Distribution Category UC-63
ERDA/JPL-954331-77/1

SILICON MATERIALS TASK OF THE LOW COST SOLAR ARRAY PROJECT (PART 2)

FIFTH QUARTERLY REPORT AND SUMMARY

1 October 76 - 31 December 76

R. H. Hopkins, J. R. Davis, P. Rai-Choudhury,
P. D. Blais, J. P. McHugh, and R. G. Seidensticker
Westinghouse Research Laboratories

and

J. R. McCormick
Dow Corning Corporation

Contract No. 954331

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS 7-100 for the U.S. Energy Research and Development Administration, Division of Solar Energy.

The JPL Low-Cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

(NASA-CR-153099) SILICON MATERIALS TASK OF THE LOW COST SOLAR ARRAY PROJECT (PART 2) Quarterly Report, 1 Oct. - 31 Dec. 1976 (Westinghouse Research Labs.) 149 p
N77-78584
Unclas
00/44 29194

Distribution Category UC-63
ERDA/JPL-954331-77/1

SILICON MATERIALS TASK OF THE LOW COST SOLAR ARRAY PROJECT (PART 2)

FIFTH QUARTERLY REPORT AND SUMMARY

1 October 76 - 31 December 76

R. H. Hopkins, J. R. Davis, P. Rai-Choudhury,
P. D. Blais, J. P. McHugh, and R. G. Seidensticker
Westinghouse Research Laboratories

and

J. R. McCormick
Dow Corning Corporation

Contract No. 954331

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS 7-100 for the U.S. Energy Research and Development Administration, Division of Solar Energy.

The JPL Low-Cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

TECHNICAL CONTENT STATEMENT

This report contains information prepared by the Westinghouse Research Laboratories under Jet Propulsion Laboratory subcontract. Its content is not necessarily endorsed by the Jet Propulsion Laboratory, the California Institute of Technology, or the National Aeronautics and Space Administration.

NEW TECHNOLOGY

No new technology is reportable for the period covered by this report.

Page
Intentionally
Left Blank

TABLE OF CONTENTS

TABLE OF CONTENTS (con't)

LIST OF FIGURES

LIST OF FIGURES (con't)

LIST OF FIGURES (con't)

LIST OF TABLES

LIST OF TABLES (con't)

SILICON MATERIALS TASK OF THE LOW COST SOLAR ARRAY PROJECT (PART 2)

Fifth Quarterly Report and Summary
1 October 76 - 31 December 76
Contract No. 954331

1. SUMMARY

The objective of this program is to develop and define purity requirements for Solar Grade Silicon by exploring the effects of metal impurities on the performance of terrestrial silicon solar cells. The first phase of this effort is now completed. Fifty-two Czochralski ingots and forty-four dendritic web specimens have been grown, chemically analyzed, samples, and tested for OCD and PCD lifetime and solar cell performance. The results of this study, compiled here with much of the experimental data, is intended both as a summary of the work and as a reference for metal impurity effects on silicon solar cells.

Our lifetime and solar cell measurements on singly-doped ingots (boron + one metal impurity) are consistent with a model in which the metal contaminants primarily degrade material lifetime and reduce the short circuit current of the solar cell. With this model and the empirically observed relations between lifetime and impurity concentration for the singly-doped ingots, we can successfully project the behavior of most of the multiply-doped ingots (those containing two or more metal impurities). This is a basic step toward the prediction of the solar cell performance of silicon containing a variety of metal contaminants. We have developed a set of empirical expressions which relate solar cell parameters such as relative open circuit voltage, short circuit current and solar cell efficiency to the impurity content of the silicon

on which the device was made. With this basic data and a knowledge of impurity partitioning during crystal growth, one may then define the maximum impurity concentration in the Solar Grade starting material which can be tolerated to obtain a particular level of device performance.

For example, when this type of analysis is carried out for Czochralski growth, we find that, for most impurities, feedstock concentrations in the 10^{18} to 10^{19} atoms cm^{-3} will produce solar cells with efficiencies about 90% of those made on uncontaminated baseline silicon. However, the Ti and V concentrations in the feedstock must be kept below about 6×10^{17} atoms cm^{-3} to achieve similar performance. The exact maximum impurity content depends on the acceptable solar cell performance and how the melt is replenished during growth. A first order analysis of crystal breakdown (cellular growth) in Czochralski pulling suggests that for growth velocities near 15 cm/hr, cell performance, rather than crystal breakdown, will limit the tolerable impurity level of the feedstock. These kinds of analyses can be performed for other growth techniques using our cell data as input information.

More recent mass spectrographic analyses indicate that the original calculation of the effective segregation coefficients for dendritic web growth were too high. The new k_{eff} values for web (1 cm/min growth rate) are about ten times higher than in the Czochralski ingots grown at 7 cm/hr. The analytical data suggest an upper limit between 10^{14} and 10^{15} atoms cm^{-3} for the impurity concentrations in the webs grown so far. These later data are consistent with the 8 to 9% solar cell efficiencies (no AR coating) measured on typical metal contaminated web specimens. Spreading resistance measurements indicate little surface to center or edge to edge variation in resistivity (boron concentration) in the web material.

2. INTRODUCTION

The objective of this program is to investigate the effects of impurities on silicon and solar cells made from silicon, so that purity requirements for a cheaper, lower purity Solar Grade material can be developed. Both standard Czochralski crystals and silicon ribbon produced by the dendritic web process were vehicles for this study, the first phase of which is now completed. The purpose of this report is two-fold: (1) to provide an up-to-date summary of the major results and conclusions of the first 14 months effort and (2) to indicate the directions for future activity.

The information we have compiled on impurity effects provides a useful data base for various tradeoff studies, so we have included much of the actual data in tabular or graphical form for ready reference. The analytical results, lifetime measurements and solar cell parameters are the most recent corrected averages; the cell measurements are calibrated against a JPL standard cell. Experimental procedures have been reiterated only when necessary for completeness. Detailed descriptions of the overall program approach and measurement techniques are available in previous reports.[1-4]

Those who contributed to the program and their responsibilities are listed below:

Dr. R. H. Hopkins -- Technical Manager and Dendritic Web Studies
Mr. P. D. Blais -- Lifetime Studies, Photolithography and Metallization
Mr. J. R. Davis -- Solar Cell Testing and Analysis
Dr. J. P. McHugh -- Web Studies

Dr. P. Rai-Choudhury -- Device Diffusion

Dr. R. G. Seidensticker -- Crystal Growth Analysis.

Dow Corning Corporation

Dr. J. R. McCormick -- Czochralski Ingot Preparation and Evaluation.

The capable technical assistance of H. F. Abt, J. C. Neidigh, D. N. Schmidt, C. S. Seiler, A. M. Stewart, and B. F. Westwood was vital to the success of this effort and is gratefully acknowledged.

Dr. R. Mazelsky, Westinghouse, has administrative responsibility for the program.

3. RESULTS AND ANALYSES

3.1 Bulk Silicon Crystal Characterization

3.1.1 Impurity Considerations

All the Czochralski and web crystals for this program were doped with boron to produce resistivities in the 3 to 6 Ω-cm range. The boron concentration is sufficiently high so that resistivity should be independent of other added impurities yet low enough that high efficiency baseline solar cells can be produced with conventional device technology. The metal impurities chosen for these initial studies -- Cr, Cu, Fe, Mn, Ni, Ti, V, Zr, Zn, Mg and Al -- are elements commonly found in metallurgical grade silicon and which produce deep levels in silicon, thus degrading minority carrier lifetime.

We began our Czochralski experiments with crystal impurity concentrations in the 5×10^{14} to 5×10^{15} atoms cm^{-3} range, values near the limits for solid solubility and crystal breakdown, and great enough for reliable mass spectrographic analysis. Subsequent crystal compositions were adjusted up or down depending on the crystal quality and device performance of their antecedents. The degree of impurity partioning for web grwoth was unknown at the outset. We assumed k to be in the range 10^{-4} to 10^{-3} so the melt concentration was fixed to give web impurity levels of 10^{14} to 10^{15} atoms cm^{-3}. As in the Czochralski experiments, the purity of later webs was set by the results obtained with earlier samples. The iterative approach promotes considerable flexibility and efficiency in planning and executing the experimental program.

3.1.2 Czochralski and Web Growth

Czochralski crystals were grown from 870 g silicon charges.[1,2] Boron was added via a silicon pellet (DOPSIL*), the metals in the forms

---

*Dow Corning Trademark.

indicated in Table 1. Baseline crystals have no intentionally added impurity save boron. Singly-doped crystals contain boron plus one metal element; multiply-doped crystals contain boron plus two or more metals. At least six inches of single crystal was produced in each run. The nominal growth parameters for all runs were:

Pull Rate	7 cm/hr
Seed Rotation	10-15 rpm cw
Crucible Rotation	2-4 rpm ccw
Charge Wt.	869 gms (avg.)
Ingot Diameter	3.2-3.5 cm
Atmosphere	1 atm argon

Dendritic web crystals, 0.8 to 1.3 cm wide, were pulled from 60 g silicon charges[4] doped in the same way as the Czochralski ingots. The pull rate was 1.3 cm/min (78 cm/hr) and the melt undercooling was nominally 4°C.

Following growth the resistivity of each ingot is verified. It is then ground to 3.2 cm diameter and ID-sawed into 14 mil thick wafers. The dendrites are removed from each web and it is cut into strips for analysis.

3.1.3 Material Analysis

3.1.3.1 Methods, Detection Limits, and Background Contamination Levels

A variety of analytical methods were employed to characterize the crystals and webs we studied.[1-4] The detection limits are listed for each in Table 2. Element to element variations in the detection limits for spark source mass spectrometry (SSMS) stem mainly from interference between the lines generated by ionized silicon species and those generated by the isotopes of interest. With high neutron flux densities and radiochemical separation, neutron activation (NAA) is also capable of very sensitive analysis. However, routine NAA

Table 1. Characteristics of Metal Dopants

Dopant		Purity %	Melting Point (°C)	Temperature For 1 mm Vapor Pressure (°C)
Chromium	Pellets	99.999	1900	1504
Manganese	Flake	99.99	1244	1251
Copper	Zone Refined Ingot	99.9997	1083	1628
Nickel	Sponge/ Wire	99.999/ 99.97	1455	1884
Titanium	Crystal	99.95	1668	~2500
Vanadium	Dendrite	99.9	2190	~2550
Zinc	Rod	99.999	419	487
Zirconium	Foil	99.99	2127	2450
Iron	Sponge/ Ingot	99.999/ 99.999	1535	1783
Magnesium	Ingot	99.99	651	605

available on a commercial basis* has higher detection limits, as Table 2 indicates. Carbon and oxygen analyses were based on the infrared absorption strengths of the 605 cm^{-1} and 1107 cm^{-1} bands compared to the absorption in standard samples.[1,2]

An assessment of the actual performance of the SSMS and NAA methods with respect to the impurities studied on this program can be ascertained with the aid of Table 3. The data presented in the second column of the table are the mean impurity concentration (before the slash) and the number of measurements (after the slash). These data are

Table 2. Detection Limits for the Analytical Techniques Used

Method of Analysis / Impurity	Resistivity (ppba)	Infrared (ppba)	Mass Spec (ppba)	NAA (ppba) / Routine (ppba)
Aluminum	4		50	----
Boron	<1		3	----
Carbon		∿5 x 10^2	500	----
Chromium			3	0.04/5
Copper			15	0.006/3
Iron			30	∿1/20 x 10^3
Magnesium			5	∿20/3,800 x 10^3
Manganese			3	.002/2
Nickel			30	0.2/8 x 10^3
Oxygen		∿100		
Titanium			5	0.5/-
Vanadium			3	∿20/-
Zinc			5	3/600
Zirconium			12-15	0.5/200

---

*General Activation Analysis, San Diego, California.

Table 3. Actual Analytical Performance of SSMS and NAA

Impurity	SSMS Mean/# of Measurements (ppba)	SSMS Standard Deviation (ppba)	Neutron Activation (ppba)
Cr	26/13	10	11
Cu	32/19	19	38
Fe	ND	--	16.8
Mg	11/3	7.8	--
Mn	29/6	16	12
Ni	64/10	19	--
Ti	8.5/6	1.6	3.5
V	8.8/5	6.2	--
Zr	ND	--	<0.6
M/e = 90	11.6/∿100	6.3	--

Table 4. Effective Segregation Coefficients of Metal Impurities Determined During This Work

Element	Segregation Coefficient
Al	3 x 10^{-2}/2.8 x 10^{-3} [†]
Cu	6.9 x 10^{-4}
Cr	1.1 x 10^{-5}
Fe	6.4 x 10^{-6}
Mg	3.2 x 10^{-6}
Mn	1.3 x 10^{-5}
Ni	3.2 x 10^{-5}
Ti	3.6 x 10^{-6}
V	4 x 10^{-6}
Zr	<1.5 x 10^{-7}

[†] Value of 2.8 x 10^{-3} based on resistivity while value of 3 x 10^{-2} is based on SSMS.

primarily from first generation ingots grown with a target concentration of 20 ppba. The rather wide departure from this value for some impurities (e.g., Ni, Ti, V, Zr) is attributable to the uncertainty in the values of the effective segregation coefficients at the beginning of the program. The standard deviations are in the range expected considering possible errors in sample preparation, sampling, and SSMS history. The value for M/e = 90 due to the Si_3^+ ion indicates the magnitude in basic measurement uncertainty independent of the other effects. The agreement between NAA and SSMS results is fairly good. The deviations are within the overlap of the relative uncertainties in each measurement. This gives confidence in the use of SSMS as the primary analytical tool.

No analytical technique is adequate to determine the purity of specimens targeted to the low end of the concentration ranges encountered during this program, Fig. 1. Therefore, a well-established crystal growth/material handling process coupled with reliable segregation coefficient data are requisite for accurate prediction of the low concentration values. These data were few or uncertain for many of the elements we studied,[1,2] so the segregation coefficients were determined during the program. This was accomplished both by the direct analysis of the solid and liquid concentrations for many of the heavily-doped ingots coupled with calculations based on the position at which crystal breakdown occurred. The values derived, Table 4, were based on the total spectrum of analytical data developed during the program.

Besides determining the concentration of intentionally added impurities another objective of the analytical effort was to assure that no contaminants entered the ingots via the polycrystalline starting material or the growth process itself. High-purity semiconductor-grade polycrystalline silicon was used as the charge material for all ingots grown on this program. Typical impurity analysis of this material by neutron activation and SSMS analysis is shown in Table 5. In general, the impurity concentrations are below the detection limit of SSMS detection.

Concentration Range / Impurity Element	Less than 10^{13}	10^{13} - 10^{14}	10^{14} - 5×10^{14}	5×10^{14} - 5×10^{15}	5×10^{15} - 10^{16}	Greater than 10^{16}
Aluminum				X		X
Chromium		X	X	X		
Copper			X	X	X	
Iron		X	X	X		
Magnesium	X		X			
Manganese		X	X	X		
Nickel			X	X		
Titanium	X	X	X			
Vanadium	X	X	X			
Zinc	X					
Zirconium	X	X				

Fig. 1. Impurity Matrix and singly-doped Czochralski ingots grown (X).

Table 5. Polycrystalline Silicon Analysis

Analytical Method Impurity	NAA (ppba)	Mass Spec (ppba)	Mass Spec/Freeze Out (ppba)
Cr	$<4 \times 10^{-2}$	<3	∿0.01
Cu	6×10^{-3}	20	∿0.01
Fe	<2	<30	∿0.1
Mn	<1.5	<3	∿0.01
Ni	<0.2	<30	ND
Ti	<4	<5	ND
V	--	<3	ND
Zn	--	<5	ND
Zr	--	<12	ND

Mass Spec/Freezeout
Al ∿4.8 ppba; C ∿100 ppba.

Table 6. Concentrations of Unintentionally-Added Impurities Found in Typical Czochralski Silicon Crystals

	Concentration	
Impurity	Atoms/cm^3	(ppba)
Antimony	1.3×10^{11}	(0.0026)
Arsenic	7×10^{12}	(0.14)
Cr	2×10^{12}	(0.04)
Cu	5×10^{12}	(0.1)
Gold	$\sim 1 \times 10^{9}$	(.00002)
Iron	$<5 \times 10^{13}$	(<1)
Nickel	$<5 \times 10^{12}$	(<0.1)
Titanium	$<8 \times 10^{13}$	(<1.6)
Zirconium	$<3 \times 10^{13}$	(<0.6)

To obtain an estimate of the actual purity a polycrystalline rod was zone-refined to concentrate any contaminants and the last region to freeze was analyzed. Impurities are concentrated by a factor of 100 to 1000 in this freeze-out region. This qualitative estimate of the impurity concentrations, shown in the last column of the table, is in general agreement with NAA results. We conclude from this data that the polycrystalline silicon does not contaminate the ingots in any way which could negate the results of the program. To examine the possibility that extraneous impurities were introduced during crystal growth, a total of six ingots were analyzed for trace elements by NAA. The concentration of unintentionally-added impurity is in general below the limit of detection or in the 10^{12}-10^{13} atoms/cm^3 range, Table 6. These trace impurity levels are consistent with the analytical results obtained on ingots grown for baseline cell fabrication. Based on these results, we do not believe trace impurities are present in amounts sufficient to affect cell performance.

3.1.3.2 Czochralski Crystals

The defect densities, resistivities and carbon/oxygen analyses are compiled in Appendix 1; the substance of the data is summarized here. We made no attempt to grow dislocation-free ingots due to the high melt impurity concentrations being considered. Most ingots have dislocation densities below 2000/cm^3 based on EPD after Sirtl etching. Two ingots, W039 and W052, developed high defect densities when we attempted to achieve solid concentrations near 1 x 10^{16} atoms/cm^3. With these exceptions reduction in solar cell performance by crystal defects should have been minimal.

The 3 to 6 ohm-cm target resistivity range corresponds to a boron concentration of 2.2 x 10^{15} atoms/cm^3 to 4.5 x 10^{15} atoms/cm^3. Generally, no problems were encountered in achieving this resistivity range, viz. Appendix 1. Ingot W001-00-000 was prepared for use on the program prior to establishing the lower bound on resistivity while ingot W023-00-000 was intentionally doped to a higher impurity concentration. Ingot W028-Al001 and W038-Al002 exhibit lower resistivities due to the electrically active nature of aluminum. Three doubly doped ingots (W027-Mn/Cu001, W030-Cr/Cu001 and W031-Cr/Mn001) had higher than normal resistivity values for reasons we cannot yet establish.

The carbon and oxygen concentrations found in all ingots are nominal. The typical carbon concentration for undoped ingots produced in the crystal pulling furnace used on this program varies from 2.5×10^{16} atoms/cm^3 to 25×10^{16} atoms/cm^3, while the oxygen concentration is usually between 50×10^{16} atoms/cm^3 and 150×10^{16} atoms/cm^3. The concentrations of the intentionally-doped ingots did not depart significantly from these ranges, Appendix 1.

Complete sets of analytical data for each of the fifty-two (52) Czochralski ingots we processed are tabulated in Appendix 2. The entries for each crystal include the target concentration, calculated concentration, SSMS analysis and, where applicable, the neutron activation analysis. Discussion of specific experimental difficulties such as Mg and Zn vaporization also appear there. Based on the total spectrum of analytical results -- melt analysis, SSMS data, and NAA data -- obtained during the program, effective segregation coefficients were combined (Table 4) and applied to the melt concentration to arrive at a "best estimate" of the actual concentration in each ingot, Table 7. In the table, the best estimate is compared to the "measured concentration" for each ingot. The latter value (in parenthesis) is an average of the SSMS data, the NAA data, or both for the particular sample. The average measured value is generally within ±50% of the best estimate when more than one analysis could be made and when no structural breakdown occurred during crystal growth. To significantly improve the absolute measurement accuracy beyond these levels would be both expensive and time-consuming.

We have accepted the "best estimate" value as characteristic of the metal concentrations for the ingots we studied. Thus, further references to ingot concentrations in the text refer to these values.

Table 7
Best Estimate of Impurity Concentrations

Ingot Identification	Best Estimate of Impurity Conc. (10^{15} Atoms/Cm)
W-001-00-000	--
W-002-00-000	--
W-003-00-000	--
W-004-Cr-001	1.0 (1.0)*
W-005-Mn-001	1.3 (1.3)
W-006-Ni-001	0.5
W-007-Cu-001	1.7 (1.8)
W-008-Ti-001	0.36 (0.36)
W-009-V-001	0.4 (0.4)
W-010-Ni-002	4.0 (4.0)
W-011-Zr-001	<0.015 (<0.015)
W-012-Cr-002	0.2 --
W-013-Mn-002	0.26 --
W-014-00-000	-- --
W-015-Zn-001	<0.001 (<0.3)
W-016-Fe-001	0.85 (0.9)
W-017-Cu-002	17 (32)
W-018-Fe-002	1.7 (1.7)
W-019-Cu-003	0.4 (0.4)
W-020-00-000	-- --
W-021-Mg-001	0.003 --
W-022-00-000	-- --
W-023-00-000	-- --
W-024-Mg-002	0.03 --
W-025-00-000	-- --
W-026-Mn-003	0.013 --
W-027-Mn/Cu-001	1.3/1.7 (1.0/1.0)

* Quantity in Parenthesis is Measured Concentration

† Only Single SSMS or NAA Measurement Available

Table 7 (con't)

Ingot Identification	Best Estimate of Impurity Conc. (10^{15} Atoms/Cm)
W-028-Al-001	26 (26)†
W-029-Cr-003	0.01 --
W-030-Cr/Cu-001	1/1.7 (1.0/1.0)†
W-031-Cr/Mn-001	1.0/1.3 (1.0/2.5)
W-032-Mg-003	0.32 (0.32)
W-033-Ti-002	0.0036 --
W-034-00-000	-- --
W-035-V-002	0.004 --
W-036-Zr-002	<0.025 (<0.025)
W-037-Zr-Ti-001	<0.015/0.40 (<0.015/0.36)†
W-038-Al-002	34 (34)†
W-039-Ni-003	8 (4)†
W-040-Cr/Ni-001	0.8/3.5 (1.0/3.5)†
W-041-Ni/Cr/Cu-001	3.0/0.8/1.7 (3.0/1.7/2.3)
W-042-Ti-003	0.07 --
W-043-Fe/Ti-001	0.56/0.06 --
W-044-Fe-002	0.017 --
W-045-Cr/Fe/Ti-001	0.65/0.43/0.06 (0.2/0.5/0.06)†
W-046-Fe/V-001	0.56/0.07 --
W-047-Cu/Ni/Zr-001	1.7/0.75/<0.015 (2.5/<1/<1)
W-048-Ti-004	0.00036 --
W-049-V-003	0.0004 --
W-050-Ti/V-001	0.00036/0.0004
W-051-Cu/Ti-001	1.7/0.36 (4/0.36)
W-052-Ni-004	7.5 (4.0)†

---

[*] Quantity in Parenthesis is Measured Concentration

[†] Only Single SSMS or NAA Measurement Available

3.1.3.3. Web Crystals

The web studies are not yet as extensive as those for the Czochralski material. These first experiments were aimed at developing techniques, assessing the degree of homogeneity of the webs, deriving preliminary segregation coefficient data, and targeting the ranges of impurity concentrations for which structural breakdown occurs.

As Figs. 2 and 3 illustrate, the boron concentration varies little from edge to edge or through the thickness of the web specimens. The spreading resistance probe traces were made on a surface beveled at a shallow angle to the web face; the positions of the traces are indicated in the figure insets. The net impurity concentrations for the two specimens, W029-Ni/Mn-1F and W040-Ni-1C, are about 4 x 10^{15} corresponding to 3.5 Ω-cm resistivity, a value close to that targeted for the runs.

Eighteen silicon web samples and the melts from which they were grown have now been analyzed, Table 8. Samples DW017-Cr-1 and DW019-Cu-1, the first analyzed, were taken from narrow web sections near the seed. We believe the samples included some dendrite material so that high impurity concentrations previously reported[4] were not characteristic of web material in general. Indeed, the impurity concentrations of samples taken from the center of other webs are relatively low, in many cases beyond detectability. For three specimens, DW017-Cr-1, DW028-Mn/Cr-1E, and DW029-Ni/Mn-1E, both the dendrites and webs were analyzed. In each case the dendrite contained a higher impurity level than the corresponding web, indicating preferential metal segregation within the dendrite. Although the amount of impurity in the web often falls below the detection limit, an upper limit on the effective segregation coefficients still can be estimated by dividing the entries in column three of Table 8 by the corresponding entry for each specimen in colume two. The values range from about 10^{-5} to nearly 10^{-3} depending on the impurity. This places k_{eff} for impurities in the web about an order of magnitude higher than those for Czochralski growth but not

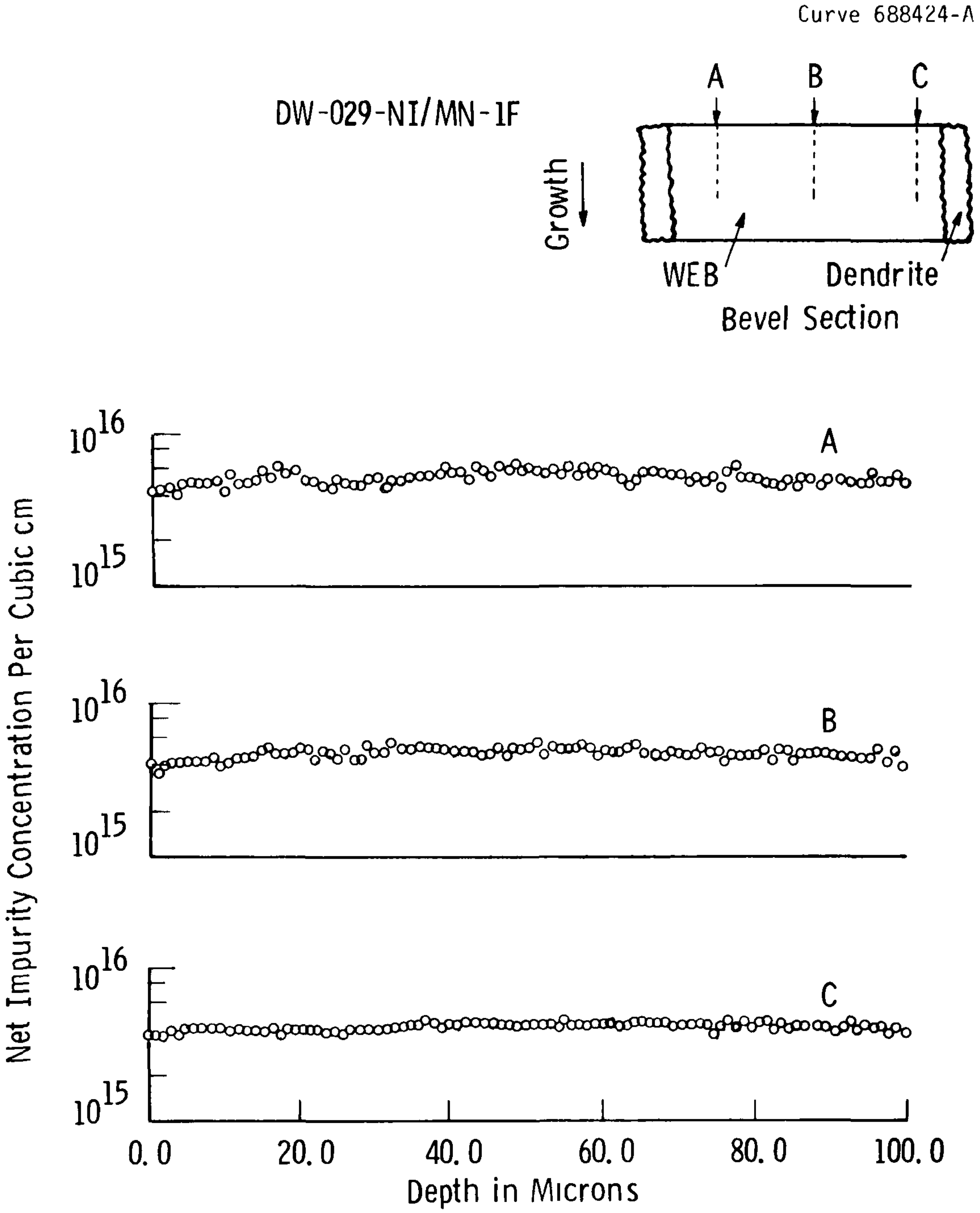

Fig. 2. Variation of net impurity concentration with thickness for web DW029-Ni/Mn-1F. Insert illustrates positions of probe traces on beveled web face.

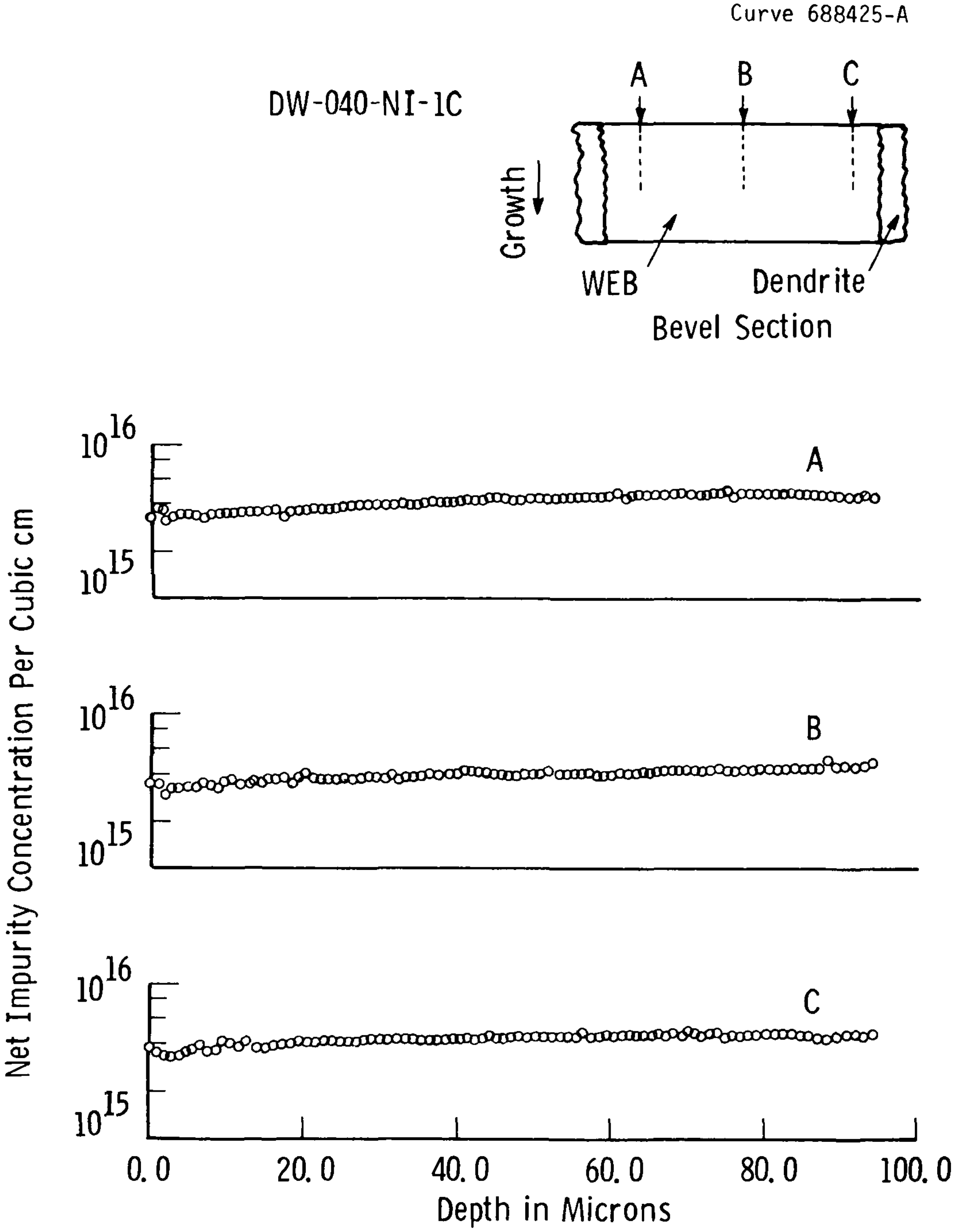

Fig. 3. Variation of net impurity concentration with thickness for web DW040-Ni-1C. Insert illustrates positions of probe traces on beveled web face.

Table 8. Silicon Web Analysis

Sample I.D.	Measured Melt Concentration (10^{18} atoms cm^{-3})	Measured Web Concentration (10^{15} atoms cm^{-3})	Structure
DW017-Cr-1	---	12	b,t
DW017-Cr-1(C)	---	<0.3	b,t
DW017-Cr-1(D)	---	1.0	b,t
DW018-Cr-1	54	---	c,t
DW019-Cu-1	5.3	800	
DW019-Cu-1D(C)	5.3	1	
DW020-Mn-1	3.8	---	
DW021-Ni-1(C)	5.5	3.5	
DW022-Ti-1(C)	9	<30	b,t
DW023-V-2(C)	12	0.3	b,t
DW024-Fe-1(C)	6.5	<30	b,t
DW025-Cr/Cu-1(C)	3.2/3.1	<0.3/2.5	
DW026-Mn/Cu-1A(C)	3.1/3.5	<0.3/1.4	
DW027-Zr-1A(C)	3.1	<0.5	t
DW028-Mn/Cr-1E(C)	3.6/3.5	<0.3/<0.3	t
DW028-Mn/Cr-1E(D)	3.6/3.5	0.5/1.0	t
DW029-Ni/Mn-1E(C)	1.7/2.3	<3.0/<0.3	
WW029-Ni/Mn-1E(D)	1.7/2.3	<3.0/8	
DW030-Al-1	1.7/2.3	---	
DW031-Zr/Ti-2A(C)	2.0/4.4	Zr<1.0; Ti<1.0	b,t

Notes: 1. The letter (C) in parenthesis indicates the sample was taken from the central portion of the web; the letter (D) indicates the dendrite was analyzed.

2. The structural notations are (c) cellular structure, (b) regions of breakdown, and (t) thirds; other runs yielded good web specimens.

nearly as high as originally believed.[4] More precise values will be determined as further samples are analyzed. Two melts were analyzed to determine the level of unintentionally-added impurities. As the data in Table 9 indicate, no significant amounts of extraneous impurities were found.

Ten other metal-doped webs have been grown, but not chemically analyzed. Examination of the structure of these specimens and the data in Table 8 suggest that breakdown in web begins when the impurity concentration reaches the mid-10^{18} atoms cm^{-3} range. This is, of course, a qualitative evaluation, since diagnosis of breakdown is somewhat subjective. For the few samples grown from melts exceeding 10^{19} atoms cm^{-3} in metal concentration, a complicated cellular structure formed within the major portion of the web. No theory for web breakdown is available yet for rationalizing the experimental results, but we hope to undertake the development of such a model soon.

Table 9. Survey Analysis of Crucible Remains for Typical Web Growth Runs

Elements in Determined %	Sample No. DW019	Sample No. DW021
Al	<0.001	<0.001
Cr	<-.001	<0.001
Cu	0.024	<0.0005
Fe	0.003	<0.001
Mn	<0.001	<0.001
Mo	<0.001	<0.001
Ni	<0.001	0.023
Ti	<0.001	<0.001
V	<0.001	<0.001
Zr	<0.001	<0.001

The intentionally added impurity is underlined.

3.2 Wafer Characterization

3.2.1 Lifetime Studies

Most of the recombination lifetime data was obtained by the photoconductive decay (PCD) method, an approach requiring only low temperature sample preparation so that lifetimes before and after processing could be compared. In the experimental arrangement we used, Fig. 4, the excess carrier concentration was generated by a GaAs infrared-emitting diode, the change in carrier population during recombination being measured by the change in conductivity of a rectangular specimen.[1,2] The low-level lifetime measured, as the ratio of peak excess minority carriers to majority carrier concentration, was near 7.6×10^{-4}. Some metals we studied introduced energy levels (shallow traps) within a few kT of the conduction band. Minority carriers trapped there are thermally released to the conduction band very slowly and can obscure the more rapid decay due to recombination. Therefore, a small incandescent lamp, "trap light" was used to assure that the transient phenomena observed on the oscilloscope was due to recombination from a fixed number of carriers in the conduction band.[1]

Particularly severe trapping occurred for Mn and V when impurity concentrations reached 10^{14} atoms cm^{-3}. The incandescent lamp had to be supplemented by a collimated 40 W lamp, focused onto the test area.[2] Sample heating and temperature fluctuations under these conditions limit measurement accuracy. Fortunately, this happened infrequently and generally only for undiffused wafers.

