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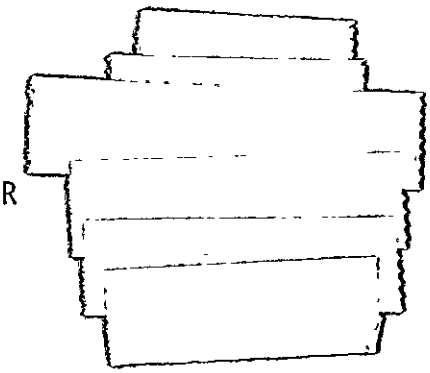
SILICON SOLAR CELL PROCESS DEVELOPMENT, FABRICATION AND ANALYSIS

THIRD QUARTERLY REPORT

FOR PERIOD COVERING

1 JANUARY 1979 to 31 MARCH 1979



BY

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JPL CONTRACT NO. 955089

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"The JPL Low-Cost Silicon Solar Array Project is sponsored by the U. S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effect toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE."

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ABSTRACT

The standard solar cells (2x2 cm) from the cast silicon (HEM) showed a maximum AMO efficiency of 10.1%. Cells from the low resistivity material (0.5 ohm-cm) showed lower performance than those of the high resistivity cast silicon (3 ohm-cm), an average efficiency 9.5% versus 7.6%

Maximum AMO efficiency of the standard solar cells (2x2 cm) from the EFG (RH) ribbons was about 7.5%. The solar cells from the controlled SiC, using the displaced die, showed more consistent and better performance than those of the uncontrolled SiC ribbons, an average efficiency of 6.6% versus 5.4%

The average AMO efficiency of the standard SOC solar cells were about 6%. These were large area solar cells (an average area of 15 cm^2). A maximum efficiency of 7.3% was obtained. The SOC solar cells showed both leakage and series resistance problems, leading to an average curve fill factor of about 60%.

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I. INTRODUCTION

The objective of this program is to investigate, develop and utilize technologies appropriate and necessary for improving the efficiency of solar cells made from various unconventional silicon sheets. During this quarterly reporting period, work has progressed in fabrication and charaterization of solar cells from cast silicon by heat exchanger method (Crystal Systems), EFG (RH) ribbon (Mobil Tyco) and silicon on ceramic (Honeywell). Silicon blanks (2x2 cm) were prepared from the HEM cast silicon and EFG ribbon, using conventional slicing techniques, and fabricated using a standard process typical of those used currently in the silicon solar cell industry. Also a back surface field (BSF) process and other process modifications were included in processing additional slices. Relatively large area (about 15 cm^2) solar cells were fabricated from silicon on ceramic substrates using a standard process that can be easily adapted to these substrates. Evaluation of the SOC solar cells has not been completed in this reporting period.

The performance parameters measured included open circuit voltage, short circuit current, curve fill factor, and conversion efficiency (all taken under AM0 illumination). Also measured for typical cells were spectral response, dark I-V characteristics, minority carrier diffusion length, and photoresponse by fine light scanning. The results were compared to the properties of cells made from the conventional single crystalline Czochralski silicon with an emphasis on statistical evalution. Limited efforts were made to identify defects which will influence solar cell performance.

A. CAST SILICON (HEM) SOLAR CELLS

1.0 SOLAR CELL FABRICATION

Blanks (2x2 cm) were prepared by slicing the cast silicon blocks (2x2 cm cross section) using an ID saw. Silicon blocks were prepared from two casting experiments of different resistivities; nominal 3 ohm-cm and 0.5 ohm-cm. Measured resistivity of the sliced blanks from 3 ohm-cm material showed resistivity variation between 2.6 and 3.3 ohm-cm from end-to-end of the 3" block, while those of 0.5 ohm-cm cast silicon indicated between 0.4-0.8 ohm-cm. Most of the blanks were single crystalline, with a few partly polycrystalline with large crystallites. Some of the blanks were measured for minority carrier diffusion lenghts using the SPV method and results indicated a range of 30-60 μm for the low resistivity blanks (0.5 ohm-cm) and 40-70 μm for the 3 ohm-cm blanks.

NOTE: Czochralski control blanks (1-3 ohm-cm) showed diffusion lengths in the range 130-160 μm.

Thickness of the sliced blanks was about 16 mils and the blanks were thinned down to 13 mil using a planar etching solution. Standard and BSF solar cells were fabricated from the blanks with a mechanical yield (ratio of unbroken solar cells to initial starting blanks) above 90%, which is about the same yield as for Czochralski blanks.

[See reference (1) for detailed description of standard and Back Surface Field (BSF) processes. Reference (2) provides technical details of casting techniques by Heat Exchanger Method (HEM).]

2.0 SOLAR CELL PERFORMANCE AND CHARATERIZATION

Characteristics Under Illumination

Final finshed solar cells had SiO AR coatings and about 90% active area with Ti-Pd-Ag metallizations. Solar cell parameters, such as I_{SC}, V_{OC}, CFF and η, were measured under an AMO simulator at 25°C block temperature.

NOTE: Detailed information on solar simulator and measurement techniques are discussed in Appendix II of reference (1). Appendix III in this report provides the parameters of individual solar cell from HEM cast silicon.

Table 1 summarizes the cell parameters from the standard process. Solar cells from HEM cast silicon showed maximum efficiency of 10.1% for the 3 ohm-cm material and 9.2% for the 0.5 ohm-cm silicon with an average efficiency of 9.5% and 7.4%, respectively. The average efficiency of control solar cells was about 11%. Solar cells from the low resistivity cast silicon generally showed low curve fill factor, in the range of 40-75%, which is suspected to be due to the imperfections in the cast silicon. This will be discussed in the later part of this section. Substrates exhibiting polycrystallinity were also fabricated into solar cells and the results are summarized in Table 2, indicating no basic difference in cell performance. Note: Most substrates had large crystallites.

Solar cells from BSF processes showed lower cell performance than the standard cells, mainly due to the leaky characteristics of the cells. A few of the control cells showed the same problem. This BSF process

showed slight improvement in short circuit current and the results are given in Table 3. However, no improvement in open circuit voltage was observed possibly due to overshadowing effect on reduction of V_{OC} by shunting rather than improvement in V_{OC} by the BSF process. Maximum AMO efficiency of these cells was 9.8% for the 3 ohm-cm material and 7.4% for the 0.5 ohm-cm material, while that of the control cell was 11.4%. Solar cells from low resistivity cast silicon, 0.5 ohm-cm, showed a higher degree of leakage than those of the higher resistivity cast silicon.

Dark I-V Characteristics

Dark I-V characteristics (forward and reverse) at room temperature were obtaned from the selected sample cells. The plots were made by point-by-point measurements and a typical results are given in Figure 1 for the solar cells from the standard process and Figure 2 for the BSF solar cells. The "A" factor from the simple diode equation, was derived from the data at the high bias conditions (bias voltage >0.4 volt). A standard HEM solar cell yielded about 1.8 while that of a control cell was about 1.6. Saturation current (I_o) was also obtained from the plots, indicating $4x10^{-8}$ A/cm^2 for the HEM cast cell and $2x10^{-9}$ A/cm^2 for the control cell. The characteristics of BSF cells were slightly leakier than the standard cells (this was always the case in the past), showing "A" factors of 2.2 for the HEM cell and 2.0 for the control cell. The increased saturation current (I_o) of about $3x10^{-7}$ A/cm^2 for the HEM cell and about $8x10^{-8}$ A/cm^2 for the control, was probably due to the leaky characteristics.

The characteristics indicated that shunting and space change recombination effects are higher in the cells from the HEM cast silicon than in the control cells. Saturation current of the HEM solar cells seem to be approximately an order of magnitude higher than those of the controls, which might have been caused by the higher degree of shunting and low lifetime effects.

Spectral Response

Absolute spectral response (A/W) was obtained using a filter wheel set-up which is a combination of a set of narrow bandwidth filters and a light source. [See reference (1) for the detailed techniques of the measurement procedure.] Responses of the standard HEM cells are plotted in Figure 3, in which the cells from the cast silicon of 3 ohm-cm resistivity, Cell No. 1-852-13, showed relatively good response in overall wavelength. However, the cell from 0.5 ohm-cm resistivity indicated significantly lower response than that of the control, especially at wavelength below 0.6 μm, suggesting low minority carrier diffusion lengths.

Minority Carrier Diffusion Length

Minority carrier diffusion length (Le) was measured using the surface photovoltage (SPV) method for the bulk cast silicon substrates and a short circuit current method for the finished solar cells. [See reference (1) for the detailed description on measurement procedures.] Le by SPV method (spot measurement) showed ranges of about 30-60 μm for the 0.5 ohm-cm cast silicon and 40-70 μm for the 3 ohm-cm cast silicon.

Le measurement of the finished cast cells were slightly higher than those of the bulk silicon, 50-60 μm for the 0.5 ohm-cm material and 100 μm for the 3 ohm-cm material. The cause of the increases are not known at present. There might be a possibility of gettering effects from oxides formed in the diffusion process.

Photoresponse by Small Light Spot Scanning

Localized photoresponse of the solar cells were made using a small light spot scanning technique. [Detailed descriptions on measurement techniques and procedures are given in reference (3).] The light source used was a white light from a tungsten lamp filtered by a thin transparent layer of silicon, generating a beam spot size on a flat sample of around 50-100 μm. Relative photoresponse of both cells from cast silicon and control are given in Figure 4. Generally, the cast solar cell indicated lower response than the control cell everywhere. Also the cast cell from the low resistivity material showed lower response than those of the cells from the high resistivity material. This agrees well with the minority carrier diffusion length measurements of the finished cells. By inspection, the solar cells from the cast silicon in the figure do not seem to possess any grain structure or other defect sites. However, reduction of response in some localized area was noticed. This dip in response is in contrast with the response from the localized area containing microcracks which will be discussed in the following section.

Defect Study

Limited efforts were made in an attempt to identify defects which will influence solar cell performance. The efforts were concentrated on the cast silicon of 0.5 ohm-cm resistivity since those cells showed shunting problems and low cell efficiency. The most common defects, other than grain boundaries existing in some part of the cast ingot, were inclusions and microcracks. Figure 5 shows photographs of defects found in solar cells from the low resistivity cast silicon; (a) An inclusion surrounded by either gross lineage (low angle grain boundary) or microcracks, (b) Microcracks. Photoresponse by small light spot scanning was also carried out on a solar cell showing microcracks. Figure 6 is the scanning result in which sharp drops in response were observed in areas having microcracks.

Small mesa solar cells (about 2 mm in diameter) were fabricated from a solar cell (2x2 cm) showing severe shunting problems. Their open circuit voltages were measured using tungsten light source of intermediate light intensity. Figure 7 is the result of the V_{OC} mapping, showing some areas of low V_{OC}. However, an effort to correlate low V_{OC} to any specific defects was not successful.

TABLE 1

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED FROM CAST SILICON BY HEM; STANDARD PROCESS

		CAST SILICON "A"	CAST SILICON "B"	CONTROL
V_{OC} (mV)	Average	568	571	591
	Standard Deviation	4	18	3
	Range	557-574	535-588	588-595
J_{SC} (mA/cm^2)	Average	30.8	28.4	33.4
	Standard Deviation	0.6	0.8	0.2
	Range	29.5-31.5	27.2-28.9	33-33.6
CFF (%)	Average	73	61	75
	Standard Deviation	2	11	2
	Range	67-75	46-75	73-77
η (%)	Average	9.5	7.4	10.9
	Standard Deviation	0.4	1.4	0.2
	Range	8.4-10.1	5.3-9.2	10.7-11.2

NOTE: 1. Measured at 25°C under AMO conditons (with SiO AR)

2. Cast Silicon "A": 3 ohm-cm
   Cast Silicon "B": 0.5 ohm-cm

3. Number of Samples: Cast Silicon "A" - 18
   Cast Silicon "B" - 12
   Control Cells - 6

TABLE 2

SUMMARY OF PARAMETERS OF STANDARD
HEM SOLAR CELLS HAVING SOME DEGREE OF POLYCRYSTALLINITY

		SILICON	
		"A"	"B
V_{OC} (mV.)	Average	565	557
	Standard Deviation	4	23
	Range	558-571	527-589
J_{SC} (mA/cm^2)	Average	30.9	27.3
	Standard Deviation	0.6	1.3
	Range	29.8-32	25-28.4
CFF (%)	Average	74	55
	Standard Deviation	2.4	12
	Range	68-76	44-73
η (%)	Average	9.5	6.3
	Standard Deviation	0.4	1.6
	Range	8.7-10.1	4.3-8.6

NOTES: 1. Measured at 25°C under AMO Conditions.

