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Quarterly Report No. 3

LITHIUM-DIFFUSED SOLAR CELLS

January 1969

For the Period
1 October 1968–31 December 1968

Contract No. 952248

Prepared by

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Don L. Kendall

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Dallas, Texas 75222

for

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Avenue
Pasadena, California

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ABSTRACT

A discussion on lithium diffusion from an evaporated source and in a silicon enclosure is presented. The electrical performance and fabrication techniques utilized on shipping lots 5, 6 and 7 are discussed. The spectral response of the cells from lot T-5 were determined to be virtually identical to the response of standard N/P silicon solar cells. Three basic Li concentrations at the junction will be evaluated during the contract.

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SECTION I

INTRODUCTION

This report presents the third quarter performance on a 12-month program to determine process parameter effects on lithium-diffused silicon solar cell electrical and mechanical characteristics.

SECTION II

LITHIUM DIFFUSION BY EVAPORATION

The technique we have emphasized in our cell manufacture is the use of pure evaporated lithium on side A of a chemically or mechanically polished slice where side B has already been diffused with boron. The latter p+ layer is quite heavily doped (approx. 10^{20} cm^{-3}) and acts as an infinite sink for the interstitial donor lithium arriving from side A, at least for the early parts of the diffusion run. Eventually, however, this p+ layer will reach a point where it is no longer an effective sink for the lithium. This is shown schematically in Figure 1.

This situation will be maintained until the integrated atom flux crossing the junction (x_j) becomes comparable to the maximum amount of lithium that can be put into the boron doped layer. For simplicity, we choose a 10^{-4} cm thick p-layer and an average lithium concentration of 10^{20} cm^{-3} in this layer. This permutes into an integrated concentration, $Q_{max} = 10^{16}$ cm^{-2}. The maximum flux across the silicon slab occurs when Δ (Li)/Δ x = a constant, which is represented by