The effective lifetime, τ_r', was obtained directly by allowing sufficient time for the conductivity decay to become exponential and measuring the time required for the signal to reach half its initial value. Due to surface recombination, the effective lifetime is very dependent on specimen thickness. Rigorous mathematical equations were used to determine the bulk lifetime τ_r from measurements performed on specimens of finite dimensions. The relationship for specimens which are thin compared to their width and length is,[2]

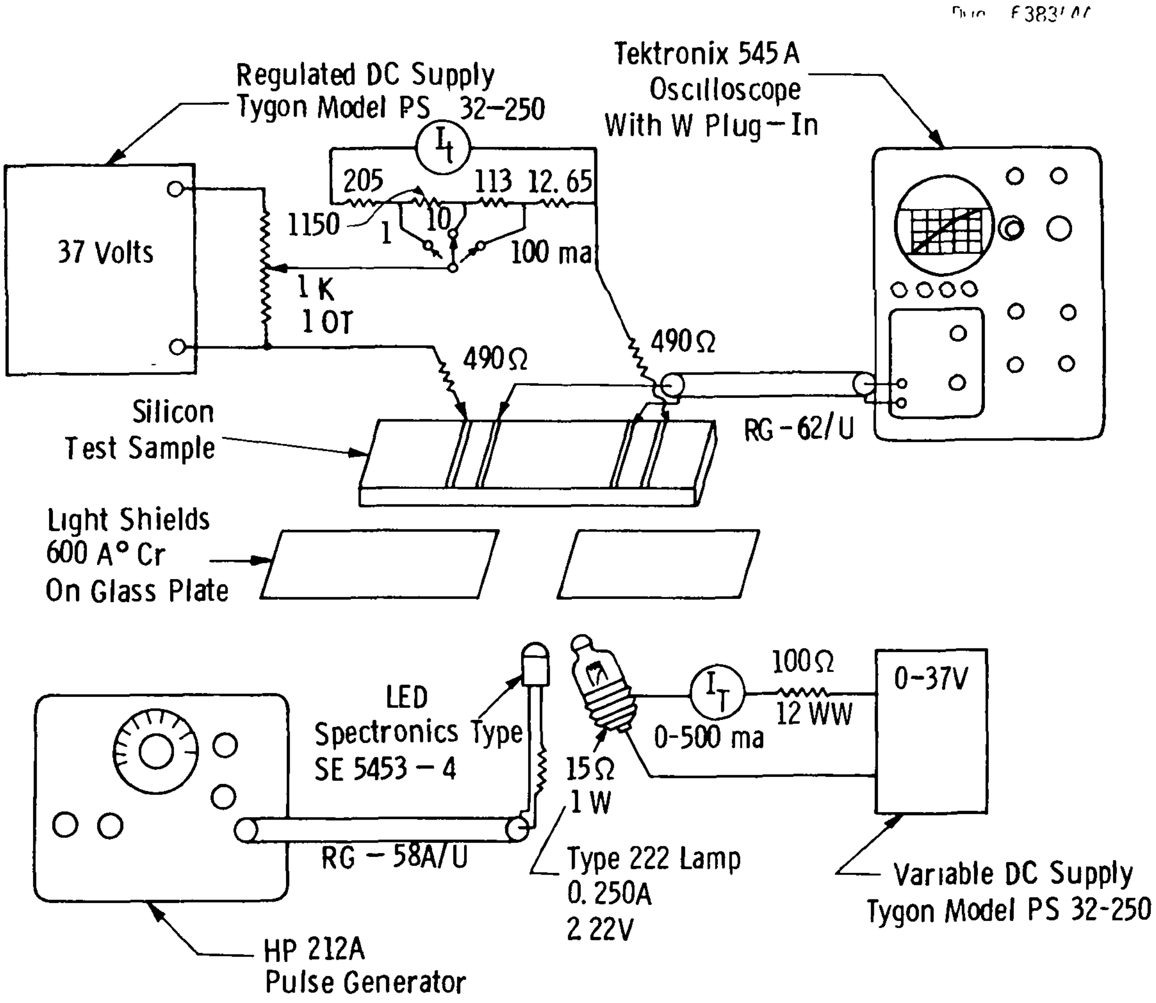

Fig. 4. Schematic diagram of photoconductive decay lifetime measurement apparatus.

$$\frac{1}{\tau_r'} = \left[\frac{1}{\tau_r} + D\left(\frac{\zeta_o^2}{d^2}\right)\right] \qquad (3.1)$$

where D is the diffusivity of the appropriate minority carrier (cm^2/s), d is one-half the specimen thickness (cm), and ζ_o is defined by the equation

$$\zeta_o \tan \zeta_o = sd/D \; ; \qquad 0 \leq \zeta_o \leq \pi/2 \; , \qquad (3.2)$$

in which s is the surface recombination velocity (cm/s). The derivation assumes uniform light generation, low electric fields, and that higher modes of ζ are made negligible by measuring τ_r' after the voltage decay becomes logarithmic.

The surface recombination velocity, s, must be known before Eq. (3.1) can be applied to correct direct measurements. A method for determining s is to fit theoretical curves with experimental data for a specimen whose thickness is varied by etching. A second method to determine s is to solve Eq. (3.1) for a sample with τ_r known to be very large compared to $d^2/(D\zeta_o^2)$. This method yielded a value of 9×10^3 cm/s for s, when CP-4A (25:15:15/HNO_3:HF:CH_3COOH) was used for etching.

3.2.1.1 Lifetime Measurements for Czochralski Wafers

I_{sc} Lifetime Relationships. The search for a simple technique to assess the suitability of a metal-doped ingot for solar cell fabrication was the initial motivation for our lifetime studies. The basis for the approach lay in the concept that a photon-generated minority carrier must survive, without recombination, long enough to diffuse from the point of generation to the barrier region of the device. Thus, we expect a relation between the short circuit current density of the solar cell, I_{sc}, and τ_r to have the form shown in Fig. 5. The lifetime data in the figure are from diffused material; a complete tabulation of τ_r for all ingots is in Appendix 3.

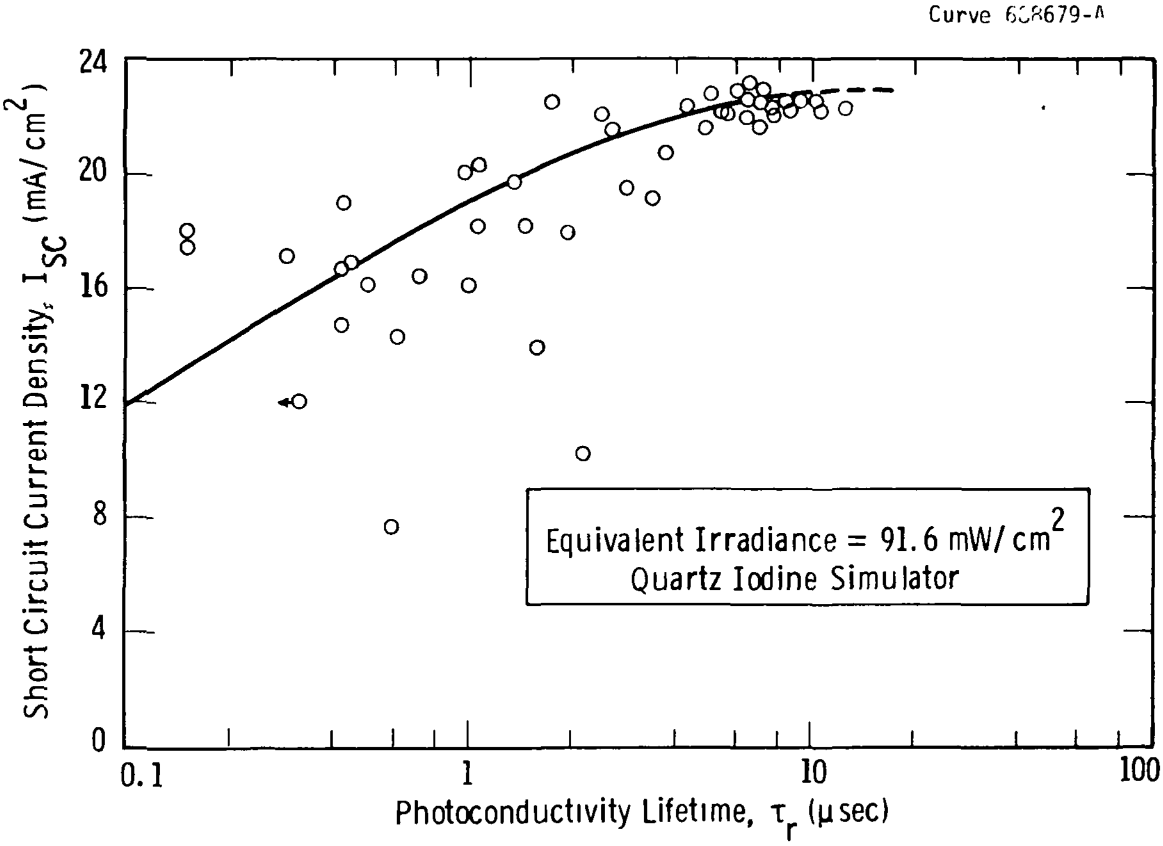

Fig. 5. Correlation between bulk recombination lifetime and short circuit current density of an uncoated silicon solar cell.

The curve through the data was judiciously drawn to indicate the probable relationship. The considerable data scatter evident may stem from several sources of error. Uncontrolled variations in the fabrication procedure would result in a vertical displacement of the I_{sc} values which would predominate when the lifetime was large. The close grouping of the data between 5 to 13 μsec clearly shows that the fabrication control was excellent and probably that I_{sc} varies less than ± 0.5 mA. Conversely, the data dispersion increases for low lifetime values. Variations in the corrections for surface recombination velocity are not indicated since the correction factor becomes small as bulk lifetime decreases. Thus, the two most likely sources of error are trapping and an accurate determination of τ_r'. As the lifetime diminishes with increased impurity concentration, the density of shallow trapping centers also increases; measurement error due to the trapping effects described earlier become appreciable. The amplitude of the oscilloscope signal also decreases as the lifetime decreases and the resulting decrease in the slope makes precise readings of τ_r' very difficult.

One way to reduce the uncertainty in the relationship between τ_r and I_{sc} is to develop a reasonable theoretical model for the expected behavior. The generation rate for the minority carriers by monochromatic radiation can be readily calculated from Beer-Lambert's Law. Neglecting the effects of electric fields and assuming isotropic recombination lifetime, the collection efficiency for the minority carriers is expressed in the closed form mathematical equation,[4]

$$I(\lambda) = \frac{q\, E_o\, \lambda}{hc} \left(\frac{\alpha\, L_n}{1 + \alpha L_n}\right) \left[1 - e^{-d(\alpha + 1/L_n)}\right] \text{ Amps ,} \qquad (3.3)$$

where d is one-half the solar cell thickness and α is the optical absorption coefficient. Equation (3.3) can be corrected to account for the effects of reflection at the two boundaries.[4] Unfortunately, the solar spectrum cannot be represented by a simple function. Computer integration of Eq. (3.3) over the entire spectrum is tedious and outside the scope of this project. A first order approximation can be made by using Plank's distribution law; again, no closed form of integration is known to exist. An approximation was obtained, however, by assuming monochromatic light. The expression within the second set of brackets in Eq. (3.3) is very close to unity for all values of L_n. Assuming the worst case, $L_n = \infty$, the numerical value of the bracket is 0.999 for $d = 0.0127$ cm and $\alpha = 606\ \text{cm}^{-1}$. Thus, Eq. (3.3) can be simplified to:

$$I_{sc} = K \left[\frac{\alpha L_n}{1 + \alpha L_n} \right] , \tag{3.4}$$

where $K = \alpha E_o \lambda / hc$. A least squares fit was performed for Eq. (3.4) using the experimental I_{sc} and τ_r data and calculating L_n from $L_n = \sqrt{D_n \tau_r}$, with $D_n = 32\ \text{cm}^2/\text{sec}$. The values for K and α obtained by linear regression were 23.21 mA and $568.7\ \text{cm}^{-1}$ respectively. A plot of Eq. (3.4) with these constants is shown in Fig. 6. The curve drawn through the experimental data in Fig. 4 is also shown for reference. The best fit absorption coefficient of $568.7\ \text{cm}^{-1}$ corresponds to an actinic radiation wavelength of 860 nm. The AM-2 solar irradiance spectrum in photons/sec/m^2/μm reaches a maximum value at 750 nm^5 close to the best fit wavelength of 850 nm.

Equation (3.4), besides giving confidence to the trends in the experimental data, is most useful in extending the relationship between I_{sc} and τ_r beyond the range of available experimental information. However, in doing so it must be remembered that the unsymmetrical variance between the two curves in Fig. 6 stems from the fact that the curve originally drawn in Fig. 5 was not a least squares fit to the data. Specifically, the ordinate for $L_n = 0.1$ μsec should be somewhat less than 12 mA/cm^2.

In contrast to the reasonable correlation between I_{sc} and τ_r measured for diffused material, no such correlation was found for the

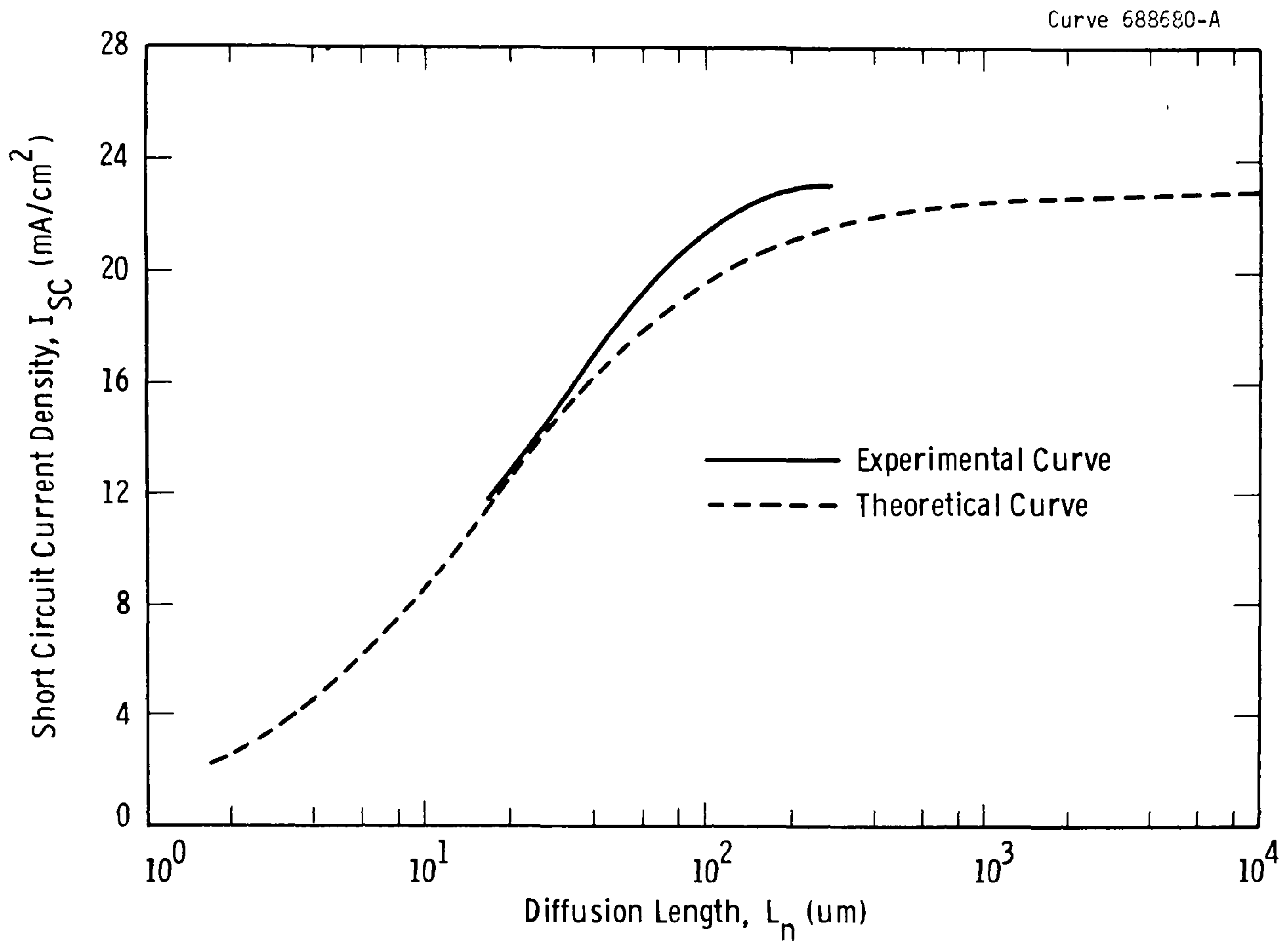

Fig. 6. Effect of diffusion length on the short circuit current density of an uncoated silicon solar cell.

case where τ was measured prior to diffusion (data in Appendix 3). The significance of this observation is that the lifetime of the silicon in a fabricated solar cell cannot be predicted by simply measuring the lifetime of the as-grown ingot. This is because processing affects lifetime (see following sections). However, a combination of data such as as-grown lifetime, coupled with impurity types and concentrations, may allow a reasonable prediction of I_{sc} for the finished cell when a calibrated process is used.

Lifetimes of Multiply-Doped Wafers. From the data in Appendix 3 we can generate curves which display the empirical relationship between recombination lifetime and impurity concentration of diffused wafers containing a given metal contaminant. The curves would be useful for putting upper limits on the impurity concentration of one element, but would not serve in the more general, and practical, case where several impurities are present in an ingot. For the latter case, the large permutation of impurity/concentration combinations makes calibration by strictly empirical means impractical, if not impossible. Thus, modeling of lifetimes for multiple doping is a desirable method for extrapolating the range of experimental measurements. A preliminary model, assuming independent action for recombination centers, has been developed which lends support to this approach.

The recombination lifetime for the case of low level injection in silicon containing a low concentration of Shockley-Read-Hall (SRH) recombination centers is given by[6]

$$\tau_p = \tau_n = \frac{\tau_{no}\,(p_o+p_1) + \tau_{po}\,(n_o+n_1)}{(p_o + n_o)}\ , \qquad (3.5)$$

where p_o and n_o are the thermal equilibrium hole and electron concentrations and p_1 and n_1 are the thermal equilibrium concentrations based on the Fermi level coinciding with the energy level of the SRH centers. The terms τ_{no} and τ_{po} are defined by,

$$\tau_{po} = \frac{1}{N_T C_p} = \frac{1}{N_T v_{th} \sigma_p} \tag{3.6}$$

$$\tau_{no} = \frac{1}{N_T C_n} = \frac{1}{N_T v_{th} \sigma_n} \tag{3.7}$$

where N_T is the density of SRH centers; C_p and C_n are the hole and electron capture coefficients, respectively; v_{th} is the thermal velocity of the carriers; and σ_p and σ_n are the capture cross-sections for the holes and electrons.

Equation (3.5) is plotted for examination in Fig. 7 to show the effect on lifetime of doping type and position of the SRH level relative to the intrinsic Fermi level. The significant feature of this figure is that the lifetime of p-type silicon with resistivity less than 10 ohm-cm is equal to τ_{no}, and the position of the energy level for the recombination center only enters into the capture cross-section. In this study the concentration of SRH recombination centers is generally large so Eq. (3.5) is not strictly valid. A more rigorous solution indicates that τ_n and τ_p are not equal when N_T is large and the silicon is lightly doped. The value of τ_n is given by the equation

$$\tau_n = \frac{\tau_{no}(p_o+p_1+N_T(1+p_o/p_1)^{-1}) + \tau_{po}(n_o+n_1)}{n_o+p_o+N_T(1+n_1/n_o)^{-1}(1+p_1/p_o)^{-1}} \tag{3.8}$$

which is plotted in Fig. 8 for variation SRH concentrations. The silicon used in this study was 4 Ω-cm p-type and the value of n_o is $\approx 10^4$ cm^{-3}, where $\tau_n = \tau_p = \tau_{no}$. Thus, even for the case of high SRH centers concentration the lifetime can be obtained by Eq. (3.7) for the material used in this study.

Assuming that each impurity atom added to the silicon does not react metallurgically with the other impurities and that atoms are sufficiently separated to preclude electron transfer between their independent set of energy levels and capture cross-sections, the total recombination rate, dn/dt, can be written as,

Curve 586235-A

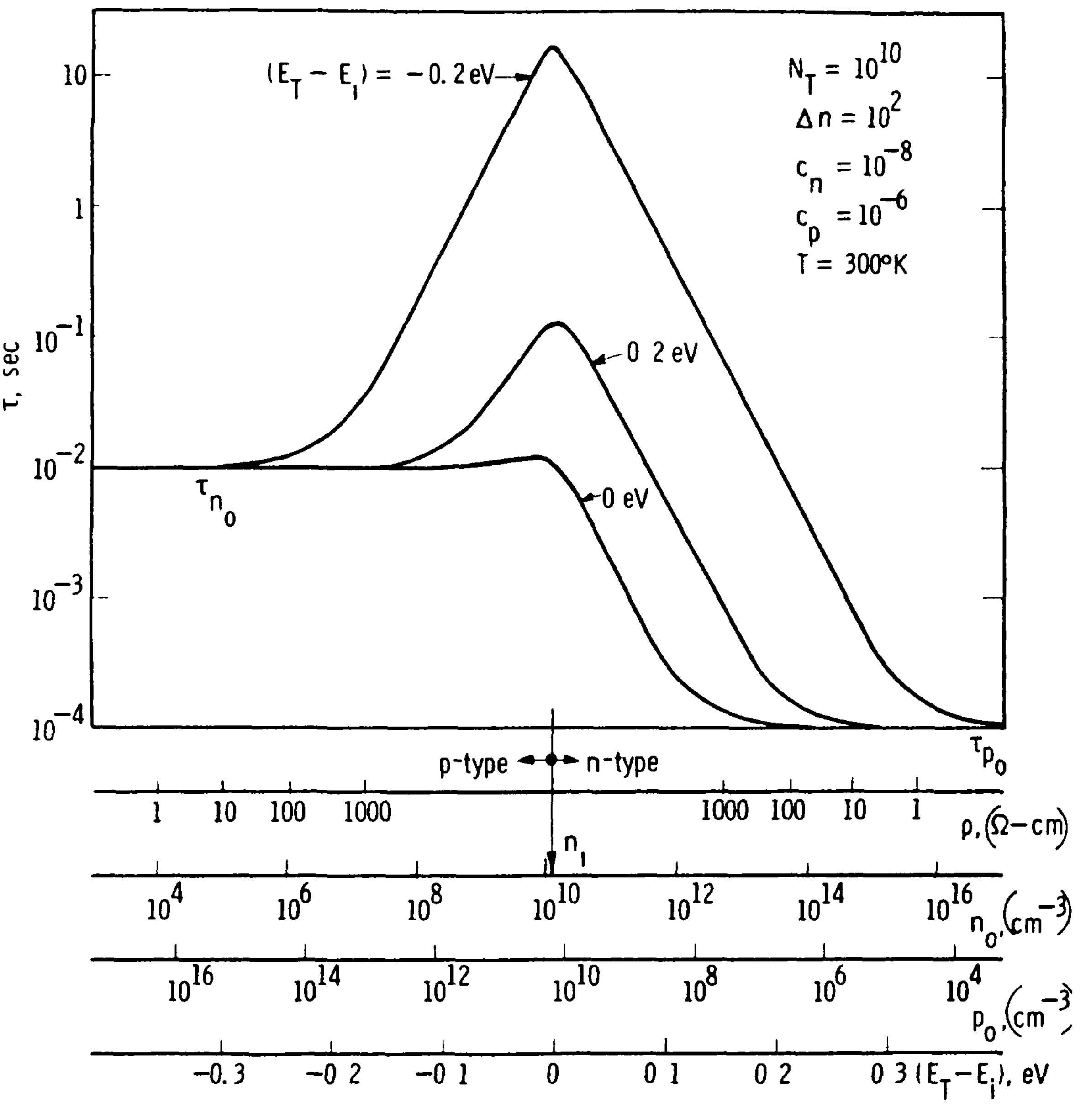

Fig. 7. Lifetime as a function of equilibrium carrier concentration and SRH center energy level for low concentration of SRH centers.

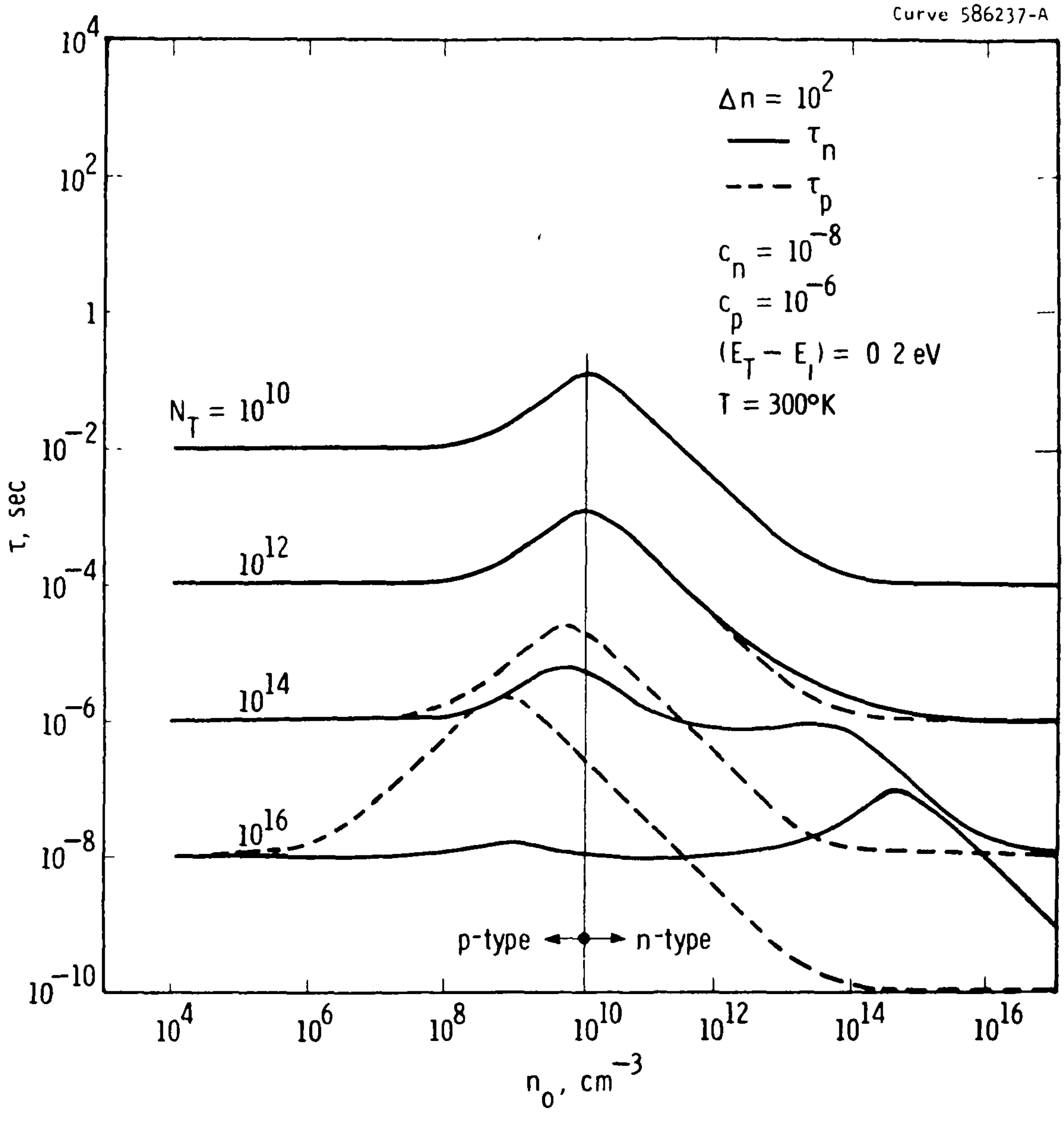

Fig. 8. Lifetime as a function of equilibrium carrier concentration and recombination center concentration.

$$\frac{dn}{dt} = -(n - n_o)\left[N_o\sigma_o v_{th} + N_1\sigma_1 v_{th} + \dots N_n\sigma_n v_{th}\right] \qquad (3.9)$$

where N_n = density of traps for impurity n

σ_n = capture cross-section of traps for impurity n

v_{th} = thermal velocity of carriers.

$$\frac{dn}{dt} = -\left(\sum_{\ell=0}^{n} N_\ell\sigma_\ell v_{th}\right)(n - n_o) . \qquad (3.10)$$

The solution is

$$\left(n(t) - n_o\right) = \left(n(0) - n_o\right) \exp\left[-\sum_{\ell=0}^{n} (N_\ell\sigma_\ell v_{th})t\right] . \qquad (3.11)$$

The reciprocal effective lifetime is

$$\frac{1}{\tau_r} = \sum_{\ell=0}^{n} (N_\ell\sigma_\ell v_{th}) \qquad (3.12)$$

or

$$\frac{1}{\tau_r} = \sum_{\ell=0}^{n} \frac{1}{\tau_\ell} . \qquad (3.13)$$

Let the term τ_o represent the lifetime of a baseline ingot. The trap levels corresponding to τ_o are those introduced by the boron doping and the normal defects due to growth thermodynamics. As an example of the model's application, we consider an ingot doped with boron, chromium, and titanium. The reciprocal lifetime is given by

$$\frac{1}{\tau_r} = \frac{1}{\tau_o} + \frac{1}{\tau_{Cr}} + \frac{1}{\tau_{Ti}} . \qquad (3.14)$$

The average reciprocal lifetime $1/\tau_o$ determined from PCD measurements on 3 baseline and 4 audit ingots is $1.14 \times 10^5\ s^{-1}$. The terms $1/\tau_\ell$ for $\ell > 0$ are dependent on the impurity type and their concentration. No adequate mathematical model exists for calculating these terms and they must be determined by solving Eq. (3.14) for the case of a single metallic impurity of known concentration where

$1/\tau_\ell = 1/\tau_r - 1/\tau_o$. The doubly-doped ingots grown during this program constitute a limited but valuable source of data (Appendix 3) on which to base these calculations. A plot of $1/\tau_\ell$ for several impurities is shown in Fig. 9. The curves drawn through the three or more points for each impurity allow interpolation to other desired impurity concentrations. The shapes of the curves vary and no explanation of this phenomenon will be attempted here this time. Let us accept the curves as a pragmatic representation of the measured data.

An evaluation of the model is possible by making a comparison of the calculated and the measured lifetime for several multiply doped ingots grown on this program. Such a comparison is presented in Table 10. With a few exceptions there is reasonable agreement between

Table 10

Comparison of Measured and Calculated Recombination Lifetimes for Diffused Multiply-Doped Wafers

Ingot	Impurity Types	Impurity Concentration atoms/cc (10^{15} atoms/cm)	τ_r (cal) (μsec)	τ_r (meas) (μsec)
W027	Mn/Cu	1.3/1.7	0.28	0.45
W030	Cr/Cu	1/1.7	1.05	0.42
W031	Cr/Mn	1/1.3	0.23	<0.32
W037	Zr/Ti	<0.015/0.40	>0.38	0.42
W040	Cr/Ni	0.8/3.5	1.39	1.35
W041	Ni/Cr/Cu	3.0/0.8/1.7	1.41	0.43
W043	Fe/Ti	0.56/0.06	0.92	0.50
W045	Cr/Fe/Ti	0.65/0.43/0.06	0.71	0.99
W046	Fe/V	0.56/0.07	2.14	<0.15
W047	Cu/Ni/Zr	1.7/0.75/<0.015	>2.30	2.61
W050	Ti/V	0.00036/0.0004	3.25	1.07
W051	Cu/Ti	1.7/0.36	0.44	1.57

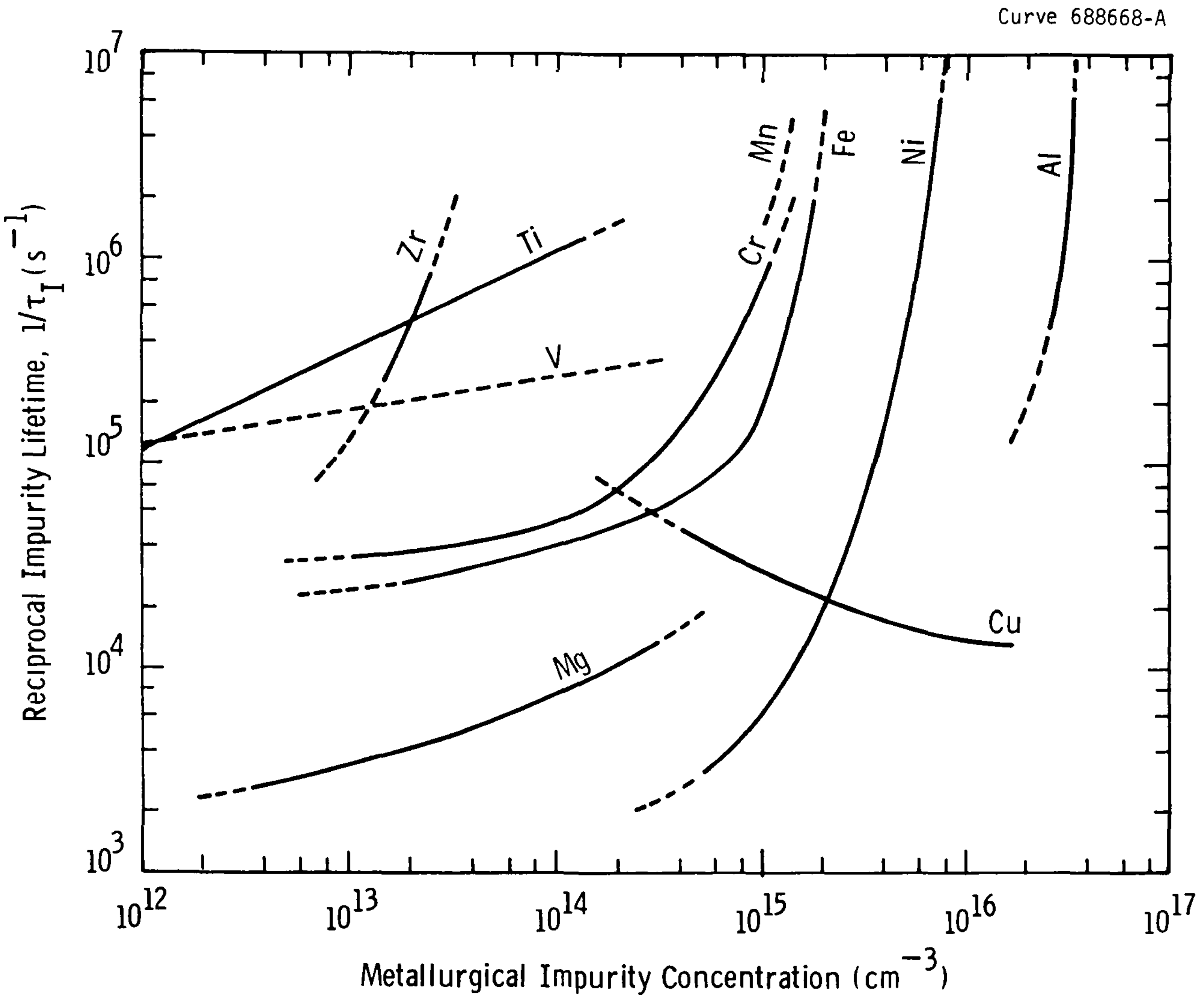

Fig. 9. Reciprocal lifetime contribution due to metallic impurities in silicon grown by the Czochralski method.

the two lifetime values. A graphical comparison of the results is shown in Fig. 10; the dashed line represents a one for one correlation. The model adequately represents most of the data points. However, additional data will be required to increase confidence in the model and also to explain the more serious deviations observed. Figure 10 is based on the combined accuracy of many lifetime and impurity concentration measurements and some scatter should be expected.

3.2.1.2 Lifetime Measurements on Silicon Dendritic Web

The first recombination lifetime measurements for metal-doped dendritic web are collected in Table 11. The lifetime was measured only on the as-grown silicon since the quantity of material originally available was limited and rapid feedback to the growing facilities was desired. The I_{sc} measurements derived from solar cells fabricated on this material (see Section 3.2.2) are also given to provide convenient comparison of the observations. The recombination lifetime after diffusion will be measured in the future, since this parameter has been shown to be more significant in predicting solar cell performance.

3.2.2 Solar Cell Studies

It is our intent that this report provides an up-to-date review and summary of the program progress and results; therefore, some previously reported material has been repeated in the following discussion.

3.2.2.1 Cell Design

The central purpose of the program was to determine the effects of various impurities on solar cell performance. To this end, a solar cell and a number of test structures were designed. The design was not optimized for high efficiency but for ease of processing and reproducibility and to provide acceptable data for characterizing the impurity effects.

The basic design incorporates a 3000 Å, 60 Ω/□ phosphorus diffusion into a 250 μm thick, 2 to 4 Ωcm p-type (boron-doped) wafer.