2. Cast Silicon "A": 3 ohm-cm
   Cast Silicon "B": 0.5 ohm-cm

3. Number of Samples: "A" - 10
   "B" - 5

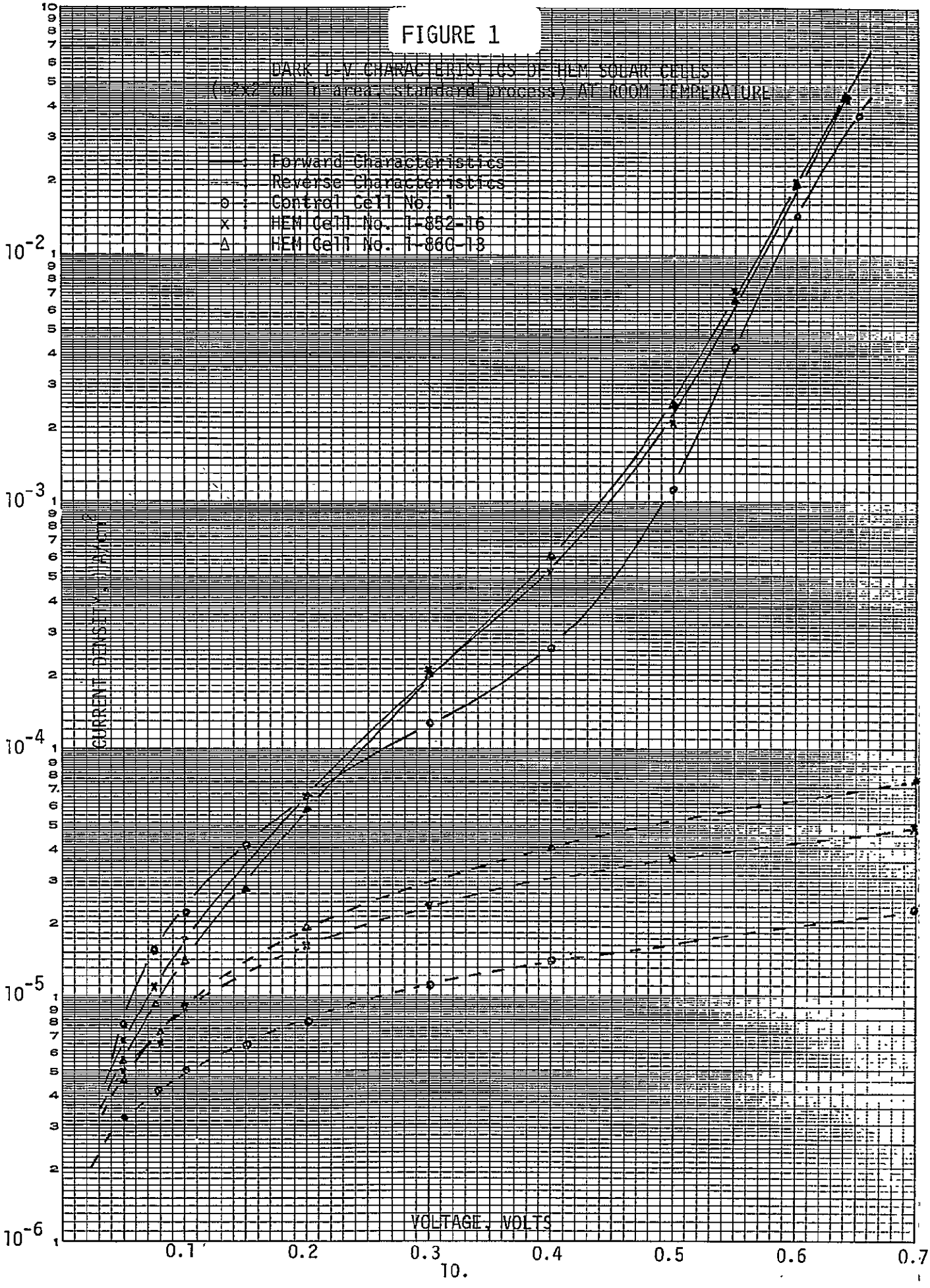


FIGURE 1
DARK I-V CHARACTERISTICS OF HEM SOLAR CELLS
(~2x2 cm² area, standard process) AT ROOM TEMPERATURE
—: Forward Characteristics
- - -: Reverse Characteristics
o: Control Cell No. 1
x: HEM Cell No. 1-852-16
Δ: HEM Cell No. 1-860-13
CURRENT, AMPS
VOLTAGE, VOLTS
10.

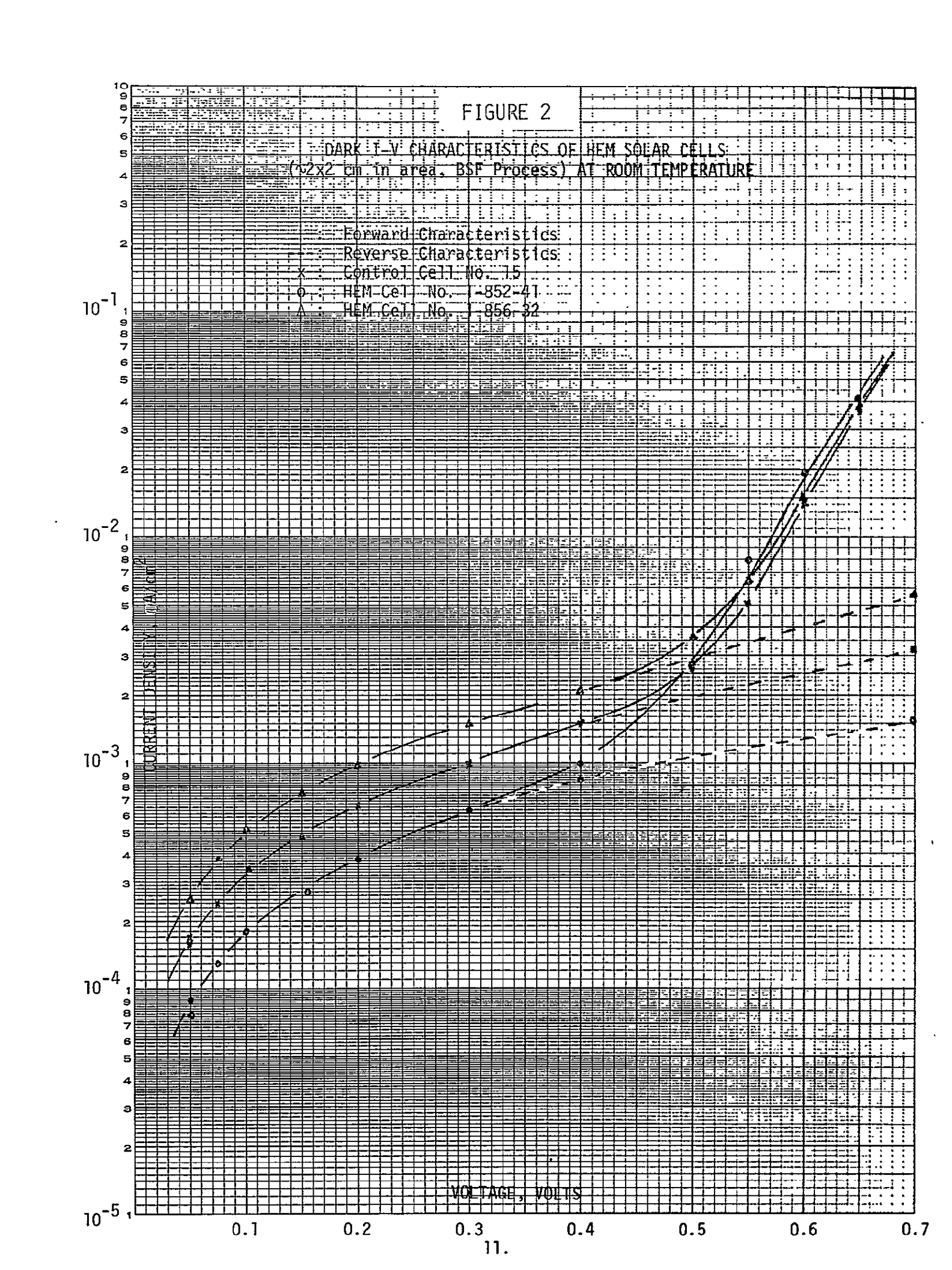


FIGURE 2
DARK I-V CHARACTERISTICS OF HEM SOLAR CELLS
(~2x2 cm in area, BSF Process) AT ROOM TEMPERATURE
: Forward Characteristics
---: Reverse Characteristics
x : Control Cell No. 15
o : HEM Cell No. 1-852-41
Δ : HEM Cell No. 1-856-32
CURRENT DENSITY, I, AMPS/CM²
VOLTAGE, VOLTS
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0.1
0.2
0.3
0.4
0.5
0.6
0.7

TABLE 3

SHORT CIRCUIT CURRENT DENSITY OF
HEM CAST SOLAR CELLS FROM BSF PROCESS

	CAST SILICON "A"	CAST SILICON "B"	CAST SILICON "C"	CONTROL
AVERAGE	32.7 (32.1)	29.3 (29.3)	30.9	35.1
STANDARD DEVIATION	0.4 (0.7)	0.7 (0.4)	0.7	0.5
RANGE	32.2-33.5 (30.6-32.8)	28.3-30.4 (28.9-29.8)	29.6-31.5	34.5-35.7

NOTE: 1. Measured at 25°C under AMO conditions.

2. Cast Silicon "A": 3 ohm-cm 1-852 Series (18 cells)
"B": 0.5 ohm-cm 1-860 Series (10 cells)
"C": 0.5 ohm-cm 1-856 Series (5 cells)

3. Parenthesis numbers for the cells containing polycrystallinity.

4. Units: mA

FIGURE 3

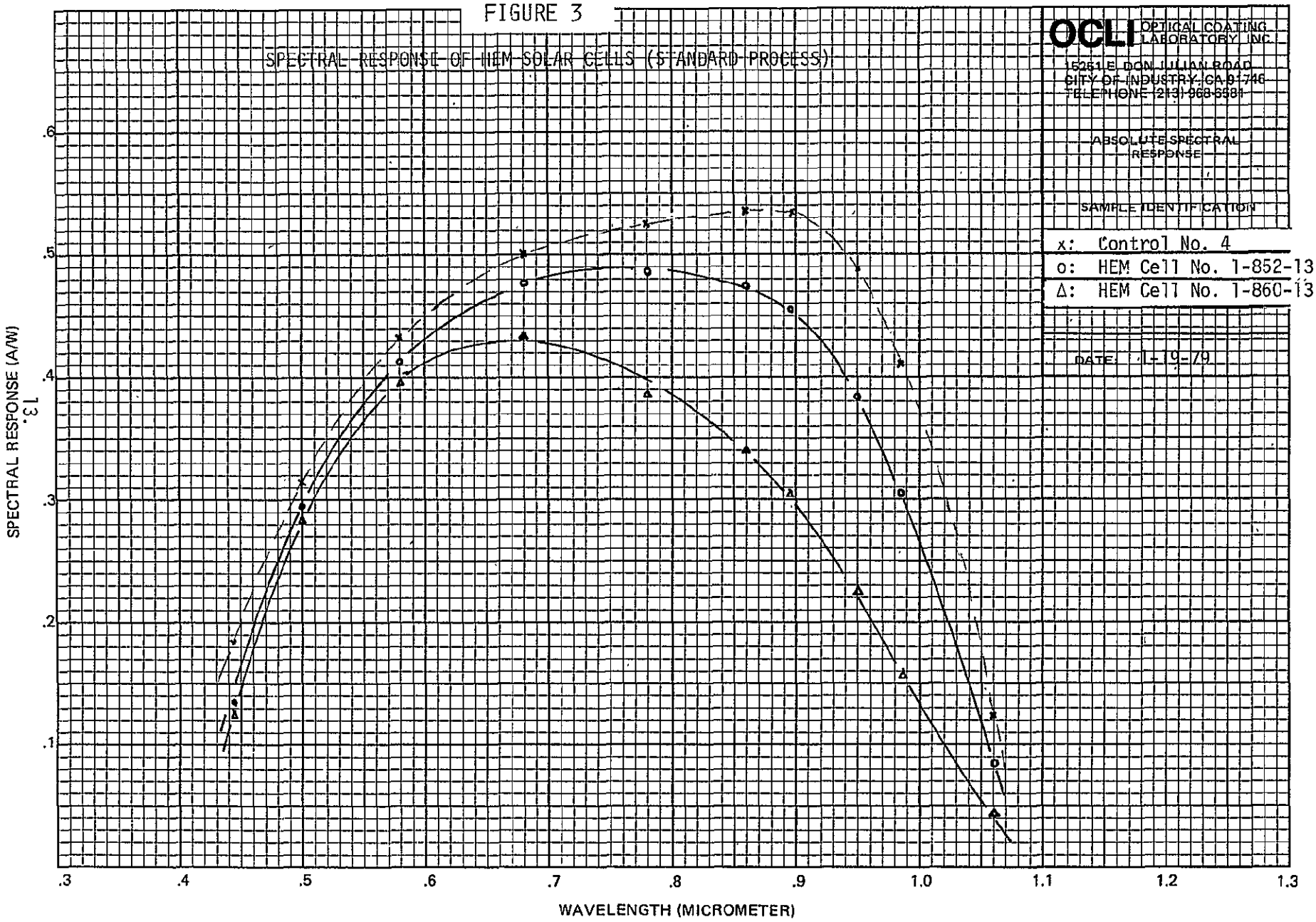

SPECTRAL RESPONSE OF HEM SOLAR CELLS (STANDARD PROCESS)
OCLI OPTICAL COATING LABORATORY, INC.
15261 E. DON JULIAN ROAD
CITY OF INDUSTRY, CA 91746
TELEPHONE (213) 968-6381
ABSOLUTE SPECTRAL RESPONSE
SAMPLE IDENTIFICATION
x: Control No. 4
o: HEM Cell No. 1-852-13
Δ: HEM Cell No. 1-860-13
DATE: 1-19-79
SPECTRAL RESPONSE (A/W)
.6
.5
.4
.3
.2
.1
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
WAVELENGTH (MICROMETER)

