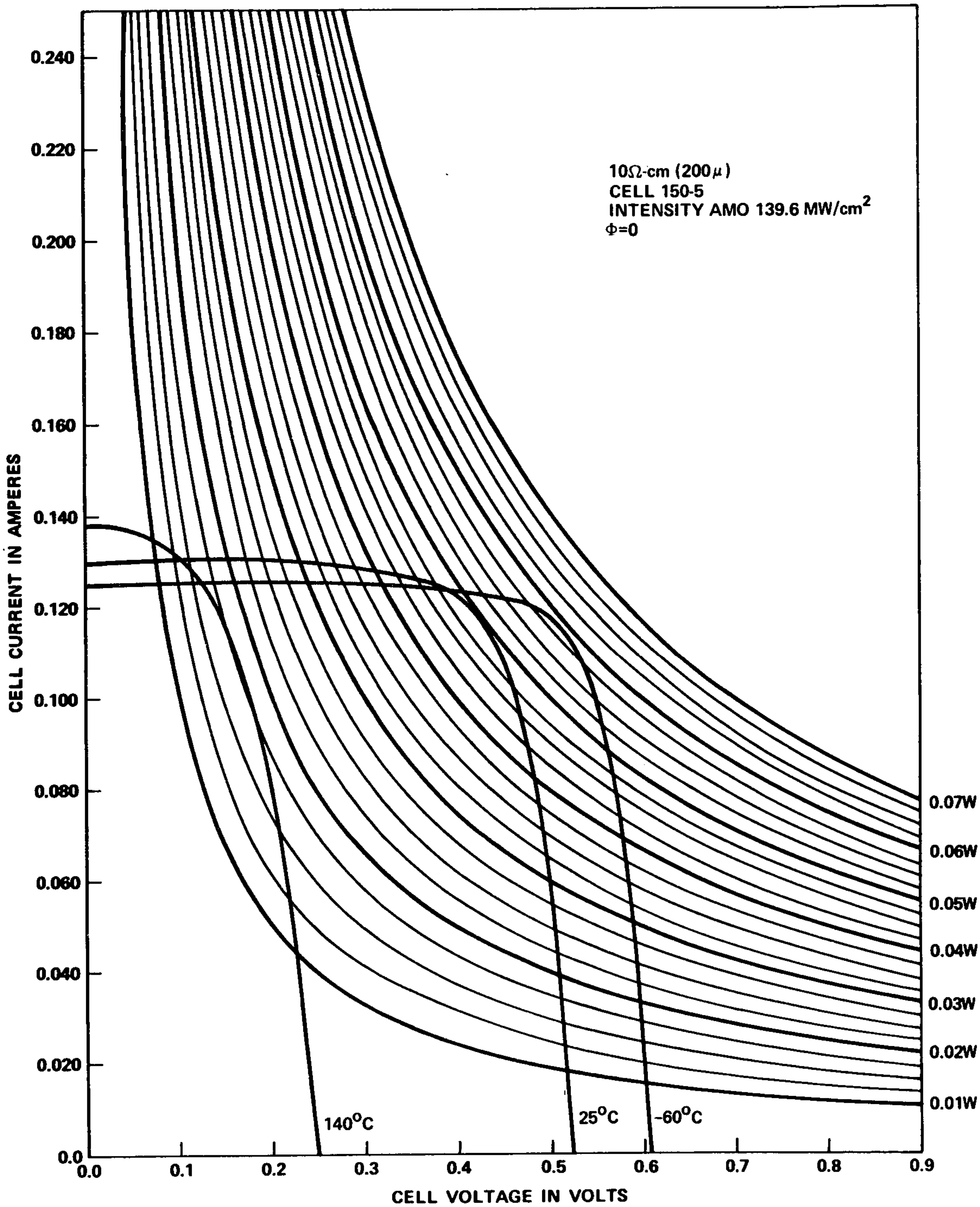


Figure 4

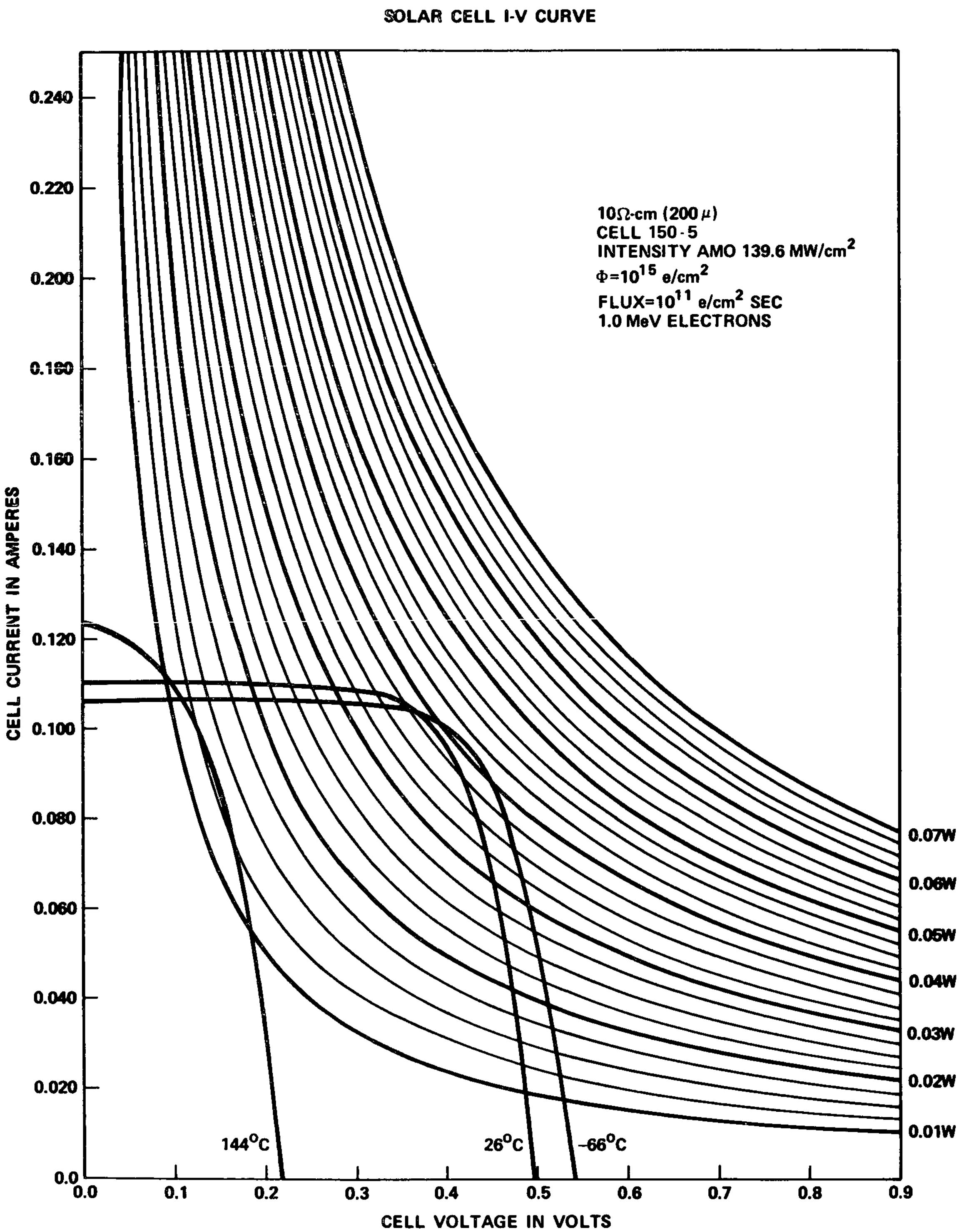
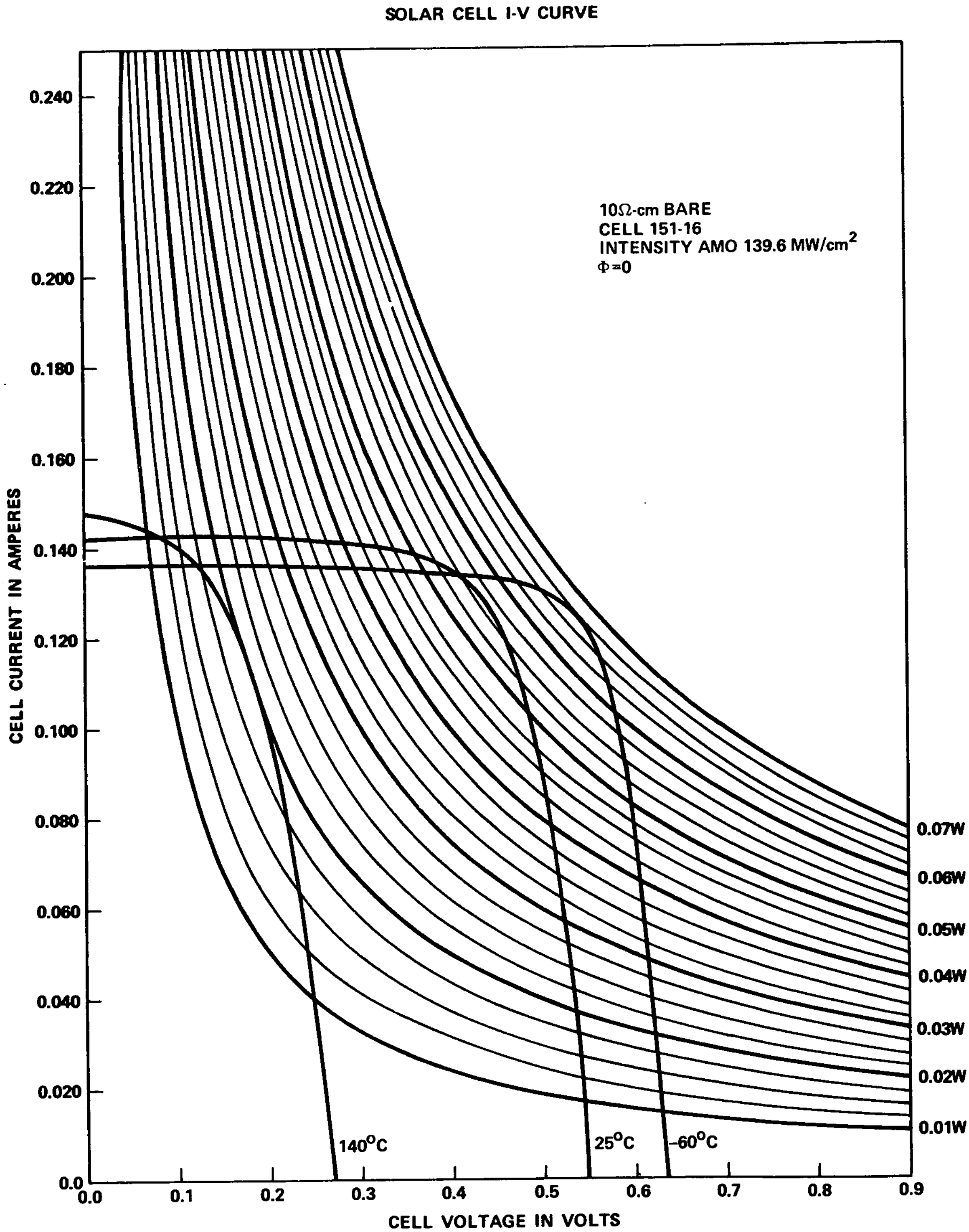