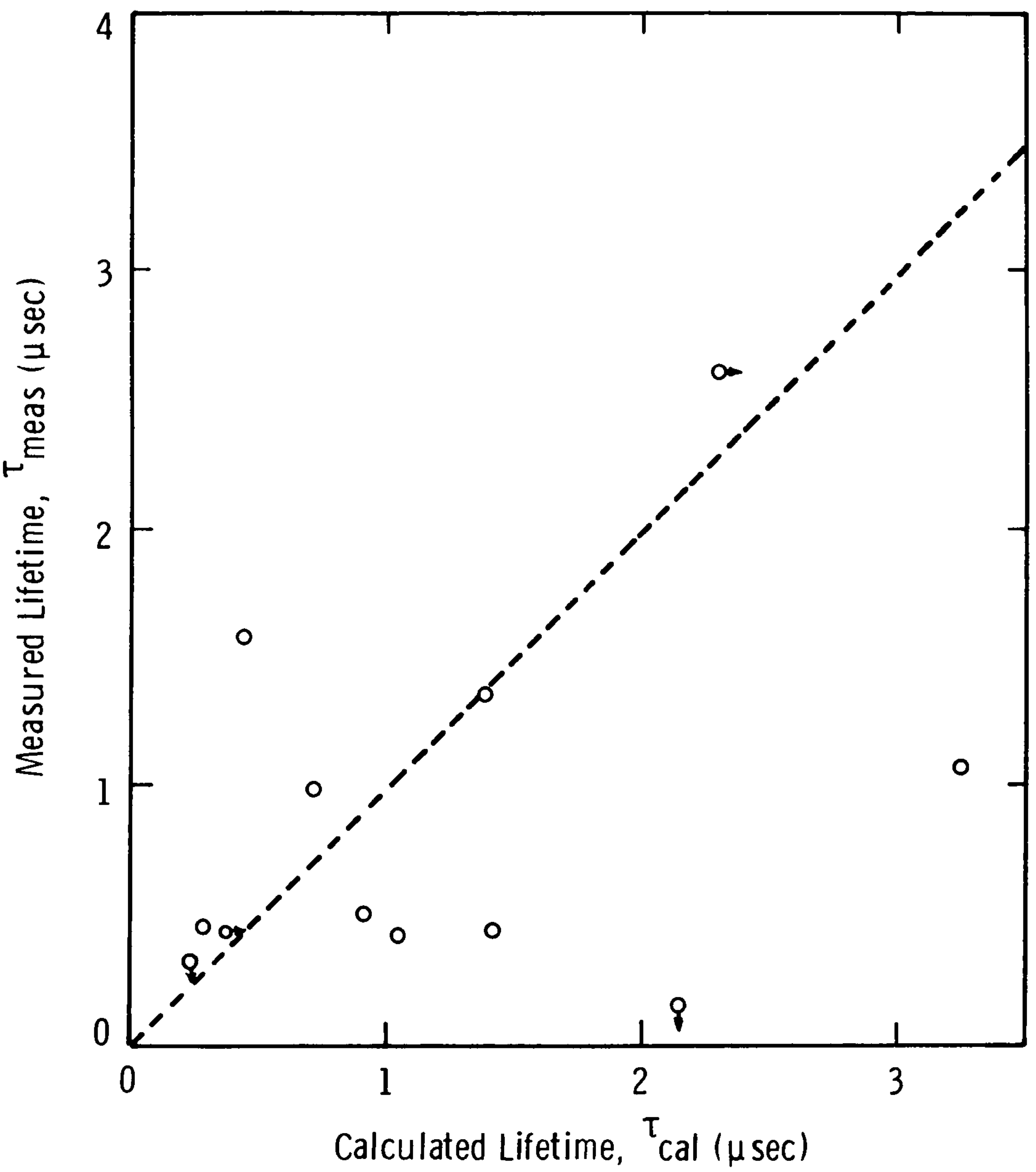

Fig. 10. Evaluation of proposed recombination lifetime model based on the independent effects of multiple impurities.

Table 11

Recombination Lifetime and Solar Cell Short Circuit Current for Silicon Dendritic Web Specimens

Web Run Number	Impurity Types	τ_r (μsec) (As-Grown)	I_{SC} (mA/cm^2)
DW019			
DW021-1	Ni	--	20.7 (2)
DW025-2	Cr/Cu	0.34 (2)	9.35 (2)*
DW026-1	Mn/Cu	--	19.20 (2)
DW027-1	Zr	--	20.15 (2)
DW028-1	Cr/Mn	0.47	--
DW029-1	Ni/Mn	0.60	19.8 (1)
DW030-1	Al	--	15.05 (2)
DW033-1	--	--	20.7 (1)
DW034-2	Baseline	0.44	--
DW035-1	Cu	0.42	20.75 (2)
DW036-1	Cu	0.32	--
DW037-1	Cr	0.46	10.0 (1)
DW038-5	Cu	(Note 2)	--
DW039-2	Ni	0.34	20.9 (2)
DW040-1	Ni	0.49	19.55 (2)
DW042-1	Cr	0.31	20.65 (2)
DW043-1	Mn	0.65	--
DW044-1	Ti	0.47	17.40 (2)

Note 1. Sample size shown in parentheses.

Note 2. Specimen broken.

*2.5 x 20 mm solar cell.

The active junction regions are defined by a mesa etch, 5 to 8 μm in depth. Contact metallization is Ti/Pd/Ag (1500 Å, 300 Å, 2 μm) sintered 15 min at 550°C; a sample processing log is shown in Fig. 11.

The geometry of the photomask set illustrated in Fig. 12 indicates a nominal one square centimeter solar cell (actual measured cell area is 1.032 cm^2). The contact coverage area is 5.4%. Test structures include six van der Pauw patterns for measuring diffused layer sheet resistance; six small test diodes; four small solar cells (0.0576 cm^2 active area); and a test pattern for measuring the specific contact resistance. The master masks were generated and are stored in a computer graphics system which greatly facilitates any needed modifications.

A one square centimeter cell size was chosen originally because of anticipated difficulties in growing large diameter crystals containing some of the metallic impurities. This cell size proved satisfactory and was retained even though the expected crystal growth problems did not materialize for most of the ingots.

Antireflection coatings were considered an unnecessary process complication and were not included in the design. Recent experiments, although incomplete and providing limited data, have shown that SiO antireflection coatings resulted in an average of a 36% increase in short circuit current and produced baseline cell efficiencies between 13 and 14 percent.

Overall, the performance of the cell design and fabrication procedures has been very successful. Based on data from more than 60 experimental runs, baseline cell efficiencies have averaged 10.26 ± 0.24% without AR coatings and yields have been between 80 and 90%.

3.2.2.2 Cell Measurements

During the early part of the program dark I-V measurements were made of the cells and test diodes. It was found, however, that these

Start Date:	**PROCESSING LOG**	**Page** ○	**Run or Sample**
Material:			
Quantity:	**Engr.**		

Date Tech.	*Process	Special Instructions, Measurements, etc.	Disp.	
			C	E
	LAP (1)	Wafer Thickness		
	CLEAN (2)	Trichloroethylene, Acetone, Methanol		
	CHEM POLISH (3)	Surface Quality Wafer Thickness		
	CLEAN (4)	$HF \cdot H_2O$ (1 to 10 ratio) dip 15 sec. H_2O_2 - NH_4, H_2O_2 - HCℓ		
	POCℓ (5) DIFFUSION	Source Temp. = 0°C Flow Rates 200 cc/min - N_2/Source, 1560 cc/min - N_2 Carrier 62.5 cc/min O_2		
		Diffusion Temp. 825°C Time 50 min. X_j = C_o = ρ_s =		
	P-ETCH (6)	H_2O HF : HNO_3 Time = 300 : 15 " 10 (Remove all oxides)		
	CLEAN (7)	H_2SO_4 : H_2O_2 87°C, 5 min 10/1 H_2O/HF Dip 10 sec		
	METAL (8)	Top Side Only Ti 1500 Å 50 Å/sec Pd 500 Å 50 Å/sec		
		Ag 20000 Å 60 Å/sec		
	LAP (9) BACK	Check Conductivity Type		
	PHOTO- (10) RESIST	Mask #1 (contact grid) Waycoat IC, 4000 rpm, h = 1.7 μm Exposure time = 3 sec (I_d = 0.2 μa)		
	ETCH (11) METAL	Ag-20-60 H_2O_2 & Ammonium Hydrox.-10-15 sec. Pd + 30cc HCℓ + 10cc HNO_3-5 sec. Ti-150cc H_2O + 60cc HCℓ + 30cc Ammonium Fl. 5 sec		
	CLEAN (12)	H_2SO_4 at 100°C - 5 min Rinse in D.I. H_2O.		
	METAL BACK (13)	Ti-1500 Å - Pd 500 Å Ag - 20 KA		
	SINTER (14)	Temperature Time 550°C 15 min/H_2		
	PHOTO-RESIST (15)	Mask #2 (Mesa) Waycoat SC, 7000 rpm, h - 4.0 μm Exposure time = 15 sec (I_d = 0.6 μa), Apiezon wax back side		
	ETCH (16) SILICON	44 cc HF + 26 cc HNO_3 + 29 cc Acetic 5°C, Etch time = 5-10 sec Etch silicon between 5 to 8 μm deep, Talystep ________μm.		
	TEST (17)			

* SEE DETAIL PROCESS INSTRUCTIONS

Fig. 11. Process log for solar cell fabrication sequence.

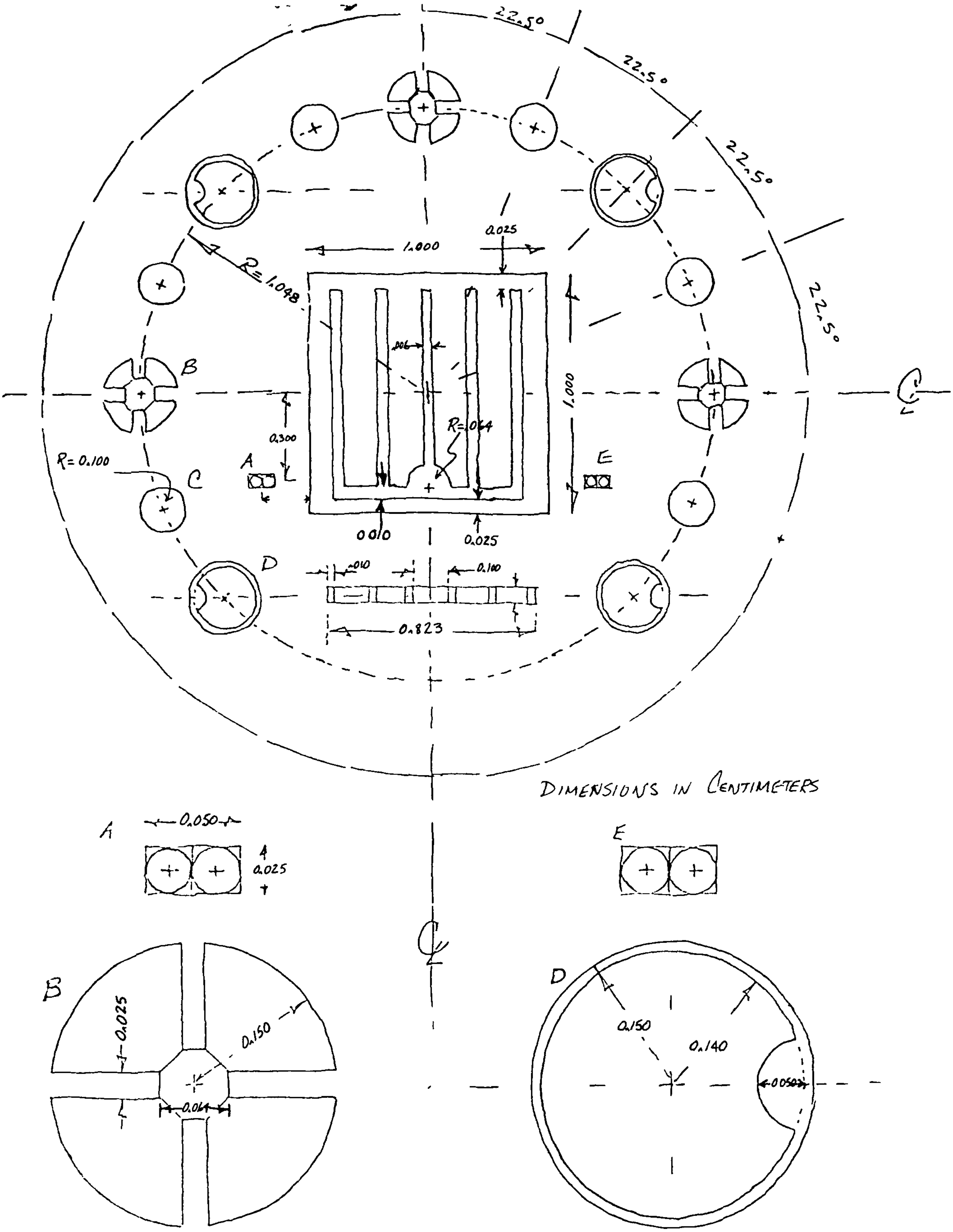

Fig. 12. Standard solar cell and test pattern design.

data correlated poorly with the illuminated cell data and were therefore not continued.

The illuminated cell data were obtained using a GE-ELH quartz iodine lamp in a forced-air-cooled housing. A programmable voltage/current source with digital readouts was developed and built to obtain the I-V data. After experiencing problems with the stability of the light intensity a constant voltage regulator was added to the system.

An air-cooled heat sink was designed to hold the cell samples and included a calibrated secondary reference cell with which the light level was checked during each set of measurements.

During the first half of the program, the light intensity was set at 100 MW/cm^2 AM1 using an International Rectifier Standard cell (#284). JPL later provided a standard cell (#S/N005) calibrated by NASA-Lewis which indicated our light intensity to be 91.6 MW/cm^2. We have continued to use this illumination level to simplify the cross-comparison of experimental data.

In addition to the photovoltaic I-V data, measurements were made of minority carrier lifetime in the cell. The measurements were made using the open circuit voltage decay method.[7,8] Data are taken using a Tektronix type-S plug-in. The forward current injection level was set at 20 mA/cm^2 which results in a base carrier concentration approximately equal to that produced by 100 mW/cm^2 illumination. Under these conditions we obtained reliable base lifetime data which were in good agreement with those obtained using the photoconductive decay method.

3.2.2.3 Data Base

The large amount of data entailed by this program necessitated the use of a computer for data storage, reduction and analysis. A data base system was developed which contains the measured cell data, ingot analysis, OCD and PCD lifetimes along with necessary sample and run identifiers. Sufficient coding is provided to permit addressing data by content or by location.

An editing program was also written to facilitate modifying, correcting or adding data.

At the present time data is available in the files for 65 experimental runs and over 800 individual cells.

3.2.2.4 Data Reduction

The voltage-current data must be reduced to some standard form to allow comparisons of cell performances. In order to do this, it is necessary to provide a mathematical model which describes the cell operation. Because the solar cell is a distributed three-dimensional structure, no completely successful closed form expression is possible. Furthermore, the large volumes of data preclude using detailed carrier transport calculations to characterize the cell behavior. However, for the purposes of this program, we have found that the two traditional one-dimensional models are satisfactory.

The more accurate of these, the double-exponential model, derives from the solar cell acting as two dissimilar diodes connected in parallel. The device characteristics are dominated by one of these diodes at high current levels and by the other at low levels, the dividing current level being typically between 0.6 and 2 mA/cm^2. The governing equation is:

$$I = I_{sc} \quad I_{01}\left\{\exp(qV/n_1kT+IR_S)-1\right\} - I_{02}\left\{\exp(qV/n_2kT+IR_S)-1\right\} - V/R_{SH} \qquad (3.15)$$

Where the unknown parameters are:

I_{01} is the saturation current for the high current diode,
I_{02} is the saturation current for the low current diode,
n_1 and n_2 the corresponding non-idealized diode factor,
R_S and R_{SH} are respectively the series and shunt resistances of the cell.

In theory, n_{01} and n_{02} should be one and two respectively; however, experimentally n_{01} is typically between 1 and 2 and $n_{02} > n_{01}$ for baseline devices.

The six parameters are determined from the voltage/current data using a nonlinear least squares algorithm.[9] Typical double-exponent behavior is shown in Fig. 13 and Fig. 14. These analyses provided several useful conclusions: 1) the shunt resistance term is negligible except in the case where processing faults occur; 2) both the saturation currents and the n-factors increase, as expected, with the addition of metallic impurities but the changes are not sensibly correlated with the metal concentration nor with other cell parameters; 3) the calculations are slow-running in the computer and occasionally the algorithm fails to produce a solution; 4) the most effective parameters for characterizing impurity effects are short-circuit current, open circuit voltage, peak power and efficiency. These parameters can be obtained directly from the measured IV data and by use of the simpler equation:

$$I = I_{sc} - I_{01}\left(\exp[q(V+IR)/n_1kT] - 1\right) \tag{3.16}$$

This equation will yield a good representation of the device for either of the exponential segments illustrated in Figs. 13 and 14 provided the IV data used lie wholly within the desired segment. In our case, the fit is made to the upper segment corresponding to voltages from slightly below the peak power point to beyond the open circuit voltages.

Initially, the fit was obtained using the same least squares method as for the double exponential model. However, the following algebraic technique was found to produce equally accurate results with a considerable reduction in computation time. The method is similar to Roger's.[10]

We introduce the dimensionless variables:

$$r = I_{sc} \cdot R/V_{oc} \, ,$$

$$i = I/I_{sc} \, ,$$

and $$v = V/V_{oc}$$

and define a variable $u = I_{sc}/I_{01} + 1$ and note that,

$$V_{oc} = V_o \ln(I_{sc}/I_o + 1) = V_o \ln(u) \tag{3.17}$$

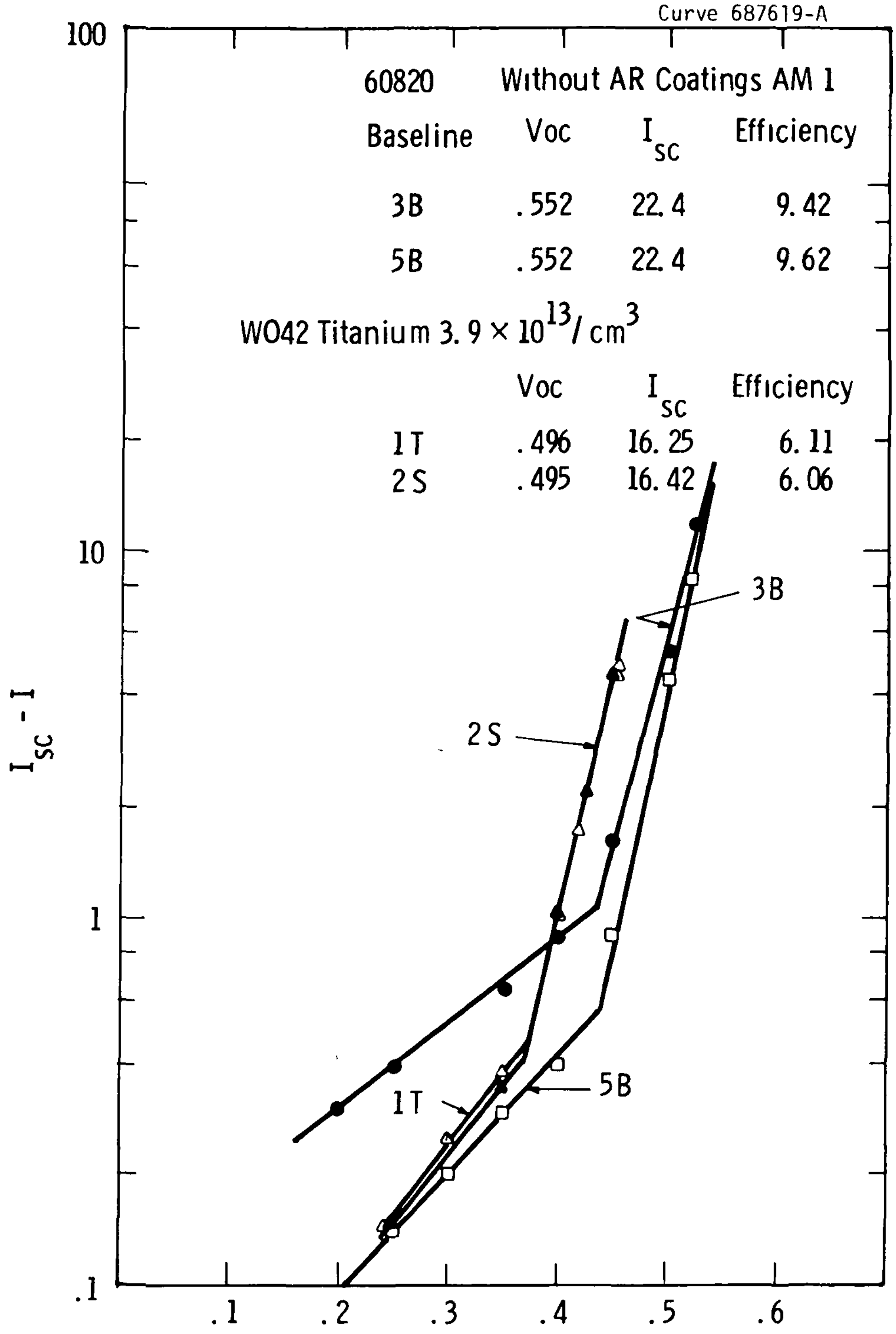

Fig. 13. Solar cell voltage versus log (I_{sc} - I) for W042-Ti003 devices under illumination.

Curve 687617-A

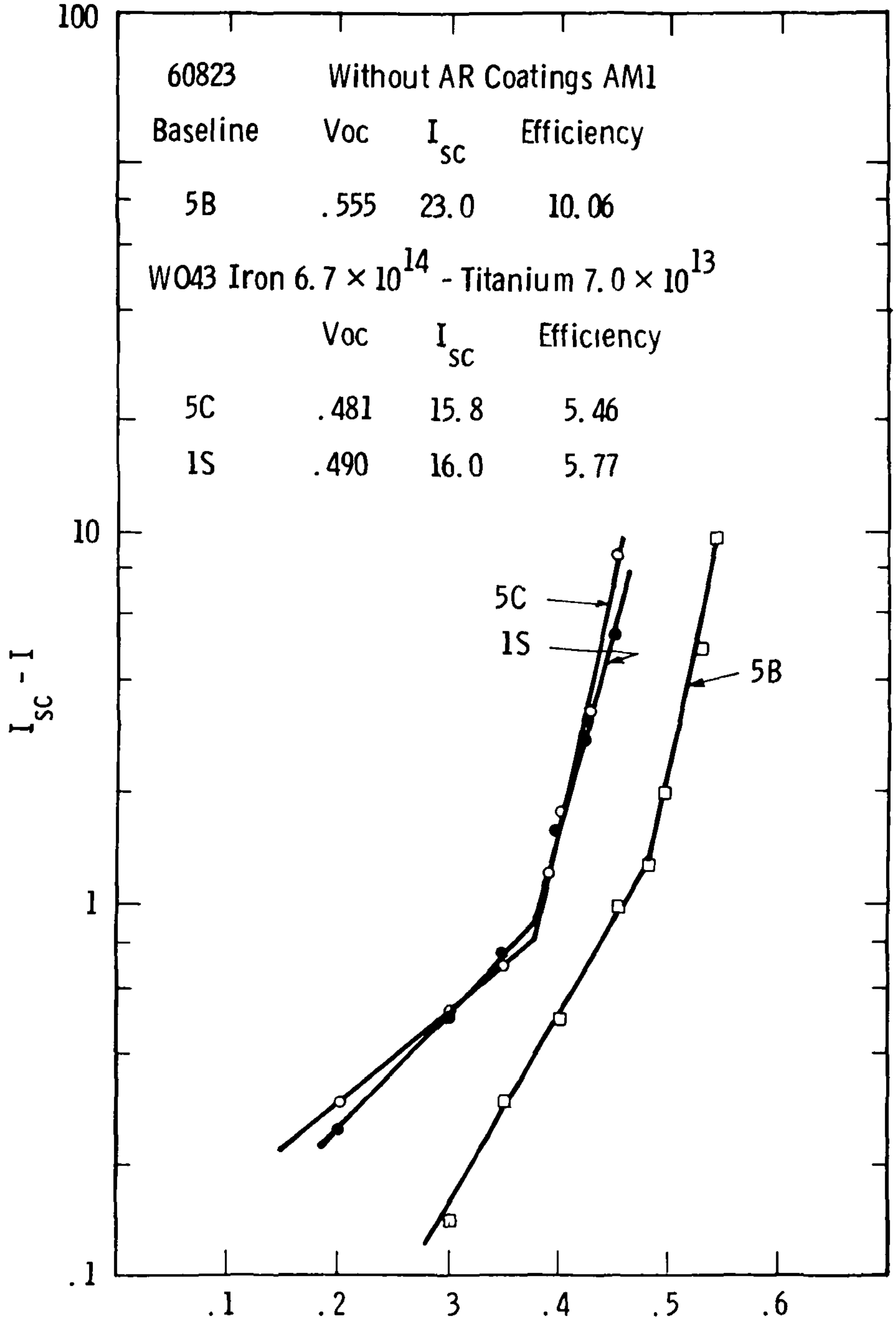

Fig. 14. Solar cell voltage versus log (I_{sc} - I) for W043-Fe/Ti001 devices under illumination.

where we define $V_o = n_1 kT/q$. Equation (3.16) can be rewritten:

$$iI_{sc} = I_{sc} - \frac{I_{sc}}{u-1}\left\{\exp\frac{(vV_{oc} + irV_{oc})}{V_o} - 1\right\} \qquad (3.18)$$

$$= 1 - \frac{1}{u-1}\left\{\exp\left(\frac{V_{oc}}{V_o}\right)(v+ir) - 1\right\}$$

$$= 1 - \frac{1}{u-1}\left\{u^{v+ir} - 1\right\}$$

$$i = \frac{u}{u-1}\left\{1 - u^{v-1+ir}\right\} \qquad (3.19)$$

For typical solar cells $u \doteq I_{sc}/I_o >> 1$ and $\frac{u}{u-1} \doteq 1$ providing:

$$i = 1 - u^{v-1+ir} \qquad (3.20)$$

Then with two data points, V_1, I_1 and V_2, I_2, we can solve for u and r which give I_{01} and R and using Eq. (3.17) we obtain n_1.

The cell efficiency is determined from the peak power; when $p = iv$ is a maximum and $\frac{dp}{di} = i\frac{dv}{di} + v = 0$ or

$$i\left\{\frac{1}{(L-1)\ln(u)} - r\right\} + \frac{\ln(1-i)}{\ln u} - ir + 1 = 0 \ . \qquad (3.21)$$

Solving Eq. (3.21) for ip and Eq. (3.20) for vp completes the fitting procedure.

It should be noted that R was introduced into the equations as a series resistance term. However, in practice, it is frequently negative in sign and should be considered a curve fitting parameter which compensates to a degree for limitations of the model.

The program also calculates average parameter values and standard deviations for the baseline and metal-containing samples. The average values are then compared and presented as a percent of the baseline value.

A compilation of the calculated parameter data are given in Appendix 4 according to the added-impurity species.

3.2.2.5 Data Synthesis and Analysis

Short Circuit Current -- Single Impurities. An examination of the data shown in Figs. 15 through 19 suggests that the effect of added metallic impurities is dominantly one of reducing the cell collection efficiency by reducing the minority lifetime. It is also apparent that the behavior of the saturation currents, n-factors and fill factors exhibit inadequate correlations to cell performance for use in constructing a useful model. The large scatter occurring with the latter deduced parameters is in part due to accuracy limitations of the data analysis model as well as to cell processing instabilities to which these parameters are acutely sensitive.

In any case, we propose a preliminary model for the impurity behavior based on lifetime or diffusion length degradation.

Short Circuit Current As a Function of Carrier Lifetime. The functional relationship between I_{sc} and effective cell lifetime can be obtained by solving the carrier transport equations with the appropriate boundary conditions and the material and spectral parameters. A one-dimensional computer solution of this problem is shown as the solid curve in Fig. 15. These calculations do not include the effect of transition region recombination nor of recombination anisotropy which may account for the optimistic performance predicted.

For our purposes, a closed form approximation is desirable and can be obtained by assuming an energy equivalent mono-chromatic illumination (for example, see Section 3.2.2.1). We then obtain the following equation:

$$I_{sc}(\tau) = \frac{I_{sc}\ (\tau = \infty)}{\frac{1}{\alpha\sqrt{D}}\ \frac{1}{\sqrt{\tau}} + 1} \qquad (3.22)$$

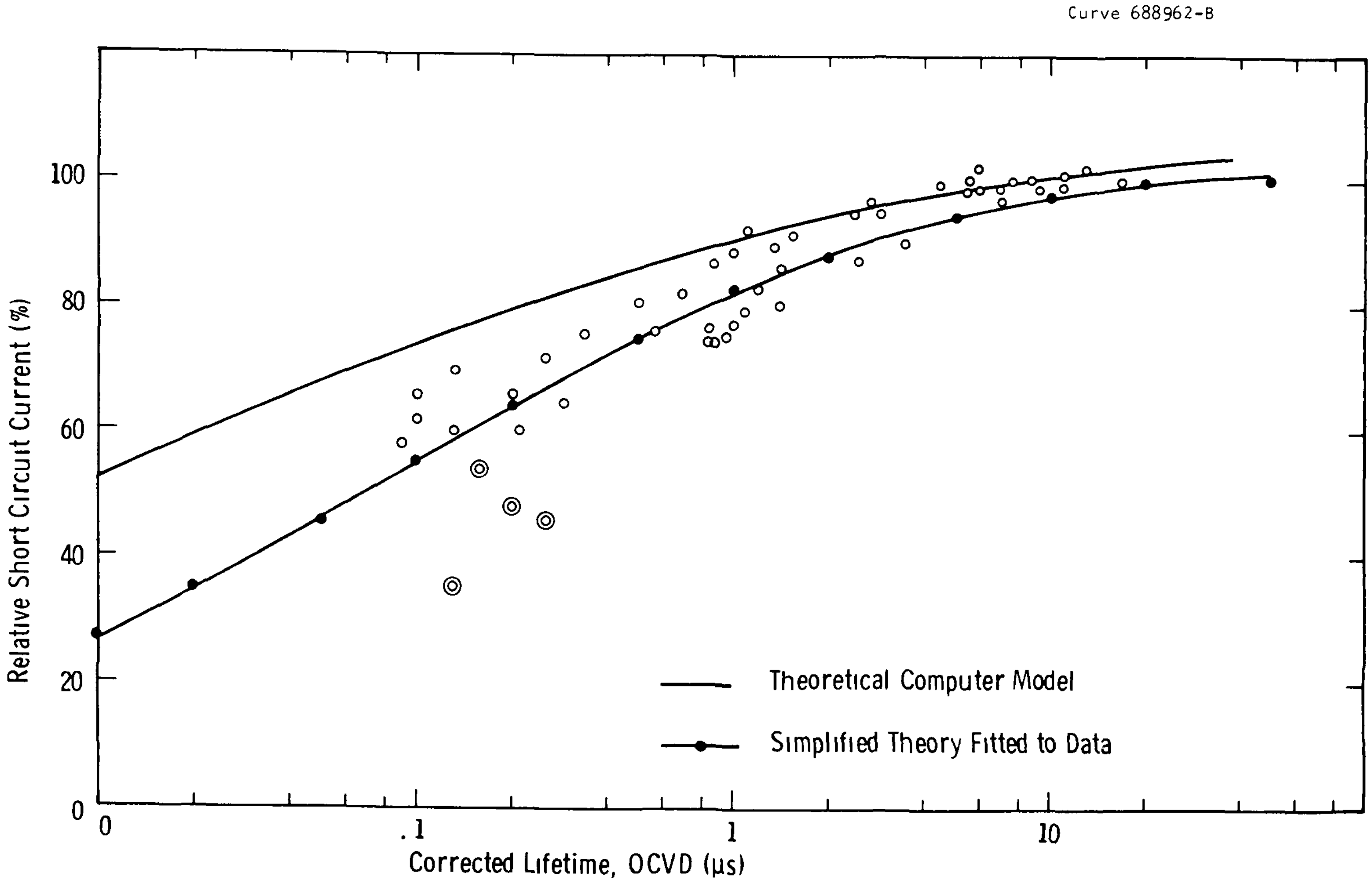

Fig. 15. Relative short circuit current as a function of corrected open circuit decay lifetime of metal-doped solar cells.

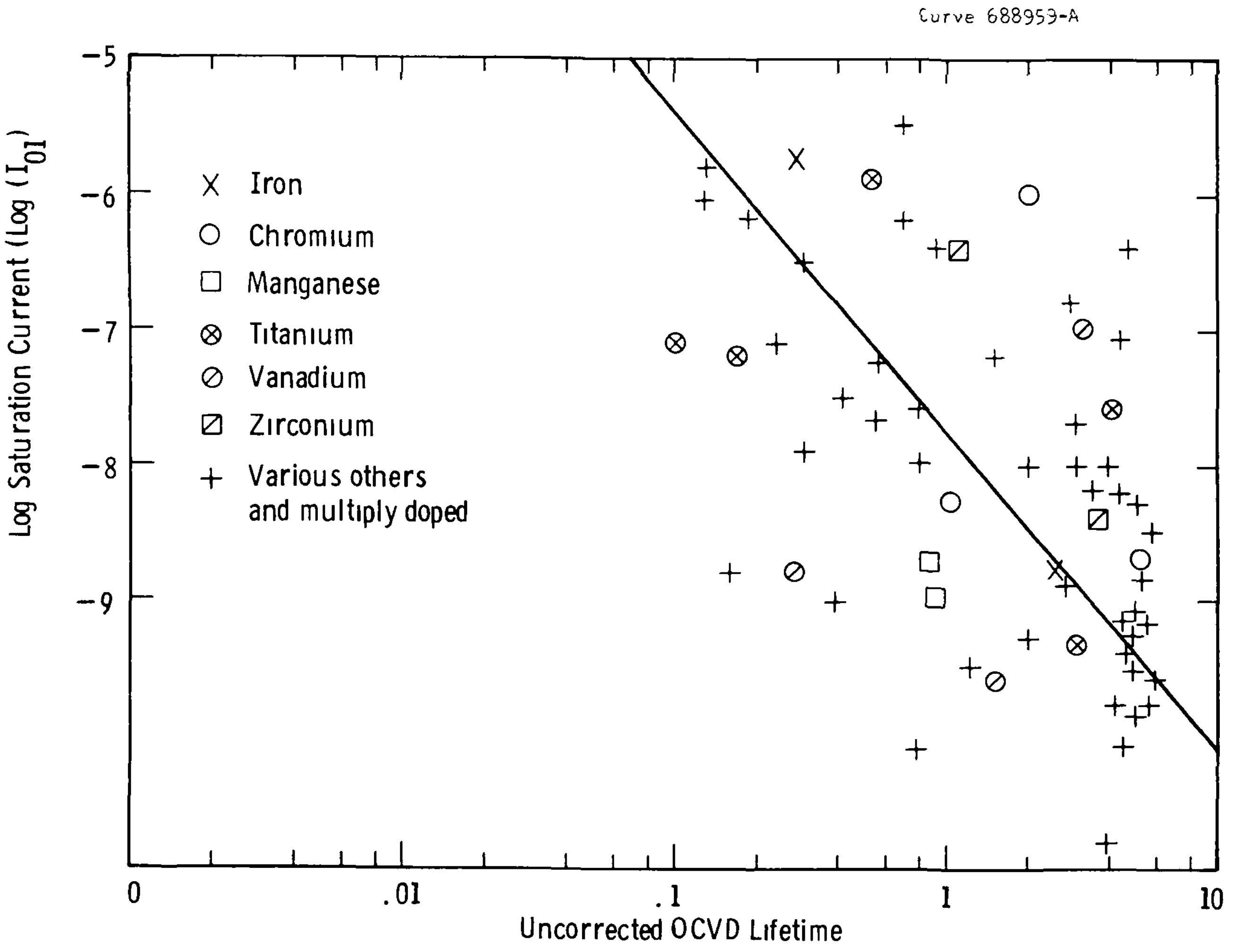

Fig. 16. Variation in the saturation current of metal-doped solar cells with the uncorrected open circuit decay lifetime of the devices.

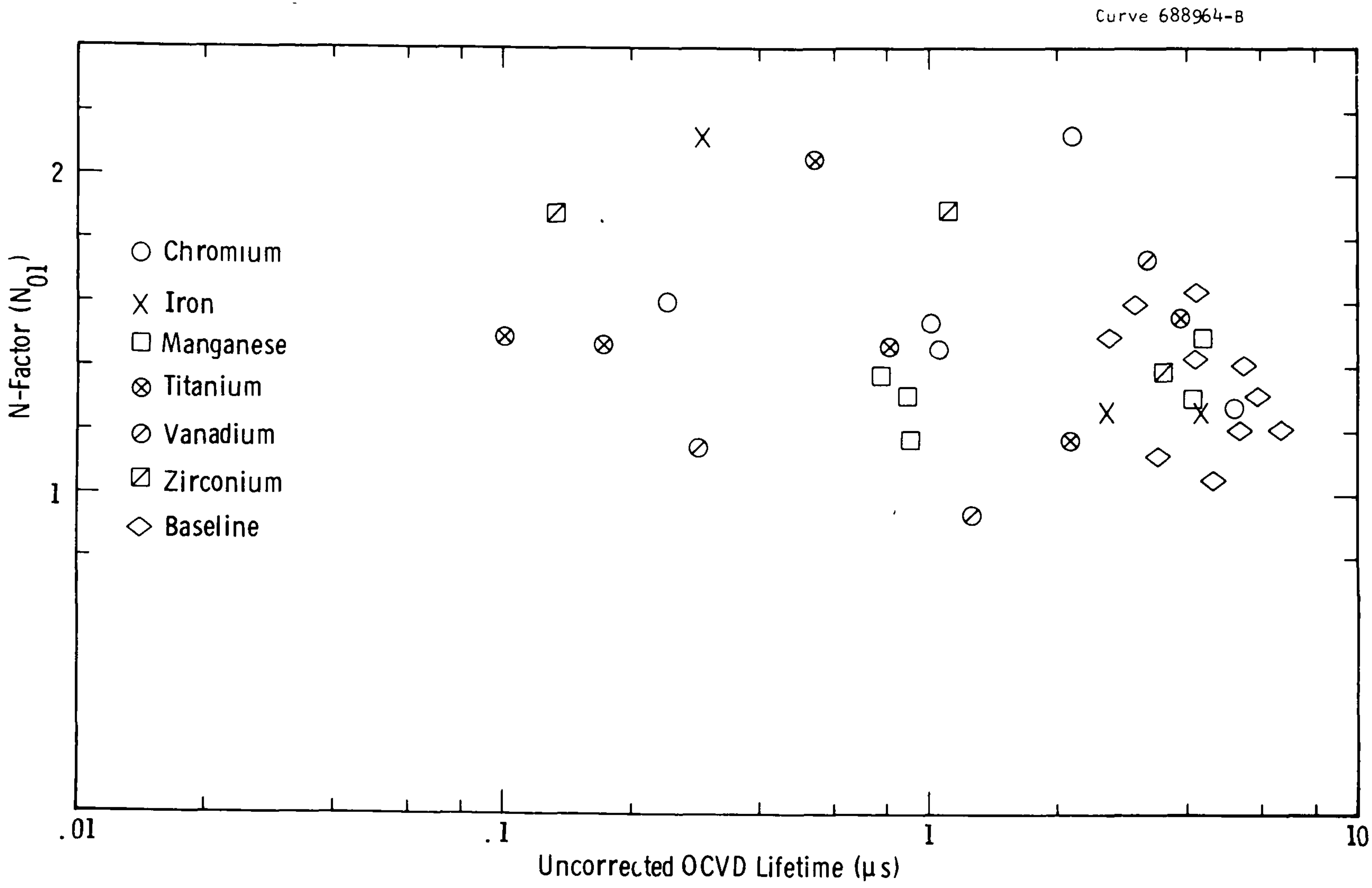

Fig. 17. Behavior of device N-factor with uncorrected open circuit decay lifetime for metal-doped solar cells.