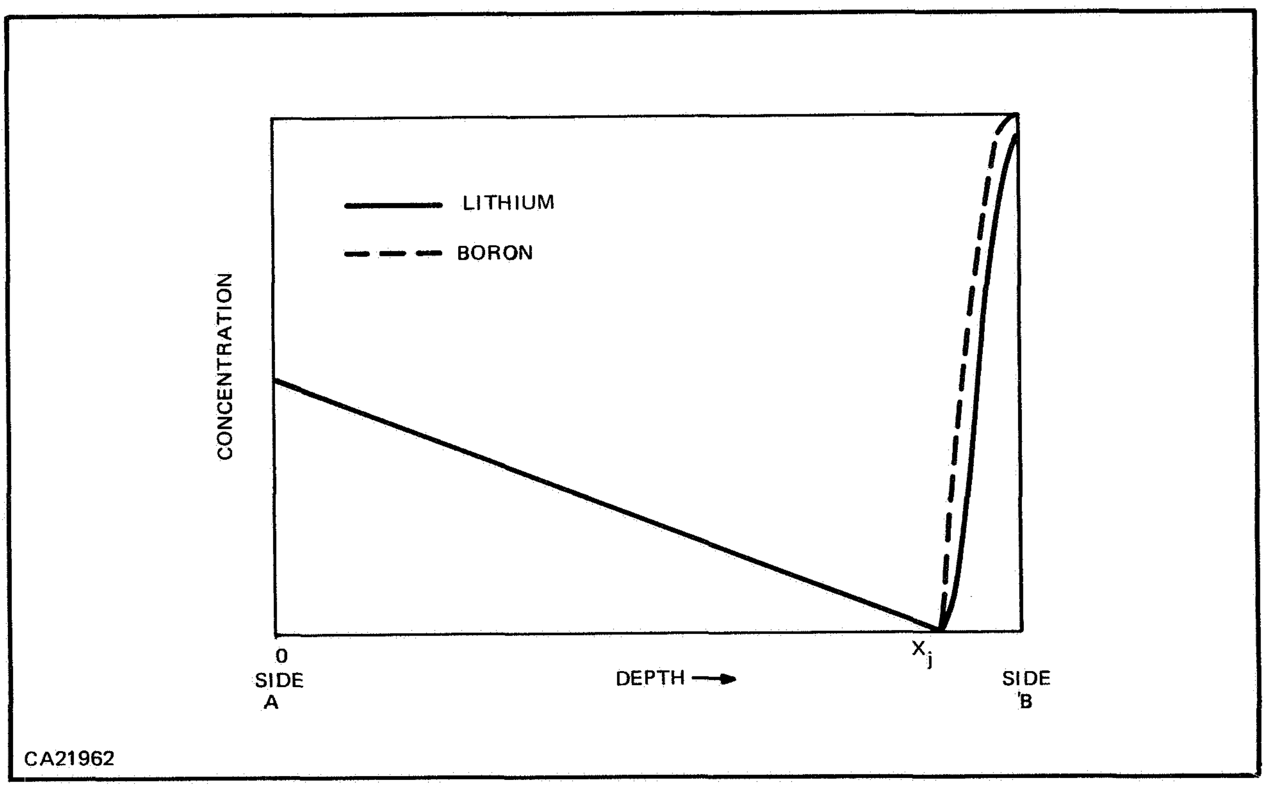

Figure 1. Assumed Lithium Distribution When a Steady State Condition is Reached

the linear gradiant of Figure 1. Assuming a solar cell slice thickness of 0.03 cm and the solid solubility of lithium at the diffusion temperature of 400°C; $\Delta(\mathrm{Li})/\Delta X = -1.2 \times 10^{18}$ cm^{-3}/0.03 cm = -4×10^{19} cm^{-4}. Taking the D value of 2.5×10^{-8} cm^2 sec^{-1} for lithium at 400°C[2], we can calculate a minimum saturation time, t_s, to give an integrated flux, Φ adequate to saturate the boron layer with lithium (i.e. to Q_{max}) from the following expression (Fick's law):

$$\Phi = Jt_s = -D \frac{\Delta C}{\Delta X} t_s = Q_{max} \qquad (1)$$

thus

$$t_s = \frac{Q_{max}}{D\, \Delta C/\Delta X} = \frac{10^{16}}{2.5 \times 10^{-8}\; 4 \times 10^{19}} = 10^4 \text{ sec} \approx 3 \text{ hours}$$

Since the time used for most of the cells was only 1.5 hours, we are well within the limit. This is especially true when the actual diffusion conditions are taken into account (as shown below in equation 2) since in the first hour of diffusion at 400°C, almost no lithium crosses the junction, so the actual time required to saturate the p-layer will be considerably longer than 3 hours.

The actual profile under constant surface concentration conditions at x = o and a permeable boundary of W is given by:

$$\frac{N}{N_o} = 1 - \frac{X}{W} - \frac{2}{\pi} \sum_{n=1}^{\infty} \left[\frac{1}{n} \exp \left(\frac{n^2 \pi^2 Dt}{W^2} \right) \sin \frac{n\pi X}{W} \right] \qquad (2)$$

Where N_o is the surface concentration, N is the concentration at any point x and W is the thickness of the slice. (This ignores the p-layer thickness). The other symbols have their classical meanings. A graph of this function at different times at both 325°C and 400°C is given in Figure 2. The D values were 5×10^{-9} and 2.5×10^{-8} cm^2 sec^{-1}, respectively.

Note the 325°C curve after 8.0 hours of diffusion is very similar to the 400°C curve at 1.6 hours, the only difference being the lower surface concentration at 325°C (6×10^{17} cm^{-3} instead of 1.2×10^{18} cm^{-3}). Thus at 325°C for 8.0 hours, the lithium concentration and its gradient should both be about one-half that of the "standard" cells we have been providing. While lot T-10 (400°C for 135 minutes and x_j twice the standard x_j) was designed to yield a lithium concentration twice that of the "standard" cells.