FIGURE 4

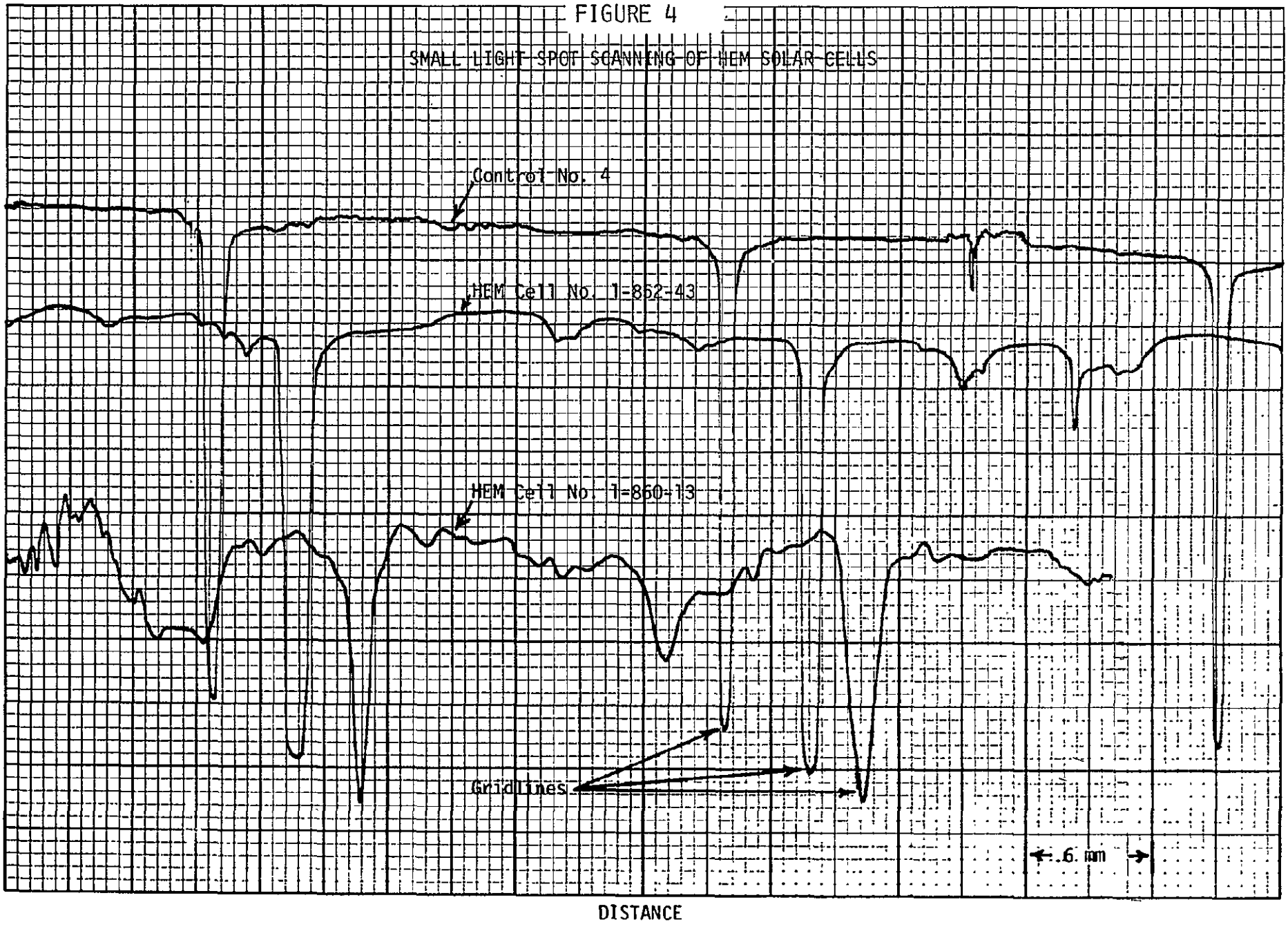
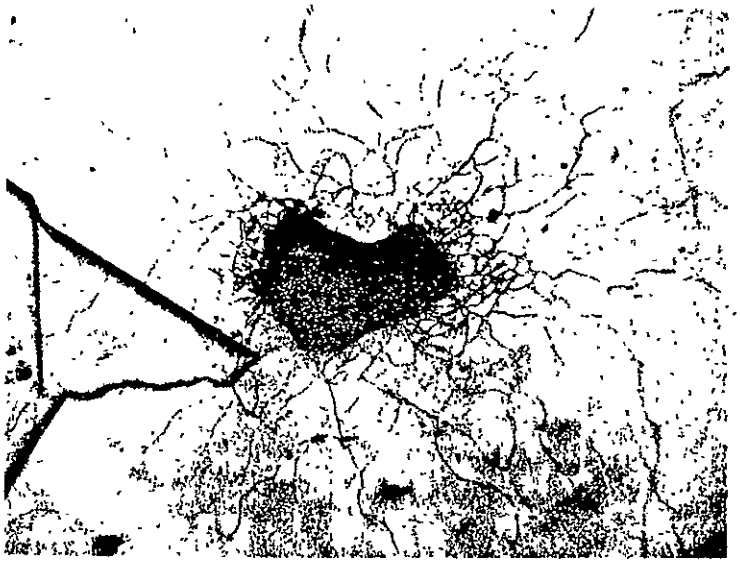
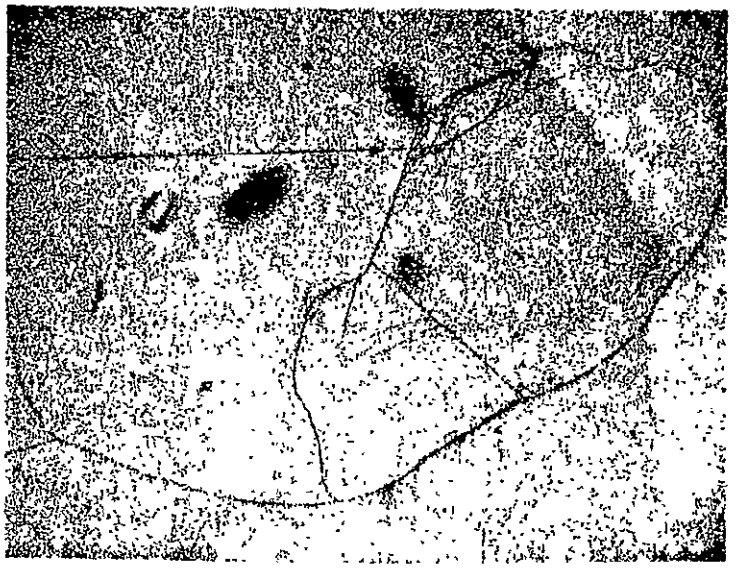

SMALL LIGHT SPOT SCANNING OF HEM SOLAR CELLS
Control No. 4
HEM Cell No. 1-862-43
HEM Cell No. 1-860-13
Grid Lines
.6 mm
RELATIVE PHOTORESPONSE
DISTANCE

FIGURE 5



(a)



(b)

MICROSCOPIC PHOTOGRAPHS OF DEFECTS
FOUND IN HEM CAST SILICON SOLAR CELLS
(200X Magnification)

(a) Inclusion (found in Cell No. 1-860-1)

(b) Microcracks (found in Cell No. 1-860-14)

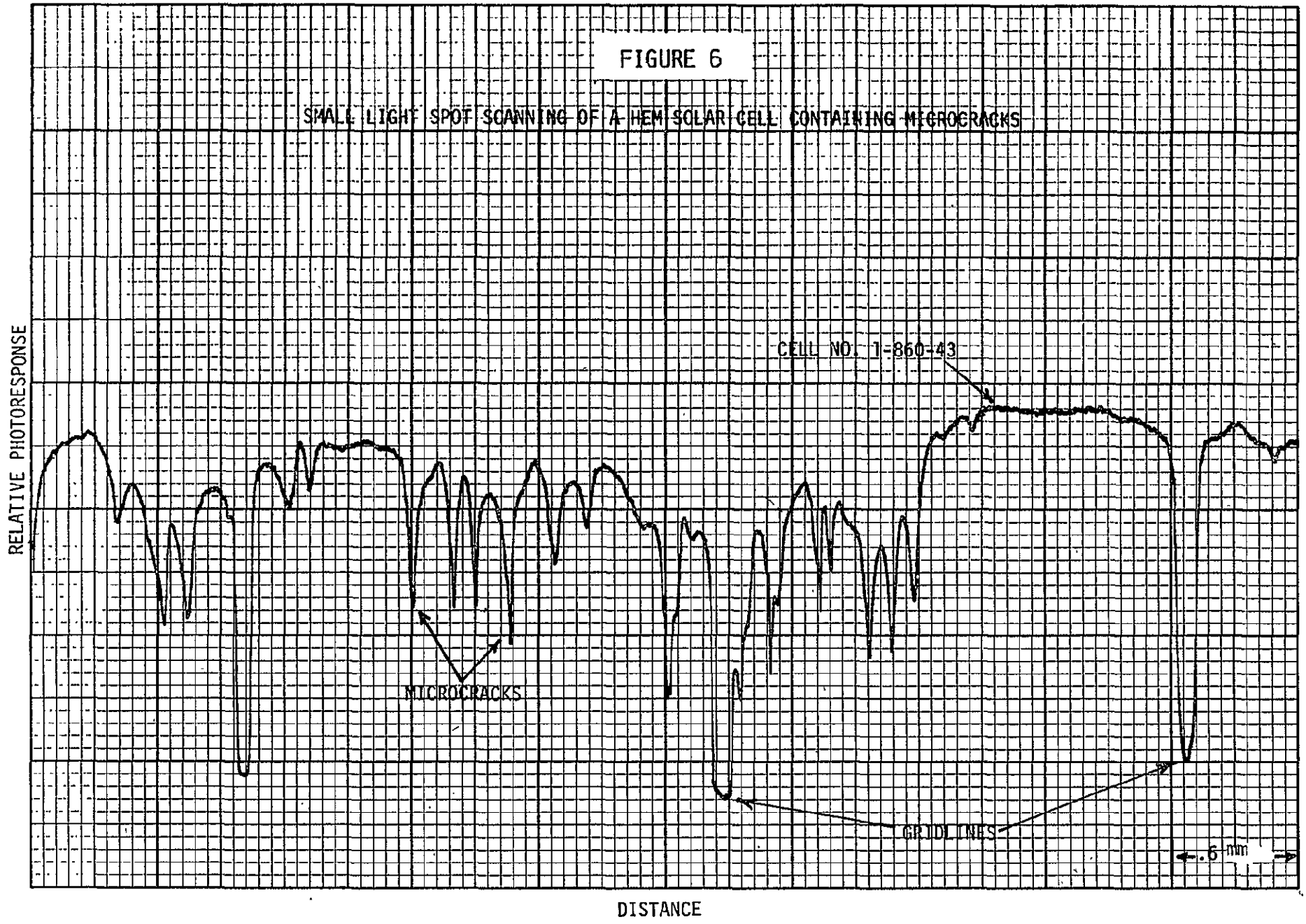
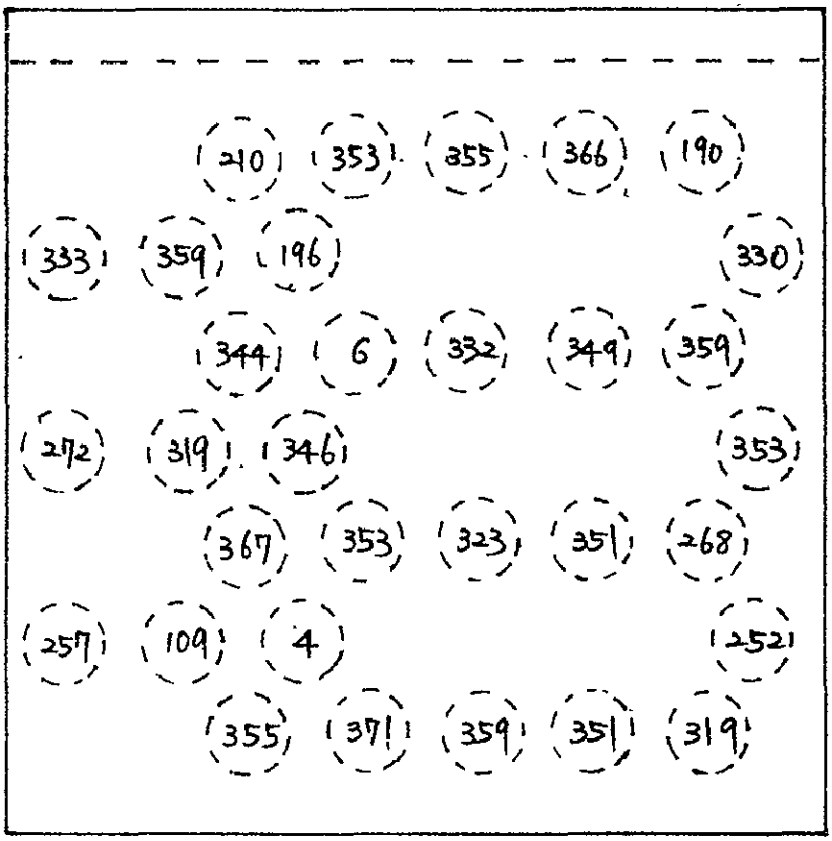


FIGURE 6
SMALL LIGHT SPOT SCANNING OF A HEM SOLAR CELL CONTAINING MICROCRACKS
CELL NO. 1-860-43
MICROCRACKS
GRIDLINES
.6 mm
RELATIVE PHOTORESPONSE
DISTANCE

FIGURE 7

OPEN CIRCUIT VOLTAGE MAPPING OF MESA SOLAR CELLS
WITHIN A HEM CAST CELL (Cell No. 1-860-1) WHICH SHOWED SHUNTING PROBLEMS



NOTE: 1. Illuminated tungsten lamp with unknown light intensity.