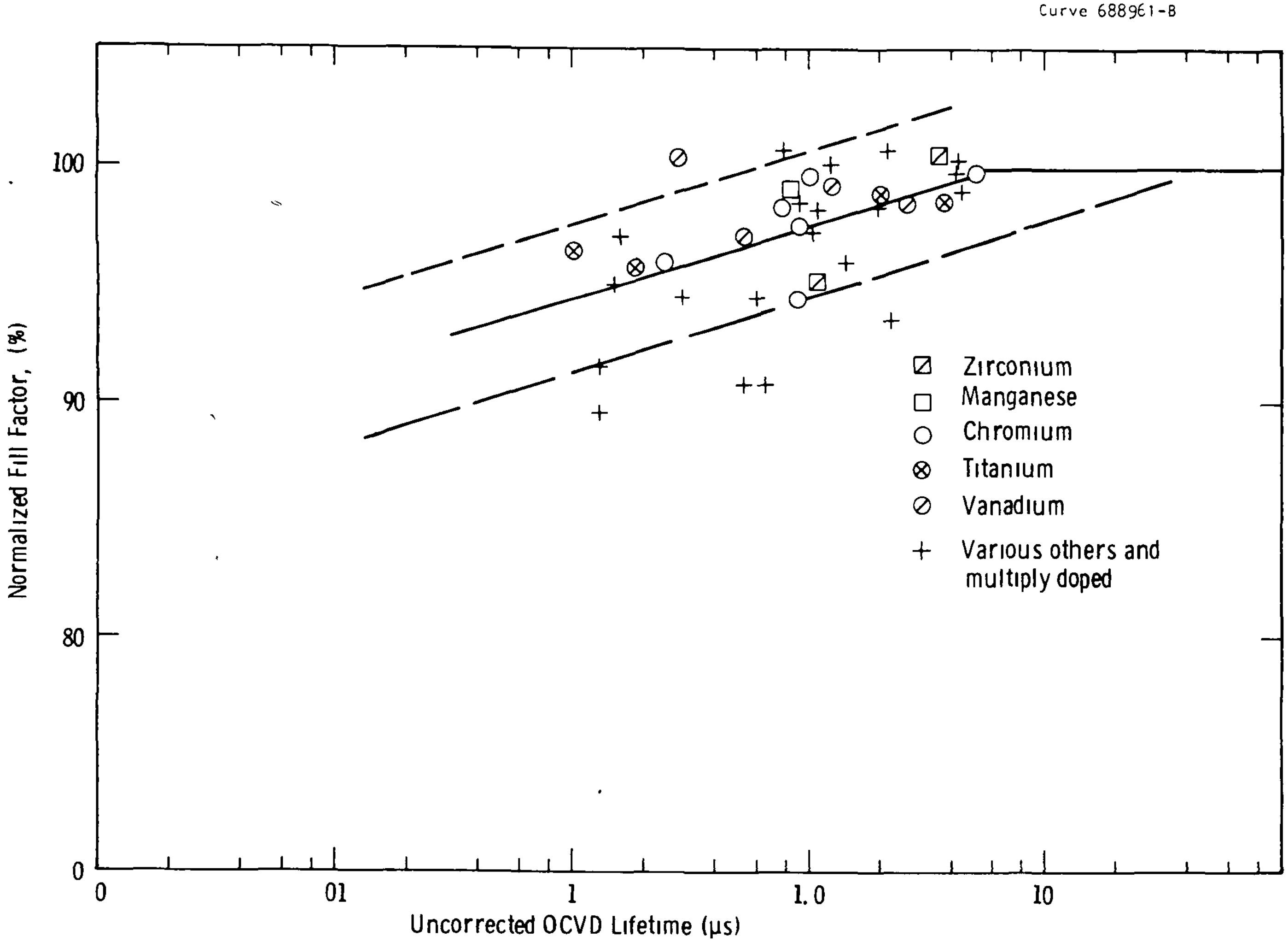

Fig. 18. Variation in normalized fill factor with uncorrected open circuit decay lifetime for metal-doped solar cells.

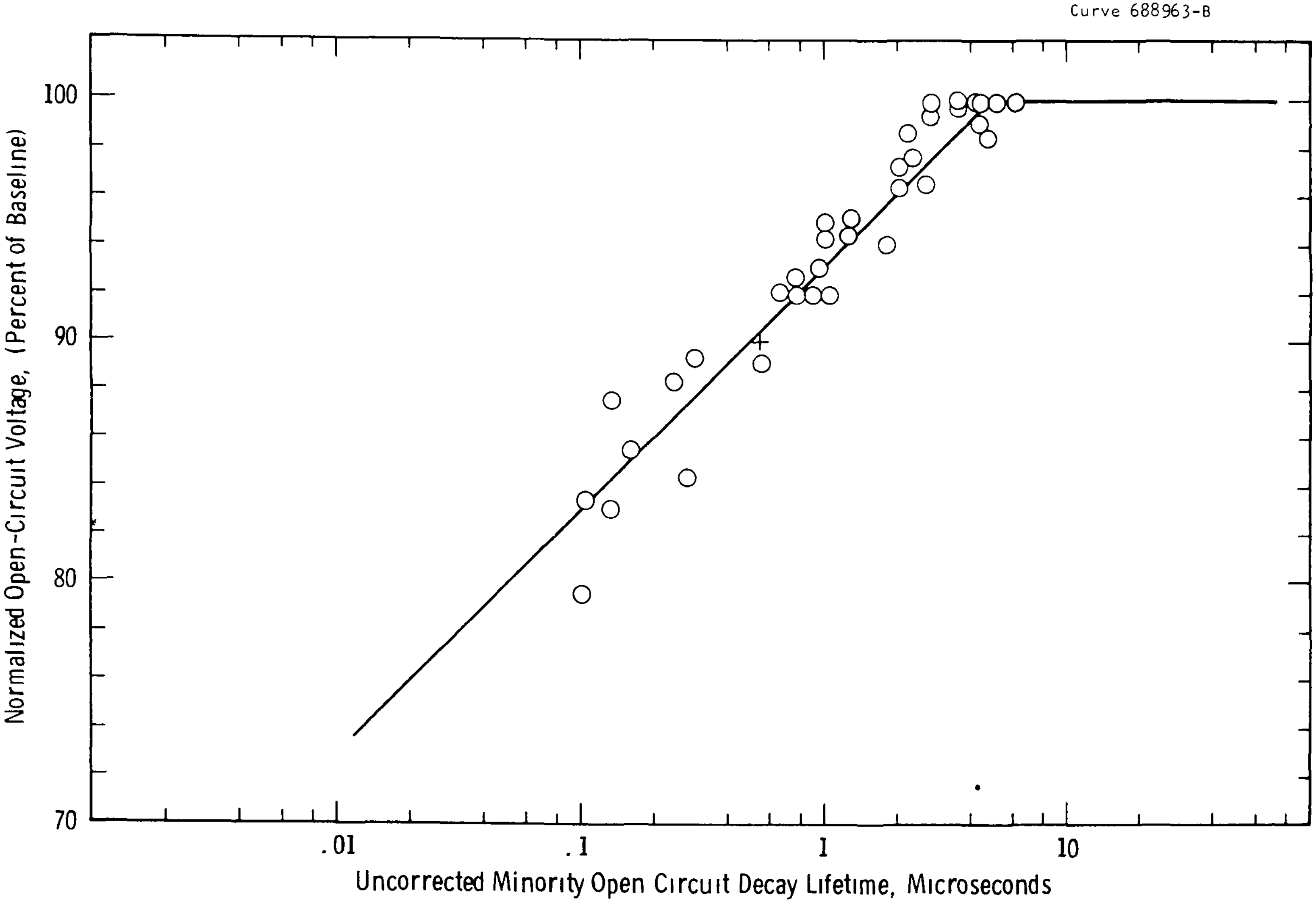

Fig. 19. Normalized cell open circuit voltage as a function of device open circuit decay lifetime for metal-doped solar cells.

where: α = absorption constant at the effective wavelength of the light,

$D = 32\ \mathrm{cm}^2/\mathrm{sec}$, the base diffusion constant.

We define a normalized short circuit:

$$I_n \triangleq \frac{I_{sc}(\tau)}{I_{sc}\ (\tau = \tau_o)} , \qquad (3.23)$$

where τ_o is the lifetime of the baseline (no added metals) devices. Equation (3.22) then becomes:

$$I_n = \frac{I_n(\infty)}{\frac{A}{\sqrt{\tau}} + 1} \qquad (3.24)$$

where $A = \frac{1}{\alpha\sqrt{D}}$.

Or restated in form more suited to curve-fitting:

$$\frac{1}{I_n} = \frac{1}{I_{n\infty}} + \frac{A}{I_{n\infty}\sqrt{\tau}} \triangleq C_1 + \frac{C_2}{\sqrt{\tau}} \ . \qquad (3.25)$$

Fitting this equation to the data of Fig. 15, we find:

$C_1 = 0.9368$

$C_2 = 0.2791$

with a coefficient of fit equal to 0.7. These values then imply:

$I_{n\infty} = 1.07$

$1/\alpha\sqrt{D} = 0.298$

$\tau_o = 19\ \mu s$ (τ such that $I_n = 1$) .

The curve is drawn in Fig. 15 and fits the data quite well, although the value for τ_o is somewhat larger than the data indicates.

Short Circuit as a Function of Metal Concentration. Returning to the question of the way in which the impurity metals act in the cells, we have assumed that lifetime degradation is dominant. Furthermore, since the metal concentrations are extremely dilute, it is highly likely that the concentration of recombination centers, N_T, is linearly proportional to the concentration of the metal impurities, N_x. Note that N_T need not be equal to N_x as a large part of metal atoms can locate at electrically inactive sites in the crystal lattice.

The lifetime as a function of N_T is given as noted before by:

$$\tau = \frac{1}{\sigma_x V_{th} N_T} \tag{3.26}$$

where σ_x is the recombination cross-section for metal-x and V_{th} is the thermal velocity of the carriers.

Assuming $N_T = a_x N_x$, we have:

$$\tau = \frac{1}{a_x \sigma_x V_{th} N_x} \overset{\Delta}{=} \frac{1}{k_x N_x} . \tag{3.27}$$

As in Section 3.2.1, when several independent recombination centers are present, the effective lifetime is obtained from the reciprocal sum:

$$\frac{1}{\tau} = \frac{1}{\tau_o} + \frac{1}{\tau_x} + \frac{1}{\tau_y} + \ldots, \quad \frac{1}{\tau_2} , \tag{3.28}$$

where τ_o is the intrinsic lifetime observed in uncontaminated baseline cells. Including Eq. (3.27) gives:

$$\frac{1}{\tau} = \frac{1}{\tau_o} + k_x N_x + k_y N_y + \ldots \quad k_3 N_z . \tag{3.29}$$

Now we can write Eq. (3.24) in the following useful form:

$$\left(\frac{I_n}{I_{n\infty}} - 1\right)^2 = A^2 \left(\frac{1}{\tau_o} + k_x N_x + k_y N_y + \ldots \quad k_2 N_2\right) . \tag{3.30}$$

For the samples containing single metal impurities, we can express Eq. (3.30) as:

$$\left(\frac{I_{n\infty}}{I_n} - 1\right)^2 = C_1 + C_2 N_x \tag{3.31}$$

or

$$\left(\frac{I_{n\infty}}{I_n} - 1\right)^2 = C_2 \left(N_{ox} + N_x\right) , \tag{3.32}$$

where N_{ox} is a threshold concentration above which degradation is observed. Table 12 presents the least squares values obtained using Eq. (3.31) and (3.32) and data from samples with single added metals. The corresponding curves are drawn in Fig. 20.

The behavior shown is more or less as expected, however, note that $C_1 = A^2/\tau_o$ should be a constant independent of contaminant metals. The value expected for C_1, based on the results obtained with Eq. (3.25) (Fig. 15), should be in the range from 0.008 to 0.015. The agreement is fairly good, particularly if one recognizes that the number of data points is statistically very small.

Short Circuit Current for Multiply-Doped Cells. We now have enough information to calculate the short circuit current behavior of multiply doped cells. The result shown in Table 13 is obtained from Eq. (3.30) rewritten as:

$$I_n = I_{n\infty} \left[\left(C_1 + C_{2x}N_x + C_{2y}N_y + \ldots C_{2z}N_z\right)^{\frac{1}{2}} + 1 \right]^{-1} , \tag{3.33}$$

with the constants, C_{zx}, C_{zy}, etc., taken from Table 12. C_1 is assigned an average value of 0.012 and $I_{n\infty} = 1.08$.

The calculated error is a consequence of the estimated error in determining the metal concentrations. The values for N_x in both the singly and multiply-doped ingots are presumed known within a factor of 2. With this allowance, the calculated currents are in good agreement with the measured values for all but two of the ingots. These results further suggest that this modeling method, with some refinement, might provide a way of improving the accuracy of the concentration estimates.

$$I_n = I_{n\infty} \left\{ (C_1 + C_{2x}N_x)^{\frac{1}{2}} + 1 \right\}^{-1}$$

$$I_{n\infty} = 1.08$$

Table 12. Calculated Coefficients of Equations (3.31) and (3.32) for the Short Circuit Current Behavior with Single Metal Additions. See also Fig. 10.

	Coefficient of Fit R^2	C_1	C_{2x}	N_{ox}
Cu	.98	0.0120	7.301×10^{-19}	1.265×10^{14}
Ni	.69	0.0192	3.271×10^{-18}	3.644×10^{15}
Cr	.81	0.0037	7.843×10^{-17}	4.76×10^{13}
Fe	.58	0.0019	1.48×10^{-16}	1.28×10^{13}
Mn	.98	0.00966	6.099×10^{-17}	1.60×10^{14}
Zr	.86	0.0130	1.841×10^{-15}	7.36×10^{12}
V	.70	0.0106	5.4×10^{-15}	1.96×10^{12}
Ti	.95	0.0105	6.98×10^{-15}	1.51×10^{12}

$$I_n = I_{sc}/I_{sc_o}$$

$$C_1 = 0.012$$

$$I_{n\infty} = 1.08$$

$$I_n = I_{n\infty}\left[\left(C_1 + C_{2x}N_x + C_{2y}N_y + \dots \; C_{2z}N_z\right)^{\frac{1}{2}} + 1\right]^{-1}$$

Table 13. Calculated and Measured Short-Circuit Currents for Multiple Metal Additions

Ingot No.	Metal Concentration (at.cm^{-3}) Ti	Cu	V	Cr	Fe	Zr	Ni	Mn	Measured I_n	Calculated I_n
37	3×10^{14}					$<1.5 \times 10^{13}$			.599 ± .019	.439 ± .183
43	6×10^{13}				5.6×10^{14}				.703 ± .014	.629 ± .159
51	3.6×10^{14}	1.7×10^{15}							.619 ± .027	.417 ± .183
50	3.6×10^{11}		4×10^{11}						.879 ± .013	.956 ± .013
45	6×10^{13}			6.5×10^{14}	4.3×10^{14}				.727 ± .078	.621 ± .161
47		1.7×10^{15}				$<1.5 \times 10^{13}$	7.5×10^{14}		.938 ± .010	.894 ± .053
27		1.5×10^{15}						1.3×10^{15}	.737 ± .028	.828 ± .088
41		1.7×10^{15}		8×10^{14}			3×10^{15}		.828 ± .061	.835 ± .084
30		1.5×10^{15}		1×10^{15}					.761 ± .029	.829 ± .087
40				1×10^{15}			3.5×10^{15}		.868 ± .079	.819 ± .092
46			7×10^{13}		5.6×10^{14}				.769 ± .015	.763 ± .116
31				1×10^{15}				1×10^{15}	.543 ± .025	.770 ± .110

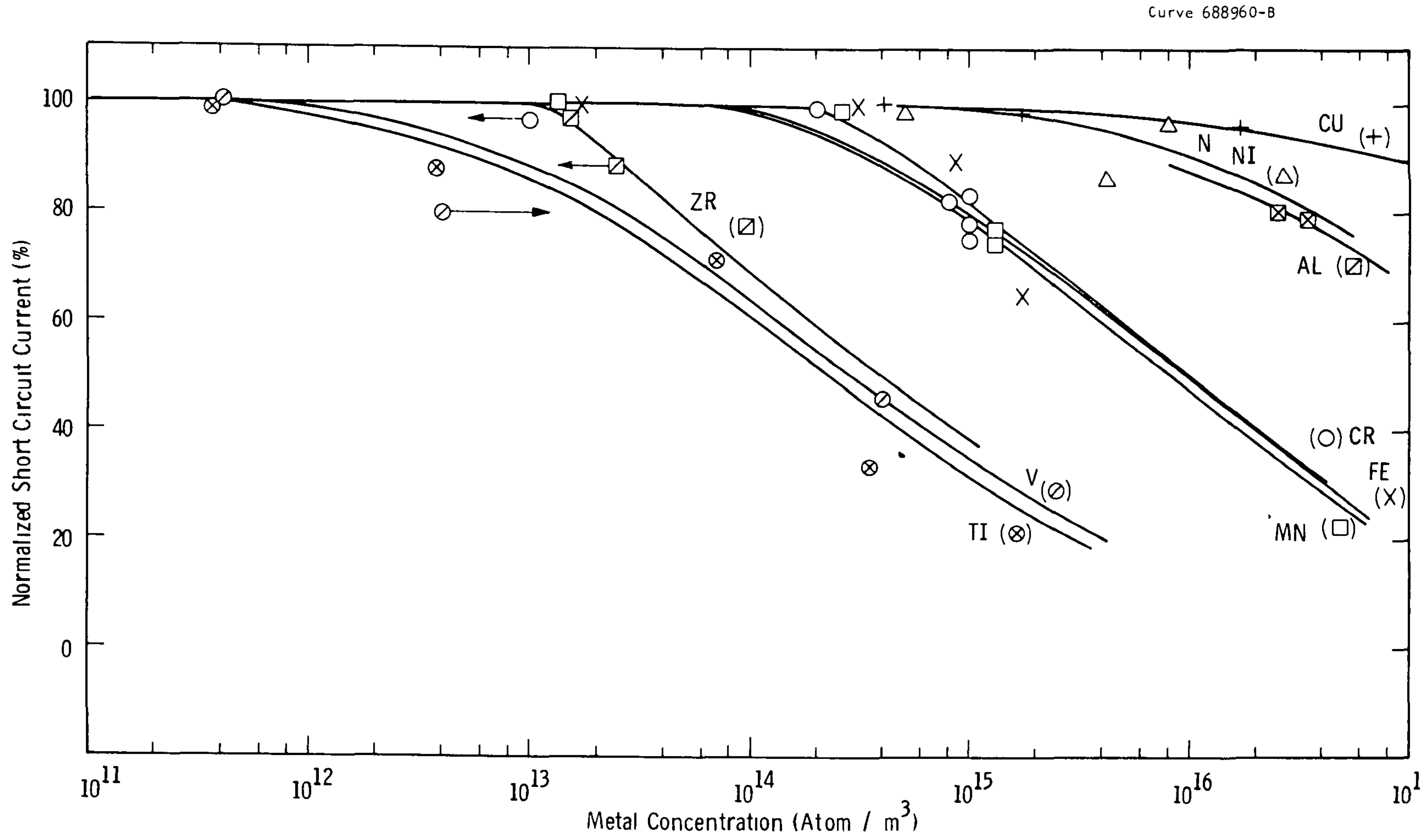

Fig. 20. Variation in normalized solar cell short circuit current with metal concentration of the solar cell substrate.

It should be noted, however, that the constants C_{2x} are very sensitive to processing history, particularly heat treatment and gettering processes (Section 3.2.3) so that the model predictions are possible only when a constant, well-controlled process sequence is maintained.

Open Circuit Voltage Behavior. In order to fully describe the impurity effects, it is necessary to examine their impact on open circuit voltage. The data shown in Fig. 19 again suggest a lifetime dependent behavior. Equation (3.25) which relates I_n to τ can be restated

$$\tau = \frac{C_2^{\,2}}{\left(\frac{1}{I_n} - C_1\right)^2} \tag{3.34}$$

where as before $I_n \overset{\Delta}{=} \frac{I_{sc}}{I_{sc_o}}$.

The open circuit voltage, V_{oc}, is given by:

$$V_{oc} = nV_T \ \ell n \left(\frac{I_{sc}}{I_o}\right) . \tag{3.35}$$

If we define a normalized open circuit voltage

$$V_n \overset{\Delta}{=} \frac{V_{oc}}{V_{oc_o}} . \tag{3.36}$$

We can write Eq. (3.35):

$$V_n = \frac{nV_T}{V_{oc_o}} \ \ell n \ \frac{I_n}{I_o} \ I_{sc_o} . \tag{3.37}$$

The saturation current, although difficult to measure accurately, has an implicit value which depends on lifetime, that is, $I_o \sim \frac{1}{\tau}$, which, using Eq. (3.34), becomes

$$I_o = \frac{C\left(\frac{1}{I_n} - C_1\right)^2}{B^2} \tag{3.38}$$

Combining (3.37) and (3.38) gives:

$$V_n = \frac{nV_T}{V_{oc_o}} \ln \frac{I_n}{\left(\frac{1}{I_n} - C_1\right)^2} + \frac{nV_T}{V_{oc_o}} \ln \left(\frac{B^2 I_{sc_o}}{C}\right) \tag{3.39}$$

or defining the functional parameters E and F, we have:

$$V_n = E \ln \left(\frac{I_n}{\left(\frac{1}{I_n} - C_1\right)^2}\right) + F , \tag{3.40}$$

where $C_1 = 0.9368$ as found from Eq. (3.25) and the data of Fig. 15.

We can fit Eq. (3.40) to the experimental data to obtain the curve shown in Fig. 21. The functional behavior is seen to be in good agreement with the data. This then provides a means of predicting V_n from impurity concentration since Eq. (3.33) supplies the value of I_n required in Eq. (3.40).

It should be noted that the constant E should be equal to nV_T/V_{oc_o} or about 0.07. The value obtained, 0.0266, is too small and therefore represents an inconsistency between the measured open-circuit decay lifetime and the implied lifetime deduced from the V_{oc} data. It is also possible that some of the disparity is due to limitation of the sample device model used. Further investigation should resolve these questions and for the present the result is functionally adequate.

We are now in a position to look at the behavior of efficiency versus the concentration of impurities.

Efficiency Behavior. The solar cell conversion efficiency is given by the product of the open-circuit voltage, short circuit current and the fill factor:

$$\eta = V_{oc} \times I_{sc} \times F \tag{3.41}$$

or normalized by the baseline values:

$$\eta_n = V_n \times I_n \times F_n . \tag{3.42}$$

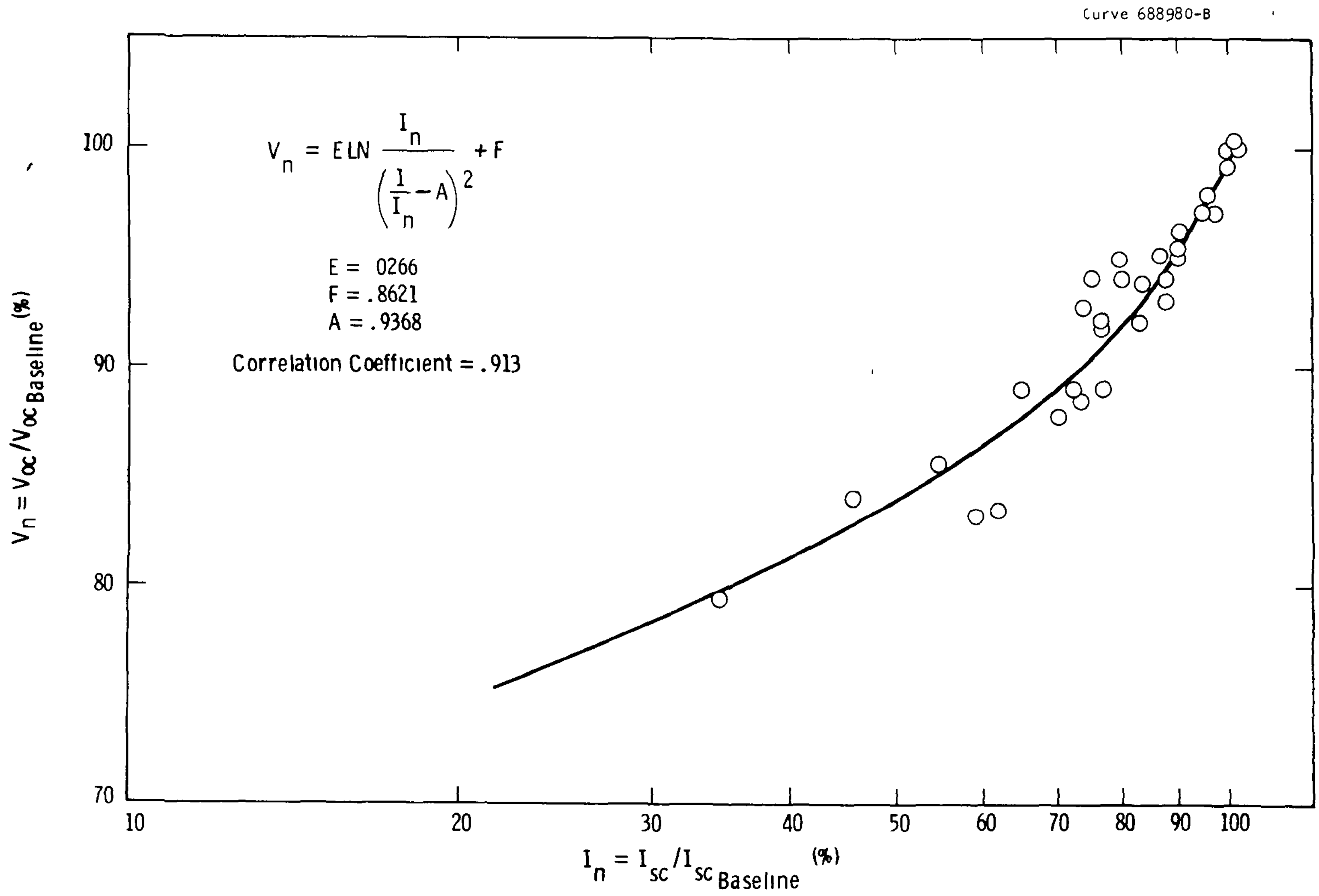

Fig. 21. Variation of normalized open circuit voltage with normalized short circuit current for metal-doped solar cells. Data fit to model indicated in the inset.

The data shown for F_n in Fig. 18 provide little basis for a functional description. In fact, if we simply assume F_n has the constant value 0.975, that is, approximately equal to the average of the experimental values, we then obtain fairly good agreement between calculated efficiencies and the experimentally observed values shown in Fig. 22.

A direct fit of the model equations to the experimental efficiency data is possible, in principle; however, closed form solutions for fill-factor and efficiency are not obtainable and the calculations are therefore greatly complicated. Preliminary results indicate an improved agreement with experiment as compared to the constant fill-factor assumption. Further results of this analysis will be reported at a later date.

The efficiency data shown in Fig. 22 are presented with free-hand curves drawn to assist visualizing cell performance behavior. These curves, however, do not represent functionally the behavior implied by the model equations. New curves will be drawn in accordance with the model analysis when it is complete.

3.2.2.6 Conclusions

We have developed a functional model for the effects of impurities on solar cell performance. The underlying hypothesis was that impurity metal atoms in the silicon act additively and independently of each other and only as carrier recombination centers. All other possible electrical effects are considered negligible.

Theoretically derived functions of the observable solar cell operating parameters are compared to experiment with excellent overall agreement. It is concluded that no clear evidence exists to contradict the basic analytic hypothesis.

Although the experimental curve-fitting constants exhibit some disagreement with the theoretically derived values, the differences are believed to derive the approximations used and from the statistically limited data available.

Curve 688812-B

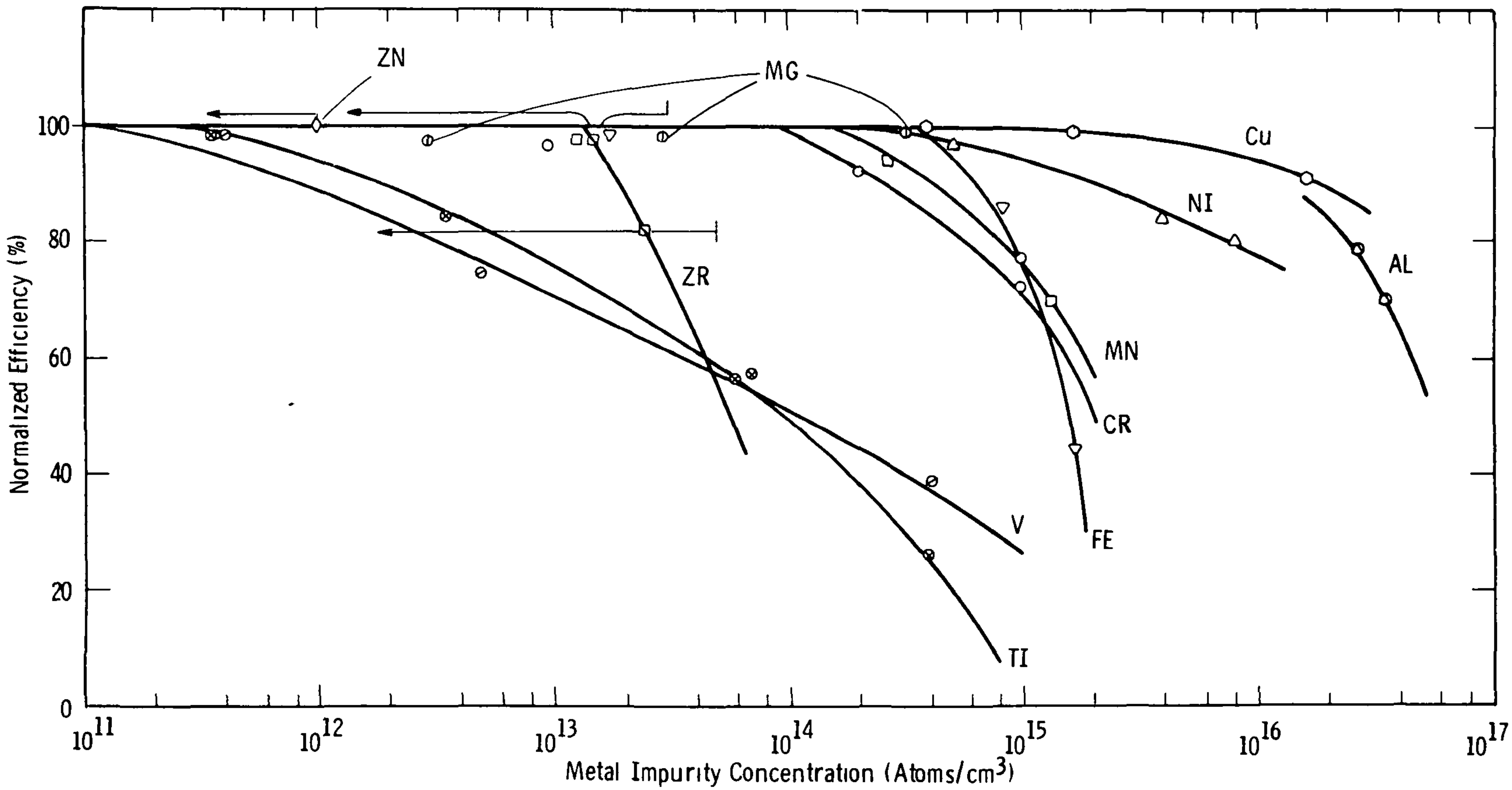

Fig. 22. Normalized solar cell efficiency as a function of substrate metal impurity concentration.

Further development of this approach is in progress and for the present the method provides functionally effective method for predicting the effect of impurities either singly or in combination.

3.2.2.7 Web Solar Cell Data

Solar cells fabricated on web samples are rectangular in shape, a better match in geometry to the present web than are the standard 1 x 1 cm cells used for the Czochralski ingots. Two mask designs, 0.5 x 2 cm and 0.25 x 2 cm, have been used; the data for the metal-doped web in Table 14 were obtained with the aid of the larger mask.

The web cell data though so far scanty represent a cross-section of the contaminants under investigation. The cell efficiencies range from a bit over 9% (no AR coating) for the Ni-doped material to about 7% for the Mn/Cu-doped specimens. Statistically valid comparisons between the effects of various impurity species can't yet be drawn, but compared to specimen DW033 which was not intentionally doped, most of the metal-doped webs exhibit lower efficiencies. The degree of depreciation in the metal-doped webs is consistent with the impurity concentrations in the material, Section 3.1.2.3.

We expected the mask geometry used for the webs to produce cells somewhat less efficient than those made on the Czochralski material. This is because of edge losses associated with the larger perimeter-to-area ratio of the web cells, and because of the possibly larger contact area. To estimate the magnitude of the effect 1 x 2.5 cm blanks were fabricated from our baseline Czochralski ingots and processed to cells using the web masks. The results of the experiment, Table 15, indicate the average (uncoated) efficiencies on cells made with the 0.5 x 2 cm (W) cell are 9.46% compared to about 10% for the standard (B) 1 x 1 cm cell.

3.2.3 Effects of Heat Treatment and Gettering on Lifetime and Cell Performance

Conventional solar cell processing subjects silicon wafers to heat treatment cycles, e.g., during phosphorus diffusion and contact

Table 14. Initial Silicon Web Solar Cell Data (0.5 x 2 cm Cell)
No AR Coating

Sample	I_{sc}	V_{oc}	I_p	I_o	N	FF	EFF (%)	τ_{ocd} (μsec)
DW021-Ni-1B	20.70	.543	18.61	6.6E-07	1.37	.761	9.05	2.34
DW021-Ni-1C	20.70	.543	19.16	4.8E-09	1.99	.732	8.11	3.12
DW026-Mn/Cu-1	18.90	.531	16.79	1.5E-05	2.2	.719	7.63	.78
DW026-Mn/Cu-1	20.70	.531	16.87	3 E-04	2.99	.570	6.63	1.30
DW027-Zr-1	20.20	.539	18.29	2 E-06	1.83	.742	8.54	2.21
DW027-Zr-1	19.20	.528	16.68	9 E-05	2.65	.693	7.43	1.04
DW029-Ni/Mn-1C	19.80	.538	18.25	1.5E-08	1.47	.763	8.60	1.69
DW033-1	20.70	.537	19.07	1.5E-08	1.46	.760	8.93	1.95

Table 15. Comparison of Solar Cells Made on Baseline Ingot W020 with 1 x 1 cm (B) and 0.5 x 2 cm (W) Masks

```
70121 MASK EXPERIMENT NUMBER TWO W020 00 000
DENNY  1 /31/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC    VOC   IP     LOG(IO)   N       R      FF     EFF     OCD     PCDA    PCDB

1B*      22.50 .558 20.38   -6.803 1.81   -.11  .729   9.68    .00     .00     .00
1B       22.90 .559 20.54   -6.067 2.11 -1.02  .731   9.89   3.51    7.30    7.00
2B*      22.20 .486 15.61   -4.250 3.13   6.23  .420   4.79    .39    7.30    7.00
3B       23.70 .555 21.29   -6.147 2.05   -.89  .732  10.18   3.51    7.30    7.00
4B       23.00 .556 20.35   -5.466 2.43 -1.57  .719   9.72   3.25    7.30    7.00
5B       22.90 .559 20.76   -6.512 1.92 -1.00  .749  10.14   3.90    7.30    7.00
6B       23.20 .556 21.02   -6.617 1.86   -.63  .741  10.10   3.90    7.30    7.00
7B*      22.70 .515 17.00   -3.256 5.30 -2.53  .535   6.61    .39    7.30    7.00
8B       23.20 .559 20.70   -5.819 2.23 -1.22  .726   9.96   4.16    7.30    7.00
1W       21.30 .557 19.57   -7.474 1.60   -.48  .762   9.56   3.90    7.30    7.00
2W       21.60 .555 19.61   -6.692 1.84   -.84  .748   9.48   4.16    7.30    7.00
3W*      21.70 .507 16.17   -3.889 3.80   2.56  .486   5.65    .39    7.30    7.00
4W       21.60 .556 19.83   -7.382 1.62   -.55  .761   9.67   4.03    7.30    7.00
5W       21.10 .558 19.13   -6.764 1.83   -.48  .738   9.19   4.55    7.30    7.00
6W       21.40 .558 19.52   -6.977 1.75   -.73  .754   9.52   3.64    7.30    7.00
7W       21.00 .558 18.93   -6.246 2.04 -1.32  .743   9.21   3.51    7.30    7.00
8W       21.40 .559 19.54   -7.025 1.74   -.73  .756   9.56   3.51    7.30    7.00
9W       21.10 .558 19.10   -6.447 1.95 -1.25  .750   9.34   3.64    7.30    7.00
10W      21.50 .560 19.62   -6.956 1.77   -.82  .756   9.63   4.29    7.30    7.00

AVERAGES: 70121  BASELINE  W020 00 000
         23.15 .557 20.78   -6.105 2.10 -1.06  .733  10.00   3.71    7.30    7.00
  STD      .28 .002   .31     .392  .19    .29 .010    .16    .31     *       *
          70121 MASK EXPERIMENT NUMBER TWO
         21.33 .558 19.43   -6.885 1.80   -.80  .752   9.46   3.91    7.30    7.00
  STD      .21 .001   .28     .377  .13    .29 .007    .16    .35     *       *
PERCENT OF BASELINE
         92.2 ****  93.5    112.8   86    75.7 102.6   94.6  105.7  100.0   100.0
 STD%     2.0   .6   2.8     13.8   15    55.9   2.4    3.2   19.0     .1      .0
```

sintering, which may alter the minority carrier lifetime and solar cell performance of impurity-bearing material. Potential mechanisms for these changes in electrical properties include gettering, precipitation, complex formation, and structural damage in the crystalline material. To delineate the magnitudes of these property changes, as well as their variation with impurity species and process history, we earlier conducted some gettering and heat treatment experiments.[2,3] For completeness, the results of these studies are summarized below.