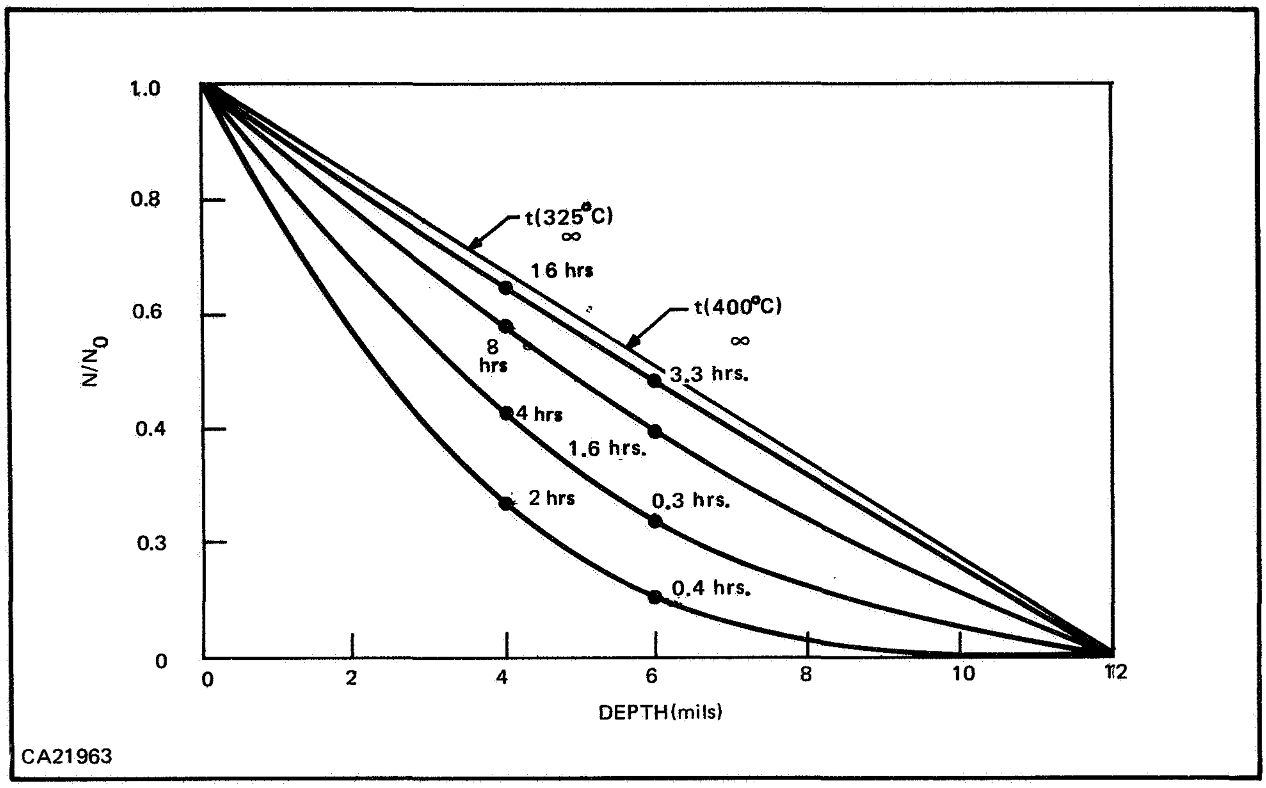

Figure 2. Theoretical Curves for Lithium Diffusion in a Silicon Slice of 12 mils Thickness at 325°C and 400°C, Assuming Source at X = 0 and Sink at X = 12 mils

SECTION III

DIFFUSION OF EVAPORATED LITHIUM IN A SILICON ENCLOSURE

The vapor diffusion of lithium in the "silicon box" approach discussed in Quarterly Report No. 2 is limited in its range of application to temperatures greater than about 525°C when diffused in a furnace tube under forming gas. The data in the critical range of temperature are shown below where ρ_o is the original P-type resistivity and ρ_f is the resistivity after a given lithium diffusion process. These diffusion runs were in the range 8 to 16 hours. The results did not depend on diffusion time over this range. Note that at 547°C and above the lithium solubility limit is reached in the samples, with negligible surface damage.

Table I. Effect of Temperature on Lithium Diffusion in the Silicon Box

T(°C)	ρ_o(ohm-cm) (ρ)	ρ_f(ohm-cm)
400	1.8	1.8 (p)
500	1.8	1.8 (p)
525	1.8	3.5 (p)
547	1.8	0.013 (n)
600	1.8	0.007 (n)

SECTION IV

VAPOR DIFFUSION USING A LITHIUM: TIN ALLOY

We have made cells using the "silicon box" technique with various lithium:tin compositions. These were quite irreproducible and additional engineering work needs to be done before this could be utilized as a cell manufacturing method. Therefore, it is not anticipated that cells will be fabricated by this technique for shipment to JPL on this contract.

SECTION V

CELL FABRICATION

Three 60-cell lots, T-5, T-6 and T-7 were shipped during this reporting period. Three basic material types have been investigated on the contract-Lopex*, Float-zoned and Czochralski. All starting silicon on the contract will have phosphorus as the base dopant with the Czochralski resistivity being > 20 Ω cm and the Lopex and Float zoned being > 50 Ω cm. Three Li diffusion cycles have also been evaluated on cells shipped to JPL. One basic fabrication process has been utilized to date with the exception of lot T-5, which was processed as a whole slice through contact sintering. Two 1 X 2 cm, 5-grid cells were then sawed from each slice. Figure 3 is a photograph of the "N" contact surface of one of the these slices prior to the sawing operation. The whole slice processing technique was designed to eliminate the edge problems (non-uniform Li source and edge out-diffusion) encountered on the "standard" Li-diffused cells. The balance of the lots were fabricated from sized blanks ie, crystals were cut into 1 X 2 cm blanks, polished, boron diffused, Li diffused, etc. Table II. reviews the variables on each shipping lot to date and the anticipated variables on the remaining lots.