2. Diameter of mesa cells; 2 mm.

3. Unit in millivolts.

B. EFG (RH) RIBBON SOLAR CELLS

1.0 SOLAR CELL FABRICATION

The EFG ribbons supplied had been grown in a resistance heated (RH) furance. Two types were included, one with controlled silicon carbide on one face of the ribbon using a displaced die and the other with an uncontrolled silicon carbide die. [See reference (4) for detailed information on EFG process.] The former ribbon was about 2 inches wide (thickness between 16-18 mils) while the other ribbon was about 3 inches wide with thickness of about 10 mils. These ribbons were mounted on cermaic blocks using wax and sliced into 2x2 cm blanks for the convenience of cell fabrication. Resistivities range from 1-3 ohm-cm with P-type conductivity. Minority carrier diffusion lengths were measured to be around 15-40 (μm). Following a standard cleaning procedure, cells were fabricated using the standard and BSF processes with back contacts formed intentionally on the side containing the most SiC in both cases. Standard process resulted in about 80% mechanical yield (ratio of unbroken cells to starting blanks) in which most of the breakage occurred in the metallization steps, both front and back contacts; (this can be corrected, or minimized, by redesign of the mask fixture).

A limited number of cells were fabricated using BSF process. Heat treatments on back contacts (standard process) were also carried out in an effort to improve open circuit voltage. Temperature used for the heat treatment tests was 650°C (600°C in standard process) and cells were treated for 5 minutes and 10 minutes. [See reference (1) for the detailed information on standard and BSF processes.]

2.0 SOLAR CELL PERFORMANCE AND CHARACTERIZATION

Characterization Under Illumination

Finished solar cells had about 90% active area with a SiO AR coating. Solar cell parameters, such as V_{OC}, I_{SC}, CFF, and n, were measured at 25°C (test block temperature) under an AMO simulator. [Refer to Appendix II of reference (1) for description of the simulator.] Appendix IV in this report provides the parameters of individual solar cells from EFG RH ribbons; standard and BSF cells, and solar cells from the heat treatment test.

Solar cell parameters from the standard process are summarized in Table 4. EFG "A" and "B" are cells from the controlled SiC while EFG "C" are not. Average efficiencies of the controlled EFG ribbon cells were about 6.6%, showing 6.2% for EFG "A" and 6.9% for EFG "B". However, EFG cells from the uncontrolled SiC showed an average efficiency of 5.4% which is a considerably lower value than those of the cells from the controlled SiC. This is mainly due to the low curve fill factor (CFF) which is likely to be caused by shunting problems from surface inclusions (SiC). A lower V_{OC} of EFG "C" cells compared with those of "A" and "B" cells also indicates the same problem an average V_{OC} of 508 mV for the uncontrolled SiC ribbon cells versus 515-517 mV for the controlled samples. Short circuit current density remains around 25 mA/cm^2 in all three ribbon cases, indicating consistent quality of grown EFG ribbons.

A few cells were fabricated using BSF process. However, shunting problems from aluminum alloying step prevented the process from obtaining reliable statistical evaluation at present. [Note: Even control cells showed shunting chracteristics.] The solar cells from heat treatment on back contact did not show any improvement in V_{OC} or other cell parameters. Slight degradation of the cells at 10 minutes of sintering (650°C) was apparent in both EFG and control cells.

Dark I-V Characteristics

Dark diode I-V plots were obtained by using a semi-automatic dark I-V plotter for the cells in a reasonably short time. This has provided reliable statistical data on the cell characteristics which is otherwise very difficult to do by point-by-point measurement techniques. Based on this data, the characteristics of the cells of interest can be replotted by point-by-point measurement. Figure 8 shows the forward plots using the plotter and Figure 9 represents the characteristics of a typical good EFG cell measured by point-by-point techniques from which diode parameters ("A" factor and saturation current from simple diode equation) were derived. The "A" factor of EFG cell and the control cell (in Figure 9) was 1.6 and 1.4, respectively. Saturation current (I_0) of the EFG cell was considerably higher than that of the control, $2x10^{-8}$ A/cm^2 versus $6x10^{-10}$ A/cm^2. This seems to be the reason why V_{OC} of the EFG cells is relatively low, an average V_{OC} of 520 mV for EFG cells and an average 580 mV for the control cells. The higher value of the saturation current of

the EFG cell seems to be mainly due to low diffusion lengths of the EFG ribbons, 20-40 μm (EFG) versus 120-160 μm (control), with the doping levels of both materials about the same.

Spectral Response

Absolute spectral response (A/W) was made using a filter wheel set-up. [See reference (1) for the details.] Response versus wavelength of solar cells from the standard process is given in Figure 10. Generally EFG cells showed much lower response in especially long wavelength region (λ>0.6 μm) than those of the control cells. This indicates that the quality of the EFG ribbon is not as good as Czochralski controls, in other words low minority carrier lifetime.

Minority Carrier Diffusion Length

Minority carrier diffusion length was measured using the surface photovoltage (SPV) method for the bulk EFG and the short circuit current method (see first quarterly report for details) for the finished solar cells. Bulk diffusion lengths were measured to be in the range between 20-40 μm (generally from spot-to-spot measurement) and diffusion lengths obtained from the solar cells by short circuit current method (illuminated on whole area of a cell) indicated similar results. Diffusion lengths were also obtained by measurement on a localized area (about 3-4 mm in diameter) by short circuit current method and the results showed a range between 15-40 μm. Table 5 summarizes the results of minority carrier diffusion length measurements by short circuit current method.

Photoresponse by Small Light Spot Scanning

Localized photoresponse of solar cells (standard) were obtained by light spot scanning. Scanned light source was a tungsten lamp filtered through thin film of silicon with a beam size estimated to be around 50-100 μm. [See reference (3) for the detailed description of the measurement.] Defocusing effect by the non-flat surface feature of EFG sibbons might have resulted in the modulation of beam size during scanning, consequently leading to loss of sharp contrast in response at electrically active defect sites. Figure 11 and Figure 12 are the results of the scanning. The first scanning direction was perpendicular to ribbon growth direction (across ribbon width) and the second was the scanning parallel to grow direction. In both cases, some of the localized areas showed lower response than others of which areas of low response seemed to have a higher density of the electrically active defects. Response across the ribbon width showed a considerable high density of defect sites, which can be understood if we consider that grain boundaries and twins (or closely spaced parallel twins) exist in a direction parallel to the growth direction.

Defect Study

Besides crystallograhpic defects, such as grain boundaries and stacking faults, etc., dominant defects in EFG ribbon are the surface inclusions (SiC). These inclusions, especially when they exist in the surface of the shallow diffused layer (this is the case for the EFG ribbons of uncontrolled SiC), are likely to cause shunting or severe leakage

characteristics, consequently leading to a low curve fill factor and power output. The surface inclusions do not always seem to lead to shunting problems (same results were reported in earlier EFG RF report). Figure 13 shows microscopic photographs of the inclusions, where case one (a) the inclusion caused severe shunting problems and in case two (b) the inclusion does not significantly influence cell performance, even though a front gridline fell across the top of the inclusion.

TABLE 4

SUMMARY OF PARAMETERS OF SOLAR CELLS
FABRICATED FROM EFG RH RIBBON; STANDARD PROCESS

		EFG "A"	EFG "B"	EFG "C"	CONTROL
V_{OC} (mV)	Average	517 (492)	515 (502)	508 (500)	580
	Standard Deviation	9 (19)	2 (2)	- -	-
	Range	490-526 (464-510)	510-508 (498-506)	480-527 (492-514)	576-588
J_{SC} (mA/cm^2)	Average	25.2 (17.9)	24.9 (17.6)	25 (18)	33.5
	Standard Deviation	0.6 (0.3)	0.7 (0.6)	- -	-
	Range	24.8-26.1 (17.5-18.4)	23.5-25.5 (16.5-18.2)	24-25.5 (17.2-18.6)	33-33.8
CFF (%)	Average	64 (60)	73 (72)	56 (60)	73
	Standard Deviation	12 (14)	1 (2)	- -	-
	Range	47-74 (42-73)	71-74 (69-74)	34-75 (49-72)	67-73
η (%)	Average	6.2 (4.0)	6.9 (4.8)	5.4 (4)	10.5
	Standard Deviation	1.4 (1.1)	0.2 (0.2)	- -	-
	Range	4.3-7.5 (2.6-5.1)	6.6-7.2 (4.5-5.0)	2.9-7.4 (3.0-4.9)	9.7-11.2

NOTE:

1. Measured at 25°C under AMO Conditions (cells with SiO AR). Parenthesis Numbers are for the Parameters Before AR Coating.
2. Identification and Sample Numbers of EFG RH Ribbon Cells:

"A": 5-866 - 5 Cells
"B": 5-868 - 7 Cells
"C": 5-870 Uncontrolled SiC - 3 Cells
Control: 1-3 ohm-cm Czochralski - 3 Cells

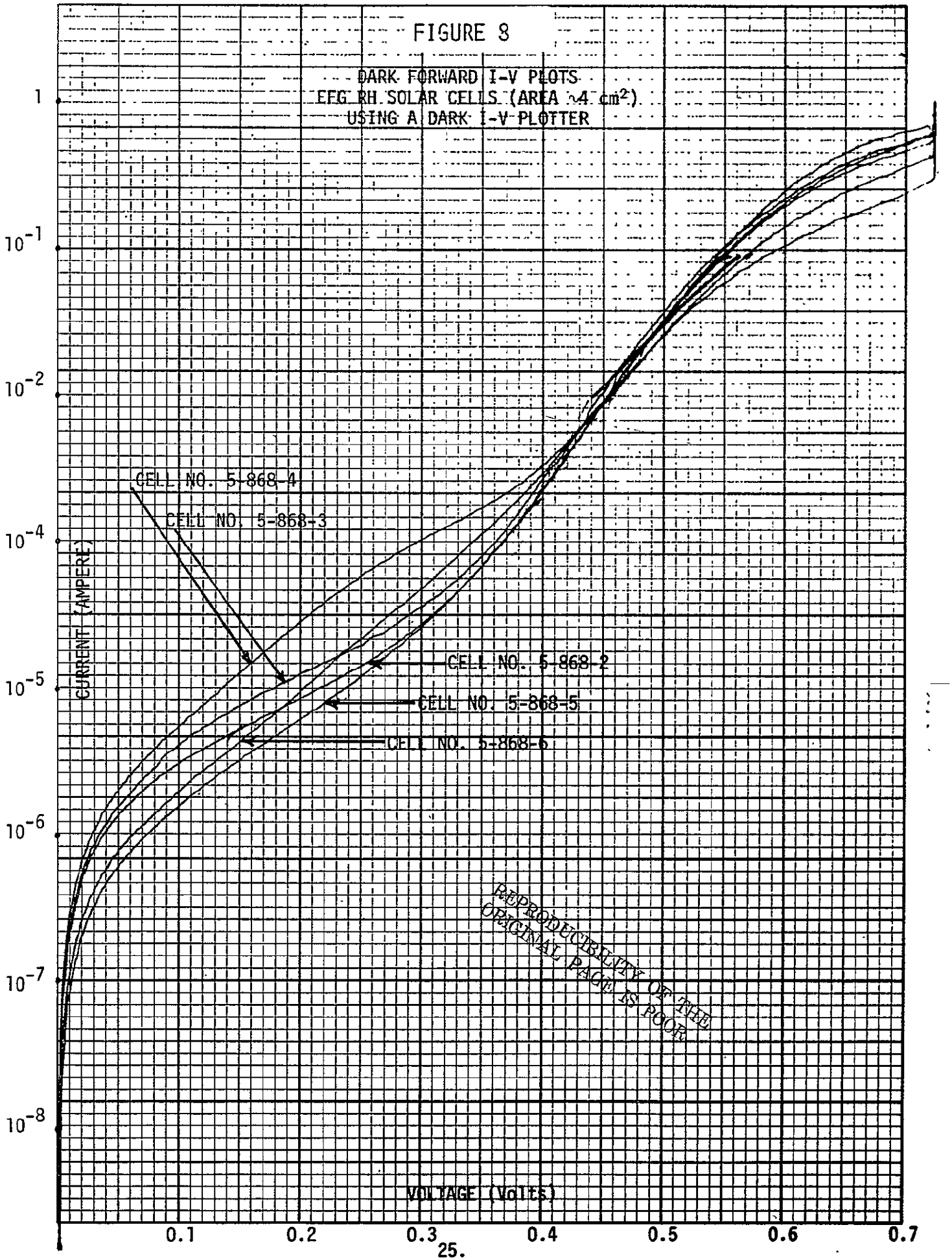


FIGURE 8
DARK FORWARD I-V PLOTS
EFG RH SOLAR CELLS (AREA ~4 cm²)
USING A DARK I-V PLOTTER
1
10⁻¹
10⁻²
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
CURRENT (AMPERE)
CELL NO. 5-868-4
CELL NO. 5-868-3
CELL NO. 5-868-2
CELL NO. 5-868-5
CELL NO. 5-868-6
0.1
0.2
0.3
0.4
0.5
0.6
0.7
VOLTAGE (Volts)
REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