Photoconductive decay lifetime measurements were used for much of the early work since the method is convenient for tracing the behavior of silicon through a sequence of processing steps: specimens can be prepared without heating, but modest heat treatment can be applied to the finished test piece. Measurements on solar cells were made in subsequent studies. A glance at Table 16, a summary of the photoconductive decay data, makes clear that significant lifetime changes occur during the cell process and that some impurities respond much more to heat treatment and phosphorus gettering than do others (diffusion was accomplished at 825°C and contact sintering at 550°C as in our standard cell process, Section 3.2.2). At 550°C, where considerable metal precipitation in silicon might be expected, lifetime improves; Ti and V are exceptions, possibly because of low diffusion constants. The 825°C heat treatment by itself generally does little to enhance lifetime, but in the presence of phosphorus as during cell diffusion, substantial increases occur, probably via gettering. The most important feature of the data is that both the process history and the impurity-type play roles in the ultimate properties of the silicon.

We followed these experiments by testing the efficacy of <u>high</u> temperature phosphorus gettering and damage gettering on Mn, Ti, V, and Fe-doped material. Each of these impurities severely degrades solar cell efficiency so that gettering provides a potential route for improving device performance. Damage gettering was initially accomplished by lapping the back surface of the polished wafers with 22.5 μm size

Table 16. Effect of Heat Treatment on Recombination Lifetime τ_r (μsec)

Specimen Identification	As-Grown	Annealed 5 Hrs @ 550°C	Annealed 50 Min @ 825°C	Phosphorus Diffused 50 Min @ 825°C
W001 Baseline	5.0	5.3	5.7	7.2
W004-CR-001	0.4	1.0	0.7	1.1
W021-CR-002	0.5	---	3.2	4.5
W010-NI-002	4.1	7.4	4.5	9.4
W013-MN-002	<0.3	2.1	4.1	10.5
W009-V-001	<0.3	<0.3	<0.3	<0.3
W007-CU-001	5.4	8.5	3.6	4.4
W008-TI-001	2.0	1.8	0.3	0.5

particles (600 mesh). Phosphorus gettering was performed at 1200°C using $POCl_3$ for 20 mins followed by slow cooling (1°C/min to 600°C and then pulled out of the furnace). The phosphorus diffused n^+-regions were removed by chemical polishing prior to cell fabrication. All cells were fabricated in one run which also included control wafers from baseline material. The detailed results were previously reported;[4] the minority carrier lifetime data compiled in Table 17 illustrate the trends.

Contrary to the low temperature results, high temperature phosphorus gettering reduced the lifetime of devices made on the baseline and Mn-containing cells, but improved the lifetimes of cells containing Ti and V, almost eight-fold in the latter case. Since the damage gettering appeared ineffective, the experiment was repeated with 60 μm grit as the lapping agent. The data, Table 18, reveal a substantial improvement in cell performance for all the impurity-doped ingots.

Auger experiments[3] confirmed that for Cu, Ni, and Cr, at least, phosphorus gettering produces a build-up of the impurities in the n^+ region rather than in the phosphorus glass formed on the wafer surface during diffusion. This is consistent with gettering profiles of other elements measured by Rutherford scattering[11] and suggests that the gettering mechanism is similar in our experiments.

The most salient feature of these results is that cell performance depends to some extent on processing for the impurity-doped material. Specification of Solar Grade silicon therefore implies some kind of process specification as well. Clearly, systematic studies of processing effects on cell performance are warranted; these tentatively will be conducted in the next phase of our program.

Table 17. Effect of Gettering on Minority Carrier Lifetime

Sample No.	Open Circuit Voltage Decay Lifetime, μs		
	Normal Process	$POCl_3$ Gettered*	Back Surface Damage Gettered†
W025 (Baseline)	4.86	2.41	5.85
W005 MN	1.30	0.91	1.43
W008 TI	0.46	0.52	0.39
W009 V	0.13	0.98	0.39

*1200°C treatment. †Back surface lapped with 22.5 μm particles.

Table 18. Effect of Back Surface Damage* Gettering on Cell Efficiency

Sample	I_{sc}, mA		V_{oc}, Volts		τ_{ocd}, μs		η	
	Ungettered	Gettered	Ungettered	Gettered	Ungettered	Gettered	Ungettered	Gettered
W005 MN	17.26	20.20	0.518	0.528	0.90	0.91	6.86	8.80
W008 TI	7.70	13.65	0.438	0.465	0.19	0.13	2.36	5.00
W009 V	10.21	16.00	0.467	0.484	0.28	0.13	3.65	6.30
W018 FE	14.25	18.80	0.493	0.509	0.28	0.78	4.92	7.62

*Back surface lapped with 60 μm particles.

4. IMPURITY SPECIFICATION FOR SOLAR GRADE SILICON

4.1 General Considerations

Our prime objective has been to delineate the effects of metal impurities in silicon so that informed judgments can be made regarding the costs and benefits of using a cheaper, lower purity, solar grade material for solar cells. The foregoing sections of this report provide some of the data on which such an analysis can be based. In this section, we formulate some of the possible tradeoffs. It will become evident that the maximum impurity concentrations in such material depends not only on the impurity type, but also on the crystal growth technique, the cell fabrication process and the solar cell performance criteria.

Visualize the making of a solar cell as a sequence of individual operations, Fig. 23, each of which produces a specific product. For example, the product of the crystal growth operation is a thin crystalline substrate. At each stage in the sequence, the impurities in the silicon are manipulated in ways that influence the properties of the ultimate product. For example, the particular crystal growth technique determines the fraction of the starting impurity content incorporated in the crystal. The device fabrication steps, viz. Section 3.2.2, then in turn determine how this impurity affects the ultimate solar cell performance. Thus, for the <u>individual</u> operations, there are potential costs involved -- lower material throughput, reduced yield, or degraded properties -- which stem from using lower purity silicon. In order to evaluate the impact of Solar Grade silicon on ultimate device performance and cost, the various effects, cost factors and tradeoffs in the individual process blocks must be determined. The problem is one of multi-variate optimization which requires an evaluation of the transfer functions of the individual process elements.

Dwg. 6401A10

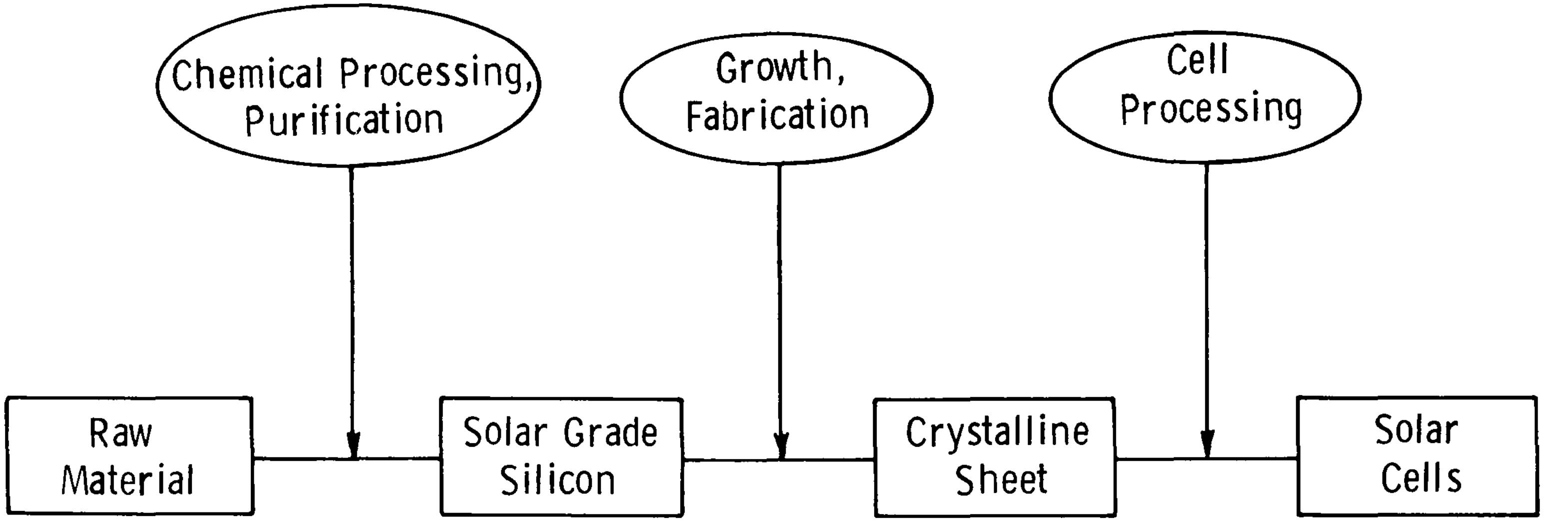

Fig. 23. Schematic description of the solar cell process sequence.

We consider below two kinds of interactions which arise in the crystal growth operation. The first is a relationship between the purity of the crystal growth feed stock and solar cell performance. The second is the effect of feed stock purity on the throughput of the crystal growth process. We have chosen the Czochralski technique to illustrate the approach and identify the parameters required. Similar analyses can and should be done for other crystallization methods. We have begun studies of this type for the dendritic web process.

4.2 Cell Performance -- Impurity Relationships

Figure 22 portrays the relation between solar cell performance and the purity of the silicon substrates from which the cells were made. To link this data with the purity of the silicon feed stock for the growth operation requires a knowledge of the dynamics of impurity partitioning for the particular crystallization technique. The key parameter is k (the effective distribution coefficient), the ratio of the impurity concentration in the crystal to the impurity concentration in the bulk liquid from which it is growing. For the Czochralski and dendritic web methods, our data in Section 3.1.3 indicate that $10^{-7} < k < 10^{-3}$ for the metals of interest.

Given a specific cell performance level, say η_o(baseline) or $0.9\ \eta_o$, and a knowledge of the partitioning of impurities during crystal growth, the impurity level can be extracted from Fig. 22. For any desired relative efficiency, η/η_o, a set of critical metal impurity concentrations $C_s^*(\eta)$ are defined. If the melt concentration were invariant, the feedstock composition could be determined directly from Fig. 22 by dividing the $C_s^*(\eta)$'s by the appropriate k's. In practice, however, consideration must be given to the changes in solid and liquid concentration that often occur during growth. Moreover, since some form of melt replenishment or quasi-continuous growth will probably be required for process economy, this too must be considered.

4.2.1 Impurity Build-Up

In order to illustrate the nature of impurity build-up, we shall examine crystallization from a melt which is well stirred save perhaps for an interfacial boundary layer, e.g., Czochralski growth. As the crystal grows, most of the metallic impurities ($k < 10^{-3}$) are rejected by the solid and accumulate in the remaining melt. Thus, the impurity concentration of the melt, C_ℓ, continuously increases. Since the impurity concentration in the crystal, C_s, is related to the melt concentration by $C_s = kC_\ell$, the last portion of the crystal to freeze has a higher impurity content than the first portion.

Normal Freeze. The simplest case of impurity build-up in the melt, the "normal freeze", has been discussed by Pfann.[12] He derived the following relation for the melt concentration when a fraction, g, has been frozen:

$$C_\ell = C_\ell^i \, (1-g)^{k-1} \tag{4.1}$$

where C_ℓ^i is the initial melt concentration and k is the effective distribution coefficient. It follows that the impurity concentration in the crystal is simply

$$C_s = kC_\ell^i \, (1-g)^{k-1} \, . \tag{4.2}$$

For small k's such as we are considering for metallic impurities, Eq. (4.1) is well approximated by

$$C_\ell \simeq \frac{C_\ell^i}{1-g} \, . \tag{4.3}$$

Thus, if a reasonable fraction of the melt were transformed into a crystal, say g = 0.9, the final concentration would be roughly ten times the initial concentration both in the remaining melt and in the crystal itself.

Sequential Melt Replenishment. The quartz crucibles used for the growth of large diameter silicon crystals are expensive and cost improvements can be realized by recharging the furnace one or more times. Generally, some fraction, g, of the melt is grown as a crystal and the remaining portion of the melt is then frozen but not cooled much below the melting temperature. New material is then added to make up for the amount lost and the whole process repeated. In principle, this process could be continued indefinitely. In this section, we will determine the effect of this strategy on the build-up of impurities in the melt.

For simplicity, consider an operation in which a fraction, g, of the melt is grown into a crystal, after which, the melt is replenished to its original volume with feed material of impurity concentration C_o. The operation is repeated n times, and during each growth run, the impurity content of the liquid builds up according to the normal freeze equation, (4.1). At the beginning of the first growth run, the initial liquid has an impurity concentration $C_\ell^1 = C_o$. It can be shown (Appendix 5) that at the beginning of the n-th run, the initial impurity concentration in the melt is:

$$C_\ell^i(n) = C_o p^{n-1} + C_o g(p^{n-2} + p^{n-3} + \ldots + 1) \tag{4.4}$$

$$= C_o \left\{ p^{n-1} + g\left[\frac{p^{n-1} - 1}{p - 1}\right]\right\} \tag{4.5}$$

where $p = (1-g)^k$. At the <u>end</u> of the n-th growth run, the impurity concentration in the melt has increased according to the normal freeze law which in the present notation can be written:

$$C_\ell^f(n) = \frac{p}{1-g} C_\ell^i(n) \tag{4.6}$$

If k << 1, then $p \simeq 1$ and Eqs. (4.4) and (4.6) can be approximated by

$$C_\ell^i(n) \simeq C_o \ (1 + g(n-1)) \tag{4.7}$$

and

$$C_\ell^f(n) \simeq C_o \ (1 + \frac{ng}{1-g}) \ . \tag{4.8}$$

The sequential build-up of impurities for $k \leq 10^{-3}$ and $g = 0.9$ is shown as the series of solid curves in Fig. 24; the curve for $n = 1$ is the behavior for a simple normal freeze. Curves of this type can be developed for other initial conditions. Also shown in Fig. 25 is a dashed curve representing the impurity build-up for a melt continuously replenished with feed material of composition C_o.

Continuous Melt Replenishment. An alternative to replenishing the melt after each run is to replenish the melt continuously as the crystal or crystals are being grown. This procedure leads to a much slower build-up of solute than the sequential technique; in fact, the build-up of impurity in the melt is governed by the equation (Appendix 5):

$$\frac{C_\ell}{C_o} = \frac{1}{k}\left[1 - (1-k)\,\exp\,(-\frac{kV_c}{V_o})\right] \qquad (4.9)$$

or approximately

$$\frac{C_\ell}{C_o} = (1 + (1-k)\,\frac{V_c}{V_o}) \qquad \text{for} \quad \frac{kV_c}{V_o} << 1 \, , \qquad (4.10)$$

where V_c is the volume of crystal that has been grown and V_o is the melt volume. If $k = 10^{-3}$ and $V_c = 4.5\ V_o$ (equivalent to growing five crystals of volume $0.9\ V_o$), the solute concentration in the melt increases to $5.5\ C_o$ compared with $45.7\ C_o$ for a sequentially replenished melt.

Clearly, the manner in which the melt is replenished has a strong effect on the ultimate impurity content of the crystalline material and hence on the performance of the final device; thus, tradeoffs with respect to replenishment strategy exist. Continuous replenishment would appear to have advantages over sequential replenishment; however, the capital costs needed to implement the process may not be inconsiderable. It should be emphasized again that the details of the model we have presented apply only to a particular class of crystallization processes and that similar analyses should be performed for other crystal growth techniques. For example, the effective distribution coefficient, k, is

Curve 688429-A

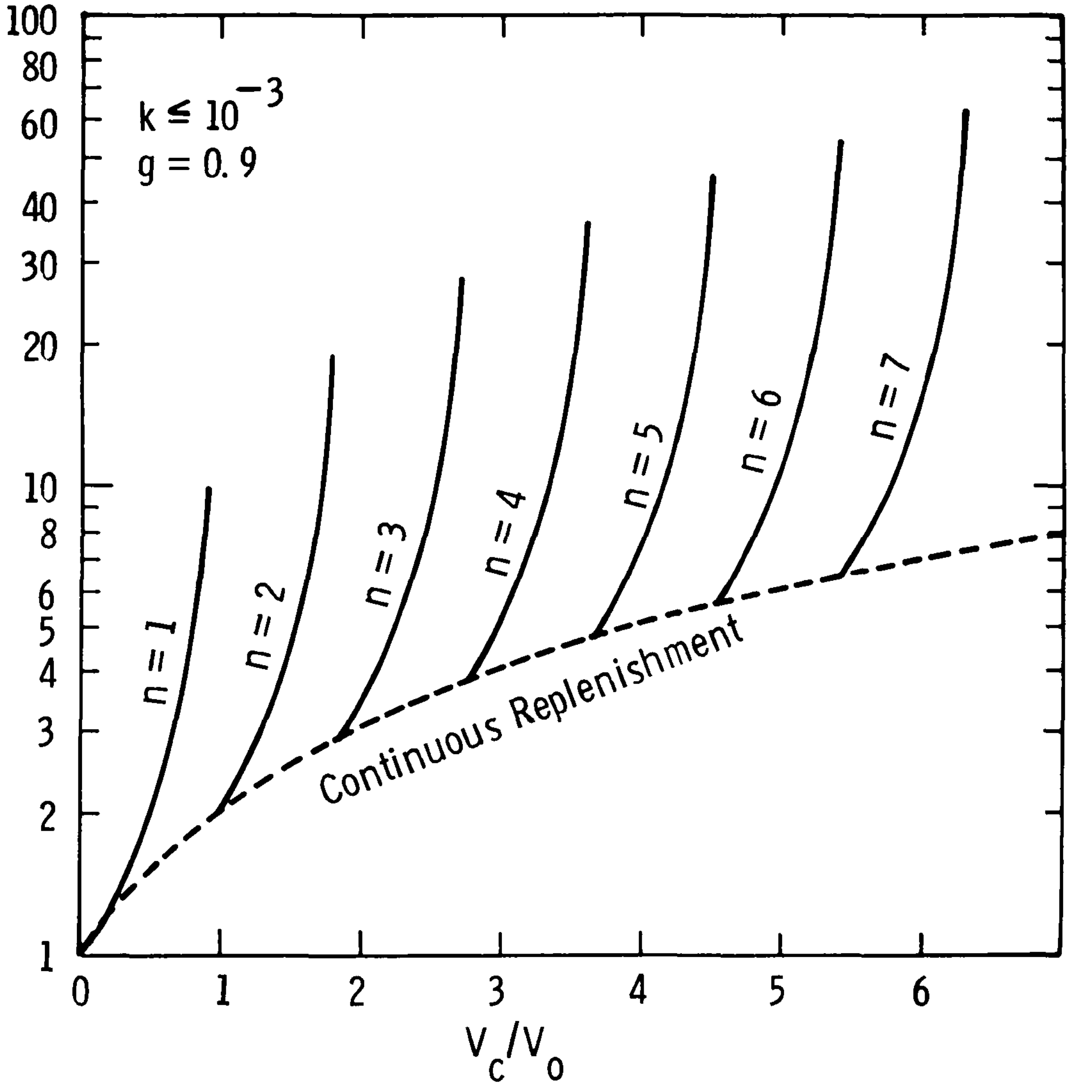

Fig. 24. Solute build-up in the liquid (or crystal) as a function of the volume of crystal grown for sequential (solid) or continuous (dashed) melt replenishment.

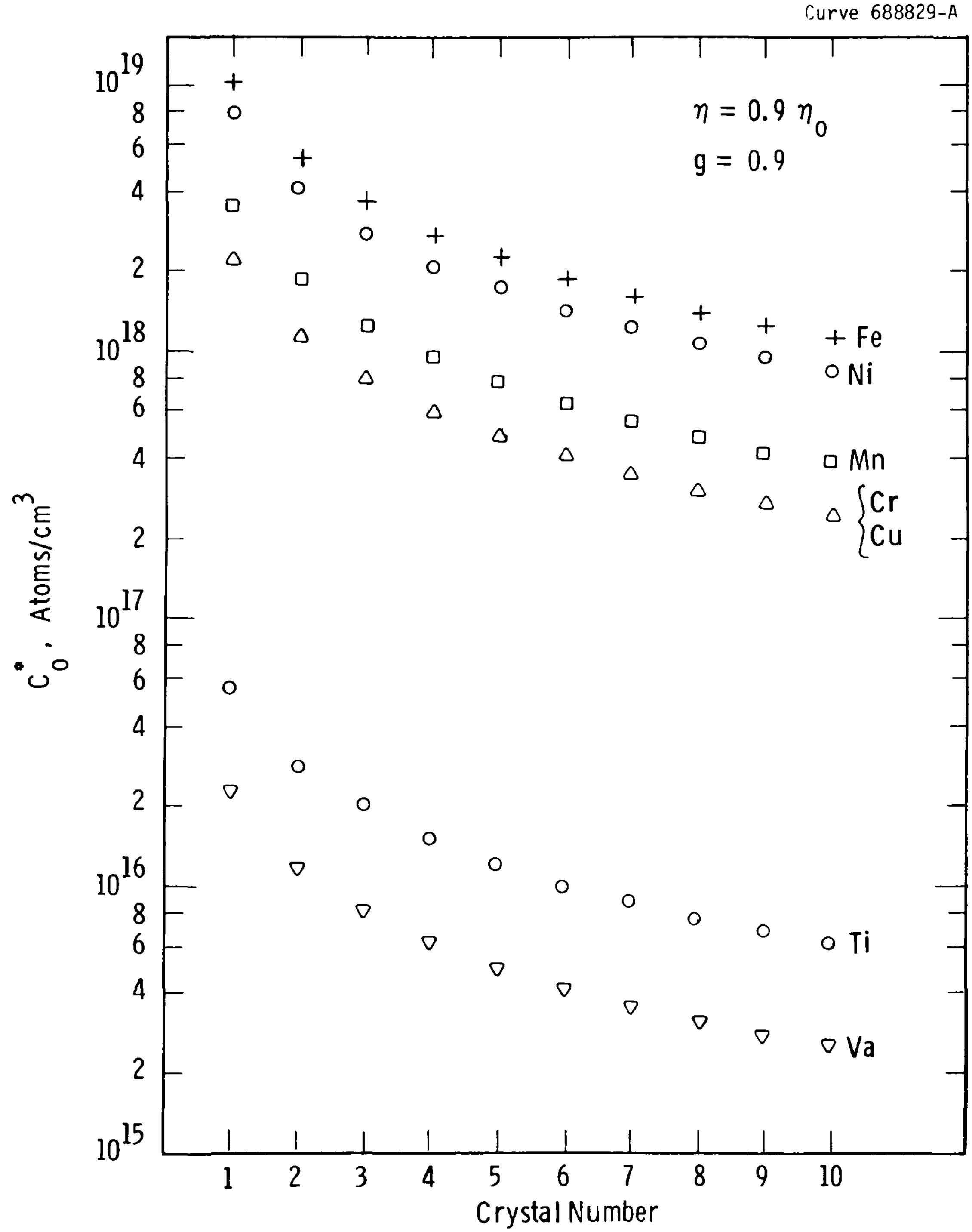

Fig. 25. Critical liquid metal impurity concentrations (feedstock purity) to produce solar cells 90% as efficient as the unintentionally-doped baseline material. Sequential Melt Replenishment.

dependent on the nature of the process and may in fact nearly equal unity for some. This change would drastically affect the "transfer function" relating the impurity content of the feed stock to the impurity content of the final substrate.

4.2.2 Impurity Content and Cell Efficiency

In the previous section, we formulated an example of the "transfer function" relating the feed stock purity to substrate purity. In this section, we carry the analysis one step further and relate the solar cell performance to the feed stock purity. As before, the analysis is based on the performance data of cells fabricated by a specific technology, phosphorus diffusion, and the numerical data are not necessarily applicable to other techniques.

As noted above, the critical data for the analysis are given in Fig. 22 of Section 3.2.2 which relates cell efficiency to the metal content of the substrate. It is apparent from the curves that if one can accept something less than maximum efficiency, then higher impurity concentrations can be tolerated in the substrate. For purposes of example, we extracted some data from the figure which illustrate (1) how the solid concentration $C_s^*(\eta)$ varies from impurity to impurity for fixed $\eta = 0.9\ \eta_o$, Table 19 and (2) how $C_s^*(\eta)$ increases for a given impurity, Ni, as the acceptable relative cell efficiency η/η_o declines. For the case of Czochralski pulling with sequential melt replenishment we find the critical impurity concentration in the liquid by forming the ratio of the critical solid concentration $C_s^*(\eta)$ and the effective distribution coefficient, k (third column, Table 19). Then C_o is calculated by dividing this critical liquid concentration by the impurity build-up ratio from Eqs. (4.5) or (4.9) or from Fig. 24. The results obtained for the series of metallic impurities in the table are shown in Fig. 25. The limiting impurity content of course depends on the cell efficiency which can be tolerated. The Ni data in Table 20 and Fig. 26 illustrate this point. For a given n, or number of crystals grown, almost two orders of magnitude exist between $\eta = \eta_o$ and $\eta = 0.8\ \eta_o$.

Table 19. Critical Solid Concentration and Liquid Concentration to Produce Solar Cells 90% as Efficient as Baseline Cells (η/η_o = .9)

Metal	C_s^* (0.9)	k	C_ℓ
Ni	2.5 (15) at.cm^{-3}	3.2 (-5)	7.8 (19) at.cm^{-3}
Fe	6.5 (12)	6.4 (-6)	1.0 (20)
Cu	1.5 (16)	6.9 (-4)	2.2 (19)
Mn	4.5 (14)	1.3 (-5)	3.5 (19)
Cr	2.5 (14)	1.1 (-5)	2.3 (19)
Ti	2.0 (12)	3.6 (-6)	5.5 (17)
Va	9 (11)	4 (-6)	2.3 (17)

Table 20. Variation in Critical Solid and Liquid Concentration with Relative Solar Cell Efficiency for Ni

η/η_o	C_s^* (η/η_o)	k	C_ℓ
1.0	1.5 (14)	3.2 (-5)	4.7 (18)
0.95	9.8 (14)		3.1 (19)
0.90	2.5 (15)		7.8 (19)
0.80	8.0 (15)		2.5 (20)

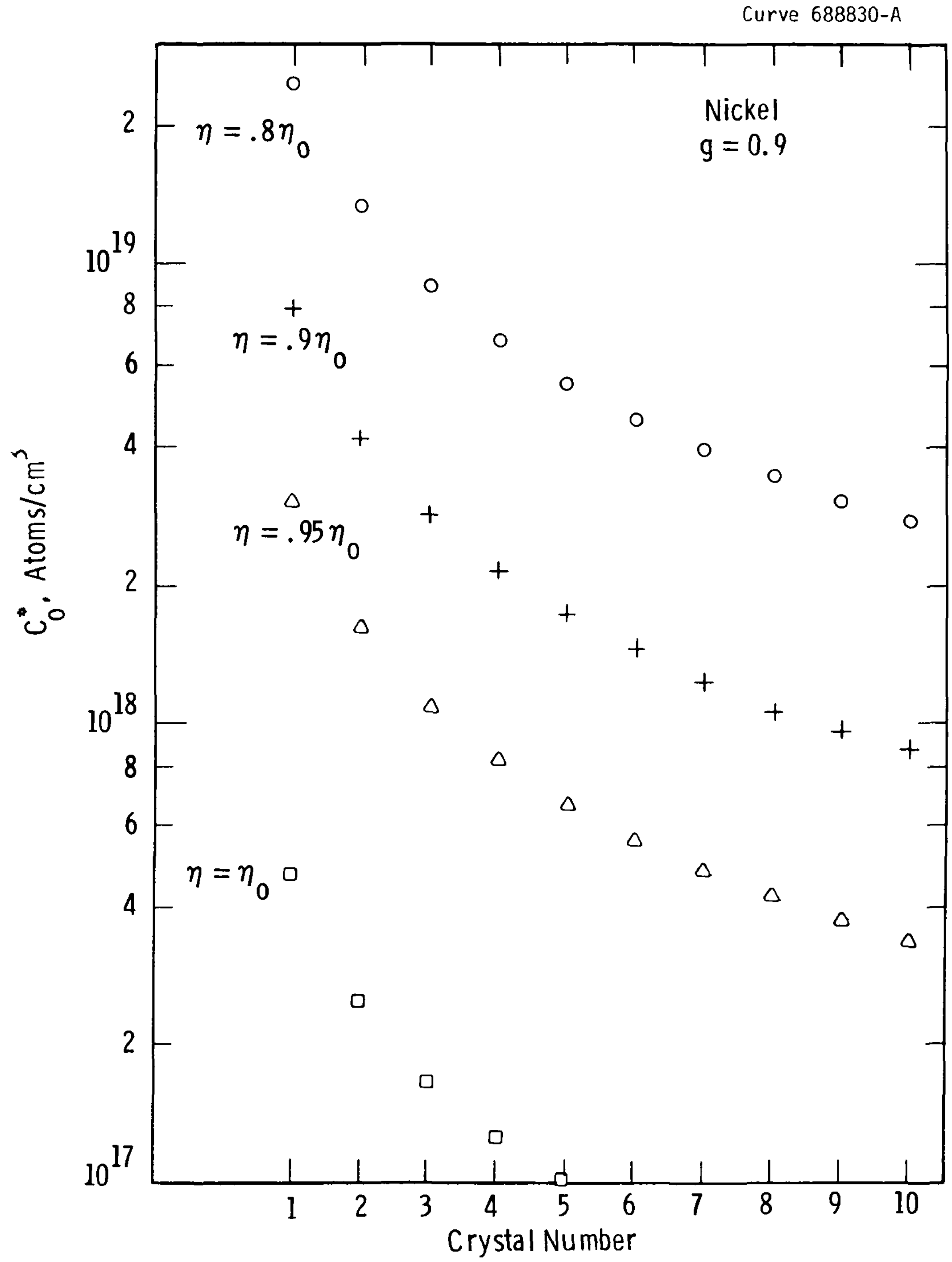

Fig. 26. Variation of critical nickel feedstock impurity concentration with number of Czochralski crystals grown using sequential replenishment. Relative solar cell efficiency displayed parametrically.

4.2.3 System Throughput -- Impurity Relations

Besides their direct electrical effects on the lifetime of solar cell devices, impurities can also limit the range of conditions for which single crystals can be grown. This is because a corrugated, crystal-liquid interface can develop in the presence of impurities when the ratio of liquid temperature gradient, G_ℓ,[13] to growth velocity, R, falls below a critical value. In extremis the phenomenon -- called constitutional supercooling -- may lead to the growth of a polycrystalline dendritic array.

Briefly, at steady-state, the conditions required to sustain stable crystal growth from a liquid of concentration C_ℓ are that $G_\ell/R > \frac{(-m\, C_{\ell o})}{D} \left(\frac{1-k_o}{k_o}\right)$. The liquidus slope, m, and the equilibrium distribution coefficient, k_o, are obtained from the respective phase diagram ($m < 0$ for $k < 1$) and D is the impurity diffusion coefficient in the liquid. Hurle[14] reformulated the expression to account for stirring in the liquid during Czochralski growth:

$$\frac{G_\ell}{R} > \frac{(-m\, C_\ell)}{D} \frac{1 - k_o}{\{k_o + (1-k_o)e^{-\Delta}\}} \tag{4.11}$$

where $\Delta = \frac{R\delta}{D}$; δ is the thickness of the diffusion dominated boundary layer. The remainder of the liquid has impurity concentration C_ℓ. We have adopted Hurle's analysis to illustrate the tradeoffs between impurity content and throughput for Czochralski pulling. Again similar analyses can be developed for other processes.

Equation (4.2) may be recast in terms of the solid thermal gradient G_s, a quantity more readily calculated, or measured, than is G_ℓ:

$$\frac{K_s G_s - LR}{K_\ell R} > \frac{(-m\, C_{\ell o})}{D} \frac{1 - k_o}{\{k_o + (1-k_o)e^{-\Delta}\}}\ , \tag{4.12}$$

where K_S and K are the solid and liquid thermal conductivities and L is the latent heat of fusion per unit volume.

With some cancellation, Eq. (4.12) can be rearranged to show the variation of C_ℓ^*, the critical impurity concentration for breakdown, with growth parameters,

$$C_\ell^* = \frac{D}{(-m)} \frac{K_s G_s}{K_\ell R} - \frac{L}{K_L} \frac{\{k_o + (1-k_o)e^{-\Delta}\}}{1 - k_o} \ . \tag{4.13}$$

When k_o is small, Eq. (4.13) can be further simplified since $1 - k_o \simeq 1$ and $k_o + (1-k_o)e^{-\Delta} = k_o(1-e^{-\Delta}) + E^{-\Delta} \simeq e^{-\Delta}$. Thus,

$$C_\ell^* = \frac{D}{(-m)} \left(\frac{K_s G_s}{K_L R} - \frac{L}{K_L}\right) e^{-\Delta} \ . \tag{4.14}$$

The critical impurity concentration depends strongly on the growth parameters but less so on the species of metal impurity.

G_s can be calculated from the heat flow through the growing crystal. For simplicity, we choose a solution derived for a crystal of radius r, and constant conductivity K_s, which looses heat by radiation to a 0°K environment,[15]

$$G_s = \sqrt{\frac{2\varepsilon\sigma}{5K_s r}}\, T^{5/2} \ .$$

Substituting this in Eq. (4.14) and evaluating the resulting expression with

$\varepsilon_s = 0.45$

$K_s = 0.216$ watt $\mathrm{cm}^{-k}\mathrm{K}^{-1}$

$K_\ell = 0.6$ watt $\mathrm{cm}^{-k}\mathrm{K}^{-1}$

$L = 4128.5$ J cm^{-3}

$\sigma = 5.73\ (10^{-12})$ watt $\mathrm{cm}^{-2}\mathrm{K}^{-4}$

gives $C_{\ell o}^* = \frac{D}{(-m)} \left[\frac{A}{r^{1/2}R} - B\right]$, where A = 92.44 and B = 6.88 (10^3) with r in cm and R in cm/sec.

For dilute solution the liquidus slope depends on the number rather than kind of atom in the liquid and can be obtained from the data of Thurmond and Kowalchik[16]: $m \cong -464°K$ (at. fract)$^{-1}$. Liquid diffusion coefficient data for silicon are sparse -- but D generally ranges around the value 10^{-4} cm^2/sec which we have adopted for purposes of calculation.[17] Finally, we chose $\delta/D \sim 130$ as characteristic of our experiments.[17]

As Fig. 27 indicates, the critical impurity concentration for which breakdown occurs varies inversely with R at low velocities where the latent heat term is negligible. At higher velocities C_ℓ^* falls rapidly as the velocity (R_{max}) for which G_L goes to zero is approached. Superimposed in Fig. 27 are actual values of impurity concentrations for which we observed the formation of cellular structures like the one in Fig. 28. Our crystals were about 1.75 cm in radius and grew at 6.9 cm/hr. The data points bracket the value of C_ℓ^* predicted for crystals with 2 cm radii. This spread -- about a factor of two in concentration -- is to be expected on the basis of potential measuring errors and the fact that D does vary somewhat from metal to metal.

The model for breakdown, Eq. (4.14), can be improved in two respects. First, a more refined calculation of G_s can be made.[18] Corrections for temperature-dependent conductivity and radiation to an ambient above 0°K will diminish the calculated value of G_s (and G_ℓ) shifting the curves in Fig. to lower C_ℓ^* at fixed R. Application of a more sophisticaled model for breakdown, like that of Mullins and Sekerka[19] will add stabilizing terms to Eq. (4.14) which raise the critical impurity concentration. The two corrections tend to offset one another, possibly accounting for the fairly good fit of our data to Eq. (4.14).