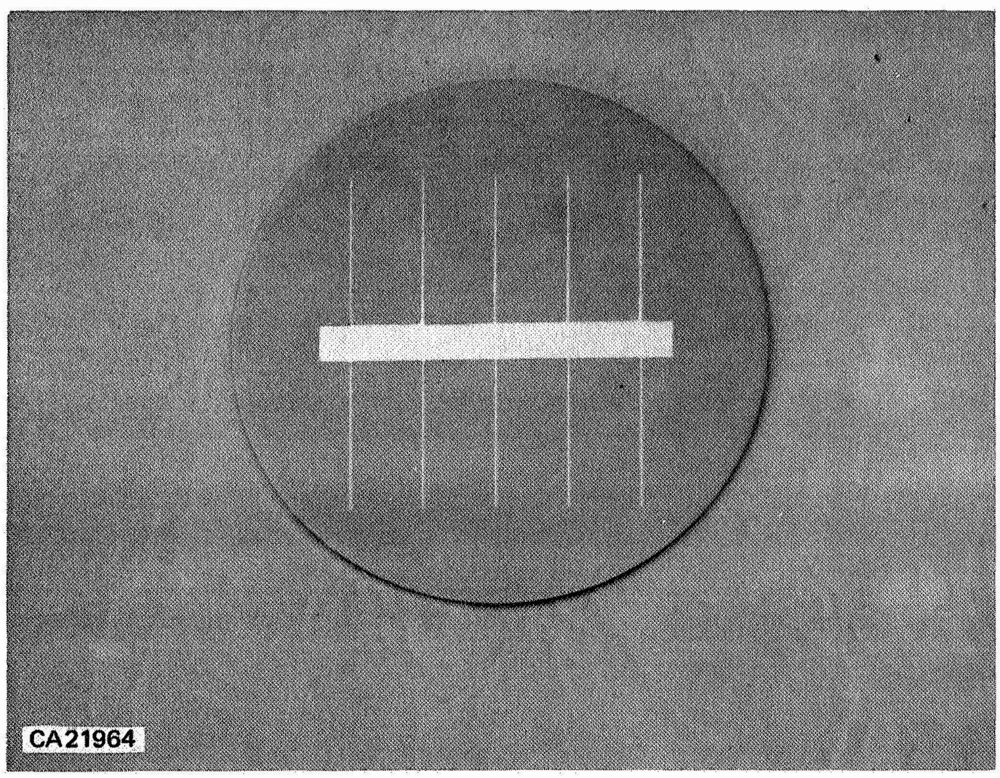

Figure 3. "N" Contact Surface of Whole Slice After Contact Deposition

Table II. Present Variables and Anticipated Variables

Lot No.	Material	Li Diffusion	Other Variables
T-1	Cz	90 min. @ 400°C (120 min. redist.)	
T-2	Cz	90 min. @ 400°C	
T-3	Lx	90 min. @ 400°C	
T-4	Fz	90 min. @ 400°C	
T-5	Lx	90 min. @ 400°C	Whole slice
T-6	Lx	8 hours @ 325°C	
T-7	Cz	8 hours @ 325°C	
T-8	Cz	8 hours @ 325°C	Whole slice
T-9	Lx	8 hours @ 325°C	Whole slice
T-10	Lx	135 min. @ 400°C	Whole slice; xj = 2 std. xj

Only lot 1 received a redistribution diffusion cycle at 400°C. However, all lots were sintered after contact deposition at 600°C for approximately 3 minutes, which is a significant redistribution cycle in itself-equivalent to one hour at 400°C. All cells were optically coated with the standard 1/4 - wave silicon monoxide evaporated layer after contact sintering.

SECTION VI

CELL ELECTRICAL TESTING

Electrical characteristics of each cell in shipping lots 5, 6 and 7 tested under the tungsten light source utilized throughout the contract are detailed in the Tables III, IV and V, respectively. The output characteristics of lots 6 and 7 tested under TI's AMO simulator are presented in Tables VI and VII, respectively. The spectral irradiance of this AMO simulator is compared to the Johnson curve for AMO sunlight in Figure 4. Although the TI simulator curve deviates significantly from the Johnson curve, especially in the 0.6 to 1.2 micron region, the total integrated result (considering a typical N/P spectral-response characteristic) would be 0.59 mA more short-circuit current output for a 2 X 2 cm cell under the TI simulator than under AMO sunlight.

The simulator was used to establish the AMO conversion efficiency of Li-diffused cells and to compare their spectral response to standard N/P solar cells. The simulator data on lot 6, (Table VI) were taken at a load voltage of 0.485V, instead of the standard comparison point of 0.430V to give a more accurate evaluation of the optimum conversion efficiency. These 60 cells averaged 9.65% AMO efficiency with the simulator calibrated by a N/P working standard (traceable to JPL balloon standard calibration).

The spectral response of cells from shipping lot 5 were determined to be virtually identical to a typical N/P solar cell. The tungsten light source and the simulator were calibrated with the same N/P standard and the output of five lithium-diffused cells (T-5) were measured under both sources. The data are presented in Table VIII. Note that the short circuit current of the cells averaged 60.6 mA under the tungsten and xenon sources, respectively.