SOLAR CELL I-V CURVE
10Ω-cm (200 μ)
CELL 150-5
INTENSITY AMO 139.6 MW/cm²
Φ=10¹⁵ e/cm²
FLUX=10¹¹ e/cm² SEC
1.0 MeV ELECTRONS
CELL CURRENT IN AMPERES
CELL VOLTAGE IN VOLTS
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.07W
0.06W
0.05W
0.04W
0.03W
0.02W
0.01W
144°C
26°C
-66°C

Figure 5



SOLAR CELL I-V CURVE
10Ω-cm BARE
CELL 151-16
INTENSITY AMO 139.6 MW/cm²
Φ=0
CELL CURRENT IN AMPERES
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
CELL VOLTAGE IN VOLTS
0.07W
0.06W
0.05W
0.04W
0.03W
0.02W
0.01W
140°C
25°C
-60°C

Figure 6

SOLAR CELL I-V CURVE

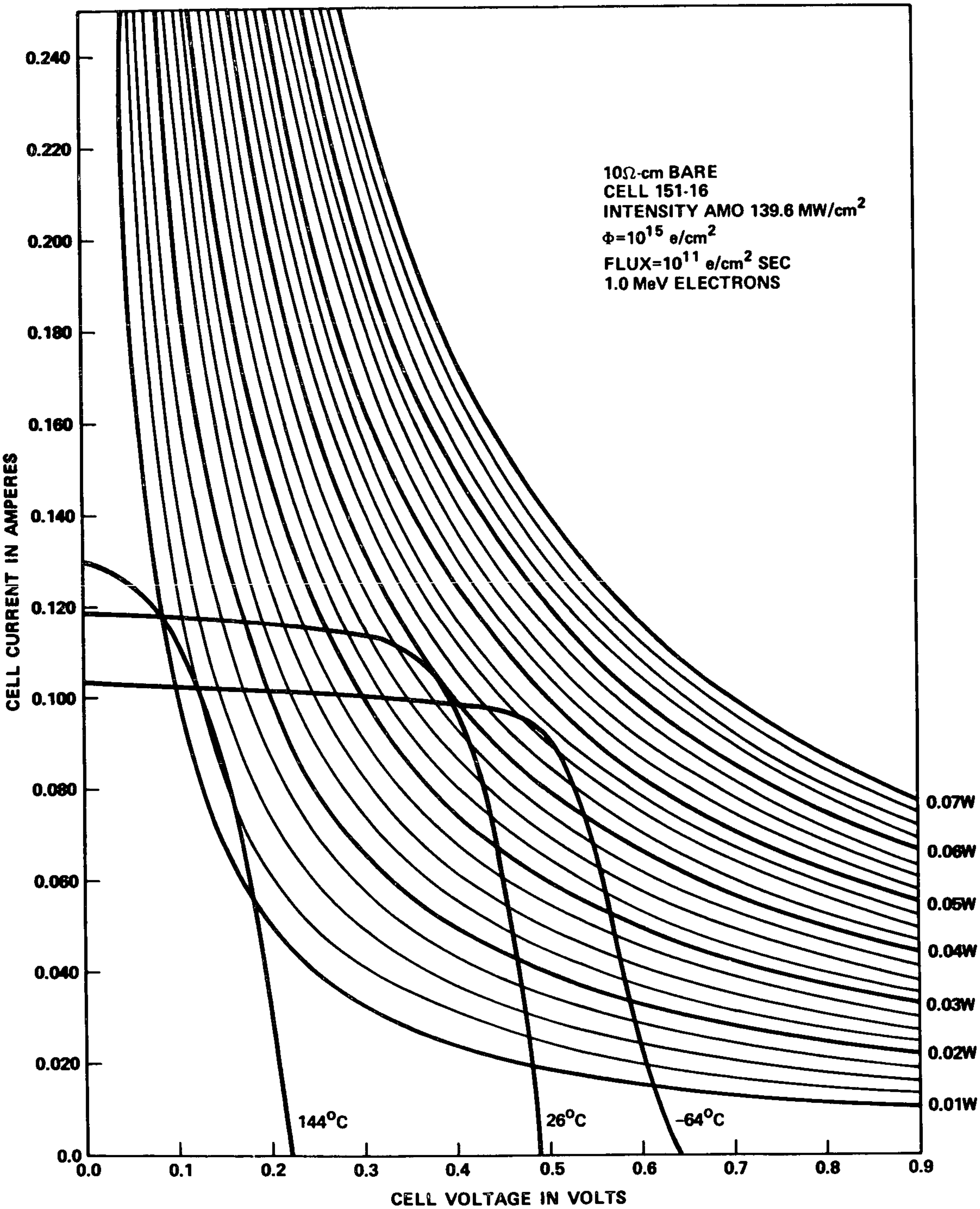


Figure 7

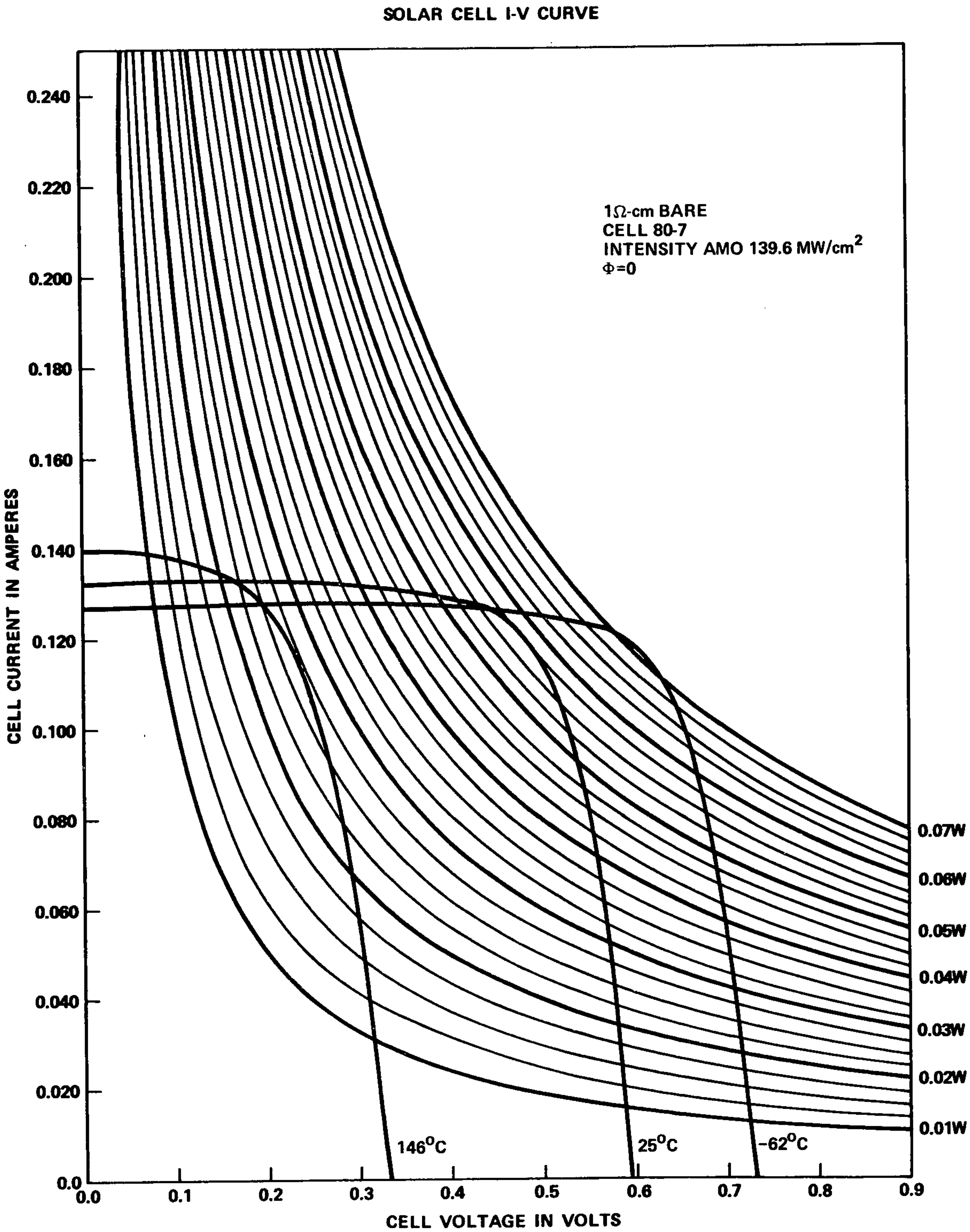

SOLAR CELL I-V CURVE
1Ω-cm BARE
CELL 80-7
INTENSITY AMO 139.6 MW/cm2
Φ=0
CELL CURRENT IN AMPERES
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.0
CELL VOLTAGE IN VOLTS
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
146°C
25°C
-62°C
0.07W
0.06W
0.05W
0.04W
0.03W
0.02W
0.01W