More important than the numerical accuracy in Fig. 27 are the trends indicated with respect to impurity tradeoffs in Czochralski growth. C_ℓ^* is strongly dependent on R but rather insensitive to the

Curve 688421-B

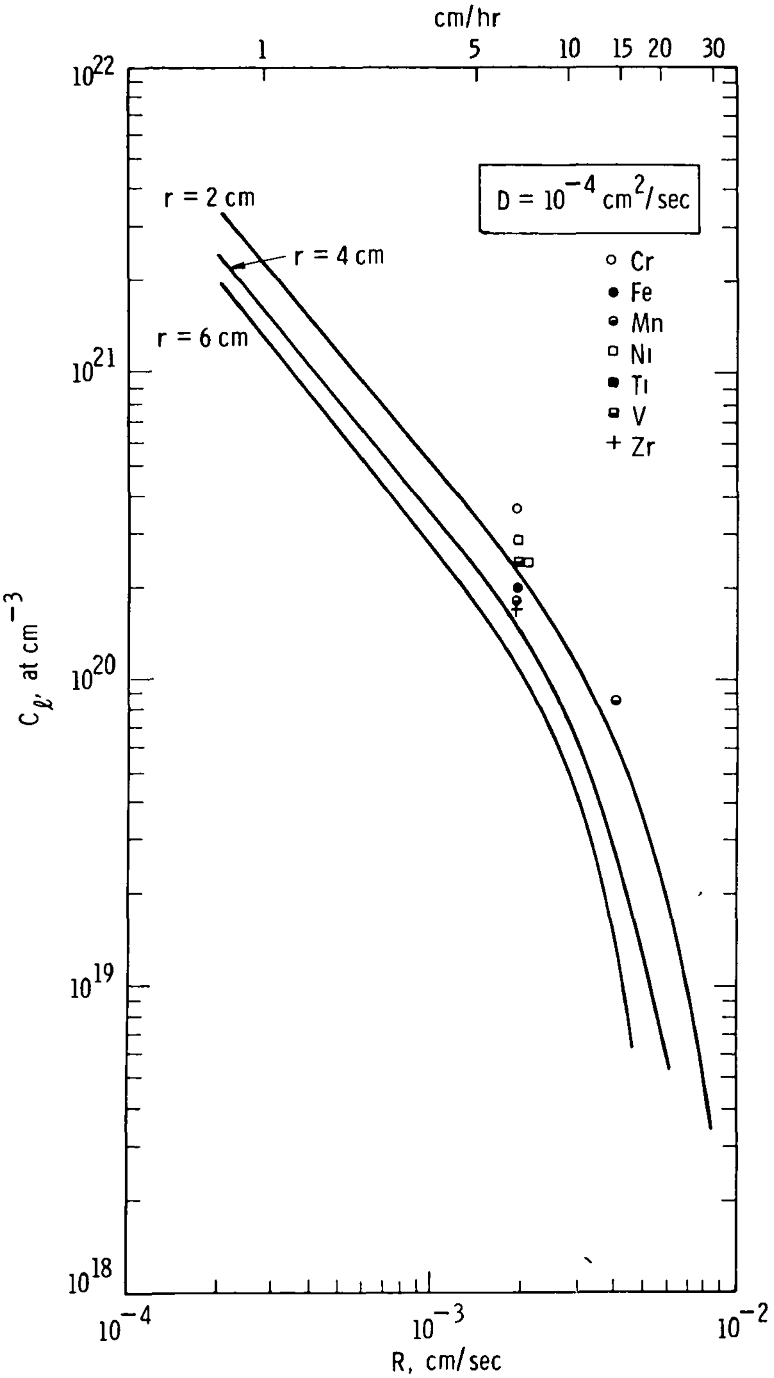

Fig. 27. Predicted variation of critical liquid impurity concentration for crystal breakdown with crystal growth velocity during Czochralski pulling of silicon. Metal concentrations for which breakdown actually occurred are indicated by the data points.

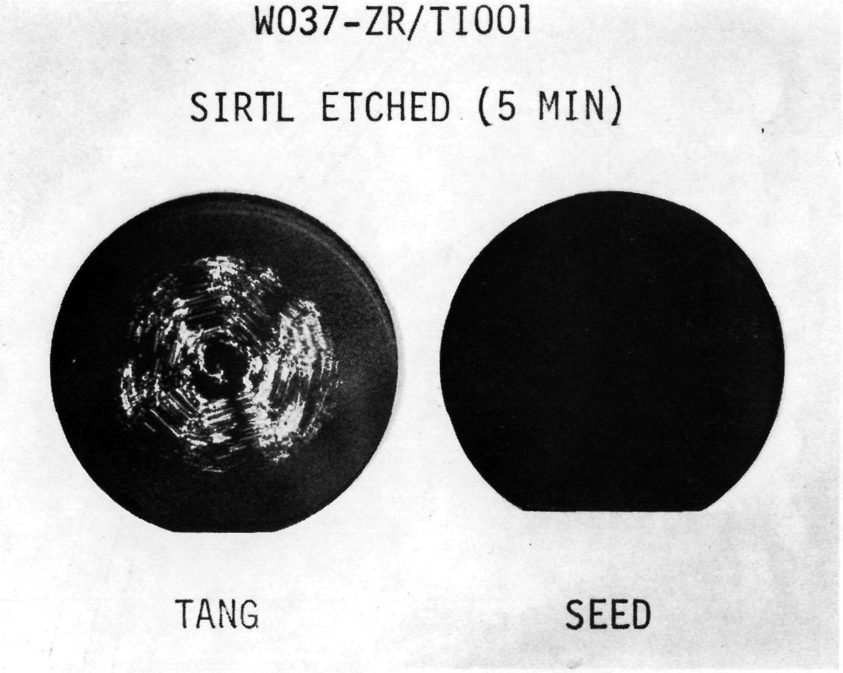

Fig. 28. Typical cellular structure which developed toward the end of a Zr/Ti-doped silicon crystal grown at 6.9 cm/hr.

magnitude of r, the crystal radius. Thus, if system throughput is to be maximized growing larger crystals rather than growing crystals more rapidly may prove to be the appropriate strategy.

Figure 27 indicates that even when R $\sim$ 15 cm/hr total impurity concentrations over 10^{19} at/cm^3 can be tolerated for stable steady-state Czochralski growth. This value is generally greater than the critical impurity concentrations for solar cell performance in Table 17 or Fig. 25. Thus, cell performance limitations, rather than crystal growth restrictions will limit impurity content for intermediate growth rates. However, at higher growth speeds impurity-induced breakdown may limit the maximum impurity content.

One other point is worth noting. Since C_ℓ^* (or $C^*(\eta)$) must eventually be exceeded, there is a reduction in material yield associated with the use of Solar Grade silicon. That is because once the critical liquid concentration is reached, the remaining material is useless and must be discarded or diluted with purer material. Either approach means that less than 100% of the original feedstock is used, and this cost must be factored into any tradeoff analysis.

5. CONCLUSIONS

The first phase of this program to investigate impurity effects on silicon solar cells is essentially completed. On the basis of structural, chemical, electrical and solar cell measurements made on silicon wafers intentionally contaminated with metal impurities, we have developed a functional model for the effect of contaminants on cell performance. The fit of the derived functions to observed solar cell operating parameters is consistent with the hypothesis that impurity atoms act independently of each other and as carrier recombination centers. With the model we have successfully predicted the behavior of solar cells containing two or more impurity species, a first step in projecting how Solar Grade material might behave.

With the solar cell/purity relationships and known crystal growth impurity partioning behavior as input information, we estimated the tolerable impurity levels for a Solar Grade feedstock material that might be used for Czochralski pulling. The acceptable purity depends on the desired solar cell performance level, and for typical growth rates, is dictated by solar cell performance not crystal breakdown. If melt replenishment is used, a continuous rather than sequential feed has advantages in Czochralski pulling. Our solar cell/purity data can be used to perform similar evaluations for other crystal growth processes.

Gettering can have a pronounced effect on the lifetime of impurity-doped silicon. The magnitude of the effect is species and temperature dependent. For some impurities, the improvement in cell performance following gettering is dramatic and may provide a means to accept higher impurity levels in the silicon substrate.

Ribbon crystals of silicon grown by the dendritic web process have been chemically analyzed and fabricated into solar cells. For material 7-13 mm wide, grown at 1.3 cm/min, solar cells with efficiencies in the 7 to 9% (no AR coating) range have been made on purposely metal-contaminated specimens. The degree of performance degradation is consistent with impurity levels near 10^{14} to 10^{15} atoms cm^{-3} estimated by spark source mass spectroscopy.

6. FUTURE ACTIVITY

Our data and modeling present a reasonably clear but somewhat incomplete picture of the effects of impurities on p-base solar cells. It is evident that several key areas require further study before sufficient data are available to provide the detailed description that is desirable for multivariate optimizations. First, the role of processing on cell performance must be more clearly defined. Our initial work indicates that the impurity-cell performance relationships are somewhat process dependent. The degree of dependency remains to be discovered and studies of this type will be undertaken for key impurities. For the crystal growth operation, both Czochralski and web improved breakdown data are needed as input to tradeoff analysis. Modeling of segregation and breakdown in web is also needed to accompany the experimental measurements. Second, our data base on p-type silicon must be expanded to include the remaining impurities found in metallurgical grade silicon and key impurities likely to be incorporated during other operations such as sheet growth. Moreover, improved data for projecting the behavior of multiply-doped ingots is a requirement. At a much lower activity level we plan experiments involving float zoning to verify the original conclusions about the effects of carbon and oxygen on cell performance, and some initial studies to evaluate grain boundary effects.

Beyond these studies which derive directly from our initial work on p-base cells, there are two other major areas which should be explored to complete the assessment of impurity/process effects in silicon. The first is an evaluation of the behavior of solar cells containing much higher boron levels (lower resistivity) than present in the devices now under study. The relevance of this effort stems from the fact that Solar Grade silicon is very likely to contain relatively high boron levels and because there is some theoretical justification to expect peak solar cell efficiencies for substrates in the 0.1 to 0.3 Ω-cm resistivity range. A second consideration is the role of cell design itself. For example, n-based solar cells, made from phosphorus-doped silicon have been widely used in the past. Since the choice of optimum cell design is yet open and impurities may affect n-base silicon in a different fasion from the p-base counterpart, work in this material is warranted.

6. REFERENCES

1. R. H. Hopkins et al., First Quarterly Report, Silicon Materials Task (Part 2), ERDA/JPL-954331-76/1, February 1976.
2. R. H. Hopkins et al., Second Quarterly Report, Silicon Materials Task (Part 2), ERDA/JPL-954331-76/2, May 1976.
3. R. H. Hopkins et al., Third Quarterly Report, Silicon Materials Task (Part 2), ERDA/JPL-954331-76/3, July 1976.
4. R. H. Hopkins et al., Fourth Quarterly Report, Silicon Materials Task (Part 2), ERDA/JPL-954331-76/4, October 1976.
5. Third Quarterly Report, Automated Array Assembly Task, ERDA/JPL-954352-76/3, September 1976.
6. D. K. Schroder, unpublished results 1968. Includes a summary of the work due to Shockley, Reed, Hall, et al.
7. S. R. Lederhandler and L. J. Giocoletto, Proc. IRE 43, 477-483 (1955).
8. B. Ross and J. R. Madigan, Phys. Rev. 108, 1428 (1957).
9. K. Levenberg, Quart. App. Math., 2, 164-168 (1944).
10. J. Roger, Proc. Photovoltaic Specialists 9, 345-352, (1974).
11. R. L. Meek and C. F. Gibbons, J. Elect. Soc. 121, 444 (1974).
12. W. F. Pfann, Transactions AIME 194, 747 (1952).
13. W. A. Tiller et al., Acta. Met. 1, 428 (1953).
14. D. T. J. Hurle, Solid St. Electronics 3, 37 (1961).
15. T. F. Cizek, J. Appl. Phys. 47, 440 (1976).

16. C. D. Thurmond and M. Kowalchik, Bell System Tech Journal 39, 169 (1960).

17. H. Kodera, Japan. J. Appl. Phys. 2, 212 (1963).

18. S. Rhea, Large Area Czochralski Growth, First Quarterly Report ERDA/JPL-954475-76/1, June 1976.

19. W. W. Mullins and R. F. Sekerka, J. Appl. Phys. 35, 444 (1964).

APPENDIX 1

Resistivity, Dislocation Density, and Carbon/Oxygen Concentration for Czochralski Ingots

Ingot Identification	Resistivity Seed/ Resistivity Tang (ohm-cm)	Etch Pit Density of Seed End (Etch Pits/cm^2)	Carbon Conc./ Oxygen Conc. (10^{16} atoms/cm^3)
W-001-00-000	2.8/3.2	0	7.5/94
W-002-00-000	3.0/4.0	0	8.3/57
W-003-00-000	3.1/3.6	0	12.5/94
W-004-Cr-001	4.6/4.3	500	6/88
W-005-Mn-001	3.6/3.1	600	6/126
W-006-Ni-001	4.1/3.5	300	7.3/96
W-007-Cu-001	5.2/3.7	0	7.5/49
W-008-Ti-001	4.2/3.1	1800	14/150
W-009-V-001	4.1/3.4	0	18/100
W-010-Ni-002	3.9/3.4	200	12.5/140
W-011-Zr-001	4.4/3.6	400	8/87
W-012-Cr-002	4.1/3.9	400	5/170
W-013-Mn-002	4.3/3.2	200	5/160
W-014-00-000	4.3/3.2	1000	5/160
W-015-Zn-001	3.9/3.6	500	9/100
W-016-Fe-001	4.6/5.2	0	5.5/95
W-017-Cu-002	3.8/3.6	2200	5.5/78
W-018-Fe-002	5.9/5.0	500	7/80
W-019-Cu-003	3.8/3.5	200	4.2/96
W-020-00-000	4.0/2.9	0	3.2/160
W-021-Mg-001	3.8/3.4	500	8/110
W-022-00-000	4.1/3.2	500	7/140
W-023-00-000	0.15/0.15	2500	N/A
W-024-Mg-002	3.8/3.6	3750	8.8/46
W-025-00-000	5.1/4.7	2000	9.6/96
W-026-Mn-003	4.5/3.9	1000	9.4/140
W-027-Mn/Cu-001	8.4/6.3	1250	<2.5/110
W-028-Al-001	2.9/2.4	750	17/80
W-029-Cr-003	5.2/4.6	0	2.5/150
W-030-Cr/Cu-001	7.3/6.9	500	3.8/140
W-031-Cr/Mn-001	8.8/4.7	1250	11/110

Resistivity, Dislocation Density, and Carbon/Oxygen Concentration for Czochralski Ingots

Ingot Identification	Resistivity Seed/ Resistivity Tang (ohm-cm)	Etch Pit Density of Seed End (Etch Pits/cm^2)	Carbon Conc./ Oxygen Conc. (10^{16} atoms/cm^3)
W-032-Mg-003	4.5/4.1	0	9/90
W-033-Ti-002	4.5/4.2	0	10/100
W-034-00-000	4.4/4.2	0	2.9/130
W-035-V-002	4.4/3.9	1500	5.1/135
W-036-Zr-002	4.4/4.1	500	5.5/137
W-037-Zr/Ti-001	5.1/4.5	500	8.3/190
W-038-Al-002	2.2/1.55	0	63/143
W-039-Ni-003	5.2/4.3	Multi Xtal	2/170
W-040-Cr/Ni-001	5.3/4.0	1000	3/150
W-041-Ni/Cr/Cu-001	5.1/4.7	2000	9/115
W-042-Ti-003	3.75/3.7	1500	13/150
W-043-Fe/Ti-001	5.7/2.8	750	7.3/159
W-044-Fe-003	3.8/3.8	0	2.4/135
W-045-Cr/Fe/Ti-001	5.3/4.3	500	10/118
W-046-Fe/V-001	5.7/5.3	500	7.7/166
W-047-Cu/Ni/Zr-001	4.8/4.4	1500	2.3/140
W-048-Ti-004	4.5/3.75	500	6.9/145
W-049-V-003	4.4/3.9	0	10.3/170
W-050-Ti/V-001	4.6/4.4	500	10.8/149
W-051-Cu/Ti-001	5.0/4.4	500	6.6/166
W-052-Ni-004	4.2/3.8	4000	12.7/170

APPENDIX 2

Metal Impurity Analyses for Czochralski Crystals

The results of the metal impurity analyses are compiled in the accompanying table. The target and calculated impurity concentrations for ingots W001 to W031 were based on effective segregation coefficients available at the beginning of the program.[1] For the remainder of the ingots, the effective segregation coefficients determined by us, Table 4, were used. The calculated concentration shown in the table derived from the impurity concentration found in the crucible remains corrected for the impurity build-up which occurred during crystal growth. The data is, for the most part, self-explanatory; however, some points should be made about specific ingots.

Ingot W006 was grown using a high purity nickel powder as a dopant source. No nickel was detected in the ingot (i.e., $<5 \times 10^{14}$ atoms/cm^3); analysis of the crucible remains indicated that in excess of 80% of the nickel had been lost from the melt. Nickel wire was used for subsequent runs and nickel loss from the melt was substantially reduced. When we attempted to prepare very heavily nickel-doped samples, e.g., ingots W039-Ni003 and W052-Ni004, high defect concentrations developed and the analytical results are therefore less certain than for the other ingots.

No zirconium was detected in ingot W011-Zr001 by either SSMS or NAA. From this data and some ancillary NAA results, we conclude that effective segregation coefficient is much smaller than 10^{-5} as initially supposed. A value of $\sim 10^{-7}$ seems consistent with the small amount of data available.

Mg and Zn are highly volatile at the melting point of silicon and rapidly evolve from the melt. Although two ingots were grown from melts initially containing zinc, it proved impossible to retain zinc in the liquid. No Zn was detected in ingot W015-Zn001 and less than 0.1 percent of the original four grams of Zn added to the melt was detected in the crucible remains. Mg loss during the growth of ingots W021, W024 and W024 was also significant. Prior to growth of the latter crystal the loss rate was calculated from experimental measurements and a smaller effective segregation coefficient was employed in establishing crystal concentration.

A substantial difference exists between the aluminum concentration determined by electrical measurements (resistivity) and that indicated by SSMS data. The target concentrations for ingots W028-Al001 and W038-Al003 were based on an effective segregation coeffficient determined by resistivity measurement. The concentration determined by SSMS is considerably larger indicating a high concentration of non-electrically active aluminum.

APPENDIX 2 (con't)

Ingot Analysis (Intentionally Added Impurity)

Ingot Identification	Target Conc. $(10^{15}$ atoms/cm$^3)$	Calc. Conc. $(10^{15}$ atoms/cm$^3)$	Mass Spec Conc. $(10^{15}$ atoms/cm$^3)$	NAA Conc. $(10^{15}$ atoms/cm$^3)$
W-001-00-000	-	-	-	-
W-002-00-000	-	-	-	-
W-003-00-000	-	-	-	-
W-004-Cr-001	1	0.82	1.0	<4 [1]
W-005-Mn-001	1	0.82	1.35	0.6
W-006-Ni-001	1	0.17 [2]	<0.5	NA
W-007-Cu-001	1	1.18	1.80	1.65
W-008-Ti-001	1	0.82	0.36	0.15
W-009-V-001	1	1.19	0.31	NA
W-010-Ni-002	1	0.56	4.0	NA
W-011-Zr-001	1	2.67 [3]	<0.45	<0.03
W-012-Cr-002	0.2	0.18	<0.5	NA
W-013-Mn-002	0.2	0.15	<0.5	NA
W-014-00-000	-	-	ND	-
W-015-Zn-001	1	<0.0006 [4]	<0.5	NA
W-016-Fe-001	1	0.75	<3.0	0.90
W-017-Cu-002	10	7	32	25
W-018-Fe-002	2	1.6	<3	1.7
W-019-Cu-003	0.2	0.53	<0.5	-
W-020-00-000	-	-	-	-
W-021-Mg-001	1.0	0.59 [5]	<0.5	NA
W-022-00-000	-	-	-	-
W-023-00-000	-	-	-	-
W-024-Mg-002	10	7.3	<0.5 [6]	NA
W-025-00-000	-	-	-	-
W-026-Mn-003	0.01	0.0089	<0.5	NA
W-027-Mn/Cu-001	1/1	0.73/0.64	1/1.0	1.1/2.2
W-028-Al-001	1	-	26	NA
W-029-Cr-003	0.01	0.0083	<0.5	NA
W-030-Cr/Cu-001	1/1	0.82/0.75	1/1.0	0.5/2.5

Ingot Analysis (Intentionally Added Impurity) (cont.)

Ingot Identification	Target Conc. (10^{15} atoms/cm^{3})	Calc. Conc. (10^{15} atoms/cm^{3})	Mass Spec Conc. (10^{15} atoms/cm^{3})	NAA Conc. (10^{15} atoms/cm^{3}
W-031-Cr/Mn-001	1/1	0.85/0.82	1/2.5	-
W-032-Mg-003	1	0.24	0.32	NA
W-033-Ti-002	0.01	0.011	<0.3	NA
W-034-00-000	-	-	-	-
W-035-V-002	0.01	0.013	<0.2	NA
W-036-Zr-002	2	1.74	<0.45	<0.031
W-037-Zr/Ti-001	1/1	0.95/0.97	<0.45/0.30	NA
W-038-Al-002	3.4	1.84	34	NA
W-039-Ni-003	8	6.6	3.5	NA
W-040-Cr/Ni-001	0.8/3.5	0.73	1.0/3.5	NA
W-041-Ni/Cr/Cu-001	3/0.8/1.0	3/0.8	3.0/1.7/2.3	NA
W-042-Ti-003	0.07	0.038	NA	NA
W-043-Fe/Ti-001	0.8/0.07	0.65/0.06	<3/<0.3	NA
W-044-Fe-003	0.02	0.0167	NA	NA
W-045-Cr/Fe/Ti-001	0.65/0.5/ 0.06	0.47/0.37/ 0.048	ND	0.26/0.69/<0.0
W-046-Fe/V-001	0.65/0.06	0.37/0.056	NA	NA
W-047-Cu/Ni/Zr-001	1/1/ 0.3	1.1/0.47 0.35	2.5/<1/<1	NA
W-048-Ti-004	0.00035	0.00067	NA	NA
W-049-V-003	0.00030	0.00078	NA	NA
W-050-Ti/V-001	0.00035/ 0.0003	0.0035/ 0.0041	NA	NA
W-051-Cu/Ti-001	1/0.35	0.85/0 2	4.0/0.36	NA
W-052-Ni-004	10	5.4	4.0	NA

1. NAA indicated impurity concentration of less than 4 x 10^{15} atoms/cm^3 which represents the limit of detection.

2. Nickel powder used as dopant. Dopant partially lost during furnace evacuation. Figure of 0.17 x 10^{15} atoms/cm^2 indicative of actual impurity concentration.

3. The high Zr concentration is obviously in error since it greatly exceeds the amount added to the melt.

4. Zinc loss from the melt by evaporation was essentially complete.

5. Modest loss of magnesium occurred due to evaporation.

6. No Mg detected indicating much smaller segregation coefficient than suspected. Best estimate is a concentration of 1 x 10^{13} atoms/cm^3 for W-021 and 1 x 10^{14} atoms/cm^3 for W-024.

APPENDIX 3

Bulk Lifetimes (Photoconductive Decay) for Silicon Ingots Before and After Phosphorus Diffusion

Ingot Identification	Best Estimate of Impurity Conc. (10^{15} atoms/cm)	Lifetime (As-Grown)		Lifetime (Diffused)	
		τ(μsec)	σ(Note 1)	τ(μsec)	σ(Note 1)
W001-00000	--	7.1	1.1(5)	6.9	0.5(3)
W002-00000	--	6.3	0.6(2)	8.6	1.6(2)
W003-00000	--	11.6	2.3(2)	8.4	0.7(2)
W004-Cr001	1.0	0.35	0.2(3)	1.1	0.2(4)
W005-Mn001	1.3	1.8(2)	--	0.3	0.0(5)
W006-Ni001	0.5	11.3	2.7(2)	7.7	0.2(2)
W007-Cu001	1.7	6.9	0.9(4)	6.6	3.2(3)
W008-Ti001	0.36	2.0	0.5(3)	0.4	0.2(3)
W009-V001	0.4	0.4	0.1(3)	<2.2(2)	1.8(5)
W010-Ni002	4.0	6.8	2.6(3)	3.4	3.3(4)
W011-Zr001	<0.015	2.6	0.2(2)	2.4	0.7(4)
W012-Cr002	0.2	<0.4	0.1(2)	4.9	1.0(5)
W013-Mn002	0.26	1.2(2)	1.0(3)	10.5(2)	4.7(5)
W014-00000	--	7.5	0.4(2)	8.3	0.1(2)
W015-Zn001	<0.001	7.2	0.6(2)	5.3	0.4(4)
W016-Fe001	0.85	0.5	0.0(2)	3.8	1.5(4)
W017-Cu002	17	8.8	0.1(2)	7.1	0.7(2)
W018-Fe002	1.7	8.1	5.5(2)	0.6	0.3(4)
W019-Cu003	0.4	4.3	3.3(2)	5.7	0.5(2)
W020-00000	--	7.0	1.7(2)	7.3	1.2(2)
W021-Mg001	0.003	8.2	0.8(2)	7.7	0.1(2)
W022-00000	--	7.8	1.0(2)	9.1	0.2(2)
W023-00000	--	Note 4		Note 4	
W024-Mg002	0.03	7.5	0.9(2)	10.2	0.9(2)
W025-00000	--	7.6	0.0(2)	12.7	1.0(2)
W026-Mn003	0.013	5.1	0.2(2)	9.3	0.0(2)
W027-Mn/Cu001	1.3/1.7	22.3(2)	2.3(2)	0.5	0.2(3)

APPENDIX 3 (con't)

Ingot Identification	Best Estimate of Impurity Conc. (10^{15} atoms/cm)	Lifetime (As-Grown)		Lifetime (Diffused)	
		τ(μsec)	σ(Note 1)	τ(μsec)	σ(Note 1)
W028-Al001	26	2.9	0.2(2)	1.9	0.0(2)
W029-Cr003	0.01	1.1	0.6(2)	6.2	0.4(4)
W030-Cr/Cu001	1.0/1.7	<0.3	0.0(2)	0.4	0.1(2)
W031-Cr/Mn001	1.0/1.3	Note 5	--	<0.3	0.0(2)
W032-Mg003	0.32	7.2	1.1(2)	7.1	1.1(2)
W033-Ti002	0.0036	3.1	0.0(2)	2.9	0.1(2)
W034-0000	--	21.8	4.2(2)	1.7	0.1(2)
W034-V002	0.004	1.2	0.0	1.5	0.2(2)
W036-Zr002	<0.025	1.2	0.0(2)	1.0	0.0(2)
W037-Zr/Ti001	<0.015/0.40	0.5	0.1(2)	0.4	0.1(2)
W038-Al002	34	0.7	0.2(2)	<0.1	0.0(2)
W039-Ni002	8	2.0	0.1(2)	6.5	1.5(2)
W040-Cr/Ni001	0.8/3.5	<0.2	0.0(2)	1.4	0.4(2)
W041-Ni/Cr/Cu001	3/0.8/1.7	<0.2	0.0(2)	0.4	0.3(2)
W042-Ti003	0.07	0.8	0.1(2)	0.7	0.1(2)
W043-Fe/Ti001	0.56/0.06	0.9	0.0(2)	0.5	0.0(2)
W044-Fe003	0.017	1.3	0.2(2)	6.6	0.1(2)
W045-Cr/Fe/Ti001	0.65/0.43/0.06	0.1	0.0(2)	1.0	0.8(4)
W046-Fe/V001	0.56/0.07	<0.1	0.0(2)	<0.1	0.0(2)
W047-Cu/Ni/Zr001	1.7/0.75/<0.015	3.4	0.1(2)	2.6	0.1(2)
W048-Ti004	0.00036	4.30	0.2(2)	5.1	0.4(2)
W049-V003	0.0004	3.7	0.2(2)	4.3	0.1(2)
W050-Ti/V001	0.00036/0.0004	1.1	0.1(2)	1.1	0.1(2)
W051-Cu/Ti001	1.7/0.36	0.5	0.0(2)	1.6	0.3(2)
W052-Ni004	7.5	<0.1	0.0(2)	Note 3	--

Note 1. Sample size shown in parentheses.

Note 2. Lifetime measurements subject to large errors due to extreme shallow trap density.

Note 3. Polycrystalline ingot -- no evaluation performed.

Note 4. Lifetime measurements not practical due to low resistivity.

Note 5. Lifetime measurements not possible due to very low lifetime (Δv too small).

APPENDIX 4

PHOTOVOLTAIC CHARACTERISTICS OF METAL IMPURITY-DOPED SILICON SOLAR CELLS UNDER AM1 ILLUMINATION

Test Conditions: No AR coatings, nominal cell area cm^2
Quartz-iodine illumination

Key to Abbreviations:
R - calibrated reference devices (see Section 3.2.2)
C - wafers from ingot center
T - wafers from ingot tang end
S - wafers from ingot seed end
B - baseline wafer
E or N - end
* - item deleted from averages.