The average output of lots T-6 and T-3 is compared in Table IX. The diffusion cycle on T-6 theoretically should yield a Li concentration at the junction approximately ½ the value of T-3 (see section II). Both lots were .> 50Ω cm, phosphrous-doped Lopez* silicon and were fabricated identically except for the Li diffusion cycle. The data were taken under a tungsten light source calibrated with table mountain standard to 100mW/cm^2 sunlight equivalent. The average output of the cells with the 325°C Li diffusion is slightly higher initially than the cells with the 400°C diffusion. However, on cells initiated into the fabrication cycle as sized blanks (as compared to whole slices), the reduced Li concentration at the edges of the blank significantly affects the initial electrical characteristics and most likely the post-irradiation annealing. The difference in initial performance between the two different blanks is evident by comparing shipping lots T-3 (sized blanks) and T-5 (whole slices.) Two five-grid cells (1.8 cm^2 active area) were sawed from whole slice

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Table III. Cell Characteristics of Lot 5
(90 Min. Diffusion at 400°C into Whole Slice of Lopex Silicon)

Cell No. (T-5-)	I_{SC} (mA)	$I_{0.430\ V}$ (mA)	V_{oc} (V)	Cell No. (T-5-)	I_{SC} (mA)	$I_{0.430\ V}$ (mA)	V_{oc} (V)
1	53.0	49.8	0.595	31	52.8	50.9	0.605
2	53.0	50.5	0.600	32	53.0	51.0	0.604
3	52.0	49.8	0.605	33	52.0	49.0	0.599
4	51.0	49.2	0.606	34	52.0	49.8	0.600
5	54.0	51.5	0.600	35	51.2	48.8	0.599
6	52.2	50.0	0.601	36	51.0	49.1	0.600
7	52.0	50.0	0.610	37	53.0	49.0	0.600
8	52.9	50.3	0.606	38	52.0	49.3	0.600
9	53.2	50.9	0.600	39	52.0	50.3	0.602
10	54.0	52.0	0.606	40	51.5	49.5	0.600
11	55.0	51.0	0.600	41	53.0	50.3	0.600
12	52.1	50.0	0.600	42	52.8	50.0	0.600
13	52.9	50.0	0.600	43	52.2	51.0	0.609
14	52.4	49.0	0.600	44	53.8	51.5	0.600
15	51.0	48.9	0.605	45	54.5	50.0	0.590
16	52.8	51.0	0.610	46	51.4	49.6	0.600
17	53.0	49.8	0.595	47	53.9	51.0	0.595
18	54.5	51.2	0.600	48	56.5	53.9	0.602
19	52.8	50.5	0.605	49	52.5	50.6	0.600
20	51.0	48.2	0.600	50	51.8	48.8	0.600
21	51.5	50.0	0.605	51	52.5	50.2	0.600
22	51.8	49.6	0.605	52	51.2	48.0	0.596
23	51.8	49.4	0.600	53	50.0	48.0	0.599
24	51.0	49.0	0.610	54	51.5	48.8	0.600
25	52.0	49.0	0.600	55	50.0	46.2	0.595
26	51.0	49.1	0.605	56	51.0	48.0	0.595
27	51.0	49.0	0.600	57	52.2	48.0	0.595
28	53.5	51.3	0.605	58	50.5	48.0	0.600
29	52.0	49.5	0.600	59	50.0	48.0	0.601
30	54.0	49.5	0.602	60	52.8	47.9	0.591
				X	52.3	49.7	0.600
				Avg.	52.3	49.7	0.600

in the T-5 lot. Table X compares the elctrical output of these two lots with the output currents of T-5 corrected to 1.9 cm^2 active area for direct comparison with T-3. The lower V_{oc} of T-3 is attributed to the reduced Li concentration at the periphery of the cells. This point will be further investigated during the course of the contract. The post-irradiation annealing characteristics of these two lots should identify the significance of this edge area.

Table IV. Cell Characteristics of Lot 6 Under 100 mW/cm^2 Tungsten Light (8-Hour Diffusion at 325°C on Lopex* Silicon)

Cell No. T-6-	I_{SC} (mA)	$I_{0.430\ V}$ (mA)	V_{oc} (mV)	Cell No. (T-6-)	I_{SC} (mA)	$I_{0.430\ V}$ (mA)	V_{oc} (mV)
1	59.0	54.7	599	32	59.0	53.0	600
2	58.5	52.5	590	33	57.0	51.0	592
3	60.2	55.0	599	34	59.0	53.5	600
4	58.0	51.5	595	35	55.0	51.0	590
5	59.0	54.0	599	36	60.0	54.0	600
6	60.0	55.0	598	37	57.0	52.5	600
7	58.2	53.0	600	38	58.0	52.0	595
8	57.0	51.0	590	39	60.0	56.5	600
9	59.0	53.0	598	40	61.0	54.9	598
10	59.5	53.0	590	41	59.0	53.0	595
11	60.0	54.0	588	42	58.8	52.0	600
12	59.0	55.0	600	43	60.5	57.5	600
13	57.0	50.5	595	44	59.0	54.5	605
14	58.0	51.5	595	45	60.0	57.0	605
15	60.0	53.0	592	46	58.5	53.0	600
16	58.0	52.5	600	47	61.0	51.0	582
17	58.5	52.5	590	48	61.5	57.0	600
18	57.0	51.0	590	49	60.5	54.3	595
19	58.0	52.0	590	50	57.9	51.0	580
20	59.0	54.0	599	51	57.0	51.0	597
21	59.0	56.0	600	52	60.0	51.0	590
22	58.5	52.0	595	53	60.0	55.5	600
23	59.0	53.0	600	54	60.0	54.5	596
24	57.5	53.0	598	55	58.0	54.5	605
25	59.0	51.0	590	56	59.0	53.0	595
26	59.0	51.0	590	57	57.0	53.5	595
27	60.0	53.4	590	58	58.5	55.0	600
28	60.0	57.9	610	59	60.0	51.0	590
29	58.0	51.0	590	60	58.2	53.0	600
30	57.5	53.0	600				
31	61.0	55.0	599				
				Avg.	58.9	53.3	596