Figure 8

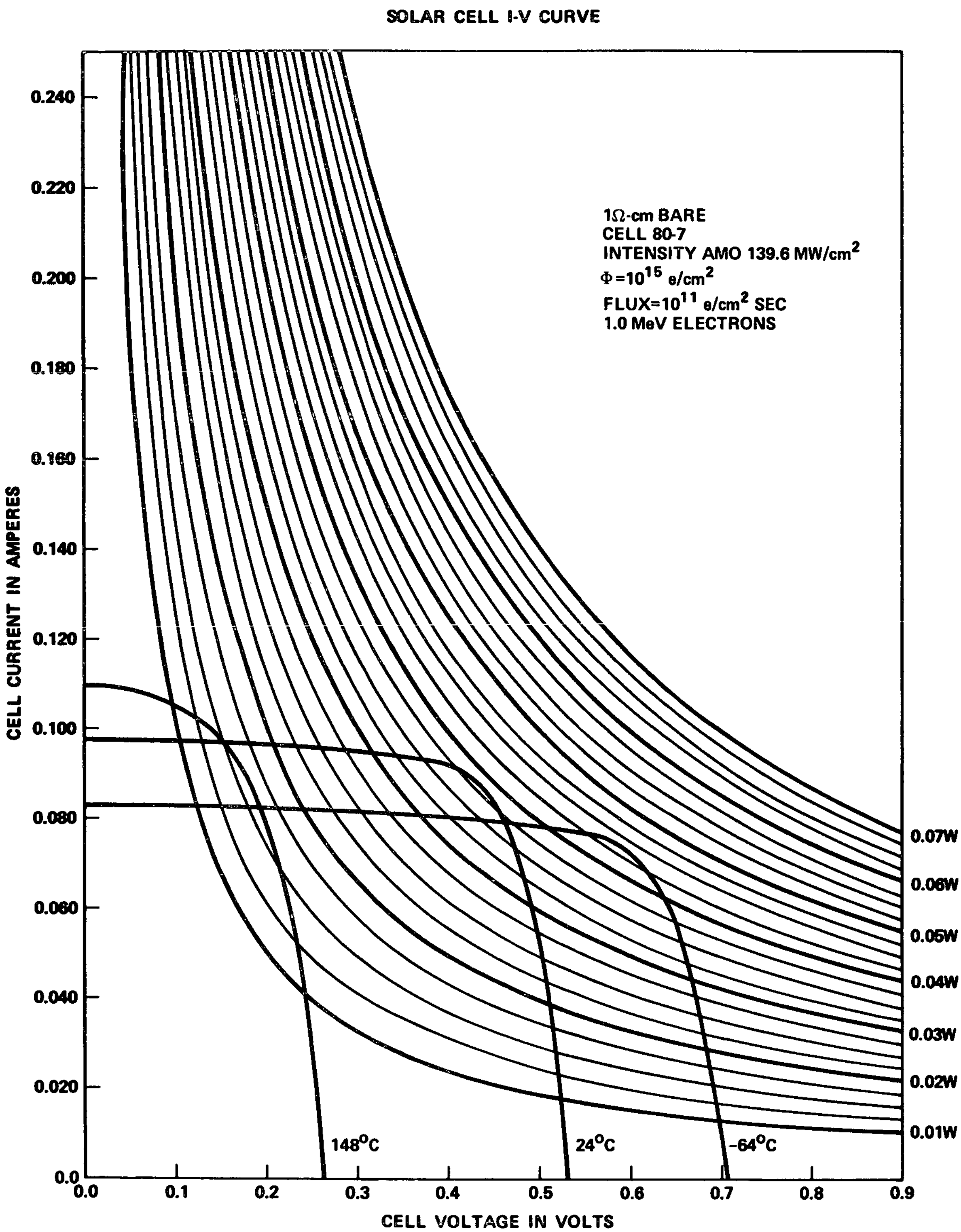

SOLAR CELL I-V CURVE
1Ω-cm BARE
CELL 80-7
INTENSITY AMO 139.6 MW/cm²
Φ=10¹⁵ e/cm²
FLUX=10¹¹ e/cm² SEC
1.0 MeV ELECTRONS
CELL CURRENT IN AMPERES
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.0
0.07W
0.06W
0.05W
0.04W
0.03W
0.02W
0.01W
148°C
24°C
-64°C
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
CELL VOLTAGE IN VOLTS

Figure 9

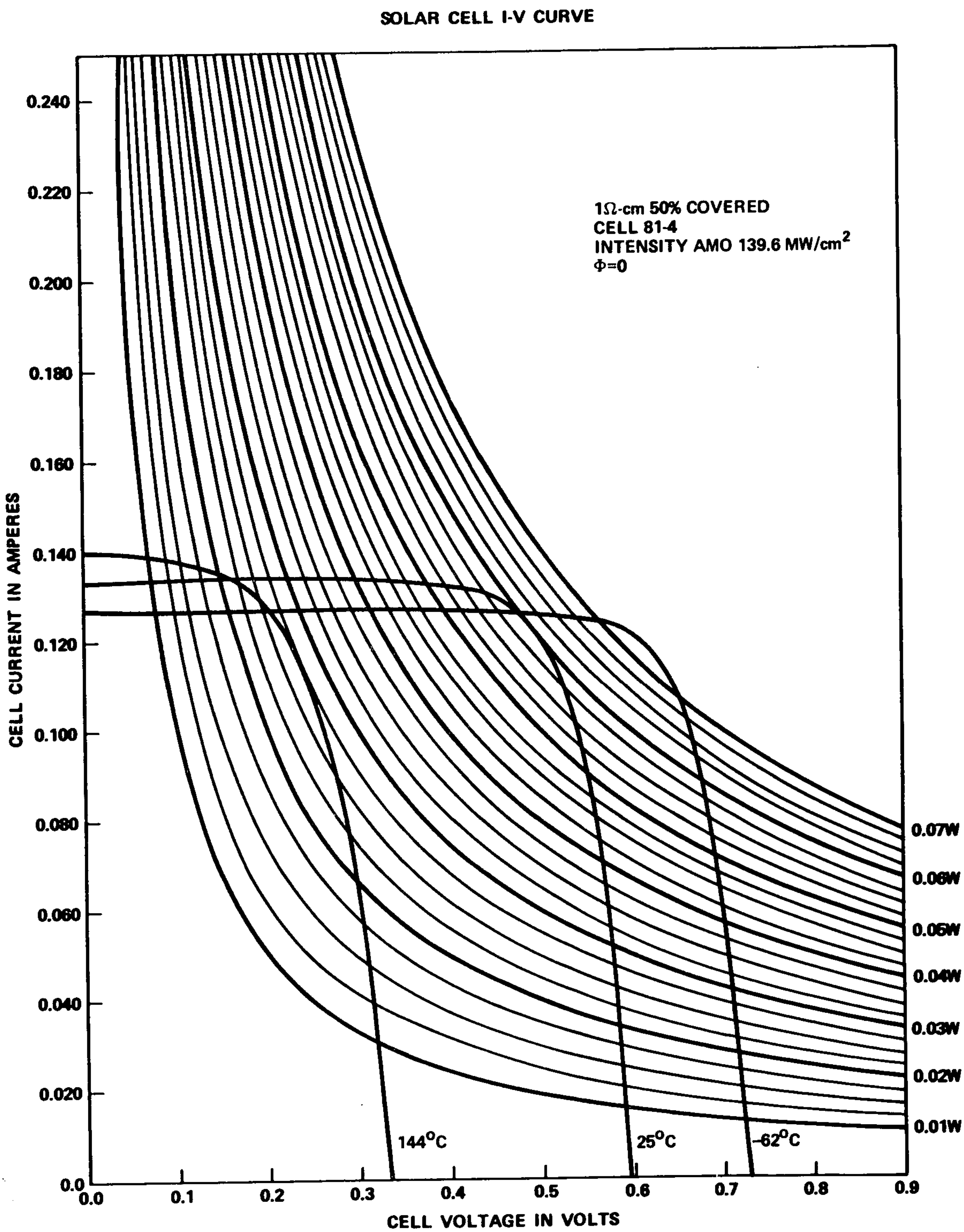

SOLAR CELL I-V CURVE
1Ω-cm 50% COVERED
CELL 81-4
INTENSITY AMO 139.6 MW/cm²
Φ=0
CELL CURRENT IN AMPERES
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
CELL VOLTAGE IN VOLTS
144°C
25°C
-62°C
0.07W
0.06W
0.05W
0.04W
0.03W
0.02W
0.01W