Ingots are listed alphabetically by impurity species so that entries for the multiply-doped ingots appear more than once. Column headings are generally self-explanatory; PCDB and PCDA are the photoconductive decay wafer lifetimes before and after cell processing.

```
                                                                          AL
60409 W028AL001 (2.6E16) BEFORE SINTER W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID        ISC   VOC  IP     LOG(IO)  N       R     FF   EFF     OCD     PCDA   PCDB

1B        22.75 .554 21.02   -8.096 1.43     .12 .759 10.12   4.55    8.57   6.30
2B        22.75 .554 21.02   -8.096 1.43     .12 .759 10.12   4.55    8.57   6.30
3B        22.40 .554 20.92   -9.220 1.22     .45 .772 10.14   4.16    8.57   6.30
4B        22.75 .547 20.52   -6.410 1.92    -.64 .733  9.65   3.90    8.57   6.30
1C        17.50 .537 16.32   -9.265 1.19     .67 .768  7.63   1.30    1.94   2.90
2C        17.50 .530 15.98   -7.406 1.57     .05 .740  7.26    .91    1.94   2.90
3C        18.50 .535 16.96   -7.799 1.47     .52 .738  7.73   1.04    1.94   2.90
4C        18.25 .539 17.16  -10.324 1.05     .94 .778  8.10   1.30    1.94   2.90
1S        18.35 .539 17.21   -9.933 1.10     .85 .774  8.10   1.30    1.94   2.90
2S        18.35 .539 16.95   -8.240 1.38     .27 .757  7.92   1.30    1.94   2.90
3S        18.35 .539 17.21   -9.933 1.10     .85 .774  8.10   1.30    1.94   2.90
4S        18.35 .539 17.21   -9.933 1.10     .85 .774  8.10   1.30    1.94   2.90

AVERAGES: 60409  BASELINE  W002 00 000
          22.66 .552 20.87   -7.956 1.50     .01 .756 10.01   4.29    8.57   6.30
  STD       .15 .003   .21    1.004  .25     .40 .014   .21    .28      *      *
             60409 W028AL001 (2.6E16) BEFORE SINTER
          18.14 .537 16.88   -9.104 1.25     .62 .763  7.87   1.22    1.94   2.90
  STD       .38 .003   .44    1.055  .19     .30 .015   .29    .14      *      *
PERCENT OF BASELINE
          80.1 97.3  80.9     85.6    83 ***** 100.9   78.6   28.4    22.6   46.0
 STD%      2.2  1.1   2.9     29.4    29 *****   3.9    4.6    5.4      .0     .0

                                                                          AL
60409A W028AL001 (2.6E16) AFTER SINTER W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID        ISC   VOC  IP     LOG(IO)  N       R     FF   EFF     OCD     PCDA   PCDB

1B.*      22.50 .540 19.86   -5.337 2.45   -1.86 .720  9.25   4.55    8.57   6.30
2B        22.75 .540 20.98   -7.691 1.49    -.45 .769  9.99   4.55    8.57   6.30
3B        22.75 .540 21.02   -7.717 1.49    -.71 .779 10.12   4.16    8.57   6.30
4B        22.75 .540 20.72   -6.830 1.74    -.71 .751  9.76   3.90    8.57   6.30
1C        17.00 .525 15.80   -8.389 1.32    -.56 .783  7.39   1.30    1.94   2.90
2C        17.00 .520 15.52   -7.141 1.62    -.73 .753  7.04    .91    1.94   2.90
3C        18.00 .530 16.70   -8.503 1.31     .04 .770  7.77   1.04    1.94   2.90
4C        18.40 .535 17.10   -8.740 1.28     .30 .768  7.99   1.30    1.94   2.90
1S        18.25 .530 17.06   -9.255 1.18     .27 .779  7.97   1.30    1.94   2.90
2S        18.25 .525 16.72   -7.356 1.56    -.62 .759  7.69   1.30    1.94   2.90
3S        18.25 .525 16.72   -7.356 1.56    -.62 .759  7.69   1.30    1.94   2.90
4S        18.30 .525 16.91   -8.033 1.39    -.26 .768  7.80   1.30    1.94   2.90

AVERAGES: 60409A BASELINE  W002 00 000
          22.75 .540 20.91   -7.413 1.57    -.62 .767  9.96   4.20    8.57   6.30
  STD       .00 .000   .14     .412  .12     .12 .011   .15    .27      *      *
             60409A W028AL001 (2.6E16) AFTER SINTER
          17.93 .527 16.57   -8.097 1.40    -.27 .767  7.67   1.22    1.94   2.90
  STD       .55 .004   .55     .709  .15     .40 .010   .30    .14      *      *
PERCENT OF BASELINE
          78.8 97.6  79.2     90.8    89 156.1 100.1   77.0   29.0    22.6   46.0
 STD%      2.4   .8   3.2     16.2    17  84.5   2.8    4.2    5.5      .0     .0
```

```
                                                                                AL
60803 W038AL002 (3.4E16)  W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC   IP     LOG(IO)  N      R     FF    EFF    OCD   PCDA   PCDB

1R*     22.50 .555 20.31   -6.595 1.87  -.23 .726   9.59   .00    .00    .00
1B      22.60 .554 20.42   -6.383 1.95 -1.02 .744   9.85  4.29   7.30   7.00
2B      22.60 .555 20.95   -8.148 1.43  -.29 .775  10.28  4.55   7.30   7.00
3B      22.60 .553 20.54   -6.693 1.83  -.86 .750   9.92  4.55   7.30   7.00
4B      22.90 .555 21.10   -7.692 1.53  -.29 .763  10.26  4.55   7.30   7.00
5B      22.70 .555 20.82   -7.318 1.63  -.53 .760  10.13  4.29   7.30   7.00
1C      17.90 .520 16.20   -6.857 1.70  -.16 .728   7.17   .52    .15    .70
2C      18.10 .518 16.07   -5.985 2.04  -.52 .703   6.97   .39    .15    .70
3C      18.40 .519 16.37   -5.976 2.04  -.83 .712   7.19   .26    .15    .70
4C      18.10 .521 16.28   -6.511 1.82  -.37 .722   7.20   .13    .15    .70
1S      17.80 .520 15.92   -6.202 1.95  -.71 .718   7.03   .13    .15    .70
2S      18.00 .522 16.37   -7.120 1.62  -.11 .736   7.31   .13    .15    .70
3S      18.00 .520 16.25   -6.726 1.74  -.22 .726   7.18   .39    .15    .70
1T      18.00 .524 16.35   -7.016 1.66  -.20 .735   7.33   .26    .15    .70
2T      17.80 .519 15.97   -6.393 1.87  -.43 .718   7.02   .26    .15    .70
3T      17.80 .520 16.07   -6.694 1.76  -.33 .727   7.12   .26    .15    .70
4T      18.30 .519 16.38   -6.298 1.90  -.46 .716   7.19   .39    .15    .70

AVERAGES: 60803  BASELINE  W020 00 000
        22.68 .554 20.77   -7.247 1.68  -.60 .759  10.09  4.45   7.30   7.00
  STD     .12 .001   .25     .643  .19   .30 .011    .18   .13    *      *
                60803 W038AL002 (3.4E16)
        18.02 .520 16.20   -6.525 1.83  -.39 .722   7.16   .28    .15    .70
  STD     .19 .002   .16     .374  .14   .22 .009    .11   .12    *      *
PERCENT OF BASELINE
        79.4 93.8  78.0    110.0   109 134.1  95.2   70.9   6.4    2.1   10.0
 STD%    1.3   .4   1.7     13.6    22  86.9   2.6    2.3   3.0     .0     .0

                                                                                CR
61019 W045CR-FE-TI001 (6.5E14-4.3E14-6E13)  W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC   IP     LOG(IO)  N      R     FF    EFF    OCD   PCDA   PCDB

1R*     22.50 .555 20.44   -6.975 1.74  -.03 .732   9.67   .00    .00    .00
1B      22.50 .544 19.23   -4.564 3.12 -2.30 .679   8.79  1.56   7.30   6.99
2B      22.70 .554 21.04   -8.117 1.43  -.35 .777  10.33  5.20   7.30   6.99
3B      22.70 .555 21.04   -8.163 1.42  -.28 .775  10.33  4.55   7.30   6.99
4B      22.80 .555 21.01   -7.605 1.55  -.55 .770  10.30  4.29   7.30   6.99
5B      22.70 .553 20.99   -7.815 1.50  -.56 .776  10.30  4.29   7.30   6.99
1C      15.50 .484 14.21   -7.652 1.38  -.07 .749   5.94   .13    .99    .15
2C      16.20 .486 14.91   -8.004 1.31   .23 .751   6.25   .13    .99    .15
3C      16.20 .490 14.83   -7.400 1.46  -.48 .754   6.33   .13    .99    .15
4C      15.70 .478 14.07   -6.162 1.83 -1.42 .731   5.80   .13    .99    .15
5C      15.80 .481 14.39   -7.090 1.52  -.63 .747   6.01   .13    .99    .15
1S      15.60 .480 14.11   -6.641 1.66 -1.01 .741   5.86   .13    .99    .15
2S      16.10 .487 14.71   -7.267 1.49  -.55 .751   6.23   .13    .99    .15
3S      16.20 .489 14.83   -7.388 1.46  -.48 .753   6.31   .13    .99    .15
1T      16.30 .487 14.95   -7.675 1.38  -.02 .749   6.29   .13    .99    .15
2T      16.30 .487 14.95   -7.675 1.38  -.02 .749   6.29   .13    .99    .15
3T      16.20 .486 14.90   -7.818 1.35  -.14 .756   6.30   .13    .99    .15
4T      16.20 .487 14.83   -7.470 1.43  -.24 .749   6.25   .13    .99    .15

AVERAGES: 61019  BASELINE  W020 00 000
        22.73 .554 21.02   -7.925 1.48  -.44 .774  10.32  4.58   7.30   6.99
  STD     .05 .001   .02     .228  .05   .13 .003    .01   .37    *      *
                61019 W045CR-FE-TI001 (6.5E14-4.3E14-6E13)
        16.52 .490 14.99   -7.139 1.60  -.55 .743   6.36   .24   1.48    .68
  STD    1.75 .016  1.26     .883  .46   .66 .020    .72   .38    *      *
PERCENT OF BASELINE
        72.7 88.4  71.3    109.9   108  73.9  96.0   61.6   5.2   20.2    9.7
 STD%    7.8  3.0   6.1     14.1    36 232.1   2.9    7.1   9.4   23.0   26.1
```

```
                                                                          CR
60225 W012CR002 (2E14) W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID        ISC   VOC  IP     LOG(IO)  N      R   FF    EFF     OCD    PCDA   PCDB

1R*       22.50 .554 20.68  -7.872 1.49   .44 .743  9.79   3.90   8.60   6.30
1B        22.60 .558 20.87  -7.965 1.48  -.07 .763 10.17   1.95   8.60   6.30
2B.*      19.70 .549 17.04  -4.813 2.95 -2.83 .699  7.99   3.90   8.60   6.30
3B        22.12 .555 20.47  -8.227 1.41   .08 .764  9.92   1.95   8.60   6.30
4B.*      21.82 .551 19.44  -5.967 2.14  -.67 .713  9.06   2.60   8.60   6.30
5B        20.10 .551 18.50  -7.523 1.58  -.78 .771  9.03   3.90   8.60   6.30
1C        21.75 .543 19.62  -6.536 1.86  -.37 .727  9.09   2.60   4.90    .40
2C        21.50 .550 19.87  -8.012 1.45  -.17 .767  9.59   3.25   4.90    .40
3C        21.75 .546 19.65  -6.447 1.91  -.84 .739  9.28   2.60   4.90    .40
4C        21.75 .546 19.44  -5.907 2.15 -1.29 .730  9.17   2.21   4.90    .40
5C        21.50 .546 19.13  -5.668 2.28 -1.66 .729  9.04   2.21   4.90    .40
1E        21.50 .535 18.65  -5.098 2.60 -1.23 .683  8.31    .13   4.90    .40
2E        22.00 .546 19.15  -5.148 2.61 -1.28 .688  8.74   1.95   4.90    .40
3E        21.63 .550 19.39  -6.128 2.06  -.89 .727  9.14   2.99   4.90    .40
4E        22.00 .550 19.94  -6.815 1.78  -.20 .732  9.37   3.12   4.90    .40
5E        21.87 .550 19.19  -5.315 2.51 -1.45 .703  8.94   2.21   4.90    .40
6E        21.00 .537 18.33  -5.159 2.58 -1.65 .697  8.32   1.04   4.90    .40
7E        20.75 .535 18.37  -5.769 2.19  -.72 .704  8.26   1.17   4.90    .40

AVERAGES: 60225  BASELINE  W002 00 000
          21.61 .555 19.95  -7.905 1.49  -.26 .766  9.71   2.60   8.60   6.30
   STD     1.08 .003  1.04    .291  .07   .37 .004   .49    .92    *       *
             60225 W012CR002 (2E14)
          21.58 .544 19.23  -6.000 2.16  -.98 .719  8.94   2.12   4.90    .40
   STD      .36 .006   .52    .822  .36   .51 .023   .42    .89    *       *
PERCENT OF BASELINE
           99.9 98.2  96.4   124.1  145 ***** 93.8  92.1   81.7   57.0    6.3
  STD%      6.8  1.5   7.7    13.6   32 *****  3.5   9.2   75.4     .0     .0
```

```
                                                                          CR
60105 W004CR001(1E15) W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID        ISC   VOC  IP     LOG(IO)  N      R   FF    EFF     OCD    PCDA   PCDB

1B        22.37 .556 20.56  -7.814 1.51   .32 .745  9.80   4.53   8.60   6.30
2B*       19.85 .554 18.29  -8.024 1.46   .28 .752  8.74   2.86   8.60   6.30
3B        22.70 .557 20.92  -7.982 1.47   .25 .752 10.06   3.90   8.60   6.30
4B        22.37 .557 20.84  -9.083 1.25   .62 .764 10.07   3.90   8.60   6.30
1C        17.25 .525 15.92  -8.404 1.32   .84 .745  7.13    .91   1.05    .35
2C        17.50 .530 16.06  -7.803 1.46   .28 .745  7.31   1.04   1.05    .35
3C        14.90 .520 12.95  -5.387 2.44 -1.19 .679  5.57    .78   1.05    .35
4C        18.37 .530 16.98  -8.492 1.31   .79 .748  7.70   1.17   1.05    .35
5C        16.12 .520 14.28  -6.024 2.05  -.33 .697  6.17    .91   1.05    .35
6C        18.90 .535 17.55  -9.046 1.22  1.11 .749  8.01   1.00   1.05    .35
1E        18.00 .534 16.75  -9.254 1.19  1.14 .754  7.66   1.04   1.05    .35
2E        18.75 .534 17.13  -7.636 1.51   .66 .730  7.73   1.04   1.05    .35
3E        18.75 .534 17.39  -8.963 1.23  1.20 .745  7.89    .91   1.05    .35

AVERAGES: 60105  BASELINE  W002 00 000
          22.48 .557 20.77  -8.293 1.41   .40 .754  9.98   4.11   8.60   6.30
   STD      .16 .000   .16    .563  .11   .16 .008   .12    .30    *       *
             60105 W004CR001(1E15)
          17.62 .529 16.11  -7.890 1.53   .50 .732  7.24    .98   1.05    .35
   STD     1.28 .006  1.46   1.282  .41   .75 .025   .79    .11    *       *
PERCENT OF BASELINE
           78.4 95.0  77.6   104.9  108 125.5 97.2  72.6   23.8   12.2    5.6
  STD%      6.3  1.1   7.7    23.0   40 315.6  4.3   8.9    4.5     .0     .0
```

```
                                                                      CR
60225A W004CR001(1E15) W002 00 000
SOL4  1 /28/77   AM1: PO=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC   IP    LOG(IO)   N     R     FF    EFF    OCD   PCDA  PCDB

1B     22.20 .559 20.69   -8.873 1.29   .14 .776 10.19   3.90  8.42 11.65
2B     22.20 .559 20.09   -6.664 1.86  -.44 .735  9.64   3.90  8.42 11.65
3B     22.20 .559 20.60   -8.524 1.36   .28 .764 10.03   4.55  8.42 11.65
4B     22.20 .559 20.39   -7.559 1.58  -.15 .754  9.90   3.90  8.42 11.65
5B     22.55 .559 20.98   -8.688 1.33   .15 .772 10.29   4.16  8.42 11.65
2C     20.70 .525 18.11   -5.201 2.49 -1.74 .703  8.08    .91  1.05   .35
3C     18.00 .525 17.02 -11.430   .91  1.45 .778  7.77    .91  1.05   .35
4C     18.50 .525 17.25   -9.368 1.15   .95 .760  7.81   1.30  1.05   .35
5C.*   18.65 .519 15.07   -3.667 4.46 -5.35 .635  6.50    .52  1.05   .35
1S     18.50 .515 17.04   -7.405 1.52 -1.38 .784  7.90   1.17  1.05   .35
2S     18.15 .530 16.96   -9.501 1.14   .80 .768  7.81   1.17  1.05   .35
3S.*   18.15 .530 14.58   -3.792 4.31 -3.75 .610  6.21    .26  1.05   .35
4S     18.75 .530 17.19   -7.479 1.54  -.29 .753  7.92   1.17  1.05   .35
1T     18.25 .523 16.69   -7.529 1.51   .19 .740  7.47    .91  1.05   .35
2T     18.00 .528 16.65   -8.410 1.32   .41 .757  7.61    .91  1.05   .35
3T*    18.00 .263 11.48   -2.774 4.11 -1.47 .415  2.08    .01  1.05   .35

AVERAGES: 60225A BASELINE  W002 00 000
       22.27 .559 20.55   -8.062 1.48  -.00 .760 10.01   4.08  8.42 11.65
  STD    .14 .000   .30     .833  .21   .26 .015   .23    .25    *     *
          60225A W004CR001(1E15)
       18.61 .525 17.11   -8.290 1.45   .05 .755  7.80   1.06  1.05   .35
  STD    .83 .004   .42    1.734  .45  1.05 .024   .17    .15    *     *
PERCENT OF BASELINE
       83.5 93.9  83.3     97.2    97 *****  99.4  77.9   25.9  12.5   3.0
 STD%   4.3   .8   3.3     34.4    49 *****   5.1   3.6    5.6    .0    .0

                                                                      CR
60510 W030CR-CU001 (1E15-1E15) W002 00 000
SOL4  1 /28/77   AM1: PO=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC   IP    LOG(IO)   N     R     FF    EFF    OCD   PCDA  PCDB

1B     22.00 .547 20.79 -10.668 1.01   .45 .797 10.14   4.94  8.57  6.30
2B     22.00 .547 20.47  -8.524 1.33  -.17 .780  9.92   4.94  8.57  6.30
3B     21.80 .547 20.41  -9.286 1.20   .05 .788  9.93   4.94  8.57  6.30
4B     22.00 .547 20.47  -8.524 1.33  -.17 .780  9.92   4.94  8.57  6.30
1C     16.00 .497 14.86  -8.731 1.20   .25 .768  6.46    .65   .42   .32
2C     15.60 .493 14.39  -8.154 1.30   .24 .754  6.14    .52   .42   .32
3C     16.50 .500 15.37  -8.968 1.16   .28 .772  6.74    .78   .42   .32
4C     17.20 .506 16.24 -10.848  .93   .89 .787  7.24    .91   .42   .32
5C     16.50 .500 15.37  -8.968 1.16   .28 .772  6.74    .65   .42   .32
1S     17.40 .510 16.31  -9.566 1.09   .17 .788  7.39    .91   .42   .30
2S     17.10 .510 16.06  -9.996 1.04   .53 .785  7.24   1.04   .42   .30
3S     17.40 .510 16.09  -8.182 1.33  -.05 .764  7.17    .91   .42   .30
2T     16.50 .500 15.33  -8.673 1.21   .16 .769  6.71    .65   .42   .30
3T     16.80 .500 15.65  -9.007 1.15   .28 .773  6.87    .78   .10   .30

AVERAGES: 60510  BASELINE  W002 00 000
       21.95 .547 20.53  -9.251 1.22   .04 .786  9.98   4.94  8.57  6.30
  STD    .09 .000   .15    .875  .13   .26 .007   .09    .00    *     *
          60510 W030CR-CU001 (1E15-1E15)
       16.70 .503 15.57  -9.109 1.16   .31 .773  6.87    .78   .39   .31
  STD    .57 .006   .60    .786  .11   .24 .010   .37    .15    *     *
PERCENT OF BASELINE
       76.1 91.9  75.8    101.5    95 806.5  98.4  68.8   15.8   4.5   4.9
 STD%   2.9  1.0   3.5     18.6    20 *****   2.2   4.4    3.1   1.1    .2
```

```
                                                                        CR
60511 W031CR-MN001 (1E15-1E15) W002 00 000
SOL4   1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC   VOC  IP    LOG(IO)  N      R   FF   EFF   OCD    PCDA   PCDB

1B       22.30 .550 20.71  -8.232 1.40  -.44 .782 10.14  4.55   8.57   6.30
2B*      22.30 .520 16.33  -2.905 6.80 -6.03 .543  6.66   .52   8.57   6.30
3B*      22.60 .500 16.06  -2.963 6.24 -3.13 .496  5.93   .26   8.57   6.30
4B       22.30 .550 21.13 -11.053  .98   .38 .805 10.44  5.20   8.57   6.30
1C       11.50 .465 10.67  -8.866 1.12   .56 .763  4.31   .39    .32    .00
2C*      12.20 .426  8.92  -3.295 5.09 -6.02 .525  2.89   .13    .32    .00
3C       12.80 .473 11.81  -7.972 1.30  -.77 .772  4.94   .13    .32    .00
4C       11.50 .465 10.73  -9.231 1.07   .23 .778  4.40   .13    .32    .00
5C       12.90 .473 11.87  -7.761 1.35  -.86 .768  4.96   .13    .32    .00
1S       12.60 .479 11.77  -9.467 1.06   .55 .776  4.95   .13    .32    .00
2S*      11.70 .445  8.73  -3.339 5.22 -8.01 .551  3.04   .13    .32    .00
3S       11.50 .470 10.70  -8.970 1.12   .18 .773  4.42   .13    .32    .00
1T       12.00 .470 11.15  -9.010 1.11   .77 .762  4.54   .13    .32    .00
2T       12.00 .470 11.15  -9.010 1.11   .77 .762  4.54   .13    .32    .00
3T*      13.20 .470 10.79  -4.137 3.47 -4.11 .627  4.12   .13    .32    .00
M1A2*    23.60 .573 21.92  -8.339 1.43  -.23 .778 11.13  5.85    .32    .00
M1A4*    23.60 .573 22.18  -9.844 1.16   .30 .789 11.29  5.20    .32    .00
C1A1*    21.40 .395 15.44  -4.794 2.11  5.92 .426  3.81   .14    .32    .00
C1A2*    22.20 .360 16.53  -5.482 1.57  5.60 .438  3.70   .14    .32    .00

AVERAGES: 60511  BASELINE  W002 00 000
         22.30 .550 20.92  -9.642 1.19  -.03 .793 10.29  4.88   8.57   6.30
  STD      .00 .000   .21   1.411  .21   .41 .011   .15   .33     *      *
               60511 W031CR-MN001 (1E15-1E15)
         12.10 .471 11.23  -8.786 1.15   .18 .769  4.63   .16    .32    .00
  STD      .56 .004   .49    .561  .10   .61 .006   .25   .09     *      *
PERCENT OF BASELINE
         54.3 85.6  53.7   108.9   97 786.4  96.9  45.0   3.3    3.7     .0
 STD%     2.5   .8   2.9    20.0   27 *****   2.2   3.2   2.1     .0     .0
```

```
                                                                        CR
60611 W029CR003 (1E13) W025 00 000
SOL4   1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC   VOC  IP    LOG(IO)  N      R   FF   EFF   OCD    PCDA   PCDB

1B       22.20 .541 20.75  -9.023 1.23  -.06 .787  9.99  5.20  12.74   7.60
2B       22.20 .541 20.75  -9.023 1.23  -.06 .787  9.99  5.20  12.74   7.60
3B       22.20 .541 20.75  -9.023 1.23  -.06 .787  9.99  5.20  12.74   7.60
4B       22.50 .541 20.91  -8.372 1.34  -.23 .778 10.02  5.20  12.74   7.60
5B       22.50 .541 21.25 -10.549 1.02   .40 .796 10.25  5.20  12.74   7.60
1C       23.00 .544 21.27  -7.915 1.45  -.38 .773 10.23  4.94   6.21   1.10
2C       23.00 .544 21.27  -7.915 1.45  -.38 .773 10.23  4.94   6.21   1.10
3C       23.20 .544 21.85 -10.116 1.07   .34 .792 10.57  5.46   6.21   1.10
4C       23.00 .544 21.27  -7.915 1.45  -.38 .773 10.23  5.20   6.21   1.10
1S       22.70 .542 21.10  -8.295 1.36  -.42 .784 10.20  5.20   6.21   1.10
2S       23.00 .542 21.45  -8.722 1.28  -.21 .786 10.36  5.20   6.21   1.10
3S       23.00 .542 21.45  -8.722 1.28  -.21 .786 10.36  5.46   6.21   1.10
1T       22.60 .540 21.30 -10.221 1.05   .35 .793 10.24  5.46   6.21   1.10
2T       23.00 .540 21.49  -8.894 1.24  -.21 .790 10.37  5.20   6.21   1.10
3T       23.00 .540 21.49  -8.894 1.24  -.21 .790 10.37  5.20   6.21   1.10
4T       22.60 .540 21.11  -9.104 1.21   .18 .780 10.06  3.90   6.21   1.10

AVERAGES: 60611  BASELINE  W025 00 000
         22.32 .541 20.88  -9.198 1.21  -.00 .787 10.05  5.20  12.74   7.60
  STD      .15 .000   .19    .721  .11   .21 .006   .10   .00     *      *
               60611 W029CR003 (1E13)
         22.92 .542 21.37  -8.792 1.28  -.14 .784 10.29  5.11   6.21   1.10
  STD      .18 .002   .20    .767  .13   .28 .007   .13   .42     *      *
PERCENT OF BASELINE
        102.7 **** 102.3   104.4  106 *****  99.6 102.4  98.2   48.7   14.5
 STD%     1.5   .3   1.9    16.5   21 *****   1.7   2.3   8.1     .0     .0
```

```
                                                                          CR
60811 W040CR-NI001 (1E15-3.5E15)  W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC   IP    LOG(IO)  N     R     FF   EFF    OCD    PCDA   PCDB

1R*    22.50 .556 20.31  -6.639 1.86  -.14 .724  9.58   .00    .00    .00
1B     22.60 .553 20.75  -7.356 1.62  -.59 .764 10.09  4.16   7.30   7.00
2B     22.70 .555 20.99  -7.951 1.47  -.29 .770 10.26  4.94   7.30   7.00
3B     22.50 .559 20.93  -8.476 1.37  -.20 .780 10.37  4.94   7.30   7.00
4B     22.50 .556 20.91  -8.374 1.38  -.30 .781 10.33  4.94   7.30   7.00
5B     23.10 .553 21.00  -6.694 1.83  -.85 .751 10.15  3.90   7.30   7.00
1C     20.40 .531 18.61  -7.064 1.65  -.51 .749  8.58  1.30   1.35    .20
2C     20.80 .532 18.89  -6.709 1.77  -.84 .748  8.75  1.43   1.35    .20
3C     20.80 .528 18.82  -6.500 1.83  -.97 .744  8.65  1.17   1.35    .20
4C     20.40 .527 18.45  -6.479 1.84  -.98 .743  8.45  1.30   1.35    .20
5C     20.20 .519 18.01  -5.843 2.09 -1.32 .725  8.04   .65   1.35    .20
1S     20.30 .523 17.97  -5.574 2.25 -1.55 .718  8.06  1.04   1.35    .20
2S     21.50 .537 19.64  -7.077 1.66  -.64 .755  9.22  1.95   1.35    .20
3S     21.50 .534 19.61  -7.020 1.67  -.51 .749  9.10  1.69   1.35    .20
1T     18.50 .501 16.48  -5.994 1.96  -.85 .715  7.01   .39   1.35    .20
2T     17.80 .493 15.85  -6.074 1.90  -.58 .709  6.58   .26   1.35    .20
3T     17.40 .488 15.49  -6.108 1.87  -.44 .706  6.34   .26   1.35    .20
4T     16.70 .485 14.97  -6.460 1.73  -.23 .714  6.12   .26   1.35    .20

AVERAGES: 60811  BASELINE  W020 00 000
       22.68 .555 20.92  -7.770 1.53  -.45 .769 10.24  4.58   7.30   7.00
  STD    .22 .002   .09    .667  .17   .24 .011   .11   .45    *      *
        60811 W040CR-NI001 (1E15-3.5E15)
       19.69 .517 17.73  -6.408 1.85  -.79 .731  7.91   .98   1.35    .20
  STD   1.58 .018  1.55    .478  .17   .36 .018  1.06   .57    *      *
PERCENT OF BASELINE
       86.8 93.0  84.8    117.5  121  23.7  95.1  77.2  21.3   18.5    2.9
 STD%   7.9  3.7   7.8     13.8   26 221.4   3.7  11.2  15.8     .0     .0

                                                                          CR
60809 W041CR-CU-NI001 (8E14-1.7E15-3E15) W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC   IP    LOG(IO)  N     R     FF   EFF    OCD    PCDA   PCDB

1R*    22.50 .553 20.30  -6.577 1.87  -.23 .725  9.54   .00    .00    .00
2B     23.10 .553 21.53  -8.666 1.31  -.19 .784 10.59  5.20    .00    .00
3B.*   22.60 .548 20.20  -5.845 2.18 -1.38 .732  9.59  3.25    .00    .00
4B     22.70 .552 21.07  -8.204 1.41  -.37 .779 10.33  4.81    .00    .00
5B     22.90 .552 21.21  -8.046 1.44  -.39 .776 10.38  4.94    .00    .00
1C     19.30 .503 16.73  -5.066 2.51 -1.55 .685  7.03   .65    .43    .20
2C     20.80 .527 18.74  -6.297 1.91 -1.01 .737  8.55  1.30    .43    .20
3C     19.00 .507 16.84  -5.725 2.12 -1.20 .713  7.26   .52    .43    .20
4C.*   20.20 .505 14.93  -2.911 6.79 -7.81 .562  6.07   .26    .43    .20
1S     19.30 .509 16.84  -5.135 2.49 -1.96 .701  7.28   .52    .43    .20
2S     20.50 .523 18.32  -5.948 2.05 -1.23 .728  8.26   .91    .43    .20
3S     20.30 .518 17.61  -4.887 2.71 -2.41 .700  7.79   .78    .43    .20
1T     18.20 .495 15.73  -5.081 2.47 -1.35 .677  6.45   .39    .43    .20
2T     17.70 .502 15.66  -5.779 2.08  -.93 .704  6.62   .39    .43    .20
3T     17.70 .498 15.53  -5.464 2.24 -1.33 .698  6.51   .52    .43    .20
4T     16.90 .496 14.94  -5.859 2.03  -.66 .699  6.20   .52    .43    .20

AVERAGES: 60809  BASELINE  W020 00 000
       22.90 .552 21.27  -8.305 1.39  -.31 .780 10.43  4.98    .00    .00
  STD    .16 .000   .19    .263  .05   .09 .003   .11   .16    *      *
        60809 W041CR-CU-NI001 (8E14-1.7E15-3E15)
       18.97 .508 16.69  -5.524 2.26 -1.36 .704  7.19   .65    .43    .20
  STD   1.26 .011  1.19    .443  .25   .48 .017   .75   .27    *      *
PERCENT OF BASELINE
       82.8 91.9  78.5    133.5  163 *****  90.3  69.0  13.0 ***** *****
 STD%   6.1  2.0   6.4      7.6   25 322.5   2.6   8.1   5.9 ***** *****
```

```
                                                                          CU
60908 W051CU/TI001 (1.7E15/3.6E14) W002 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC  IP    LOG(IO)  N     R     FF    EFF   OCD   PCDA  PCDB

1R*     22.50 .553 20.30  -6.469 1.92  -.57 .732  9.63   .00   .00   .00
1B      22.90 .560 21.35  -8.842 1.30   .09 .778 10.55  4.29  8.57  6.34
2B      22.60 .557 20.53  -6.648 1.86  -.91 .750  9.99  3.90  8.57  6.34
3B      21.00 .552 19.58  -8.797 1.30  -.08 .782  9.58  1.95  8.57  6.34
4B      22.80 .558 20.97  -7.489 1.59  -.49 .764 10.28  4.16  8.57  6.34
1C      13.90 .467 12.75  -7.748 1.32   .04 .748  5.13   .10  1.57   .50
2C      13.70 .464 12.47  -7.260 1.44  -.16 .738  4.96   .10  1.57   .50
3C      13.80 .465 12.63  -7.573 1.36  -.17 .748  5.07   .10  1.57   .50
4C      14.00 .465 12.70  -6.983 1.51  -.55 .738  5.08   .10  1.57   .50
5C      13.90 .464 12.67  -7.305 1.42  -.22 .741  5.05   .10  1.57   .50
1S      13.80 .460 12.33  -6.164 1.79 -1.40 .725  4.87   .10  1.57   .50
2S      14.00 .466 12.84  -7.778 1.31   .06 .748  5.16   .10  1.57   .50
1T      13.70 .464 12.50  -7.309 1.42  -.47 .747  5.02   .10  1.57   .50
2T      13.70 .464 12.32  -6.352 1.73 -1.65 .739  4.97   .10  1.57   .50
3T      13.70 .464 12.45  -6.991 1.51  -.84 .745  5.01   .10  1.57   .50
4T*     13.30 .523 10.98  -4.134 3.87 -5.89 .651  4.79  1.95  1.57   .50

AVERAGES: 60908  BASELINE  W002 00 000
        22.33 .557 20.61  -7.944 1.51  -.34 .768 10.10  3.58  8.57  6.34
  STD     .77 .003   .66    .925  .23   .39 .012   .36   .95   *     *
         60908 W051CU/TI001 (1.7E15/3.6E14)
        13.82 .464 12.57  -7.146 1.48  -.53 .742  5.03   .10  1.57   .50
  STD     .12 .002   .17    .515  .15   .56 .007   .08   .00   *     *
PERCENT OF BASELINE
        61.9 83.4  61.0   110.0   98  44.9  96.5  49.8   2.8  18.3   7.9
 STD%   2.7   .8   2.8     17.7   27 520.8   2.4   2.6    .7    .0    .0

                                                                          CU
61026 W047CU-NI-ZR001 (1.7E15/7.5E14/<1.5E13) W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC  IP    LOG(IO)  N     R     FF    EFF   OCD   PCDA  PCDB

1R*     22.50 .557 20.45  -6.974 1.75  -.10 .735  9.73   .00   .00   .00
1B.*    22.90 .556 20.55  -5.949 2.16 -1.50 .741  9.98  3.25  7.30  7.00
2B      23.00 .558 21.37  -8.418 1.37  -.16 .777 10.55  4.55  7.30  7.00
4B      22.80 .559 21.14  -8.107 1.44  -.40 .778 10.49  4.55  7.30  7.00
5B      22.90 .560 21.41  -9.032 1.27  -.04 .786 10.66  4.55  7.30  7.00
1C      21.60 .545 19.51  -6.141 2.03 -1.88 .759  9.45  1.95  2.61  3.37
2C      21.50 .545 19.99  -8.656 1.30   .19 .770  9.54  1.95  2.61  3.37
3C      21.50 .543 19.83  -7.863 1.46  -.17 .763  9.42  1.95  2.61  3.37
4C      21.70 .543 20.08  -8.119 1.41  -.15 .769  9.58  1.95  2.61  3.37
1S      21.30 .543 19.41  -6.883 1.74  -.83 .754  9.23  1.95  2.61  3.37
2S      21.50 .544 19.99  -8.533 1.32  -.03 .775  9.58  1.95  2.61  3.37
3S      21.60 .543 20.01  -8.236 1.38  -.02 .767  9.52  1.95  2.61  3.37
1T      21.20 .543 19.65  -8.283 1.37  -.07 .770  9.37  1.95  2.61  3.37
2T      21.40 .543 19.91  -8.687 1.29   .12 .773  9.50  1.95  2.61  3.37
3T      21.40 .543 19.96  -8.987 1.24   .26 .775  9.52  1.95  2.61  3.37
4T      21.60 .543 20.11  -8.352 1.26   .28 .771  9.56  1.95  2.61  3.37

AVERAGES: 61026  BASELINE  W020 00 000
        22.90 .559 21.31  -8.519 1.36  -.20 .781 10.57  4.55  7.30  7.00
  STD     .08 .001   .12    .384  .07   .15 .004   .07   .00   *     *
         61026 W047CU-NI-ZR001 (1.7E15/7.5E14/<1.5E13)
        21.48 .543 19.86  -8.113 1.44  -.21 .768  9.48  1.95  2.61  3.37
  STD     .14 .001   .22    .832  .23   .60 .006   .10   .00   *     *
PERCENT OF BASELINE
        93.8 97.2  93.2   104.8  106  94.6  98.4  89.7  42.9  35.8  48.1
 STD%   1.0   .3   1.6     14.5   23 605.0   1.3   1.6    .0    .0    .0
```

```
                                                                                CU
61213 W055CU004 (1E14) W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC    VOC   IP     LOG(IO)   N      R     FF     EFF    OCD     PCDA    PCDB

1R*     22.50 .553 20.24   -6.410 1.94   -.36 .723   9.51    .00     .00     .00
1B      22.90 .555 20.92   -7.065 1.71   -.55 .754  10.13   4.29    7.30    7.00
3B      22.90 .557 21.17   -7.903 1.49   -.34 .771  10.40   5.20    7.30    7.00
5B      22.70 .556 20.57   -6.519 1.90   -.97 .748   9.98   3.90    7.30    7.00
1C      22.70 .552 20.62   -6.634 1.85   -.93 .751   9.95   3.90     .00     .00
2C      23.20 .553 20.96   -6.352 1.96  -1.00 .743  10.08   4.55     .00     .00
3C      23.20 .553 21.14   -6.828 1.78   -.81 .755  10.24   5.20     .00     .00
4C      23.20 .553 20.96   -6.352 1.96  -1.00 .743  10.08   2.86     .00     .00
5C      22.70 .551 20.80   -7.180 1.66   -.72 .763  10.09   4.16     .00     .00
2S      22.80 .552 20.97   -7.479 1.58   -.54 .766  10.19   4.42     .00     .00
3S      23.20 .554 21.35   -7.549 1.56   -.42 .764  10.39   4.94     .00     .00
1T      23.00 .555 21.12   -7.361 1.62   -.57 .763  10.31   4.81     .00     .00
2T      22.90 .553 20.94   -7.070 1.70   -.67 .758  10.15   4.55     .00     .00
3T      23.20 .554 21.30   -7.331 1.62   -.60 .764  10.38   5.20     .00     .00
4T      23.40 .551 21.17   -6.457 1.91   -.85 .743  10.13   3.90     .00     .00

AVERAGES: 61213  BASELINE  W020 00 000
        22.83 .556 20.89   -7.162 1.70   -.62 .757  10.17   4.46    7.30    7.00
  STD     .09 .001   .24     .569  .17    .26 .010    .17    .54     *       *
           61213 W055CU004 (1E14)
        23.05 .553 21.03   -6.963 1.75   -.74 .756  10.18   4.41     .00     .00
  STD     .23 .001   .20     .436  .14    .19 .009    .13    .65     *       *
PERCENT OF BASELINE
       100.9 99.4 100.7   102.8   103   81.6  99.8 100.1   98.8      .0      .0
 STD%    1.4   .4   2.2    14.3    20   92.6   2.5   3.0   28.5      .0      .0
```

```
                                                                                CU
61221 W056CU005 (50E15) W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC    VOC   IP     LOG(IO)   N      R     FF     EFF    OCD     PCDA    PCDB

1R*     22.50 .549 20.34   -6.757 1.79   -.02 .725   9.46    .00     .00     .00
1B.*    22.30 .540 18.99   -4.563 3.10  -2.00 .669   8.52   2.21    7.30    7.00
2B.*    22.30 .537 18.59   -4.157 3.58  -2.59 .649   8.22   1.95    7.30    7.00
3B.*    22.50 .537 18.41   -3.950 3.89  -2.48 .625   7.98   1.56    7.30    7.00
4B.*    22.30 .535 18.02   -3.853 4.05  -2.31 .608   7.67   1.82    7.30    7.00
1C.*    20.70 .503 13.98   -3.873 3.83   6.58 .401   4.42    .52    4.85    6.66
2C      22.40 .533 18.91   -4.496 3.13  -1.54 .651   8.22   1.82    4.85    6.66
3C      22.50 .529 19.27   -4.713 2.88  -1.65 .673   8.47   1.82    4.85    6.66
4C      22.50 .534 19.50   -5.031 2.64  -1.29 .683   8.68   2.08    4.85    6.66
5C      22.90 .536 20.06   -5.277 2.46  -1.23 .698   9.06   2.34    4.85    6.66
1S      22.30 .538 19.91   -5.985 2.07   -.79 .719   9.12   2.34    4.85    6.66
2S      22.70 .535 20.12   -5.759 2.17   -.71 .706   9.07   2.34    4.85    6.66
1T      22.40 .533 19.91   -5.962 2.06   -.38 .705   8.90   2.34    4.85    6.66
2T      22.60 .532 19.55   -4.914 2.72  -1.62 .686   8.73   2.08    4.85    6.66
3T.*    22.40 .522 17.95   -3.642 4.37  -3.32 .611   7.56    .91    4.85    6.66
4T      22.00 .524 17.72   -3.753 4.17  -2.90 .612   7.46   1.04    4.85    6.66

AVERAGES: 61221  BASELINE  W020 00 000
BASELINE DATA INVALID OR MISSING
           61221 W056CU005 (50E15)
        22.48 .533 19.44   -5.099 2.70  -1.35 .681   8.63   2.02    4.85    6.66