Table V. Cell Characteristics of Lot 7 Under 100 MW/cm^2 Tungsten Light (8-Hour Diffusion at 325°C on Czochralski Silicon)

Cell No. T-7-	I_{SC} (mA)	V_{oc} (mV)	$I_{0.430\ V}$ (mA)	Cell No. T-7-	I_{SC} (mA)	V_{oc} (mV)	$I_{0.430\ V}$ (mA)
1	58.5	580	49.0	32	57.0	600	54.0
2	59.3	590	53.5	33	59.0	590	48.0
3	58.5	590	53.5	34	56.0	590	49.5
4	60.0	585	51.0	35	58.0	595	53.5
5	60.1	590	52.8	36	54.0	595	51.0
6	59.0	590	52.0	37	56.0	580	48.0
7	58.0	580	49.0	38	58.0	591	50.0
8	57.2	590	51.9	39	56.8	590	51.3
9	58.0	585	51.0	40	60.0	590	53.0
10	57.5	589	50.5	41	59.0	580	47.0
11	59.0	580	48.5	42	57.5	582	50.0
12	61.0	590	50.0	43	57.2	595	53.9
13	58.0	590	57.0	44	50.9	592	47.9
14	57.0	582	48.5	45	60.0	581	49.2
15	61.0	590	53.0	46	57.9	585	49.9
16	58.8	582	51.2	47	56.5	573	47.9
17	60.0	580	49.1	48	58.5	585	48.0
18	59.0	590	53.0	49	57.0	590	51.0
19	59.0	585	51.9	50	58.8	585	50.5
20	59.1	585	53.0	51	59.0	592	52.9
21	59.8	595	55.5	52	60.0	595	55.0
22	58.0	598	54.0	53	56.0	590	49.8
23	57.0	570	43.8	54	57.9	595	54.5
24	58.5	600	55.5	55	58.0	584	49.3
25	59.9	580	51.2	56	60.0	585	51.6
26	58.0	589	48.0	57	54.8	589	49.5
27	57.0	590	50.0	58	57.5	572	48.6
28	57.8	580	49.0	59	59.5	598	53.8
29	58.5	595	53.0	60	60.3	588	51.9
30	58.8	592	52.0				
31	56.6	585	50.1				
				Avg.	85.2	588	51.1

Table VI. Cell Characteristics of Lot 6 Under AMO Simulator (8-Hour Diffusion at 325°C on Lopex* Silicon)

Cell No. T-6-	I_{SC} (mA)	$I_{0.485}$ (mA)	V_{oc} (mV)	Cell No. T-6-	I_{SC} (mA)	$I_{0.485}$ (mA)	V_{oc} (mV)
1	66.5	53.6	595.8	32	68.9	51.9	593.5
2	67.3	49.9	587.9	33	64.6	50.4	589.6
3	69.1	54.9	596.3	34	69.7	55.2	598.3
4	66.9	50.1	583.3	35	64.0	49.3	586.9
5	66.3	52.1	596.2	36	69.4	52.7	597.1
6	68.9	54.2	595.3	37	66.6	52.8	597.2
7	68.2	55.0	599.9	38	67.1	52.1	597.8
8	65.7	48.8	585.8	39	68.7	56.1	600.3
9	67.4	51.7	595.3	40	70.5	53.1	595.2
10	68.6	51.8	592.2	41	67.2	52.3	590.6
11	67.7	52.7	587.7	42	67.8	51.4	595.8
12	67.5	54.6	597.8	43	69.9	60.3	602.9
13	67.7	50.2	593.2	44	69.6	50.1	587.2
14	67.9	51.3	595.0	45	70.9	58.9	600.4
15	68.2	49.4	588.4	46	68.7	53.7	597.7
16	67.2	53.1	594.3	47	69.8	51.3	595.8
17	67.1	50.3	587.8	48	70.3	53.8	592.9
18	68.2	50.6	588.2	49	69.4	52.2	593.5
19	68.8	52.7	590.4	50	67.1	49.9	583.7
20	68.3	53.6	593.8	51	65.9	51.3	594.1
21	66.4	55.0	594.7	52	68.9	49.4	592.1
22	68.1	49.9	588.5	53	70.3	58.4	601.8
23	66.2	53.8	597.4	54	70.6	54.6	598.0
24	66.1	53.3	594.5	55	67.3	58.0	607.0
25	66.7	49.2	581.8	56	68.1	52.8	597.9
26	68.0	51.9	598.2	57	66.7	56.1	600.5
27	68.6	51.8	588.9	58	67.4	57.7	604.0
28	69.8	61.0	606.2	59	67.3	52.4	597.7
29	68.4	49.6	590.3	60	68.4	53.7	601.0
30	67.9	54.0	596.4				
31	70.7	54.9	596.2				
				Avg.	68.0	52.8	594.3