Figure 10

SOLAR CELL I-V CURVE

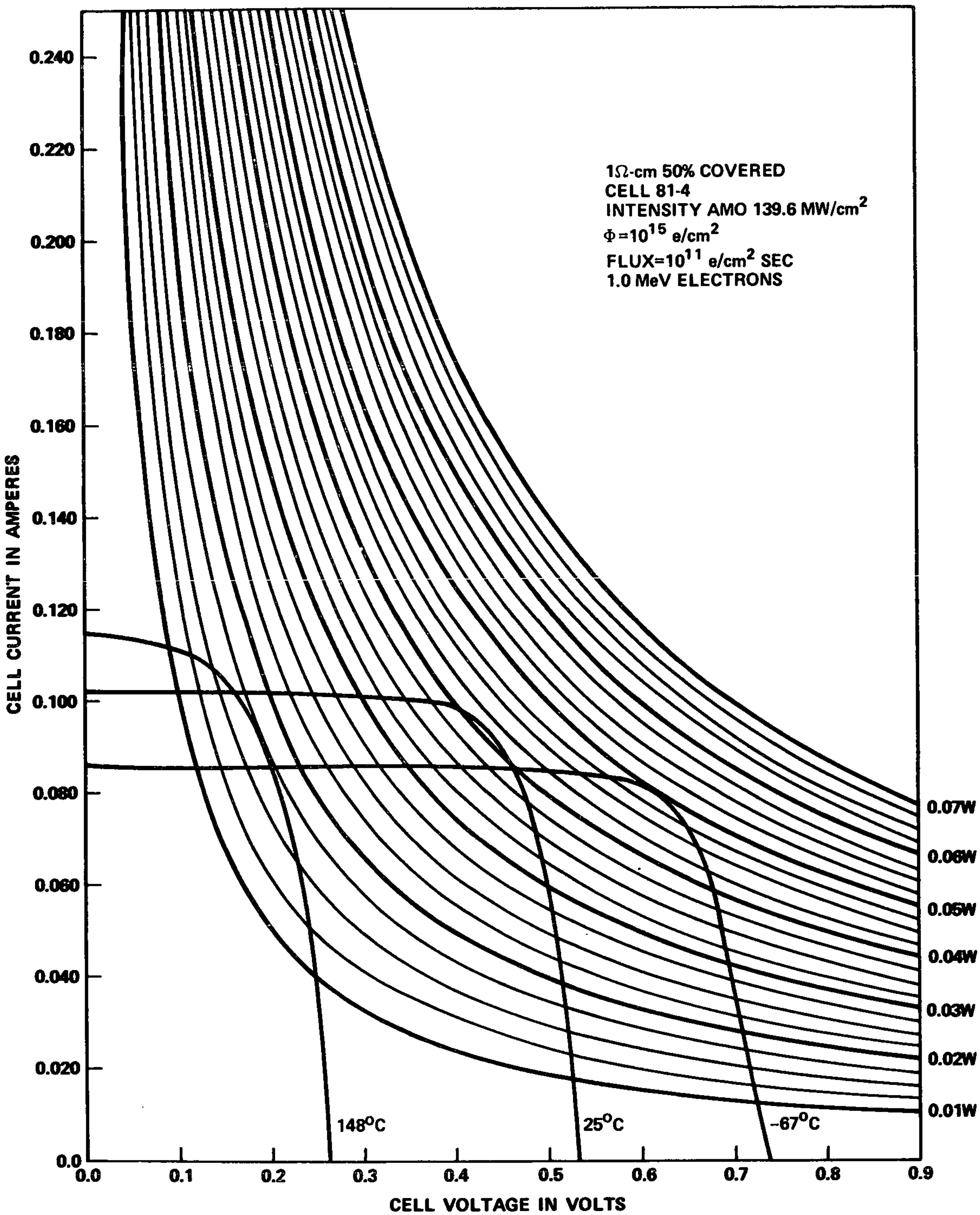


Figure 11

SOLAR CELL I-V CURVE

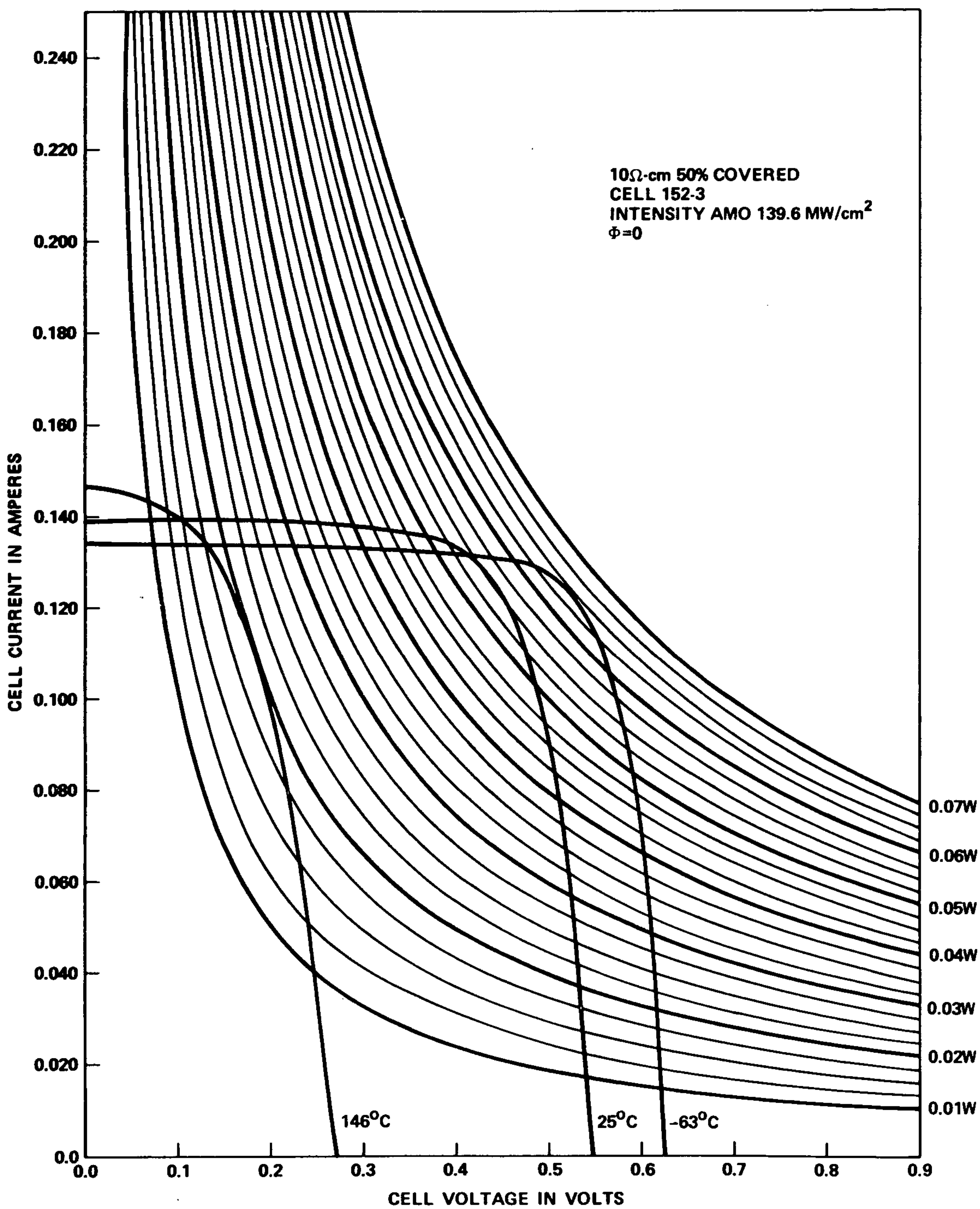
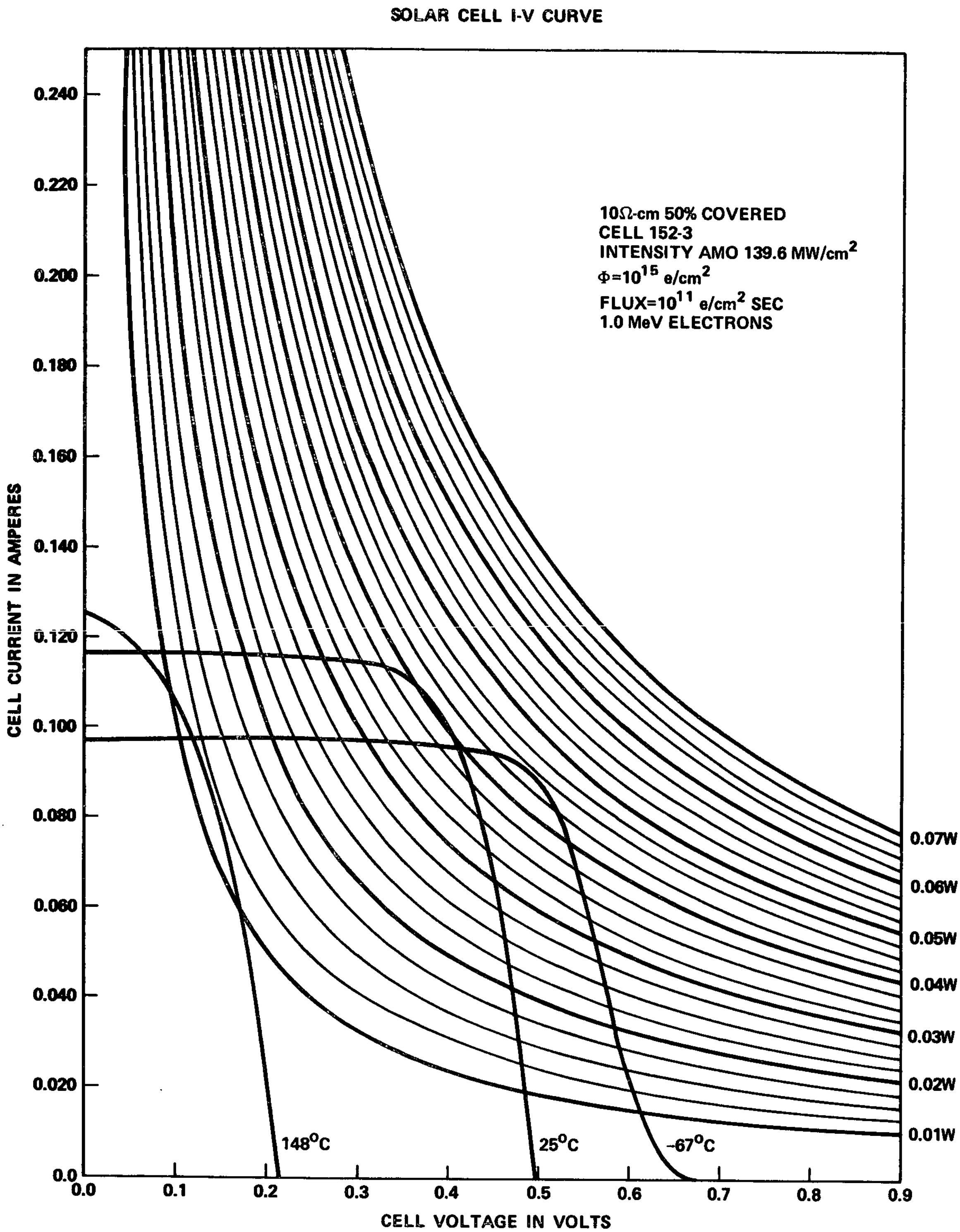


Figure 12



SOLAR CELL I-V CURVE
10Ω-cm 50% COVERED
CELL 152-3
INTENSITY AMO 139.6 MW/cm2
Φ=10^15 e/cm2
FLUX=10^11 e/cm2 SEC
1.0 MeV ELECTRONS
CELL CURRENT IN AMPERES
CELL VOLTAGE IN VOLTS
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.07W
0.06W
0.05W
0.04W
0.03W
0.02W
0.01W
148°C
25°C
-67°C