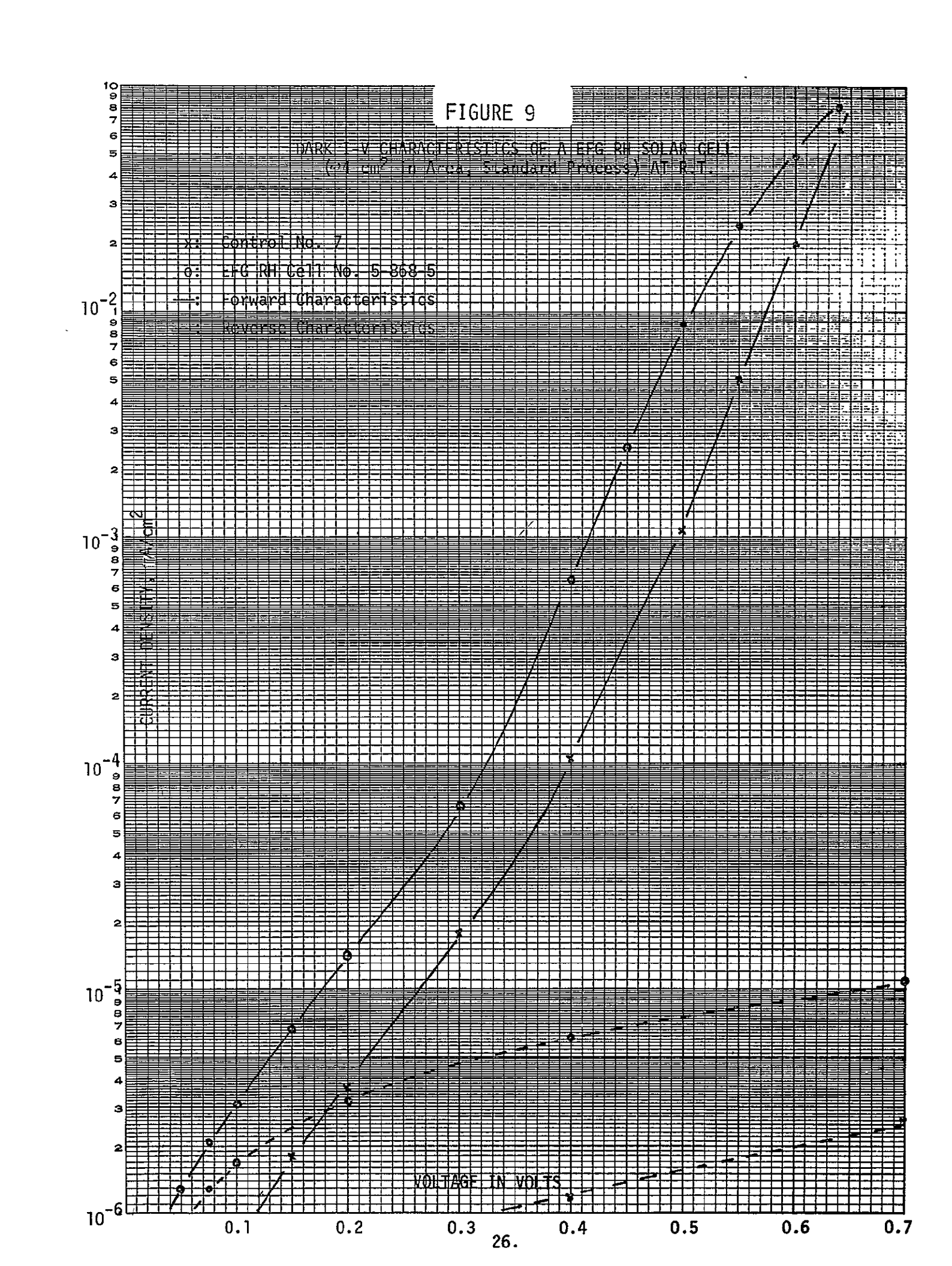


FIGURE 9
DARK I-V CHARACTERISTICS OF A EFG RH SOLAR CELL
(2 cm² in Area, Standard Process) AT R.T.
x: Control No. 7
o: EFG RH Cell No. 5-868-5
—: Forward Characteristics
: Reverse Characteristics
CURRENT IN AMPS
VOLTAGE IN VOLTS
10
9
8
7
6
5
4
3
2
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.1
0.2
0.3
0.4
0.5
0.6
0.7

FIGURE 10

SPECTRAL RESPONSE OF EFG RH SOLAR CELLS
(Standard Process)

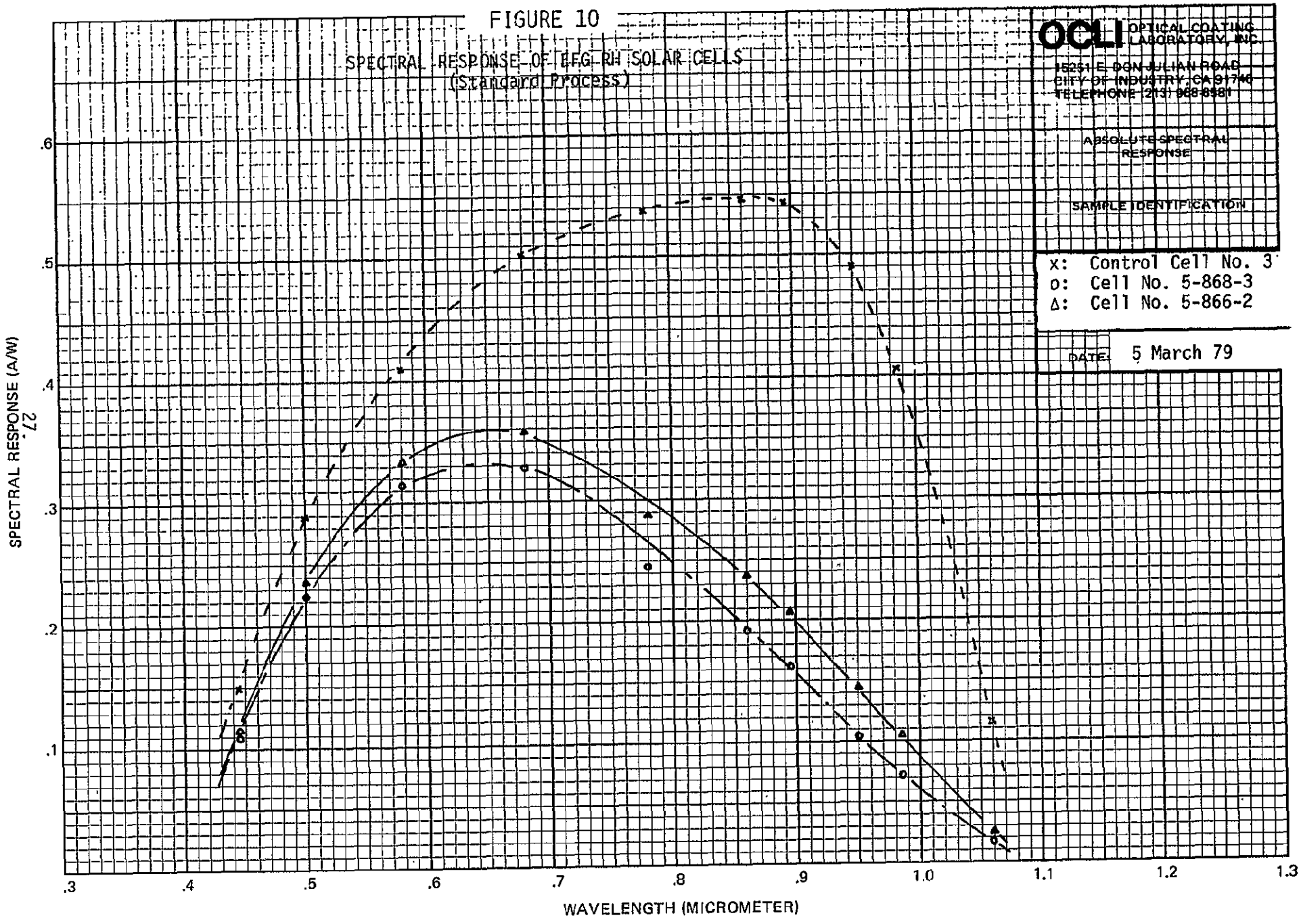


TABLE 5

SUMMARY OF MINORITY CARRIER DIFFUSION LENGTH OF THE STANDARD CELLS FROM EFG (RH) RIBBON CELLS, MEASURED BY I_{SC} METHOD

CELL NO.	POSITION					WHOLE AREA
	1	2	3	4	5	
5-866-2	38	40	19	20	28	26
5-868-3	18	22	14	18	18	18
5-870-5	--	--	--	--	--	24
5-870-7	--	--	--	--	--	14

NOTE: Units in μm.

IDENTIFICATION OF BEAM SPOT (BEAM SIZE 3-4 mm IN DIAMETER) FOR DIFFUSION LENGTH MEASUREMENT ON LOCALIZED AREAS OF A 2x2 CM CELL

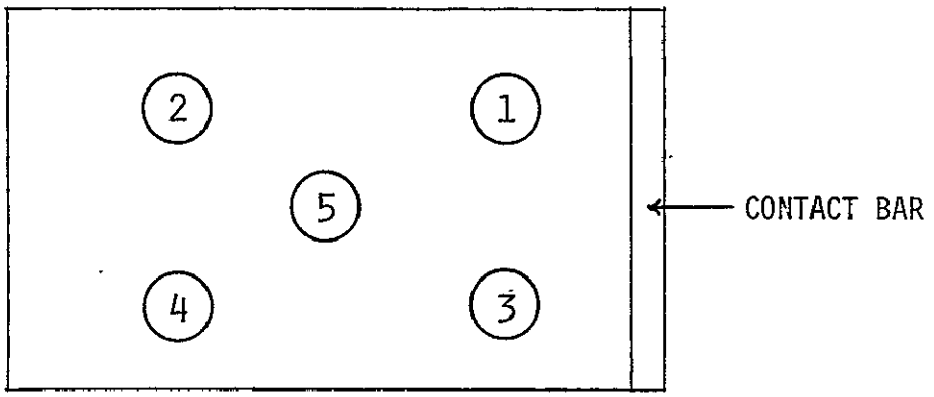


FIGURE 11

SMALL LIGHT SPOT SCANNING OF A EFG RH SOLAR CELL
(Scanning Direction Perpendicular to Growth Direction)