Table VII. Cell Characteristics of Lot 7 Under Amo Simulator (8-Hour Diffusion at 325°C on Czochralski Silicon)

Cell No. T-7-	I_{SC} (mA)	V_{oc} (mV)	$I_{0.430\ V}$ (mA)	Cell No. T-7-	I_{SC} (mA)	V_{oc} (mV)	$I_{0.430\ V}$ (mA)
1	68.7	584.7	60.2	33	68.7	591.3	58.8
2	70.0	590.5	63.2	34	66.8	593.8	59.3
3	68.6	589.7	62.2	35	68.3	595.8	63.5
4	72.9	593.3	62.8	36	63.8	595.4	60.8
5	71.4	593.8	62.5	37	66.5	583.8	57.7
6	68.8	592.8	61.2	38	68.9	591.5	60.7
7	68.1	581.4	58.2	39	66.8	592.6	61.4
8	68.0	594.1	61.7	40	70.3	594.6	62.7
9	68.1	585.8	60.2	41	69.8	570.7	55.5
10	66.7	589.0	59.1	42	68.3	586.6	60.5
11	71.2	585.5	59.4	43	68.4	595.5	64.4
12	73.3	593.8	60.7	44	60.6	596.9	57.8
13	68.1	593.3	61.2	45	70.6	585.5	58.5
14	68.0	586.1	58.2	46	68.3	588.8	59.3
15	72.8	587.2	61.8	47	67.3	578.4	57.5
16	69.0	586.4	60.7	48	70.0	589.3	59.1
17	71.4	594.4	63.1	49	67.5	592.8	61.3
18	69.1	594.9	62.4	50	70.3	588.6	61.3
19	68.8	587.5	61.3	51	70.2	595.4	63.8
20	69.8	588.9	62.8	52	72.4	598.5	66.5
21	70.0	596.6	65.8	53	66.6	591.6	59.6
22	69.8	598.3	64.6	54	67.6	598.3	63.9
23	68.1	589.6	55.5	55	69.4	588.0	59.6
24	69.8	602.5	66.5	56	70.5	588.5	61.4
25	70.9	587.1	62.0	57	65.1	589.7	60.0
26	69.0	591.9	59.0	58	67.8	577.9	58.6
27	67.3	592.8	60.3	59	70.7	600.5	65.5
28	67.6	582.8	58.4	60	72.3	587.7	62.5
29	69.9	596.5	63.8				
30	71.7	596.4	64.4	Aug.	68.9	590.9	61.2
31	66.8	589.0	60.3	Low	63.8	570.7	55.5
32	68.0	604.1	65.3	High	73.3	604.1	66.5