Figure 13

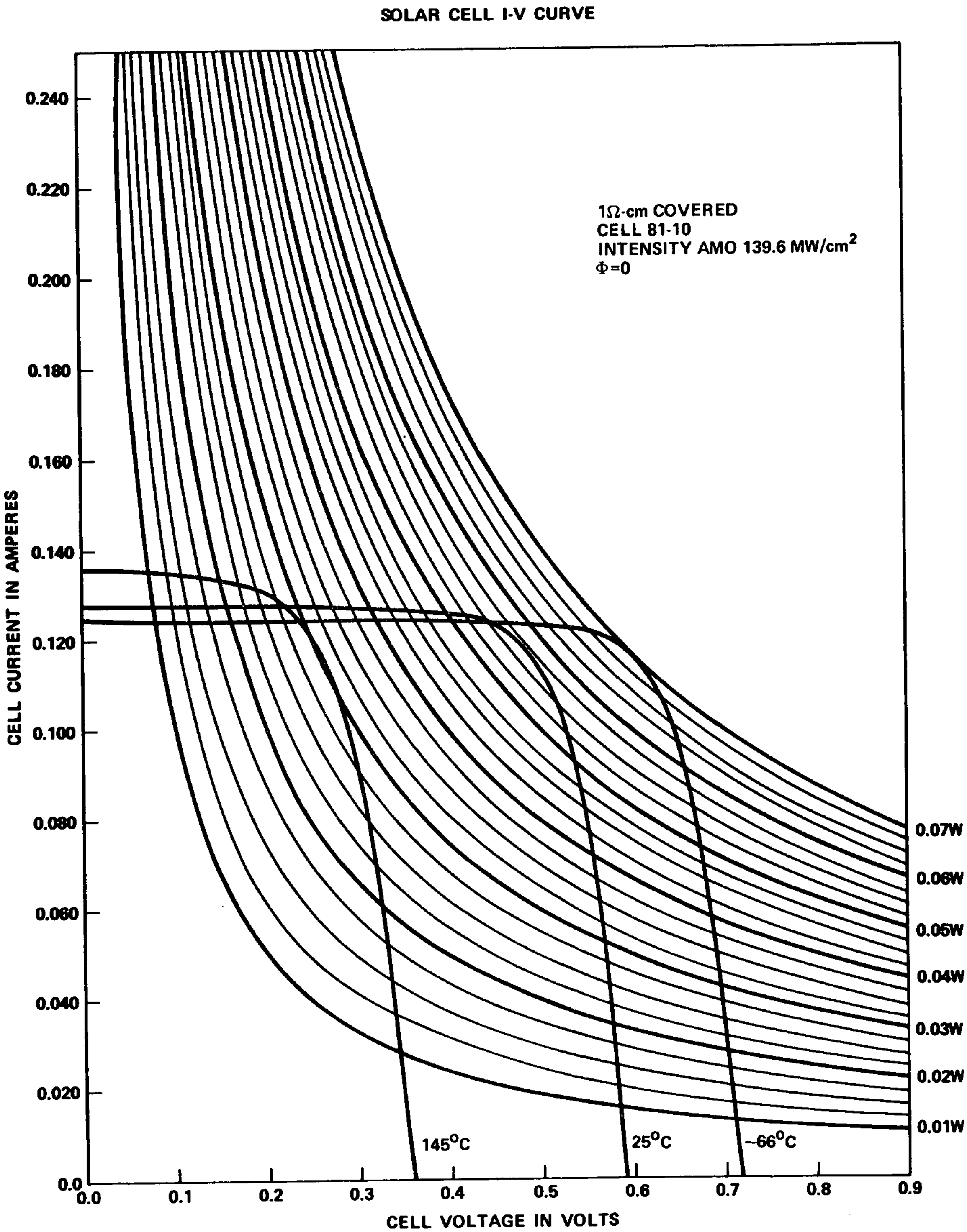

SOLAR CELL I-V CURVE
1Ω-cm COVERED
CELL 81-10
INTENSITY AMO 139.6 MW/cm²
Φ=0
CELL CURRENT IN AMPERES
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
CELL VOLTAGE IN VOLTS
145°C
25°C
-66°C
0.07W
0.06W
0.05W
0.04W
0.03W
0.02W
0.01W

Figure 14

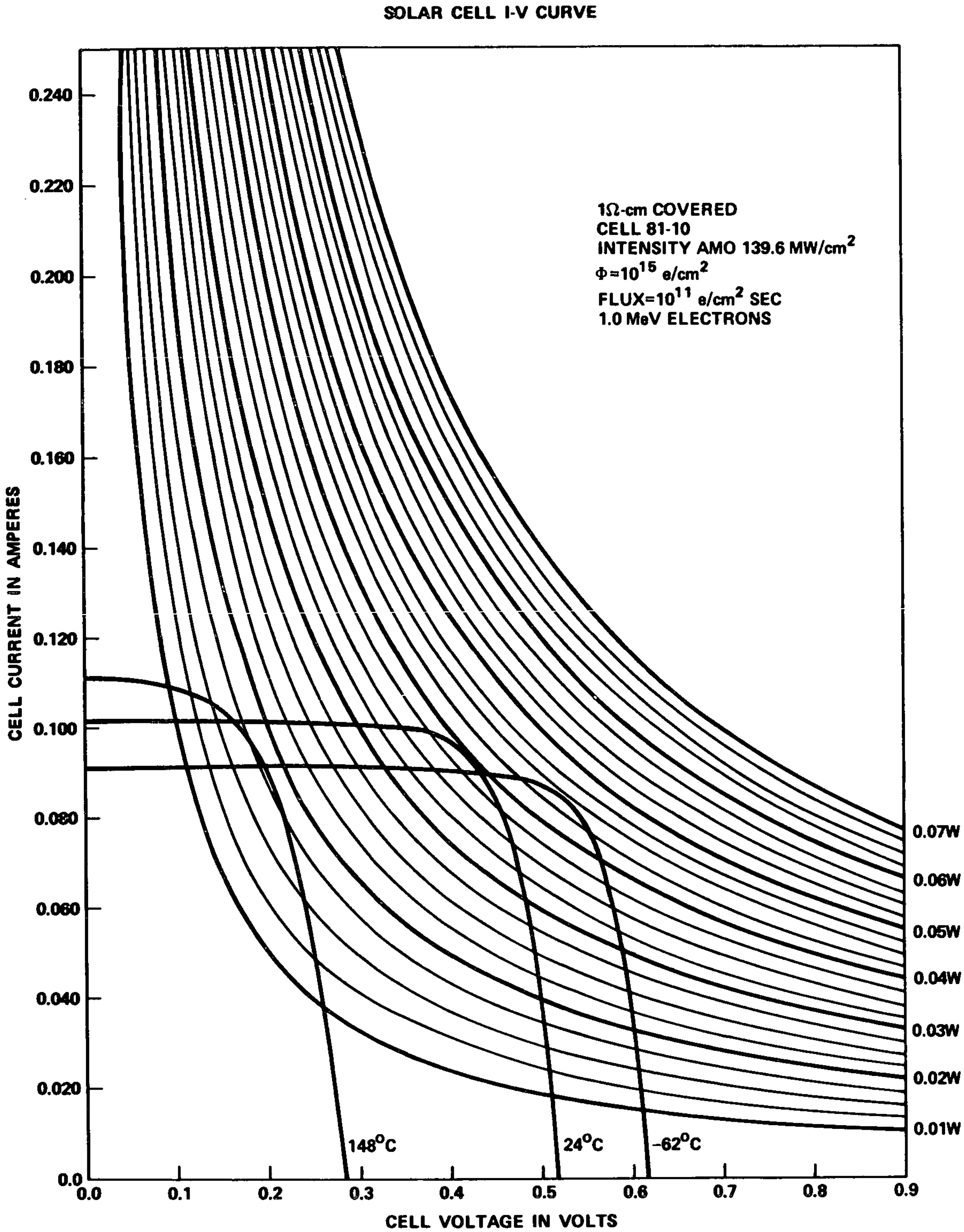

SOLAR CELL I-V CURVE
1Ω-cm COVERED
CELL 81-10
INTENSITY AMO 139.6 MW/cm²
Φ=10¹⁵ e/cm²
FLUX=10¹¹ e/cm² SEC
1.0 MeV ELECTRONS
CELL CURRENT IN AMPERES
0.240
0.220
0.200
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.0
0.07W
0.06W
0.05W
0.04W
0.03W
0.02W
0.01W
148°C
24°C
-62°C
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
CELL VOLTAGE IN VOLTS