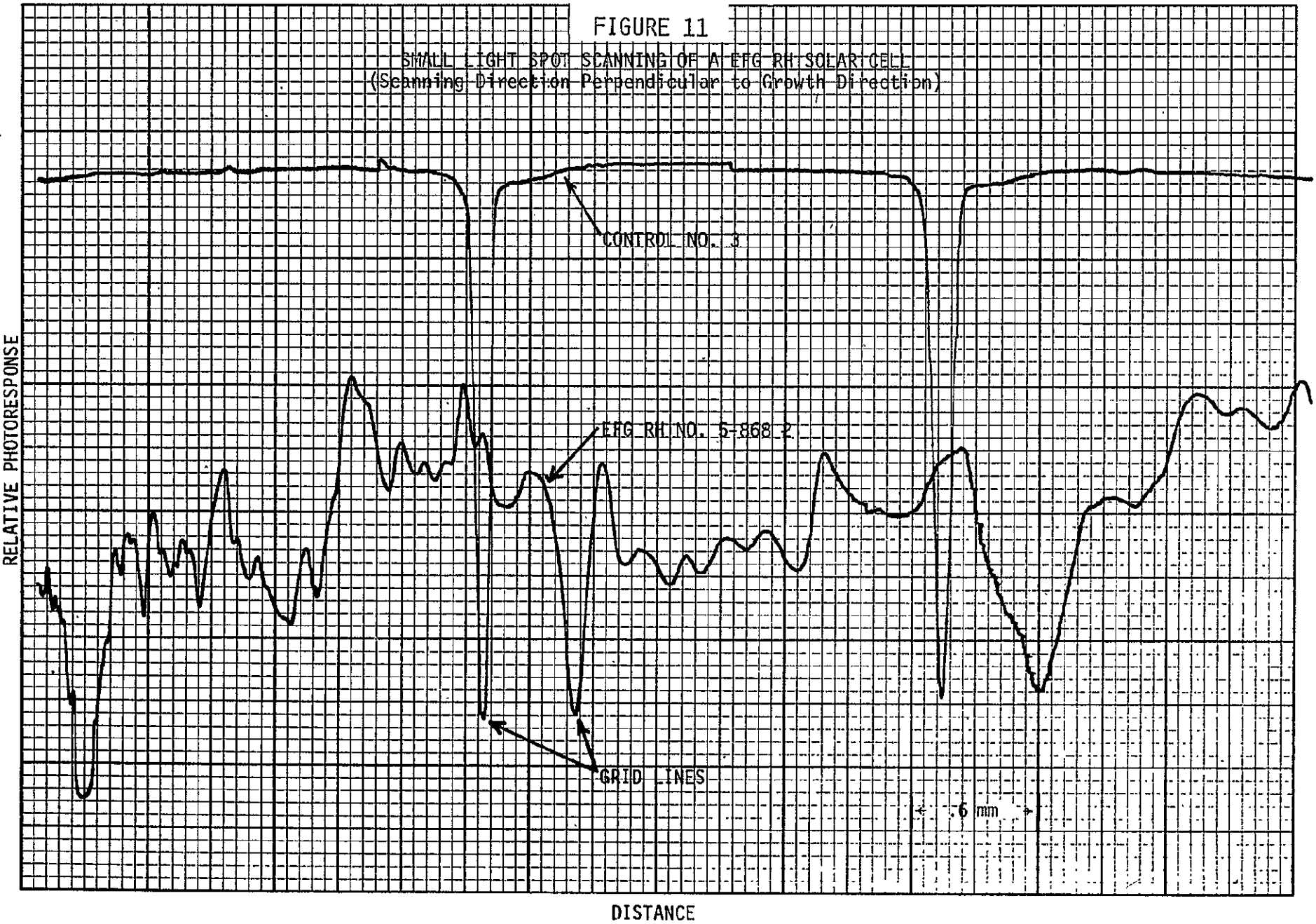


FIGURE 12

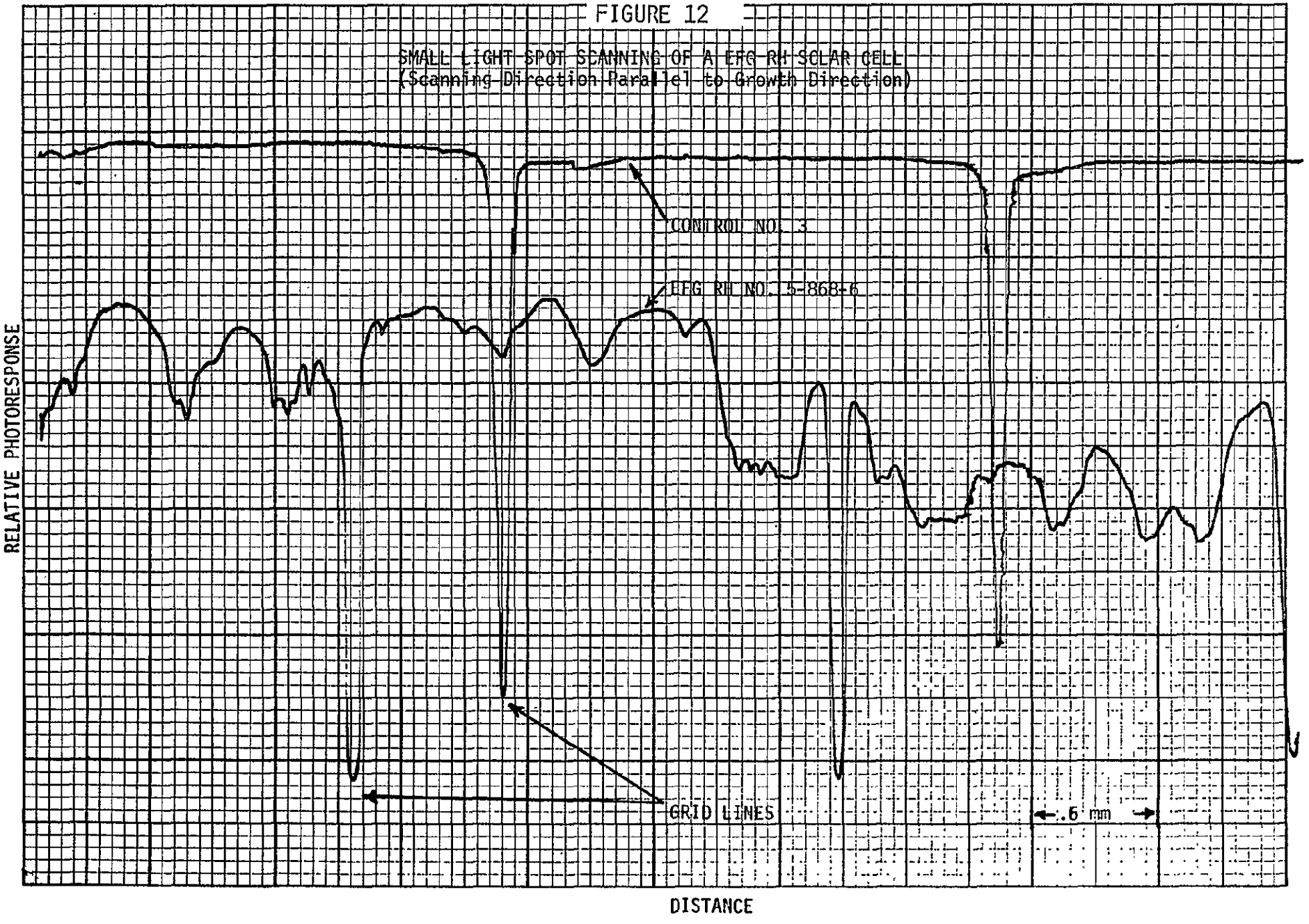
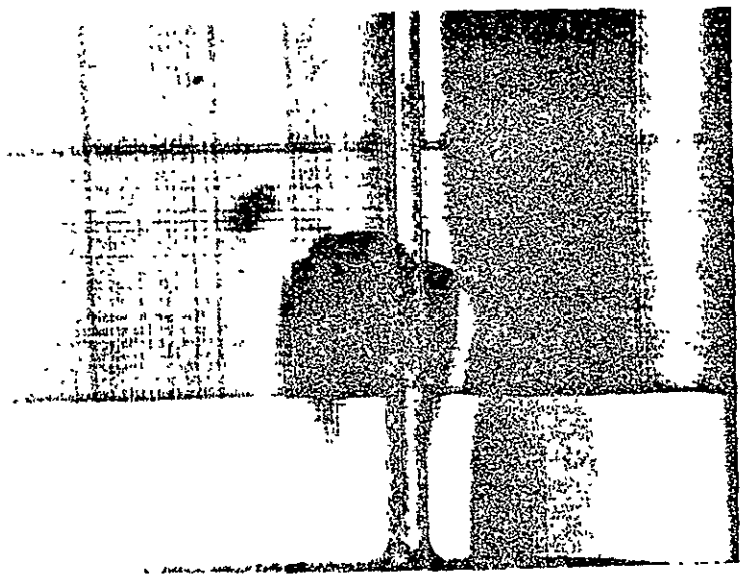

SMALL LIGHT SPOT SCANNING OF A EFG RH SOLAR CELL
(Scanning Direction Parallel to Growth Direction)
CONTROL NO. 3
EFG RH NO. 5-868-6
GRID LINES
.6 mm
RELATIVE PHOTORESPONSE
DISTANCE

FIGURE 13

(a)



(b)

MICROSCOPIC PHOTOGRAPHS OF SURFACE INCLUSIONS IN EFG (RH) RIBBONS

(a) A inclusion found in Cell No. 5-870-2 (200X Magnification).

(b) A inclusion found in Cell No. 5-870-5 (200X Magnification).

C. SILICON ON CERAMIC (SOC) SOLAR CELLS

1.0 SOLAR CELL FABRICATION

The SOC substrates were cleaned first in organic solvents and baked in a oven (set at 120°C in N_2 atmosphere) overnight. Immediately after removing from the oven, a standard diffusion procedure was applied to form a junction. After removal of the diffused oxide, a back contact metallization was applied by evaporation of metals (Ti-Pd-Ag in sequence) on whole back area, follwed by heat treatment at 600°C for about 10 minutes to form the proper ohmic back contact. Several attempts were tried to fill the opening of the slots in the substrates; by

(1) Solder dipping

(2) Squeeze-in of silver paste, followed by baking, and

(3) Filling with indium solder.

First method was not successful since difficulty in wetting of the solder inside the slots was experienced. Second method was also not impressive, because discontinuity of the silver was observed after baking typically in a furance set at 300°C. Finally, indium solder (indium; tin = 1:1) was successfully filled in the slots by applying the solder to the back while heating the cells on a hot plate. Observation of the cross-section of the slots indicated that the slots were well filled with the solder, assuring a good contact to the back side of silicon. Front contact metallization was done by conventional metal shadow masking techniques. Bowing of the substrates caused a problem of metallization smearing and made it

difficult to get cells of good active areas (>90%). Measured active areas were in the range between 80-85% depending on the degree of warpage of the substrates.

Finally, the periphery of the cells were defined by using waxing and etching methods. Mesa solar cells were made as large as possible, resulting in an average area of about 15 cm^2. Mechanical yield of the solar cells is expected to be good if proper front contact metallization techniques are developed. [Note: It was difficult to apply metal shadow masking techniques since quite a few breakage happened during the tightening step.]

Four-point probe measurement showed resistivity of about 1 ohm-cm with P-type conductivity. Minority carrier diffusion lengths of the bulk SOC by SPV method were in the range between 20-40 μm. [See reference (5) for the detailed description on SOC process.]

2.0 SOLAR CELL PERFORMANCE AND CHARACTERIZATION

Characteristics Under Illumination

First batch of standard cells was a trial run in which most of the cells were wasted, except for a few in establishing a reliable process adaptable to these substrates.

The second batch was successfully carried out to provide reliable cell performance data. Solar cell parameters from the first two batches were measured under AMO conditions at 25°C, with individual

cell data appearing in Appendix V. Good performance of the control cells from both batches strongly indicates that there is no cross contamination of the impurities. Table 6 is the summary table of the SOC cells (second batch) performance. An average efficiency of about 6% was obtained in the relatively large area cells (15 cm^2 average). If the improved active area was achieved by using other metallization techniques, such as photoresist method, the average efficiency would have increased. SOC solar cells generally showed slightly low curve fill factor, an average of 60%, which seems to be due to the combination of both shunting and series resistance problems. Work is in progress to improve the series resistance problems.

Dark I-V Characteristics

The characteristics of all the cells were measured using the dark I-V plotter. A typical good cell was selected for point-by-point measurement and results are plotted in Figure 14. The saturation current (I_o) and "A" factor of the SOC cell were about 10^{-7} A/cm^2 and 2, while those of the controls were $2x10^{-9}$ A/cm^2 and 1.6, respectively. Since a cell of larger area generally shows a higher degree of shunting this might not be the proper way to make a direct comparison of both SOC and the control cells. Series resistance problem of the SOC cell was also noticed from the characteristics at high bias conditions (forward V_B >0.6 volt).

Spectral Response

Absolute spectral response (A/W) of SOC solar cells were measured using a filter wheel set-up. Typical response curves are given in Figure 15. Effect of low lifetime of the minority carriers is also indicated at long wavelength response.

Minority Carrier Diffusion Length

Minority carrier diffusion lengths were measured using the SPV method for the bulk and the short circuit current method for the finished solar cells. The exposed beam size (monochromatic) on the bulk sample was about 2-3 mm in diameter yielding diffusion length calculated to be in the range between 20-40 μm. Short circuit current method also indicated similar results.

Defect Study

The SOC substrates were sectioned and potted to see the cystallographic details at the cross-section of the substrates. After the final polishing using 0.2 μm alumina powder the polished surface was etched in Sirtl etch or a planar etch for about a minute. (Note: Original polished surface was not free from scratches.) Planar etched surface seems to reveal better structural details than those with the Sirtl etch. Thus, the discussion is based on the results from the planar etch. Figure 16 is the microscopic pictures of the cross-section, silicon bridging ceramic slots in (a) and showing parallel twins in (b).

The main purpose of the sectioning of the substrate was to see if there exist any grain boundaries parallel to the surface of the substrate, which might introduce the high series resistance problem. However, no such grain boundaries have been found so far. A number of parallel twin boundaries were observed, in Figure 16 (b), extending from the bottom to the top surface. A surface inclusion was also detected in Figure 17, whose identity is not clear at present.

TABLE 6

SUMMARY OF PARAMETERS OF SOLAR CELLS
FABRICATED FROM SOC; STANDARD PROCESS

		SOC	CONTROL
V_{OC} (mV)	Average	547	589
	Standard Deviation	3.7	4
	Range	541-553	581-592
J_{SC} (mA/cm^2)	Average	24.1	33.8
	Standard Deviation	1.4	0.8
	Range	22-26.3	32.4-34.8
CFF (%)	Average	60	72
	Standard Deviation	6	3
	Range	52-69	67-77
η (%)	Average	5.9	10.6
	Standard Deviation	0.6	0.5
	Range	5.1-6.8	10-11.3

NOTE: 1. Measured Under AMO Condition.

2. SOC Solar Cells:

Average Cell Size:	15.1 cm^2
Number of Cells Evaluated:	7
Active Area:	80-85%
AR Coating:	SiO

FIGURE 14

DARK I-V CHARACTERISTICS OF A SOC SOLAR CELL
(Standard Process) AT R.T.

x: Control No. 15 (area 4 cm^2)

o: SOC Cell No. 161-8 (area ~12.5 cm^2)

——: Forward Characteristics

– – –: Reverse Characteristics

CURRENT DENSITY, AMP/CM^2

10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}

VOLTAGE IN VOLTS

0.1 0.2 0.3 0.4 0.5 0.6 0.7

FIGURE 15

SPECTRAL RESPONSE OF A SOC SOLAR CELL
(Standard Process)

OCLI OPTICAL COATING LABORATORY, INC.
16251 E. DON JULIAN ROAD
CITY OF INDUSTRY, CA 91746
TELEPHONE (213) 968-6581

ABSOLUTE SPECTRAL RESPONSE

SAMPLE IDENTIFICATION

x: Control
o: Cell No. 159-7

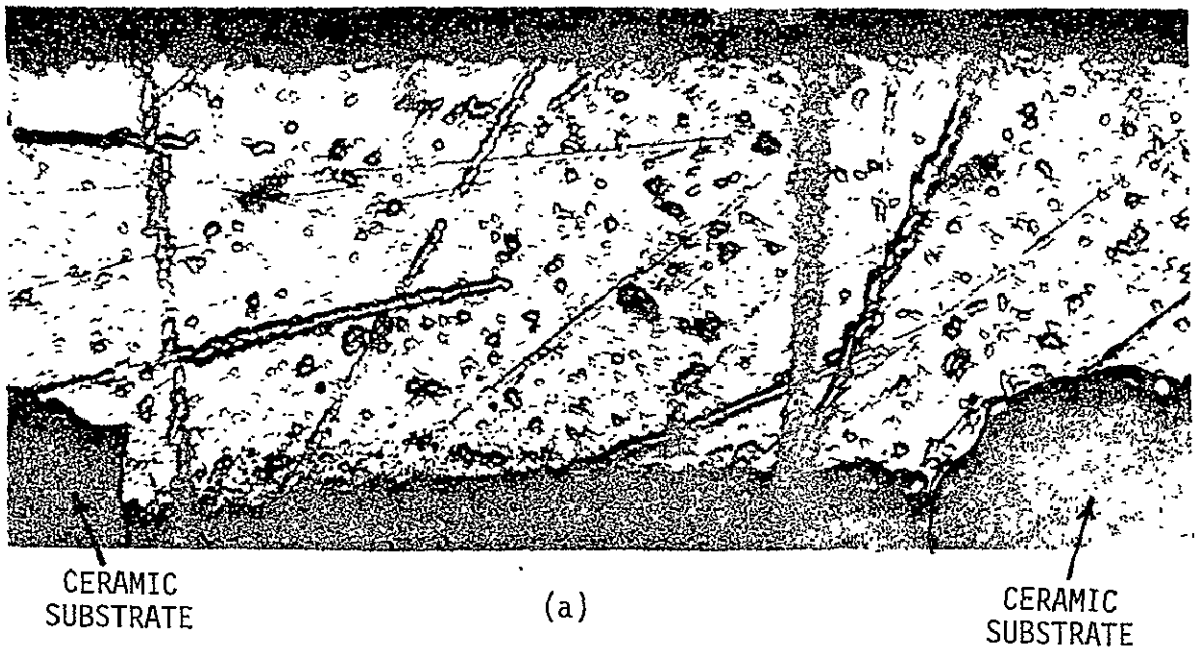
DATE

SPECTRAL RESPONSE (A/W)
.6
.5
.4
.3
.2
.1

.3 .4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3

WAVELENGTH (MICROMETER)