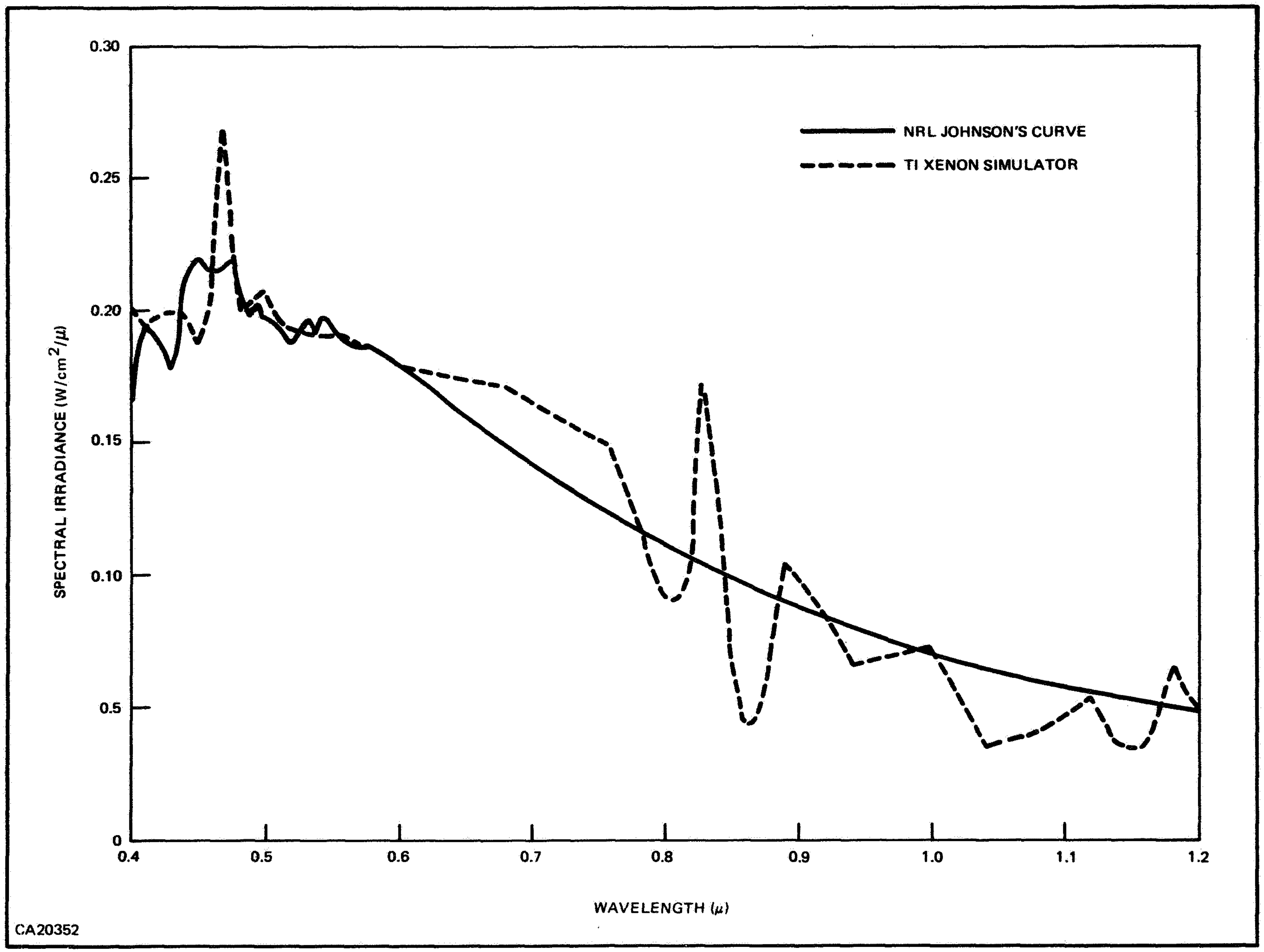

Figure 4. Comparison of Spectral AMO Simulator and Johnson Curve for AMO Sunlight

Table VIII. Results fo the Solar Simulator and Tungsten Light Source Tests

Cell Number	I_{SC} (mA) W	I_{SC} (mA) Xe	V_{oc} (V) W	V_{oc} (V) Xe	$I_{0.485\ V}$ (mA) W	$I_{0.485\ V}$ (mA) Xe	Eff (% AMO) W	Eff (% AMO) Xe
1	58.4	59.1	601.3	601.8	53.2	53.7	10.21	10.31
2	59.7	60.2	599.3	600.0	52.9	53.5	10.17	10.27
3	61.4	62.1	602.0	602.9	54.7	54.9	10.50	10.54
4	61.8	62.1	603.3	603.7	55.9	56.1	10.73	10.77
5	61.8	61.6	603.6	603.3	54.4	54.1	10.44	10.39
X	60.6	61.0	601.9	602.3	54.2	54.5	10.41	10.46

Table IX. Average Electrical Characteristics of T3 and T6

Lot No.	I_{SC} (mA)	$I_{0.430\ V}$ (mA)	V_{oc} (mV)
T3	75.1	52.3	589
T6	58.9	53.3	596

Table X. Average Electrical Characteristics of T3 and T5

Lot No.	I_{SC} (mA)	$I_{0.430\ V}$ (mA)	V_{oc} (mV)
T3	57.1	52.3	589
T5	55.4	52.5	600

SECTION VII

WORK PLANNED

The remaining three lots of the contract will be completed on schedule. It should be noted that lots 8 and 9 were designed to yield 1/2 the Li concentration at the junction of the standard cells. Lot 10, however, should yield twice the "standard" Li concentration. All three lots; will be processed by the whole slice technique to eliminate edge problems and give a more accurate analysis of the effect of Li concentration at the junction on radiation annealing characteristics of Li diffused cells.

SECTION VIII

NEW TECHNOLOGY

No reportable items of new technology have been identified during this reporting period.

SECTION IX

REFERENCES

1. D. L. Kendall and R. A. Vineyard, *Record of VI Photovoltaic Specialist Conference,* Vol III, p. 166, March, 1967.

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3. F. S. Johnson, "The Solar Constant," *J. of Meteorology,* Vol II, p. 436, 1954.