Figure 15

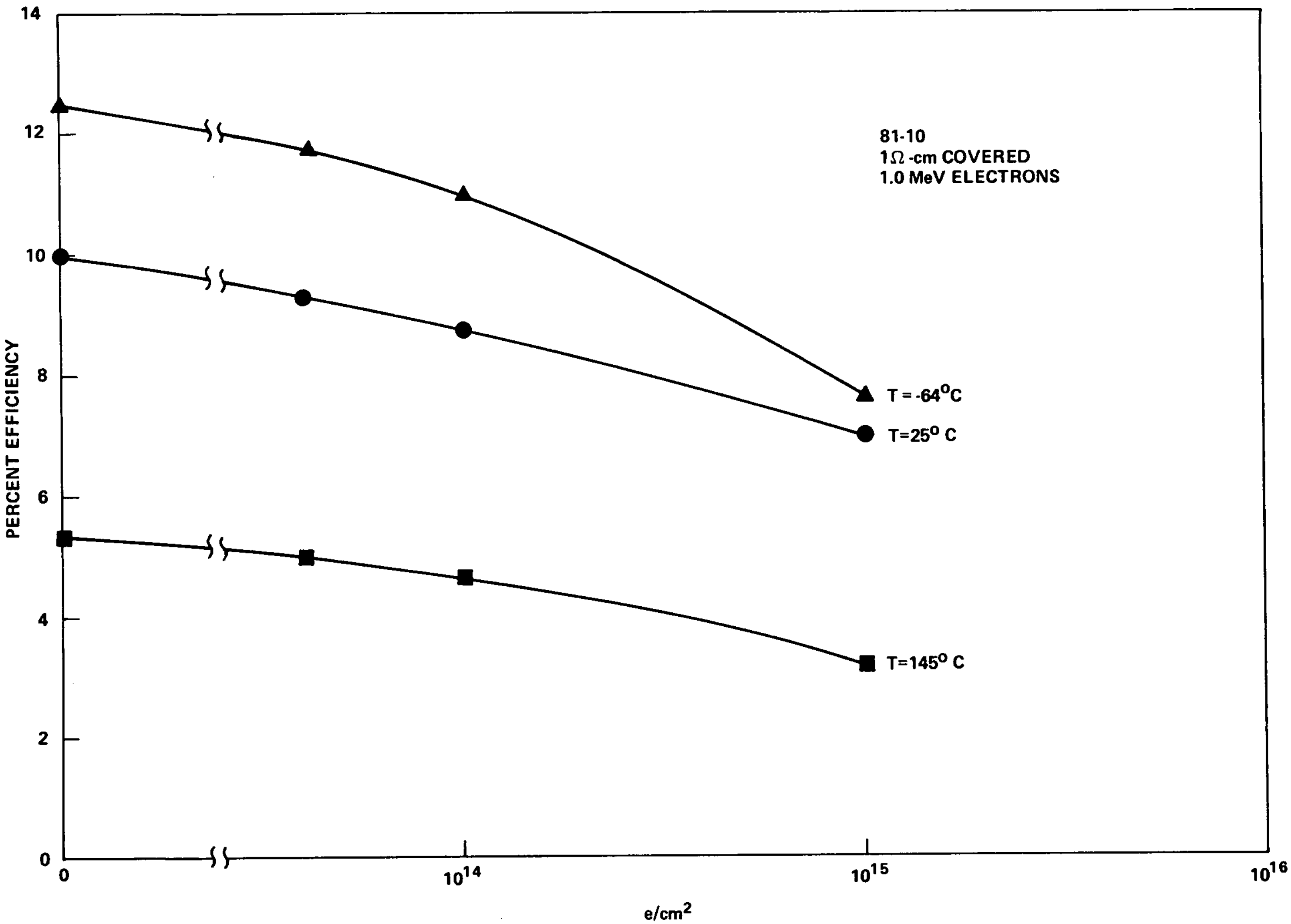

81-10
1Ω-cm COVERED
1.0 MeV ELECTRONS
T = -64°C
T=25° C
T=145° C
PERCENT EFFICIENCY
e/cm²
0
2
4
6
8
10
12
14
0
10¹⁴
10¹⁵
10¹⁶

Figure 16

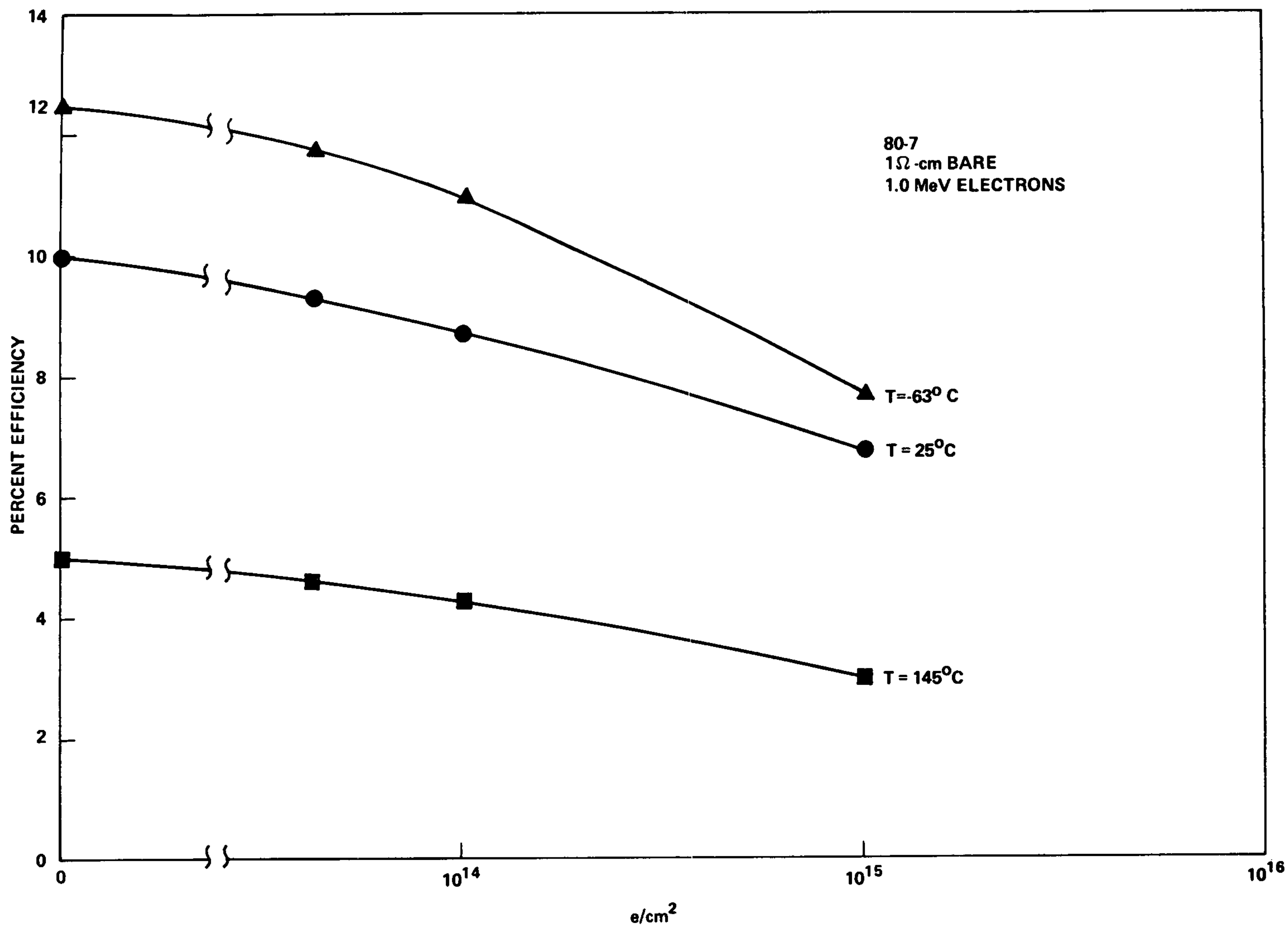

14
12
10
8
6
4
2
0
PERCENT EFFICIENCY
0
10^{14}
10^{15}
10^{16}
e/cm^2
80-7
1Ω-cm BARE
1.0 MeV ELECTRONS
T=-63° C
T = 25°C
T = 145°C

Figure 17

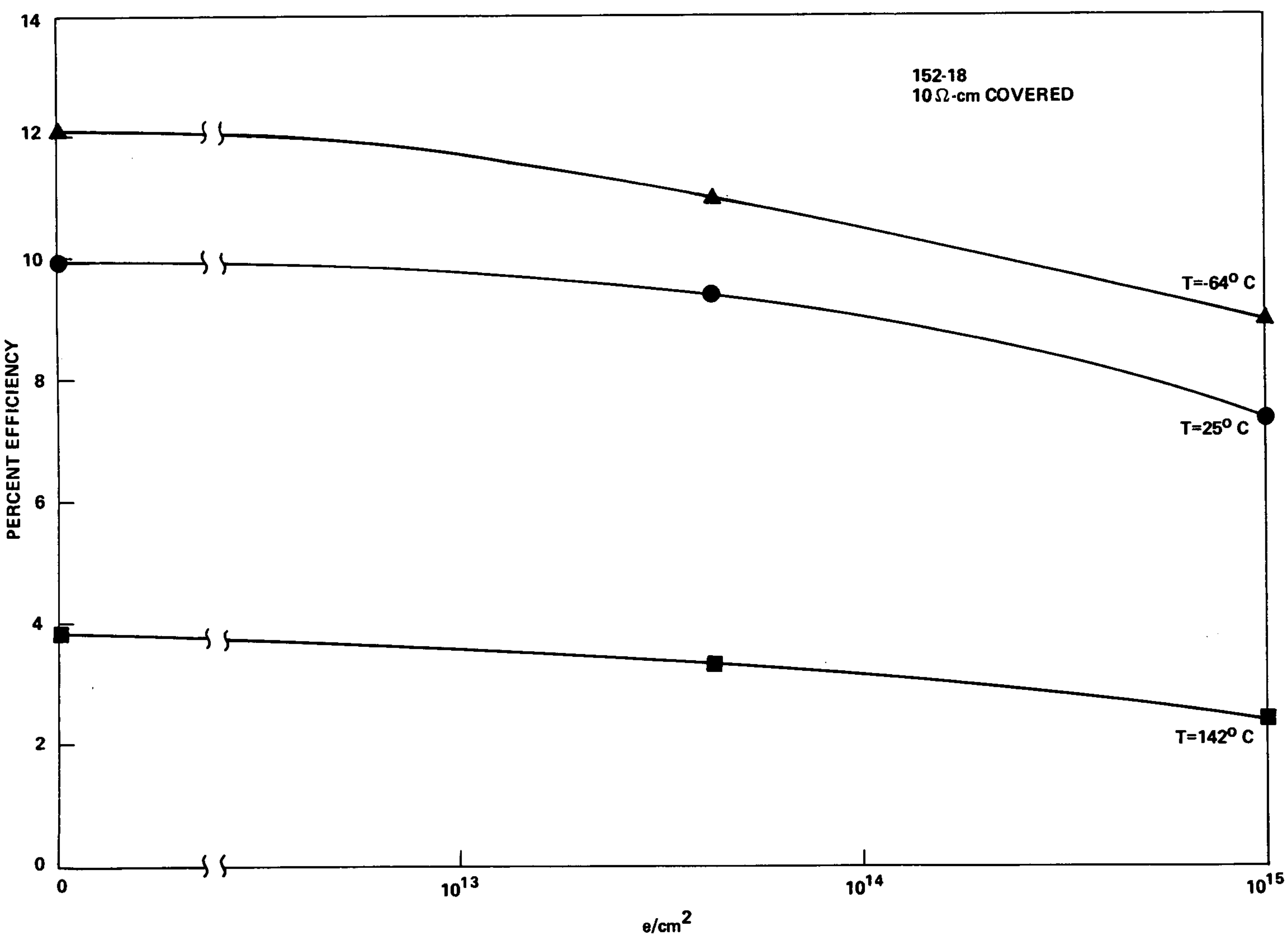
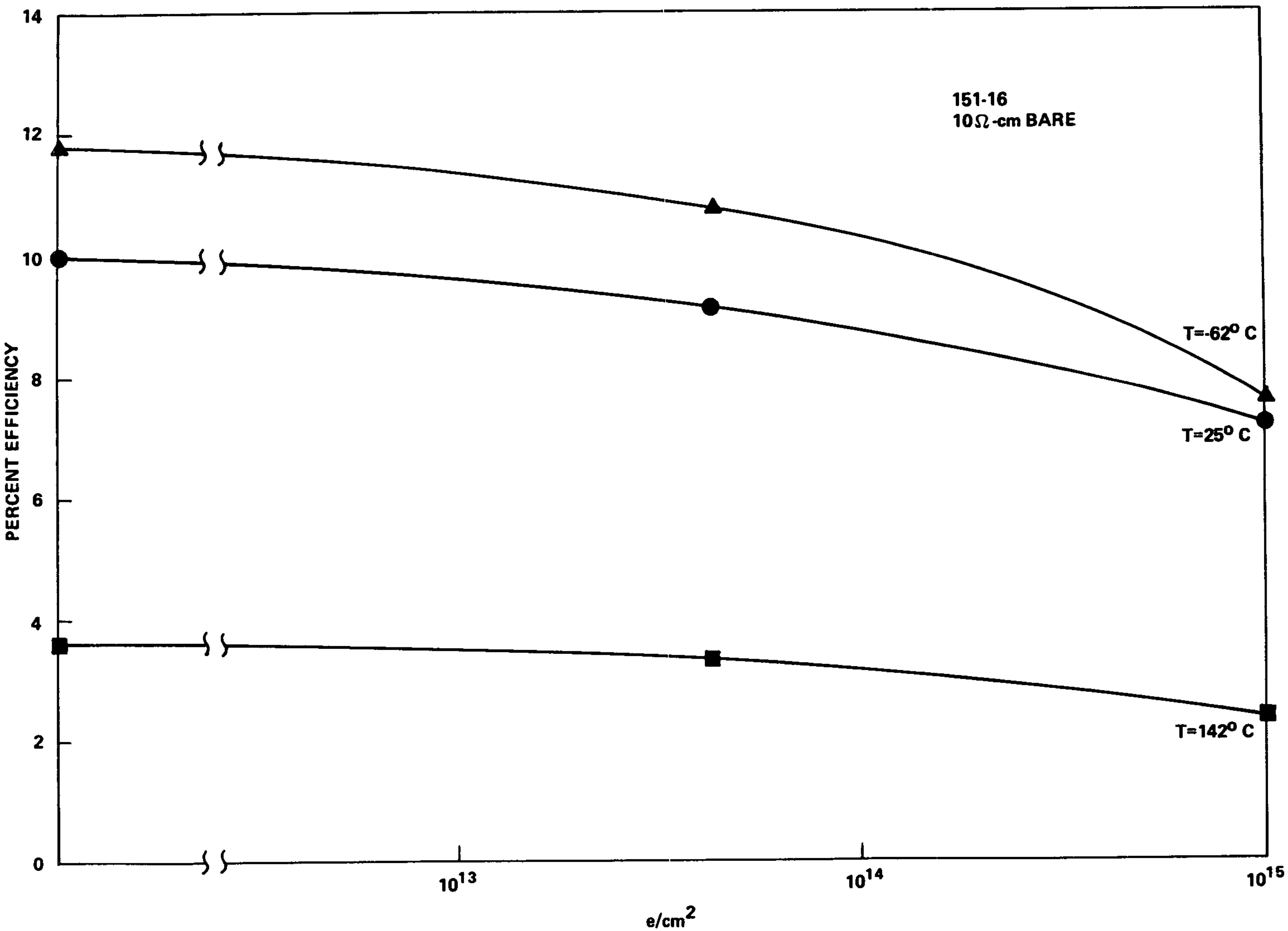