FIGURE 16



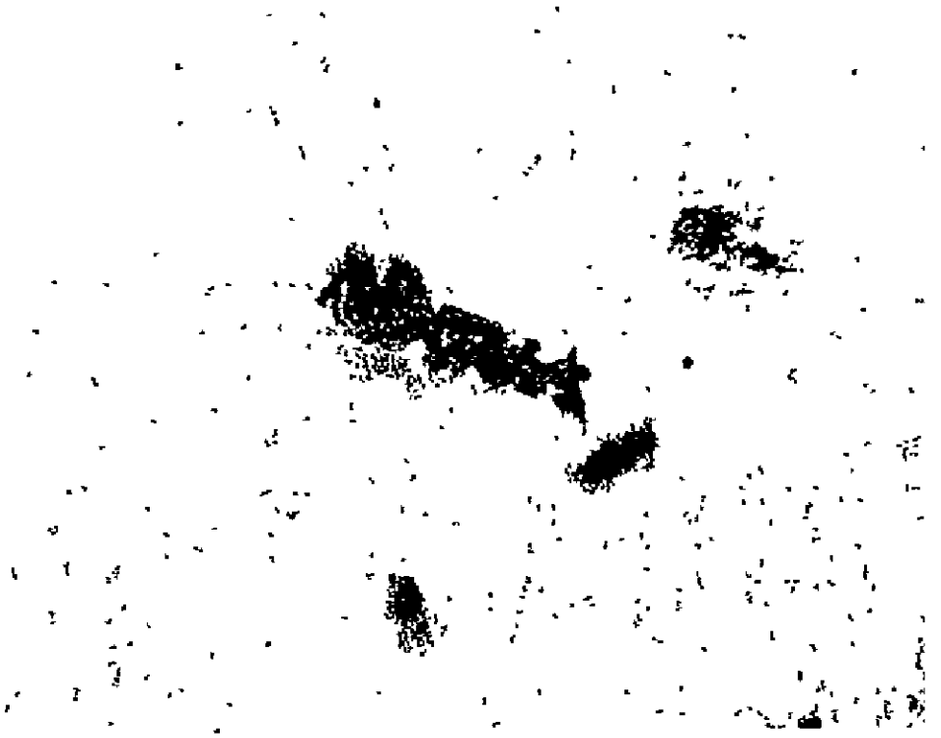
(a)

(b)

MICROSCOPIC PICTURES OF CROSS-SECTIONS OF SILICON ON CERAMIC
FOLLOWING MECHANICAL POLISHING AND CHEMICAL ETCHING
(200X Magnification)

(a) A cross-section bridging ceramic

(b) A cross-section showing parallel twins



A SURFACE DEFECT FOUND IN A SOC SUBSTRATE
(200X Magnification)

III. CONCLUSIONS AND RECOMMENDATIONS

The conclusions reached after processing and evaluation of the sheets are as follows.

Cast Silicon by HEM

- Fabrication process for conventional single crystalline solar cell can easily be adapted to this type of sheets without introducing any significant process problem, especially low yield, etc.

- The average conversion efficiency of solar cells (2x2 cm) from the standard process, measured at 25°C under AM0 conditions, was about 9.5% with the range between 8.6 and 10.1%.

- Defects, microcracks and inclusions, were found in the sheet from the specific ingot, of which the microcracks might have been formed in block shaping step of the highly stressed silicon ingots. These defects are expected to degrade solar cell performance.

EFG (RH) Ribbon

- Degree of warpage of these sheets seems to have been improved compared with the EFG (RF) ribbons processed earlier, except the wide and thin ribbons (3" in width and ∿6 mils in thickness). No major process and measurement problems are anticipated in applying conventional process techniques for the flat EFG ribbons.

- An average AMO efficiency of solar cells from the standard process, measured at 25°C, was about 6.6% for the controlled SiC ribbons and 5.4% for the uncontrolled SiC ribbons. The lower performance of the solar cells from the ribbons of uncontrolled SiC was due to the shunting problems from SiC. Maximum efficiency of the standard EFG solar cell was about 7.5%.

- Solar cells from EFG (RF) ribbons (reported earlier) showed better performance than those from the EFG (RH) ribbons and difference in minority carrier lifetime seems to be the main contributing factor.

Silicon on Ceramic

- Bowing of the substrates caused difficulties in processing, especially in metallization steps. It does not appear to be a simple way to make a proper back contact through the ceramic slots.

- An average efficiency of the SOC solar cells (average area 15 cm^2) was about 6% at 25°C under AMO conditions. There is room for improvement in cell performance, by improving active area and series resistance problems. The best SOC solar cells showed about 7.3% conversion efficiency.

- Good performance of the control solar cell indicated that there was no cross contamination between the SOC substrate and the control blanks.

IV. WORK PLAN STATUS

The following unconventional silicon sheets are expected for processing and evaluation during the next period.

- Further evaluation of the silicon on ceramic solar cells with emphasis on improving series resistance problems.

- Czochralski silicon by continuous or semi-continuous growth method from Hamco.

V. REFERENCES

1. H.I. Yoo, et.al., "*Silicon Solar Cell Process Development, Fabrication and Analysis*", JPL Contract No. 955089, First Quarterly Report, 1978, Optical Coating Laboratory, Inc.

2. F. Schmid, et.al., "*Silicon Ingot Casting - Heat Exchanger Method Multi-Wire Slicing - Fixed Abrasive Slicing Technique*", JPL Contract No. 954373, Technical Reports, Crystal Systems, Inc.

3. H.I. Yoo, et.al., "*Silicon Solar Cell Process Development, Fabrication and Analysis*", JPL Contract No. 955089, Second Quarterly Report, 1978, Optical Coating Laboratory, Inc.

4. F.V. Wald, et.al., "*Large Area Silicon Sheet by EFG*", JPL Contract No. 954355, Technical Reports, Mobil Tyco.

5. P.W. Chapman, et.al., "*Silicon on Ceramic Process*", JPL Contract No. 954356, Technical Reports, Honeywell.

APPENDIX I

TIME SCHEDULE

TIME SCHEDULE

TASK	MONTH												
	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN
1. PROCESS SHEET SAMPLES													
(a) 1/2 Samples → Cells													
(b) Analysis													
(c) Back Up Measurements													
(d) Test Alternate Process													
2. REPORTS													
(a) Monthly			▲	▲		▲	▲		▲	▲		Δ	
(b) Quarterly					▲						▲		
(c) Semi-Annual								▲					
(d) Final													Δ
3. INTEGRATION MEETING													

NOTE: The final reporting period has been incorrectly stated previously, please note revisions.

APPENDIX II

ABBREVIATIONS

ABBREVIATIONS

V_{OC}: Open Circuit Voltage

I_{SC}: Short Circuit Current

J_{SC}: Short Circuit Current Density

I_{SCR}: Short Circuit Current (Red Response) at Wavelength Above ∿.6 μm

I_{SCB}: Short Circuit Current (Blue Response) at Wavelength Below ∿.6 μm

CFF: Curve Fill Factor

η: Solar Cell Conversion Efficiency

Le: Minority Carrier Diffusion Length (D.L.)

I_{MAX}: Current at Maximum Power Point

V_{MAX}: Voltage at Maximum Power Point

P_{MAX}: Maximum Power Point

BSF: Back Surface Field

V_B: Bias Voltage

HEM: Heat Exchanger Method

EFG: Edge Defined Film-Fed Growth

SOC: Silicon on Ceramic

I_o: Diode Saturation Current

SPV: Surface Photovoltage

APPENDIX III

ELECTRICAL DATA SHEETS FOR SOLAR CELLS FROM HEM CAST SILICON

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2x2cm) from HEM cast silicon, 1st batch (standard process)
SiO A.R coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
1-852-4	571	123	51	72	108	480	51.8	74	9.6	4
" -7	569	122	50	72	111	470	52.2	75	9.7	"
" -10	566	125	51	75	109	465	50.7	72	9.4	"
" -13	572	126	51	75	110	480	52.8	73	9.8	"
" -16	574	119	48	71	107	480	51.4	75	9.5	"
" -19	570	119	48	71	105	475	49.9	74	9.2	"
" -22	570	121	49	73	108	475	51.3	74	9.5	"
" -25	567	124	51	72	108	468	50.5	72	9.4	"
" -28	570	126	51	75	113	475	53.7	75	9.9	"
" -31	565	122	51	72	105	466	48.9	71	9.1	"
" -34	568	123	51	73	111	471	52.3	75	9.7	"
" -37	557	111	47	64	90	460	41.4	67	8.4	3.63
" -40	565	123	51	73	108	465	50.2	72	9.3	4
" -43	567	126	52	75	115	463	53.2	75	9.9	"
" -46	573	125	52	74	112	475	53.2	74	9.9	"
" -49	571	126	52	75	112	479	53.6	75	9.9	"
" -52	568	125	51	74	112	475	53.2	75	9.9	"
" -55	567	122	51	71	109	471	51.3	74	9.5	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (2x2cm) from HEM Cast Silicon, 1st batch (standard process)
SnO A.R coating, ≥ 90 % active area

TEST CONDITION: AM 0

TEMPERATURE: 25 °C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
1-852-58	566	123	51	73	111	493	52.5	75	~~9.5~~ 9.7	4
" -61	562	118	50	68	106	448	47.5	72	~~9.9~~ 8.8	"
" -64	563	123	51	72	112	458	51.3	74	~~8.8~~ 9.5	"
" -67	565	115	48	67	105	468	49.1	76	~~9.5~~ 10.1	3.59
" -70	566	125	53	72	111	470	52.2	74	~~10.1~~ 9.7	4
" -73	566	114	47	67	101	485	49.0	76	~~9.7~~ 10.0	3.63
" -76	565	123	52	72	108	468	50.5	73	~~10.0~~ 9.4	4
" -79	564	123	50	73	108	460	49.7	72	~~9.4~~ 9.2	"
" -82	558	114	47	68	96	450	43.2	68	~~8.9~~ 8.7	3.69
" -85	560	119	51	68	110	462	50.8	76	~~9.6~~ 9.4	4
1-860-1	527	93	46	47	64	340	21.8	44	4.3	3.72
" -4	589	109	49	60	95	491	46.6	73	8.6	4
" -7	561	104	46	58	75	405	30.4	52	6.1	3.67
" -10	587	109	47	61	98	470	46.1	72	8.5	4
" -13	588	112	50	63	100	494	49.4	75	9.2	"
" -19	587	109	48	61	94	491	46.2	72	8.5	"
" -22	588	115	51	64	100	491	49.1	73	9.1	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2x2 cm) from HEM coat Silicon, 1st batch (standard Process)
Si_3O_4 AR coating ≥ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE:

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm^2
1-860-25	582	101	47	62	90	478	43.0	73	8.6	3.72
-28	578	110	48	62	95	455	38.7	61	7.7	3.74
-31	567	108	47	61	76	425	32.3	53	6.5	3.70
-34	569	107	47	60	78	435	33.9	56	6.8	3.71
-37	566	107	46	61	79	435	34.4	57	6.9	"
-40	543	107	47	60	75	353	26.5	46	5.3	3.72
-43	535	108	47	61	80	343	27.4	47	5.4	3.75
-46	550	106	47	59	77	370	28.5	49	5.7	3.73
-49	554	105	47	58	76	385	29.3	50	5.8	3.74
-52	565	103	47	57	78	448	34.9	60	6.9	3.73
			Control	Cells						
1	595	132	53	79	120	502	60.2	77	11.2	4
2	588	122	50	72	108	487	52.6	73	10.7	3.63
3	588	134	54	80	120	495	59.4	75	11.0	4
4	593	134	54	81	121	497	60.1	76	11.1	"
5	590	134	55	80	120	491	58.9	75	10.9	"
6	591	134	55	80	118	491	57.9	73	10.7	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2x2 cm) from HEM cast silicon, 2nd batch (BSF Process)
SiO AR coating, ≥ 90 % active area
TEST CONDITION: AM0
TEMPERATURE: 25 °C DATE:

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm^2
1-852-2	561	121	48	74	92	450	41.4	61	8.0	3.815
" -5	571	130	51	79	109	465	50.7	68	9.5	3.966
" -8	572	125	47	78	106	465	49.3	69	9.5	3.825
" -11	574	129	49	81	111	455	50.5	68	9.4	3.966
" -14	570	130	49	81	105	460	48.3	65	9.0	"
" -20	570	126	49	77	102	470	47.9	67	9.2	3.875
" -23	536	130	50	81	79	370	29.2	42	5.5	3.966
" -26	559	128	48	80	96	440	42.2	59	7.9	"
" -29	555	131	52	80	93	435	40.5	56	7.6	"
" -32	546	131	52	80	85	420	35.7	50	6.7	"
" -35	565	127	52	76	105	455	47.8	67	8.9	"
" -38	564	130	51	79	99	455	45.0	61	8.4	"
" -41	571	128	52	76	113	465	52.5	72	9.9	3.95
" -44	559	130	49	81	89	445	39.6	54	7.4	3.966
" -47	570	133	50	83	106	455	48.2	64	9.0	"
" -50	571	130	52	79	113	460	52.0	70	9.7	"
" -53	562	131	50	81	98	440	43.1	59	8.1	"
" -56	565	130	51	79	110	460	50.6	69	9.5	"

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SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2x2 cm) from HEM cast Silicon, 2nd batch (BSR Process)
Si$_3$O$_4$ AR coating ≈ 90% active area
TEST CONDITION: AM0
TEMPERATURE: 25 °C DATE:

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm^2
1-852-59	566	123	47	76	103	460	47.4	68	8.8	3.966
-62	563	128	50	78	104	460	47.8	66	8.9	"
-65	558	126	47	79	101	450	45.5	65	8.5	"
-68	561	122	48	74	94	460	43.2	63	8.1	"
-71	564	124	49	79	108	460	49.7	71	9.3	"
-74	568	130	50	79	112	435	48.7	66	9.1	"
-77	559	130	50	80	101	445	45.0	62	8.4	"
-80	565	128	48	79	106	465	49.3	68	9.2	"
-83	563	128	50	78	109	445	48.5	67	9.1	"
1-856-6	554	123	~~51~~ 49	73	84	360	30.2	44	5.6	3.966
" -11	576	118	46	72	88	455	40.0	59	7.8	3.805
-21	567	121	48	73	86	380	32.7	48	6.3	3.840
-71	565	118	50	69	73	390	28.5	43	5.3	3.991
-81	429	126	53	73	70	235	16.5	30	3.1	"
										"
1-860-5	570	115	48	66	84	435	35.7	54	6.9	3.850
-8	557	117	49	68	84	350	29.4	45	5.5	3.966

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (≈ 2x2 cm) from HEM coat silicon, 2nd batch (BSD Process)
SiO A.R coating, ≈ 90% active area

TEST CONDITION: 4MO

TEMPERATURE: 25°C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
1-860-11	572	117	49	68	86	425	~~40~~ 36.6	55	7.0	3.850
" -14	581	113	47	66	80	475	38.0	58	7.4	3.81
" -17	475	113	47	66	64	255	16.3	30	3.1	3.966
" -20	578	117	48	69	80	455	36.4	54	6.8	"
" -23	576	116	48	68	78	190	14.8	22	2.8	"
" -26	563	114	48	66	79	395	31.2	49	~~5.8~~ 6.1	3.8
" -32	491	115	47	68	70	280	19.6	35	3.7	3.966
" -35	568	115	47	68	76	425	32.3	49	6.0	"
" -38	535	108	44	64	69	345	23.8	41	4.6	3.825
" -41	510	110	44	65	72	300	21.6	39	4.2	3.77
" -44	486	117	48	68	74	300	22.2	39	4.1	3.966
-47	520	115	48	66	78	315	24.6	41	4.6	"
			Control	Cells						
10	596	134	51	83	114	490	55.9	70	10.8	3.825
11	584	131	49	83	88	475	41.8	55	8.1	3.800
13	590	135	49	86	104	465	48.4	61	9.4	3.795
15	601	135	51	84	118	500	59.0	73	11.4	3.820

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2×2 cm) from HEM cast Silicon, 3rd batch (BSH process)
SiO A.R coating, ≈ 90 % active area
TEST CONDITION: AMO
TEMPERATURE: 25°C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
1-852-6	560	121	48	73	85	445	37.8	56	7.1	3.935
" -18	566	123	49	74	93	459	42.7	61	8.0	"
" -30	568	121	49	72	106	459	48.7	71	9.2	"
" -45	567	125	49	76	93	460	42.8	60	8.1	"
" -54	566	122	50	72	108	454	49.0	71	9.2	"
" -60	560	122	50	72	100	446	44.6	65	8.4	"
" -72	565	123	50	73	110	440	48.4	70	9.1	"
" -84	559	121	49	72	103	442	45.5	67	8.6	"
" -86	545	115	47	67	93	415	38.6	62	7.3	"
1-856-2	~~531~~	~~94~~	~~46~~	~~47~~	~~79~~	~~424~~	33.5	67	6.3	3.935
" -12	582	121	49	72	97	465	45.11	64	8.5	"
" -22	562	120	50	70	69	400	27.6	41	5.2	"
" -40	582	119	51	68	86	465	40.0	58	7.5	"
" -32	590	121	50	71	104	468	48.7	68	9.2	"
" -52	584	119	50	70	94	467	43.9	63	8.3	"
" -62	554	115	48	67	66	385	25.4	40	4.8	"
" -72	574	115	49	67	78	455	35.5	54	6.7	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2x2 cm) from HEM cast silicon, 3rd batch (BSF process)
Si_3O_4 AR coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
1-856-82	586	120	50	69	90	462	41.6	59	7.8	3.935
			control cells							
37	590	135	54	81	111	472	52.4	66	9.9	3.935
38	564	128	49	79	66	400	26.4	37	5.0	"
39	586	134	54	81	94	463	43.5	55	8.2	"
41	550	131	50	82	82	390	32.0	44	6.0	"
42	596	135	51	84	118	475	56.1	70	10.6	"
43	563	133	54	80	95	437	41.5	55	7.8	"

APPENDIX IV

ELECTRICAL DATA SHEETS FOR EFG (RH) SOLAR CELLS

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2x2 cm) from EFG ribbon (RH), 1st batch (standard process)
SiO AR coating, ≈ 90 % active area, Parenthesis numbers for before AR coating.

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
5-866-1	526	98	42	54	88	431	37.9	74	7.5	3.756
	(510)	(69)	(31)	(37)	(61)	(420)	(25.6)	(73)	(5.1)	
" -2	522	99	43	55	88	431	37.9	73	7.3	3.875
	(508)	(70)	(32)	(37)	(62)	(413)	(25.6)	(72)	(4.9)	
" -4	505	96	42	53	67	400	26.8	55	5.1	"
	(485)	(69)	(32)	(36)	(44)	(375)	(16.5)	(49)	(3.2)	
" -5	514	96	42	53	85	412	35.0	71	6.7	"
	(495)	(68)	(31)	(36)	(52)	(400)	(20.8)	(62)	(4.0)	
" -6	490	97	43	53	60	375	22.5	47	4.3	"
	(464)	(69)	(32)	(36)	(38)	(356)	(13.5)	(42)	(2.6)	
5-868-1	514	97	42	53	88	415	36.5	73	7.0	3.875
	(501)	(69)	(32)	(37)	(62)	(406)	(25.2)	(73)	(4.8)	
-3	510	91	41	48	83	415	34.5	74	6.6	"
	(498)	(64)	(31)	(32)	(58)	(408)	(23.7)	(74)	(4.5)	
-4	515	91	39	51	81	418	33.9	72	7.0	3.565
	(503)	(65)	(29)	(35)	(56)	(400)	(22.4)	(69)	(4.7)	

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SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (≈ 2x2 cm) from EFG Ribbon (RH), 1st batch (standard process)
SiO A.R. coating (parentheses numbers for before A.R. coating), ≈ 90 % active area.
TEST CONDITION: AMO
TEMPERATURE: 25 °C DATE:

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm^2
5-868-5	514	99	42	50	84	420	35.3	73	6.7	3.875
	(502)	(66)	(31)	(34)	(60)	(406)	(24.4)	(74)	(4.7)	
-6	515	98	43	54	89	408	36.3	72	6.9	〃
	(503)	(70)	(32)	(37)	(62)	(410)	(25.4)	(72)	(4.9)	
-7	516	98	44	53	86	418	36.0	71	6.9	〃
	(502)	(69)	(32)	(36)	(60)	(406)	(24.4)	(70)	(4.7)	
-8	518	98	42	54	89	424	37.7	74	7.2	〃
	(506)	(70)	(32)	(37)	(63)	(416)	(26.2)	(74)	(5.0)	
5-870-2	480	95	44	53	51	305	15.6	34	2.9	3.960
	(492)	(68)	(32)	(36)	(46)	(353)	(16.2)	(49)	(3.0)	
-5	527	99	44	54	90	432	38.9	75	7.4	3.875
	(514)	(70)	(32)	(37)	(62)	(416)	(25.8)	(72)	(4.9)	
-6	517	99	43	54	78	393	30.7	60	5.9	〃
	(494)	(72)	(33)	(37)	(57)	(365)	(20.8)	(59)	(4.0)	
-7	478	85	43	39	61	332	20.3	50	3.9	〃

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: control solar cells (2x2cm) tw EFG (RH), 1st batch (standard process)
SnO A.R coating, ≥ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
1	577	128	48	80	117	478	55.9	76	10.7	3.875
3	588	131	50	81	120	489	58.7	76	11.2	〃
5	576	131	49	82	108	470	50.8	67	9.7	〃
7	594	132	50	83	123	500	61.5	78	11.4	4
8	584	134	50	85	123	488	60.0	77	11.1	〃
9	596	134	49	85	123	505	62.1	78	11.5	〃
Note;	Control cell	# 1, 3, 5			First	Control	Group			
		〃	# 7, 8, 9		Second	〃	〃			

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2x2 cm) from EFG (RH) ribbon, 2nd batch (BSF process) with SiO A.R coating ≈ 90% active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
5-866-8	499	78	35	42	52	378	19.7	51	4.7	3.11
5-868-10	505	75	33	42	58	394	22.9	60	5.9	2.859
		Control cells								
2	585	108	41	67	85	489	41.6	66	9.3	3.297
4	578	112	43	69	90	466	41.9	65	9.4	3.302
6	582	110	42	68	91	477	43.4	68	9.7	3.312
34	590	111	43	68	94	490	46.1	70	10.3	3.302
35	585	110	41	69	84	487	40.9	64	9.3	3.275
	Note:	2, 4, 6	First control Group							
		34, 35	Second "	"						

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈2x2 cm) from EFG(RH) ribbon, 3rd batch (Back contact Heat Treatment, STD)
with SiO A.R coating, ≈90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
5-868-11	519	94	42	50	84	411	34.5	71	7.0	3.677
" -12	447	79	43	36	32	310	9.9	28	2.2	3.375
30	591	128	48	80	116	484	56.1	74	10.6	3.940
		Above cells Heat Treated at 600°C for 10 minutes. (back contact)								
5-866-12	503	91	40	49	69	304	19.5	43	3.8	3.815
5-868-13	515	85	39	45	75	417	31.3	71	6.6	3.509
5-870-11	516	93	41	51	75	409	30.7	64	6.1	3.712
		Above cells Heat Treated at 650°C for 5 minutes (back contact)								
5-868-14	248	86	40	44		shunted	badly			
5-866-14	497	90	40	49	60	393	23.6	53	4.7	3.741
5-870-12	409	78	34	41	48	265	12.7	40	2.7	3.483
33	589	124	47	78	107	492	52.6	72	9.8	3.960
		Above cells Heat Treated at 650°C for 10 minutes (back contact)								
Note: cell # 30, and 33 are control cells.										

APPENDIX V

ELECTRICAL DATA SHEETS FOR SOC SOLAR CELLS

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells from SOC, 1st batch (standard process)
with Si$_3$N$_4$ A.R coating. (Parenthesis numbers for before A.R coating).
TEST CONDITION: AMO
TEMPERATURE: ≈28-30°C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
158-10	536	250			213	410	87.3	65	6.4	10.1
	(528)	(179)	(78)	(101)	(148)	(412)	(61.0)	(65)	(4.5)	
160-3	548	187	79	107	166	418	69.4	68	7.3	7
	(549)	(138)	(63)	(75)	(126)	(441)	(55.6)	(73)	(5.9)	
		control cells								
1	598	126	45	81	116	500	58.0	77	10.7	4
2	598	131	48	83	123	492	60.5	77	11.2	"
3	597	128	45	83	118	498	58.8	77	10.9	"
4	596	131	48	84	120	492	59.0	76	10.9	"
5	594	130	48	82	117	488	57.1	74	10.6	"
6	594	129	48	82	119	492	58.6	76	10.8	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells from SOC 2nd batch (standard process)
With Si_xO A.R coating Active area 80 ~ 85 % for SOC cells
TEST CONDITION: AMO
TEMPERATURE: ≈ 28 ~ 30 °C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm^2
159-11	553	431	188	244	365	405	147.8	62	6.2	17.68
159-4	548	419	185	235	355	412	146.3	64	6.8	15.94
159-6	545	190	87	103	154	392	60.4	58	6.2	7.25
159-7	544	317	140	180	234	385	90.1	52	5.2	12.75
159-9	541	423	194	240	310	390	120.9	53	5.1	17.68
159-10	548	401	178	227	315	410	129.2	59	5.7	16.81
161-9	547	274	118	156	242	428	103.6	69	6.2	12.46
161-15	546	286	128	163	232	420	97.4	62	5.8	12.46
		Controls								
10	591	134	53	81	122	480	58.6	74	10.8	4
11	591	135	52	84	120	477	57.2	72	10.6	"
13	589	139	54	86	120	458	55.0	67	10.2	"
14	581	130	50	80	115	470	54.1	72	10.0	"
15	592	135	52	83	125	490	61.3	77	11.3	"
16	588	138	53	85	120	478	57.4	71	10.6	"