152-18
10 Ω-cm COVERED
T=-64° C
T=25° C
T=142° C
PERCENT EFFICIENCY
e/cm²
0
2
4
6
8
10
12
14
10¹³
10¹⁴
10¹⁵

Figure 18



151-16
10Ω-cm BARE
T=-62° C
T=25° C
T=142° C
PERCENT EFFICIENCY
e/cm²
14
12
10
8
6
4
2
0
10¹³
10¹⁴
10¹⁵

Figure 19

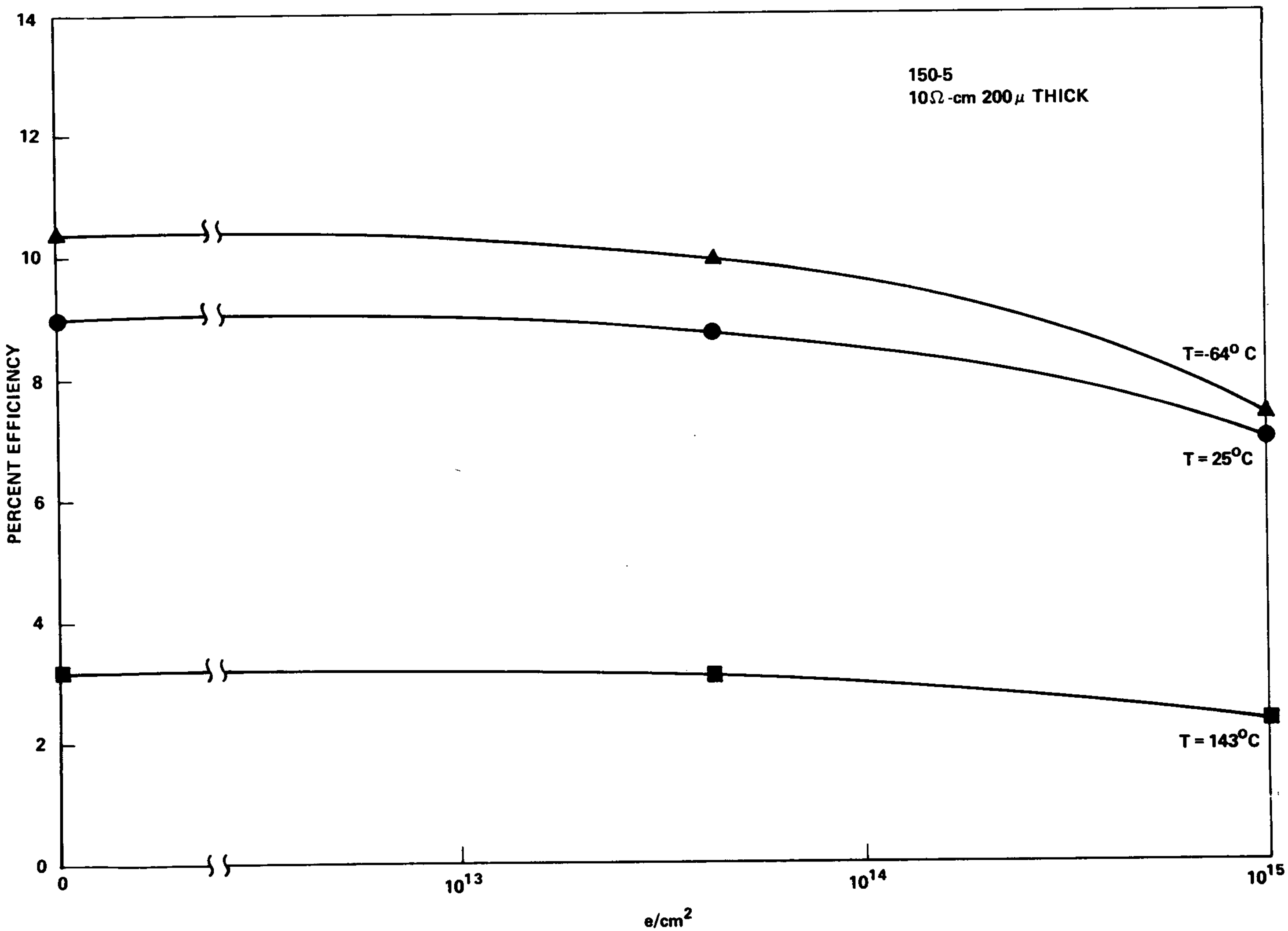

150-5
10Ω-cm 200μ THICK
PERCENT EFFICIENCY
14
12
10
8
6
4
2
0
T=-64° C
T = 25°C
T = 143°C
0
10^13
10^14
10^15
e/cm^2

Figure 20

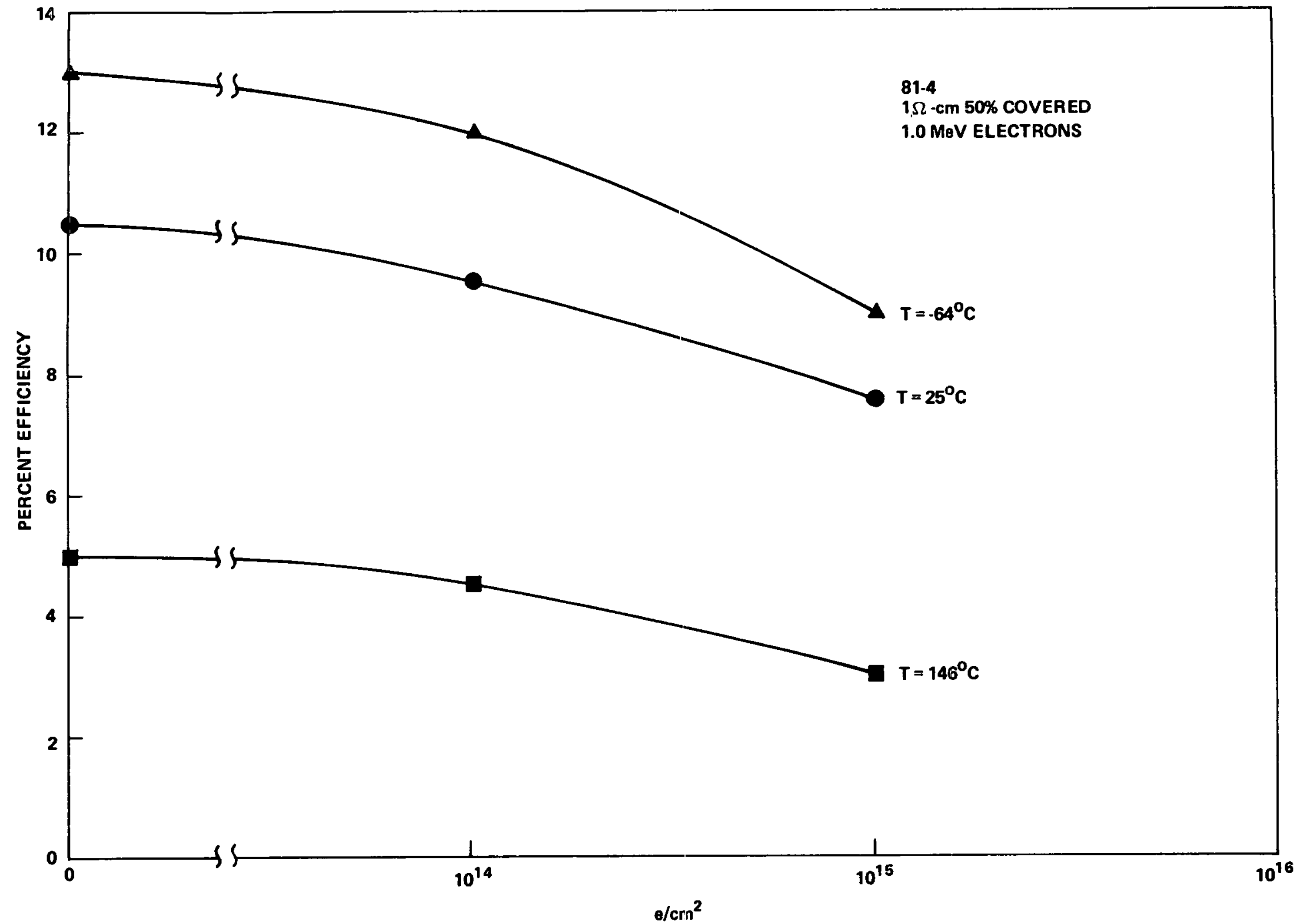

81-4
1Ω -cm 50% COVERED
1.0 MeV ELECTRONS
T = -64°C
T = 25°C
T = 146°C
PERCENT EFFICIENCY
14
12
10
8
6
4
2
0
0
10^14
10^15
10^16
e/cm^2

Figure 21

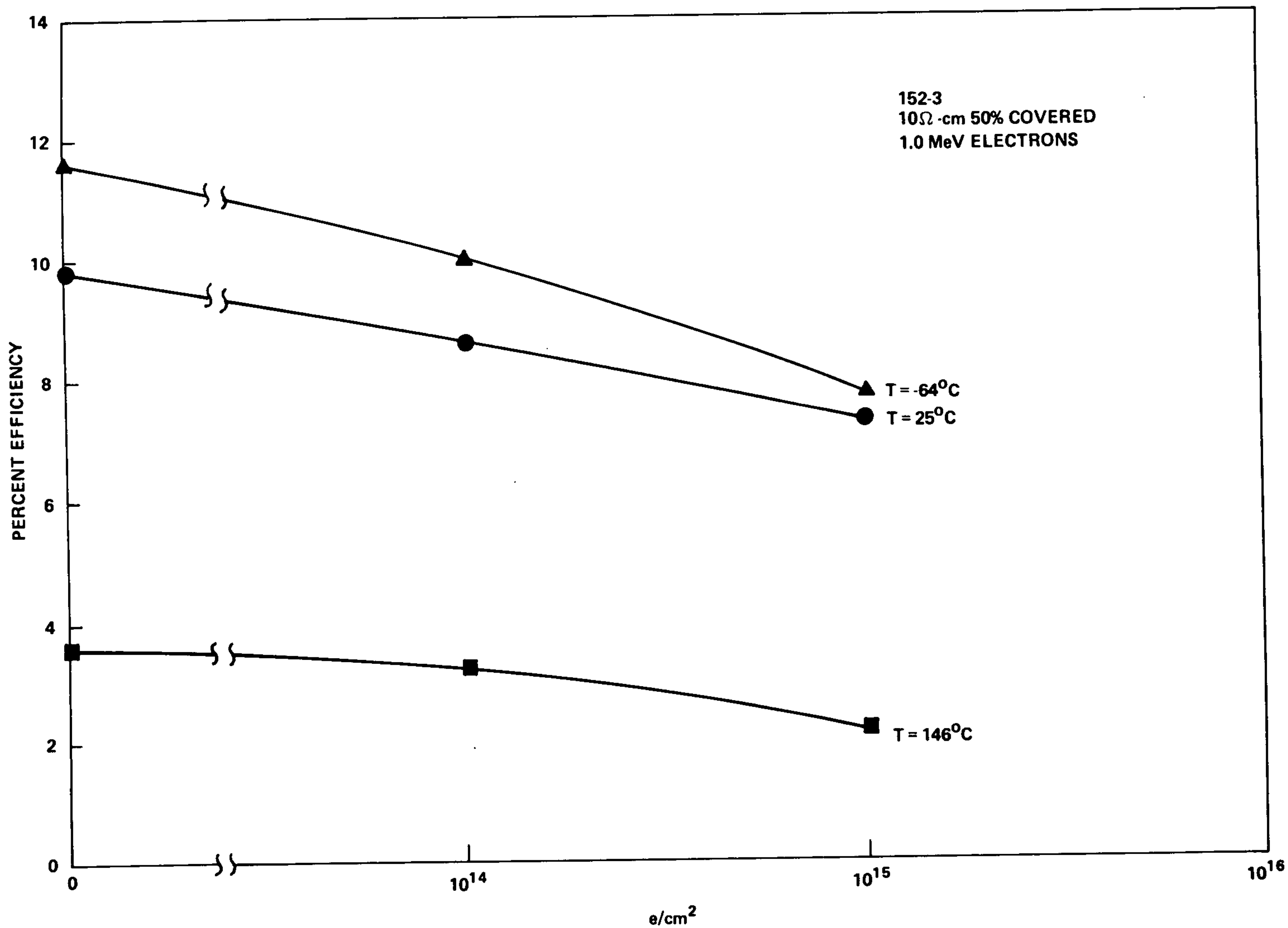

152-3
10Ω-cm 50% COVERED
1.0 MeV ELECTRONS
T = -64°C
T = 25°C
T = 146°C
PERCENT EFFICIENCY
e/cm²
0
2
4
6
8
10
12
14
0
10¹⁴
10¹⁵
10¹⁶

Figure 22

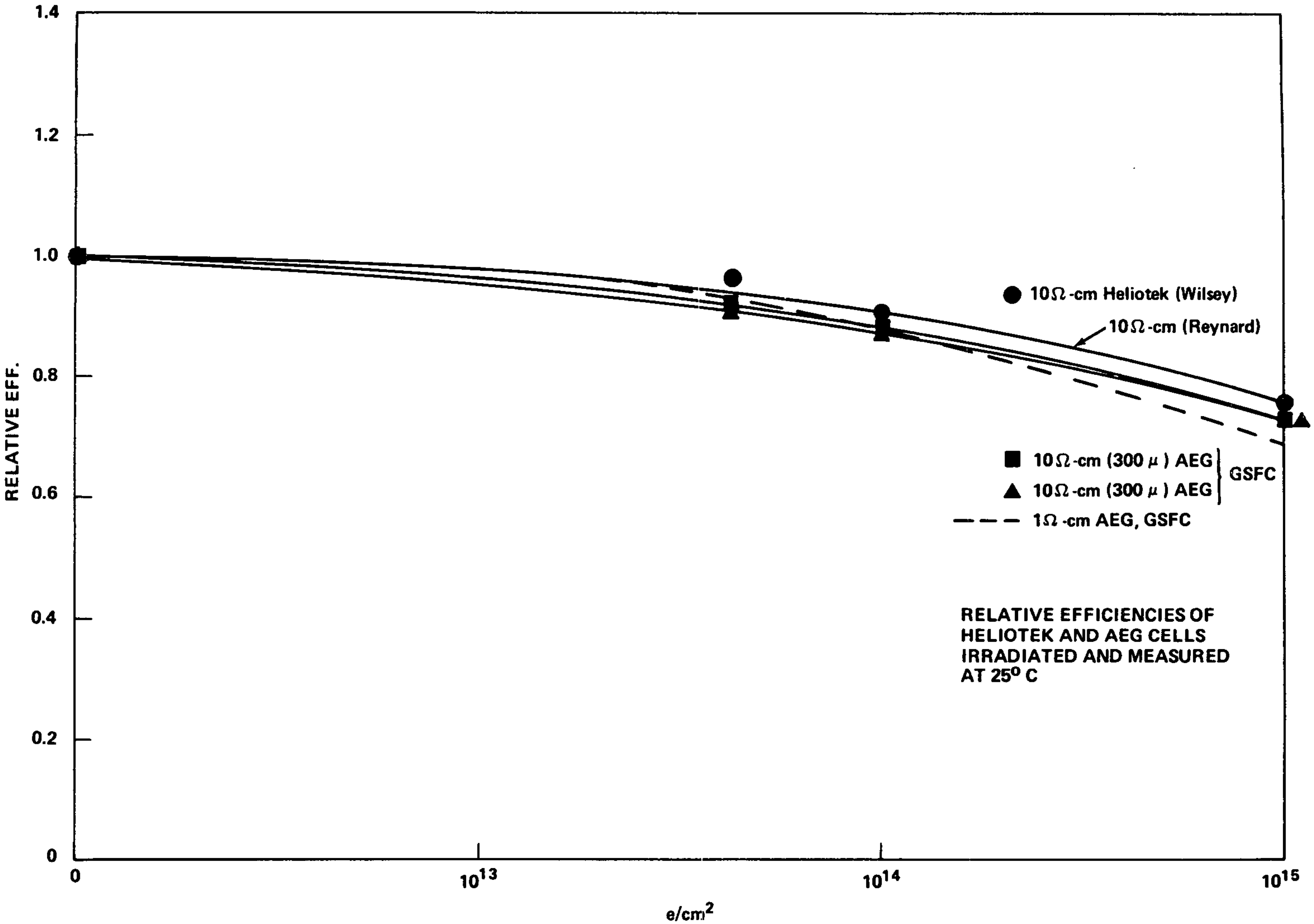

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
RELATIVE EFF.
0
10^{13}
10^{14}
10^{15}
e/cm^2
10Ω-cm Heliotek (Wilsey)
10Ω-cm (Reynard)
10Ω-cm (300 μ) AEG
10Ω-cm (300 μ) AEG
GSFC
1Ω-cm AEG, GSFC
RELATIVE EFFICIENCIES OF HELIOTEK AND AEG CELLS IRRADIATED AND MEASURED AT 25° C

Figure 23