  STD     .24 .004   .71     .696  .63    .69 .031    .50    .40     *       *
```

```
                                                                     CU
60120 W007CU001(1.7E15) W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC   IP    LOG(IO)  N     R     FF    EFF   OCD   PCDA  PCDB

1R*     22.60 .557 19.99  -5.516 2.40 -1.41 .715  9.52  7.00  5.20  6.30
2B      22.30 .550 20.65  -8.228 1.40   .01 .766  9.94   .00  8.60  6.90
3B      22.30 .545 20.78  -8.894 1.26   .25 .773  9.93   .00  8.60  6.90
4B      22.60 .550 21.20  -9.726 1.14   .50 .780 10.25   .00  8.60  6.90
1C      22.50 .550 21.06  -9.242 1.21   .10 .785 10.28   .00  6.64  6.90
2C      22.60 .550 21.16  -9.725 1.14   .79 .769 10.11   .00  6.64  6.90
3C      22.60 .550 21.11  -9.074 1.24   .13 .781 10.27   .00  6.64  6.90
4C      22.50 .545 20.94  -8.748 1.28   .23 .771  9.99   .00  6.64  6.90
5C      22.40 .545 20.74  -7.797 1.48  -.91 .788 10.17   .00  6.64  6.90
6C      22.50 .545 20.64  -7.398 1.58  -.35 .757  9.81   .00  6.64  6.90
1E      22.50 .545 21.09  -9.591 1.15   .42 .780 10.12   .00  6.64  6.90
2E      22.40 .545 20.69  -8.064 1.42   .08 .760  9.81   .00  6.64  6.90
3E      22.50 .550 20.98  -8.852 1.28   .04 .780 10.20   .00  6.64  6.90
4E      22.50 .546 20.65  -7.463 1.57  -.25 .755  9.81   .00  6.64  6.90
5E      22.50 .547 21.10  -9.791 1.12   .60 .777 10.12   .00  6.64  6.90
6E      21.75 .542 20.17  -8.441 1.34   .22 .764  9.52   .00  6.64  6.90

AVERAGES: 60120  BASELINE  W002 00 000
        22.40 .548 20.88  -8.949 1.26   .25 .773 10.04   .00  8.60  6.90
  STD     .14 .002   .23    .613  .11   .20 .006   .15   .00    *     *
            60120 W007CU001(1.7E15)
        22.44 .547 20.86  -8.682 1.32   .09 .772 10.02   .00  6.64  6.90
  STD     .22 .003   .28    .817  .16   .43 .011   .22   .00    *     *
PERCENT OF BASELINE
       100.2 99.7  99.9   103.0  104  35.6  99.9  99.8 *****  77.2 100.0
 STD%    1.6   .9   2.5    16.4   22 330.8   2.1   3.7 *****    .0    .0

                                                                     CU
60204 W007CU001(1.7E15) W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC   IP    LOG(IO)  N     R     FF    EFF   OCD   PCDA  PCDB

1R*     22.62 .547 20.69  -7.543 1.55   .41 .735  9.61  4.55  8.60  6.90
1B.*    22.87 .552 20.27  -5.434 2.43 -1.89 .727  9.71  3.90  8.60  6.90
2B      22.30 .545 20.25  -6.717 1.80  -.68 .745  9.58  3.90  8.60  6.90
3B      22.87 .552 21.28  -8.515 1.34  -.15 .779 10.40  4.55  8.60  6.90
4B      23.25 .552 21.68  -8.709 1.30  -.21 .786 10.67  5.20  8.60  6.90
5B      22.87 .552 21.05  -7.597 1.55  -.40 .764 10.21  2.21  8.60  6.90
1C      22.75 .552 21.37  -9.789 1.13   .29 .789 10.47  2.60  6.64  6.90
2C      22.75 .547 20.43  -6.068 2.06 -1.19 .737  9.69  4.55  6.64  6.90
3C      22.75 .552 21.43 -10.298 1.07   .54 .787 10.46  3.90  6.64  6.90
4C      22.75 .552 21.43 -10.298 1.07   .54 .787 10.46  3.25  6.64  6.90
5C      22.75 .547 20.71  -6.875 1.75  -.59 .749  9.85  4.55  6.64  6.90
1S*     22.62 .547 12.81  -1.573 **** ***** .501  6.55  1.95  6.64  6.90
2S      22.75 .547 21.27  -9.425 1.17   .61 .770 10.14  3.25  6.64  6.90
3S*     22.75 .540 21.37 -11.310  .93  2.26 .737  9.58  1.56  6.64  6.90
1R*     22.62 .550 20.66  -7.513 1.57   .51 .730  9.61  4.55  6.64  6.90
1T      22.62 .550 20.58  -6.769 1.79  -.78 .751  9.88  3.90  6.64  6.90
2T      22.62 .550 21.06  -8.576 1.33  -.17 .781 10.28  4.16  6.64  6.90
3T      22.62 .550 20.88  -7.904 1.47  -.17 .765 10.06  2.99  6.64  6.90

AVERAGES: 60204  BASELINE  W002 00 000
        22.82 .550 21.07  -7.884 1.50  -.36 .769 10.21  3.97  8.60  6.90
  STD     .34 .003   .52    .794  .20   .21 .016   .40  1.11    *     *
            60204 W007CU001(1.7E15)
        22.71 .550 21.02  -8.445 1.43  -.10 .768 10.14  3.68  6.64  6.90
  STD     .06 .002   .36   1.523  .34   .61 .018   .28   .65    *     *
PERCENT OF BASELINE
        99.5 99.9  99.8    92.9   95 171.6 100.0  99.3  92.9  77.2 100.0
 STD%    1.8   .9   4.2    32.0   39 287.7   4.5   6.7  47.2    .0    .1
```

```
                                                                          CU
60316 W017CU002(1.7E16) W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP     LOG(IO)  N      R     FF   EFF    OCD    PCDA  PCDB

1B     22.75 .550 20.44  -6.079 2.07 -1.20 .737  9.76   3.25   8.42 11.60
2B.*   22.25 .550 19.89  -5.951 2.14 -1.09 .726  9.40   3.25   8.42 11.60
3B     22.75 .550 20.93  -7.455 1.58  -.62 .768 10.16   3.25   8.42 11.60
4B     22.25 .542 20.07  -6.475 1.88  -.52 .731  9.32   1.95   8.42 11.60
5B     22.75 .550 20.93  -7.455 1.58  -.62 .768 10.16   4.55   8.42 11.60
1C     21.75 .532 19.33  -5.655 2.23 -1.51 .725  8.88   1.95   7.13  8.82
2C     22.20 .537 19.83  -5.855 2.13 -1.30 .730  9.20   2.60   7.13  8.82
3C     21.74 .530 19.22  -5.514 2.30 -1.40 .714  8.70   1.95   7.13  8.82
4C     22.00 .532 19.93  -6.666 1.77  -.52 .738  9.13   2.21   7.13  8.82
5C     21.75 .532 19.44  -5.907 2.09 -1.25 .729  8.93   2.21   7.13  8.82
1S     21.60 .532 19.29  -5.842 2.13 -1.37 .730  8.87   2.21   7.13  8.80
2S     21.60 .535 19.22  -5.910 2.11  -.73 .712  8.70   1.95   7.13  8.80
3S     21.60 .540 19.77  -7.419 1.57  -.02 .745  9.20   2.86   7.13  8.80
1T     21.25 .540 19.05  -6.104 2.04  -.98 .728  8.84   2.21   7.13  8.80
2T     21.25 .540 19.27  -6.614 1.83  -.87 .746  9.05   2.47   7.13  8.80
3T     21.25 .540 19.70  -8.417 1.34   .16 .765  9.29   2.47   7.13  8.80

AVERAGES: 60316  BASELINE  W003 00 000
       22.63 .548 20.59  -6.866 1.78  -.74 .751  9.85   3.25   8.42 11.60
  STD    .22 .003   .36    .605  .21   .27 .017   .35    .92    *     *
           60316 W017CU002(1.7E16)
       21.64 .535 19.46  -6.355 1.96  -.89 .733  8.98   2.28   7.13  8.81
  STD    .29 .004   .28    .838  .28   .54 .014   .19    .28    *     *
PERCENT OF BASELINE
       95.6 97.7  94.5   107.4  110  79.2  97.6  91.2   70.2   84.7  75.9
 STD%   2.2  1.3   3.1    21.4   31 144.2   4.2   5.3   30.9     .0    .1

                                                                          CU
60323 W019CU003(4E14)  W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP     LOG(IO)  N      R     FF   EFF    OCD    PCDA  PCDB

1R*    22.50 .550 20.63  -7.895 1.47   .80 .731  9.56   5.00   8.42 11.65
3B     22.00 .550 20.59  -9.707 1.14   .89 .766  9.80   4.55   8.42 11.65
1C     22.00 .540 20.25  -8.164 1.39   .78 .738  9.27   3.51   1.95  4.30
2C     22.00 .540 20.69 -10.009 1.08   .46 .786  9.88   4.55   1.95  4.30
3C     21.75 .540 20.26  -8.847 1.26   .19 .774  9.61   3.51   1.95  4.30
1S     22.40 .540 20.76  -7.990 1.42  -.60 .782 10.00   4.16   1.95  4.30
2S     22.00 .540 20.45  -8.241 1.37  -.59 .788  9.89   5.20   1.95  4.30
3S     22.00 .540 20.45  -8.241 1.37  -.59 .788  9.89   3.90   1.95  4.30
4S     22.00 .540 20.44  -8.598 1.30   .22 .767  9.64   3.90   1.95  4.30
1T     22.80 .556 21.07  -8.355 1.38   .60 .749 10.04   3.90   1.95  4.30
2T     22.30 .556 20.79  -8.936 1.27   .24 .774 10.15   4.16   1.95  4.30
3T     21.50 .556 19.74  -8.387 1.38  1.62 .717  9.06   3.64   1.95  4.30

AVERAGES: 60323  BASELINE  W003 00 000
       22.00 .550 20.59  -9.707 1.14   .89 .766  9.80   4.55   8.42 11.65
  STD    .00 .000   .00    .000  .00   .00 .000   .00    .00    *     *
           60323 W019CU003(4E14)
       22.08 .545 20.49  -8.577 1.32   .23 .766  9.74   4.04   1.95  4.30
  STD    .34 .007   .35    .555  .10   .67 .023   .33    .49    *     *
PERCENT OF BASELINE
      100.3 99.1  99.5   111.6  116  26.4 100.0  99.4   88.9   23.2  36.9
 STD%   1.5  1.3   1.7     5.7    8  75.1   3.0   3.4   10.8     .0    .0
```

```
                                                                           CU
60423 W027CU-MN001 (1E15,1.3E15) W002 00 000
SOL4   1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC   VOC  IP     LOG(IO)  N      R    FF    EFF    OCD   PCDA   PCDB

1B       22.40 .550 20.84  -8.493 1.34  -.24 .782 10.18   4.16   8.57   6.34
2B       23.00 .550 20.68  -6.145 2.04 -1.06 .736  9.85   3.90   8.57   6.34
3B       23.00 .550 21.24  -7.794 1.49  -.40 .770 10.30   4.55   8.57   6.34
4B       23.00 .550 20.74  -6.153 2.04 -1.39 .748 10.00   3.90   8.57   6.34
5B       23.00 .550 21.24  -7.794 1.49  -.40 .770 10.30   4.55   8.57   6.34
1C       17.00 .510 15.66  -7.660 1.45  -.74 .769  7.06    .91    .45  22.30
2C       17.00 .510 15.66  -7.660 1.45  -.74 .769  7.06    .78    .45  22.30
3C       17.00 .510 15.66  -7.660 1.45  -.74 .769  7.06    .78    .45  22.30
4C       16.70 .510 15.50  -8.329 1.30  -.49 .780  7.02    .78    .45  22.30
5C       17.40 .510 15.96  -7.188 1.57 -1.39 .774  7.27    .91    .45  22.30
6C       16.50 .510 15.24  -8.029 1.36  -.30 .767  6.82    .65    .45  22.30
1S       17.60 .510 16.12  -7.410 1.51  -.39 .753  7.15    .91    .45  22.30
2S       17.40 .510 16.13  -8.206 1.32  -.54 .779  7.31    .91    .45  22.30
1T       16.00 .510 14.73  -7.889 1.40  -.07 .756  6.52    .65    .45  22.30
2T       16.50 .510 15.03  -7.378 1.52   .31 .732  6.51    .52    .45  22.30
3T       16.30 .510 15.20  -9.097 1.17   .32 .774  6.81    .78    .45  22.30
4T       17.00 .510 15.91  -9.299 1.13  -.01 .788  7.22    .78    .45  22.30

AVERAGES: 60423  BASELINE  W002 00 000
         22.88 .550 20.95  -7.276 1.68  -.70 .761 10.13   4.21   8.57   6.34
   STD     .24 .000   .24    .955  .30   .45 .017   .18    .29      *      *
             60423 W027CU-MN001 (1E15,1.3E15)
         16.87 .510 15.57  -7.984 1.38  -.40 .768  6.98    .78    .45  22.30
   STD     .46 .000   .42    .632  .13   .47 .014   .26    .12      *      *
PERCENT OF BASELINE
          73.7 92.7  74.3    90.3   82 143.3 100.8  68.9   18.5    5.3  351.7
  STD%     2.8   .1   2.9    24.2   24 146.2   4.1   3.8    4.3     .0     .3
```

```
                                                                           CU
60510 W030CR-CU001 (1E15-1E15) W002 00 000
SOL4   1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC   VOC  IP     LOG(IO)  N      R    FF    EFF    OCD   PCDA   PCDB

1B       22.00 .547 20.79 -10.668 1.01   .45 .797 10.14   4.94   8.57   6.30
2B       22.00 .547 20.47  -8.524 1.33  -.17 .780  9.92   4.94   8.57   6.30
3B       21.80 .547 20.41  -9.286 1.20   .05 .788  9.93   4.94   8.57   6.30
4B       22.00 .547 20.47  -8.524 1.33  -.17 .780  9.92   4.94   8.57   6.30
1C       16.00 .497 14.86  -8.731 1.20   .25 .768  6.46    .65    .42    .32
2C       15.60 .493 14.39  -8.154 1.30   .24 .754  6.14    .52    .42    .32
3C       16.50 .500 15.37  -8.968 1.16   .28 .772  6.74    .78    .42    .32
4C       17.20 .506 16.24 -10.848  .93   .89 .787  7.24    .91    .42    .32
5C       16.50 .500 15.37  -8.968 1.16   .28 .772  6.74    .65    .42    .32
1S       17.40 .510 16.31  -9.566 1.09   .17 .788  7.39    .91    .42    .30
2S       17.10 .510 16.06  -9.996 1.04   .53 .785  7.24   1.04    .42    .30
3S       17.40 .510 16.09  -8.182 1.33  -.05 .764  7.17    .91    .42    .30
2T       16.50 .500 15.33  -8.673 1.21   .16 .769  6.71    .65    .42    .30
3T       16.80 .500 15.65  -9.007 1.15   .28 .773  6.87    .78    .10    .30

AVERAGES: 60510  BASELINE  W002 00 000
         21.95 .547 20.53  -9.251 1.22   .04 .786  9.98   4.94   8.57   6.30
   STD     .09 .000   .15    .875  .13   .26 .007   .09    .00      *      *
             60510 W030CR-CU001 (1E15-1E15)
         16.70 .503 15.57  -9.109 1.16   .31 .773  6.87    .78    .39    .31
   STD     .57 .006   .60    .786  .11   .24 .010   .37    .15      *      *
PERCENT OF BASELINE
          76.1 91.9  75.8   101.5   95 806.5  98.4  68.8   15.8    4.5    4.9
  STD%     2.9  1.0   3.5    18.6   20 *****   2.2   4.4    3.1    1.1     .2
```

```
                                                                     CU
60809 W041CR-CU-NI001 (8E14-1.7E15-3E15) W020 00 000
SOL5  1 /28/77    AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP     LOG(IO)  N      R    FF    EFF    OCD    PCDA   PCDB

1R*    22.50 .553 20.30  -6.577 1.87  -.23 .725  9.54    .00    .00    .00
2B     23.10 .553 21.53  -8.666 1.31  -.19 .784 10.59   5.20    .00    .00
3B.*   22.60 .548 20.20  -5.845 2.18 -1.38 .732  9.59   3.25    .00    .00
4B     22.70 .552 21.07  -8.204 1.41  -.37 .779 10.33   4.81    .00    .00
5B     22.90 .552 21.21  -8.046 1.44  -.39 .776 10.38   4.94    .00    .00
1C     19.30 .503 16.73  -5.066 2.51 -1.55 .685  7.03    .65    .43    .20
2C     20.80 .527 18.74  -6.297 1.91 -1.01 .737  8.55   1.30    .43    .20
3C     19.00 .507 16.84  -5.725 2.12 -1.20 .713  7.26    .52    .43    .20
4C.*   20.20 .505 14.93  -2.911 6.79 -7.81 .562  6.07    .26    .43    .20
1S     19.30 .509 16.84  -5.135 2.49 -1.96 .701  7.28    .52    .43    .20
2S     20.50 .523 18.32  -5.948 2.05 -1.23 .728  8.26    .91    .43    .20
3S     20.30 .518 17.61  -4.887 2.71 -2.41 .700  7.79    .78    .43    .20
1T     18.20 .495 15.73  -5.081 2.47 -1.35 .677  6.45    .39    .43    .20
2T     17.70 .502 15.66  -5.779 2.08  -.93 .704  6.62    .39    .43    .20
3T     17.70 .498 15.53  -5.464 2.24 -1.33 .698  6.51    .52    .43    .20
4T     16.90 .496 14.94  -5.859 2.03  -.66 .699  6.20    .52    .43    .20

AVERAGES: 60809  BASELINE  W020 00 000
       22.90 .552 21.27  -8.305 1.39  -.31 .780 10.43   4.98    .00    .00
  STD    .16 .000   .19    .263  .05   .09 .003   .11    .16     *      *
          60809 W041CR-CU-NI001 (8E14-1.7E15-3E15)
       18.97 .508 16.69  -5.524 2.26 -1.36 .704  7.19    .65    .43    .20
  STD   1.26 .011  1.19    .443  .25   .48 .017   .75    .27     *      *
PERCENT OF BASELINE
       82.8 91.9  78.5   133.5   163 *****  90.3  69.0   13.0 ***** *****
 STD%   6.1  2.0   6.4     7.6    25 322.5   2.6   8.1    5.9 ***** *****

                                                                     FE
60902 W046FE-V001 (5.6E14-7E13) W020 00 000
SOL3  1 /28/77    AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP     LOG(IO)  N      R    FF    EFF    OCD    PCDA   PCDB

1R*    22.50 .555 20.54  -7.237 1.66  -.04 .741  9.79    .00    .00    .00
1B     22.60 .558 21.13  -9.001 1.27  -.15 .790 10.53   4.42   7.30   7.00
2B     22.80 .560 21.47 -10.118 1.10   .31 .793 10.71   5.20   7.30   7.00
3B     22.70 .558 21.27  -9.440 1.20   .22 .785 10.52   4.16   7.30   7.00
4B     22.80 .559 21.47 -10.103 1.10   .31 .793 10.69   4.94   7.30   7.00
5B     22.80 .556 21.19  -8.446 1.36  -.10 .776 10.40   4.16   7.30   7.00
1C*     9.90 .480  8.15  -4.280 3.52 -6.38 .640  3.22    .10    .15    .15
2C     18.00 .499 16.83  -9.299 1.10   .24 .780  7.41    .65    .15    .15
3C     17.50 .496 15.85  -6.537 1.73 -1.33 .750  6.88    .65    .15    .15
4C     17.40 .496 15.89  -7.037 1.57 -1.02 .759  6.93    .65    .15    .15
5C     17.40 .493 15.93  -7.379 1.47  -.48 .755  6.85    .65    .15    .15
1S     17.70 .498 16.40  -8.284 1.27  -.19 .771  7.19    .39    .15    .15
2S     17.50 .498 16.21  -8.202 1.29  -.31 .773  7.12    .39    .15    .15
3S     17.60 .495 16.21  -7.710 1.39  -.55 .767  7.07    .52    .15    .15
1T     17.80 .500 16.52  -8.516 1.23   .06 .769  7.24    .52    .15    .15
2T     17.10 .497 15.62  -6.984 1.59 -1.31 .765  6.88    .52    .15    .15
3T     17.20 .496 15.66  -6.808 1.64 -1.32 .759  6.85    .52    .15    .15
4T     17.10 .496 15.83  -8.240 1.28  -.14 .769  6.89    .52    .15    .15

AVERAGES: 60902  BASELINE  W020 00 000
       22.74 .558 21.31  -9.422 1.21   .12 .787 10.57   4.58   7.30   7.00
  STD    .08 .001   .14    .645  .10   .20 .007   .12    .42     *      *
          60902 W046FE-V001 (5.6E14-7E13)
       17.48 .497 16.09  -7.727 1.42  -.58 .765  7.03    .54    .15    .15
  STD    .27 .002   .36    .815  .19   .55 .008   .18    .09     *      *
PERCENT OF BASELINE
       76.9 89.0  75.5   118.0   117 *****  97.2  66.5   11.9    2.1    2.1
 STD%   1.5   .5   2.2    14.9    27 *****   1.9   2.5    3.3     .0     .0
```

```
                                                                        FE
60827 W044FE003 (1.7E13) W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP    LOG(IO)  N     R     FF    EFF    OCD    PCDA   PCDB

1R*    22.50 .555 20.78  -8.308 1.39   .61 .747  9.87    .00    .00    .00
1B     22.80 .553 20.89  -7.319 1.63  -.35 .755 10.06   3.25   7.30   7.00
2B     23.30 .556 21.87  -9.523 1.18   .05 .792 10.86   4.94   7.30   7.00
3B     23.10 .556 21.52  -8.676 1.32  -.06 .780 10.59   4.29   7.30   7.00
4B     23.10 .555 21.45  -8.354 1.38  -.14 .775 10.51   4.55   7.30   7.00
5B     23.50 .557 21.67  -7.821 1.50  -.12 .761 10.54   4.42   7.30   7.00
1C.*   22.70 .551 18.92  -3.744 4.38 -5.90 .694  9.18   2.99   6.59   1.26
2C.*   23.10 .553 20.04  -4.637 3.08 -3.33 .718  9.71   3.38   6.59   1.26
3C     23.30 .558 21.67  -8.461 1.37  -.15 .778 10.70   5.20   6.59   1.26
4C*    22.80 .539 17.93  -3.297 5.41 -5.48 .613  7.97   1.30   6.59   1.26
1S     23.10 .559 21.73  -9.849 1.14   .20 .793 10.83   4.94   6.59   1.26
2S     23.00 .554 21.48  -8.957 1.26   .03 .782 10.54   3.90   6.59   1.26
3S     24.20 .551 22.30  -8.134 1.41   .61 .743 10.47   3.25   6.59   1.26
1T     22.50 .557 21.14  -9.799 1.14   .27 .790 10.46   4.29   6.59   1.26
2T.*   22.70 .551 19.47  -4.298 3.47 -4.32 .715  9.46   2.99   6.59   1.26
3T     22.90 .556 21.38  -8.979 1.27   .05 .782 10.53   4.42   6.59   1.26

AVERAGES: 60827  BASELINE  W020 00 000
       23.16 .555 21.48  -8.338 1.40  -.12 .773 10.51   4.29   7.30   7.00
  STD    .23 .001   .33    .752  .15   .13 .013   .26    .56    *      *
          60827 W044FE003 (1.7E13)
       23.17 .556 21.62  -9.030 1.26   .17 .778 10.59   4.33   6.59   1.26
  STD    .52 .003   .36    .632  .10   .24 .017   .13    .64    *      *
PERCENT OF BASELINE
      100.0 **** 100.6    91.7    90 334.0 100.7 100.7 101.0   90.3   18.0
 STD%    3.3   .7   3.2    18.0    18 534.7   3.9   3.7  30.3     .1     .0

                                                                        FE
61019 W045CR-FE-TI001 (6.5E14-4.3E14-6E13)  W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP    LOG(IO)  N     R     FF    EFF    OCD    PCDA   PCDB

1R*    22.50 .555 20.44  -6.975 1.74  -.03 .732  9.67    .00    .00    .00
1B     22.50 .544 19.23  -4.564 3.12 -2.30 .679  8.79   1.56   7.30   6.99
2B     22.70 .554 21.04  -8.117 1.43  -.35 .777 10.33   5.20   7.30   6.99
3B     22.70 .555 21.04  -8.163 1.42  -.28 .775 10.33   4.55   7.30   6.99
4B     22.80 .555 21.01  -7.605 1.55  -.55 .770 10.30   4.29   7.30   6.99
5B     22.70 .553 20.99  -7.815 1.50  -.56 .776 10.30   4.29   7.30   6.99
1C     15.50 .484 14.21  -7.652 1.38  -.07 .749  5.94    .13    .99    .15
2C     16.20 .486 14.91  -8.004 1.31   .23 .751  6.25    .13    .99    .15
3C     16.20 .490 14.83  -7.400 1.46  -.48 .754  6.33    .13    .99    .15
4C     15.70 .478 14.07  -6.162 1.83 -1.42 .731  5.80    .13    .99    .15
5C     15.80 .481 14.39  -7.090 1.52  -.63 .747  6.01    .13    .99    .15
1S     15.60 .480 14.11  -6.641 1.66 -1.01 .741  5.86    .13    .99    .15
2S     16.10 .487 14.71  -7.267 1.49  -.55 .751  6.23    .13    .99    .15
3S     16.20 .489 14.83  -7.388 1.46  -.48 .753  6.31    .13    .99    .15
1T     16.30 .487 14.95  -7.675 1.38  -.02 .749  6.29    .13    .99    .15
2T     16.30 .487 14.95  -7.675 1.38  -.02 .749  6.29    .13    .99    .15
3T     16.20 .486 14.90  -7.818 1.35  -.14 .756  6.30    .13    .99    .15
4T     16.20 .487 14.83  -7.470 1.43  -.24 .749  6.25    .13    .99    .15

AVERAGES: 61019  BASELINE  W020 00 000
       22.73 .554 21.02  -7.925 1.48  -.44 .774 10.32   4.58   7.30   6.99
  STD    .05 .001   .02    .228  .05   .13 .003   .01    .37    *      *
          61019 W045CR-FE-TI001 (6.5E14-4.3E14-6E13)
       16.52 .490 14.99  -7.139 1.60  -.55 .743  6.36    .24   1.48    .68
  STD   1.75 .016  1.26    .883  .46   .66 .020   .72    .38    *      *
PERCENT OF BASELINE
       72.7 88.4  71.3   109.9   108  73.9  96.0  61.6    5.2   20.2    9.7
 STD%    7.8  3.0   6.1    14.1    36 232.1   2.9   7.1    9.4   23.0   26.1
```

```
                                                                              FE
60317 W018FE002(1.7E15) W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC    VOC   IP     LOG(IO)   N      R     FF     EFF     OCD     PCDA   PCDB

1B      22.00 .556 20.32   -7.948 1.48   -.20 .766   9.91    4.55    8.42 11.65
2B      22.00 .556 20.32   -7.948 1.48   -.20 .766   9.91    4.55    8.42 11.65
3B      22.00 .556 20.32   -7.948 1.48   -.20 .766   9.91    4.55    8.42 11.65
4B      22.00 .550 19.73   -6.043 2.09  -1.22 .735   9.40    2.99    8.42 11.65
1C.*    14.30 .490 11.85   -4.114 3.60  -5.46 .659   4.88     .26     .61   8.13
2C      14.30 .500 12.81   -6.218 1.91  -1.47 .728   5.51     .26     .61   8.13
3C.*    14.30 .490 12.05   -4.370 3.24  -4.82 .675   5.00     .26     .61   8.13
4C.*    14.30 .490 12.05   -4.370 3.24  -4.82 .675   5.00     .26     .61   8.13
5C      14.30 .500 12.81   -6.218 1.91  -1.47 .728   5.51     .39     .61   8.13
1S      14.25 .490 12.48   -5.411 2.30  -2.22 .703   5.19     .26     .61   8.10
2S      14.00 .490 12.21   -5.266 2.40  -2.61 .701   5.08     .26     .61   8.10

AVERAGES: 60317  BASELINE  W003 00 000
        22.00 .555 20.18   -7.472 1.63   -.45 .758   9.78    4.16    8.42 11.65
  STD     .00 .003   .25     .825  .27    .44 .014    .22     .68     *      *
           60317 W018FE002(1.7E15)
        14.21 .495 12.58   -5.778 2.13  -1.94 .715   5.32     .29     .61   8.12
  STD     .12 .005   .25     .443  .22    .49 .013    .19     .06     *      *
PERCENT OF BASELINE
        64.6 89.3  62.3    122.7   131 *****  94.3   54.4     7.0     7.2   69.7
 STDZ     .6  1.3   2.0     15.1    37 634.6   3.5    3.2     2.7      .0     .1
                                                                              FE
60610 W016FE001 (8.5E14) W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC    VOC   IP     LOG(IO)   N      R     FF     EFF     OCD     PCDA   PCDB

1B      23.00 .554 21.47   -8.941 1.27    .08 .780  10.51    5.85    8.42 11.65
2B      23.20 .554 21.56   -8.473 1.35   -.04 .774  10.53    5.46    8.42 11.65
3B      23.20 .554 21.56   -8.473 1.35   -.04 .774  10.53    5.20    8.42 11.65
4B      23.00 .554 21.47   -8.941 1.27    .08 .780  10.51    5.20    8.42 11.65
5B      23.00 .554 21.47   -8.941 1.27    .08 .780  10.51    5.20    8.42 11.65
1C      21.00 .535 19.65   -9.281 1.18    .11 .785   9.33    2.86    3.76    .50
2C      21.70 .540 20.33   -9.329 1.18    .07 .788   9.76    3.64    3.76    .50
3C      21.20 .535 19.73   -8.612 1.29   -.08 .778   9.33    3.25    3.76    .50
4C      21.20 .535 19.73   -8.612 1.29   -.08 .778   9.33    2.99    3.76    .50
5C      21.60 .535 19.87   -7.559 1.52   -.45 .764   9.34    2.86    3.76    .50
1S      22.20 .540 20.83   -9.684 1.12    .34 .785   9.95    3.25    3.76    .50
2S      21.90 .540 20.43   -8.877 1.25    .03 .780   9.76    3.51    3.76    .50
3S      21.90 .540 20.27   -8.064 1.41   -.29 .772   9.66    2.99    3.76    .50
1T      20.50 .532 19.20   -9.411 1.15    .20 .785   9.05    2.47    3.76    .50
2T      19.50 .530 18.14   -8.947 1.22    .61 .762   8.33    1.56    3.76    .50
3T      17.60 .519 16.47   -9.527 1.12    .56 .775   7.49     .91    3.76    .50
4T      18.00 .519 16.75   -8.745 1.24   -.01 .777   7.68     .91    3.76    .50

AVERAGES: 60610  BASELINE  W003 00 000
        23.08 .554 21.50   -8.754 1.30    .03 .778  10.52    5.38    8.42 11.65
  STD     .10 .000   .04     .229  .04    .06 .003    .01     .25     *      *
           60610 W016FE001 (8.5E14)
        20.69 .533 19.28   -8.887 1.25    .09 .777   9.08    2.60    3.76    .50
  STD    1.47 .007  1.36     .598  .11    .30 .008    .78     .91     *      *
PERCENT OF BASELINE
        89.7 96.3  89.7     98.5    96 264.2  99.9   86.4    48.3    44.7    4.3
 STDZ    6.8  1.3   6.5      9.7    12 *****   1.4    7.5    20.1      .0     .0
```

```
                                                                         FE
60823 W043FE-TI001 (5.6E14-6E13)  W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC  IP     LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*     22.50 .555 20.28  -6.544 1.89  -.21 .723  9.55   .00    .00    .00
1B      23.00 .556 21.20  -7.668 1.54  -.42 .767 10.38  4.16   7.30   7.00
2B      22.80 .555 21.05  -7.800 1.51  -.40 .770 10.31  4.94   7.30   7.00
3B      22.70 .555 20.57  -6.474 1.92 -1.06 .749  9.98  3.90   7.30   7.00
4B      22.80 .554 20.58  -6.247 2.01 -1.27 .747  9.98  4.81   7.30   7.00
5B      23.50 .555 21.73  -7.981 1.46  -.24 .770 10.62  4.55   7.30   7.00
1C      16.10 .493 14.40  -6.353 1.81  -.35 .712  5.98   .13    .50    .90
2C      15.90 .490 14.29  -6.678 1.68   .12 .712  5.87   .13    .50    .90
3C      16.20 .487 14.34  -5.983 1.94  -.42 .698  5.82   .13    .50    .90
4C      16.30 .488 14.36  -5.797 2.03  -.51 .691  5.81   .13    .50    .90
5C      16.00 .481 13.86  -5.199 2.36 -1.48 .681  5.54   .13    .50    .90
1S      16.30 .490 14.10  -5.137 2.44 -1.58 .680  5.74   .13    .50    .90
2S      16.20 .489 14.16  -5.464 2.22 -1.16 .689  5.78   .13    .50    .90
3S      16.20 .486 13.74  -4.665 2.82 -2.27 .661  5.50   .13    .50    .90
1T      16.00 .484 14.25  -6.238 1.82  -.21 .704  5.76   .13    .50    .90
2T      16.10 .484 14.30  -6.125 1.87  -.28 .700  5.77   .13    .50    .90
3T      16.20 .488 14.42  -6.200 1.85  -.27 .704  5.88   .13    .50    .90
4T      16.20 .488 14.37  -6.037 1.92  -.46 .701  5.86   .13    .50    .90

AVERAGES: 60823  BASELINE  W020 00 000
        22.96 .555 21.03  -7.234 1.69  -.68 .761 10.25  4.47   7.30   7.00
  STD     .29 .001   .43    .724  .23   .41 .010   .25   .39    *      *
             60823 W043FE-TI001 (5.6E14-6E13)
        16.14 .487 14.22  -5.823 2.06  -.74 .694  5.78   .13    .50    .90
  STD     .12 .003   .21    .564  .32   .68 .014   .13   .00    *      *
PERCENT OF BASELINE
        70.3 87.8  67.6   119.5   122  90.8  91.3  56.4   2.9    6.8   12.9
 STD%    1.4   .7   2.4    16.6    38 227.2   3.2   2.6    .3     .0     .0
                                                                         MG
60421 W024MG002 (3E13) W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC  IP     LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1B      23.00 .545 21.44  -8.417 1.34  -.66 .796 10.55  5.20   8.57   6.30
2B      22.60 .545 21.10  -8.722 1.29  -.43 .794 10.34  5.20   8.57   6.30
3B      22.60 .545 21.07  -8.676 1.30  -.18 .784 10.21  4.55   8.57   6.30
4B      22.50 .545 20.88  -8.194 1.39  -.38 .780 10.11  4.55   8.57   6.30
1C      22.60 .545 21.14  -9.122 1.22   .03 .785 10.23  4.94  10.24   7.50
2C      22.60 .545 21.14  -9.122 1.22   .03 .785 10.23  5.20  10.24   7.50
3C      22.40 .545 20.73  -7.937 1.45  -.45 .775 10.01  4.94  10.24   7.50
4C      22.50 .545 21.11  -9.513 1.16   .13 .789 10.24  4.55  10.24   7.50
5C      22.60 .545 21.14  -9.122 1.22   .03 .785 10.23  4.16  10.24   7.50
1S      22.30 .535 20.61  -7.845 1.44  -.46 .773  9.76  4.16  10.24   7.50
2S      22.50 .535 20.71  -7.353 1.57  -.92 .776  9.88  4.16  10.24   7.50
3S      22.60 .532 20.62  -6.929 1.68  -.71 .755  9.60  3.38  10.24   7.50
1T      22.30 .540 20.80  -8.725 1.28  -.20 .785 10.00  4.94  10.24   7.50
2T      22.60 .540 21.22  -9.406 1.16  -.20 .799 10.32  5.20  10.24   7.50
3T      22.30 .540 20.80  -8.725 1.28  -.20 .785 10.00  4.55  10.24   7.50

AVERAGES: 60421  BASELINE  W002 00 000
        22.68 .545 21.12  -8.502 1.33  -.41 .788 10.30  4.88   8.57   6.30
  STD     .19 .000   .20    .212  .04   .17 .007   .16   .33    *      *
             60421 W024MG002 (3E13)
        22.48 .541 20.91  -8.527 1.33  -.26 .781 10.04  4.56  10.24   7.50
  STD     .13 .005   .23    .833  .17   .32 .011   .22   .53    *      *
PERCENT OF BASELINE
        99.1 99.2  99.0    99.7   100 136.0  99.1  97.5  93.6  119.5  119.0
 STD%    1.4   .8   2.0    12.5    16 136.2   2.2   3.7  17.9     .1     .0
```

```
                                                                        MG
60427 W021MG001 (3E12) W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC    VOC   IP    LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1B     22.30 .545 20.89   -9.329 1.19    .10 .787 10.11   4.55   8.57   6.30
2B     22.30 .550 21.06 -10.712 1.01    .57 .793 10.29   5.20   8.57   6.30
3B     22.00 .550 20.75 -10.407 1.05    .45 .793 10.15   4.94   8.57   6.30
4B     22.30 .550 20.83   -9.035 1.24    .12 .780 10.12   5.20   8.57   6.30
1C     22.50 .553 21.03   -9.097 1.24    .08 .783 10.30   4.16   7.74   8.20
2C     22.50 .540 21.01   -8.907 1.24   -.10 .786 10.10   4.55   7.74   8.20
3C     22.50 .558 21.04   -9.083 1.25   -.06 .788 10.46   5.20   7.74   8.20
4C*    21.50 .532 19.67   -7.266 1.59   -.36 .752  9.10   2.60   7.74   8.20
5C     21.80 .537 20.37   -9.044 1.22    .01 .784  9.71   4.16   7.74   8.20
1S     22.30 .540 20.76   -8.740 1.27    .14 .774  9.85   4.55   7.74   8.20
2S     22.00 .540 20.39   -8.266 1.36   -.04 .769  9.66   4.29   7.74   8.20
3S     22.00 .540 20.62   -9.386 1.17    .08 .788  9.91   5.20   7.74   8.20
1T     22.40 .540 20.98   -9.437 1.16    .31 .781  9.99   5.20   7.74   8.20
2T     22.50 .540 21.01   -9.104 1.21    .23 .778  9.99   4.55   7.74   8.20
3T     22.40 .540 20.98   -9.437 1.16    .31 .781  9.99   4.55   7.74   8.20
4T     22.40 .540 20.98   -9.437 1.16    .31 .781  9.99   4.94   7.74   8.20

AVERAGES: 60427  BASELINE  W002 00 000
       22.23 .549 20.88   -9.871 1.12    .31 .788 10.17   4.97   8.57   6.30
  STD    .13 .002   .12     .705  .09    .20 .005   .07    .27    *      *
        60427 W021MG001 (3E12)
       22.30 .543 20.83   -9.085 1.22    .12 .781 10.00   4.67   7.74   8.20
  STD    .24 .006   .25     .342  .06    .15 .006   .22    .39    *      *
PERCENT OF BASELINE
     100.3 98.9  99.8    108.0   109   37.0  99.1  98.3   93.9   90.3 130.2
 STD%   1.7  1.5   1.7     10.3    15 102.1   1.4   2.9   13.2     .1    .0

                                                                        MG
60607 W032MG003 (3.2E14) W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC    VOC   IP    LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1B     22.50 .552 21.08   -9.265 1.21   -.04 .791 10.39   4.94   8.42 11.60
2B     22.50 .552 21.08   -9.265 1.21   -.04 .791 10.39   4.94   8.42 11.60
3B     22.50 .552 21.08   -9.265 1.21   -.04 .791 10.39   5.20   8.42 11.60
4B     22.50 .552 21.08   -9.265 1.21   -.04 .791 10.39   5.20   8.42 11.60
5B     22.00 .548 20.51   -8.682 1.30   -.25 .786 10.02   3.51   8.42 11.60
1C     22.60 .549 21.17   -9.299 1.20    .07 .787 10.33   5.20   7.14   7.17
2C     22.60 .549 21.17   -9.299 1.20    .07 .787 10.33   3.90   7.14   7.17
3C     22.60 .549 21.17   -9.299 1.20    .07 .787 10.33   4.94   7.14   7.17
4C     22.60 .549 21.17   -9.299 1.20    .07 .787 10.33   5.20   7.14   7.17
5C     22.60 .549 20.88   -7.834 1.48   -.47 .773 10.15   4.68   7.14   7.17
1S     22.50 .545 21.14   -9.519 1.16   -.14 .799 10.36   5.20   7.14   7.20
2S     22.50 .545 20.80   -7.695 1.51   -.80 .781 10.13   5.20   7.14   7.20
3S     22.50 .545 20.80   -7.695 1.51   -.80 .781 10.13   4.94   7.14   7.20
1T     22.50 .550 20.99   -8.864 1.27   -.02 .782 10.24   5.20   7.14   7.20
2T     22.50 .550 20.99   -8.864 1.27   -.02 .782 10.24   4.55   7.14   7.20
3T     22.70 .550 21.09   -8.400 1.36   -.15 .776 10.25   4.55   7.14   7.20
4T     22.50 .550 20.99   -8.864 1.27   -.02 .782 10.24   3.90   7.14   7.20

AVERAGES: 60607  BASELINE  W003 00 000
       22.40 .551 20.96   -9.148 1.23   -.08 .790 10.31   4.76   8.42 11.60
  STD    .20 .002   .23     .233  .04    .09 .002   .15    .63    *      *
        60607 W032MG003 (3.2E14)
       22.56 .548 21.03   -8.744 1.30   -.18 .784 10.25   4.79   7.14   7.19
  STD    .06 .002   .14     .647  .12    .31 .006   .08    .47    *      *
PERCENT OF BASELINE
     100.7 99.5 100.3    104.4   106  -19.3  99.3  99.4  100.6   84.8   62.0
 STD%   1.2   .6   1.7      9.7    14 *****   1.0   2.2   24.5     .0     .2
```

```
                                                                     MN
60226 W005MN001(1.3E15)  W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP     LOG(IO) N      R    FF   EFF    OCD   PCDA  PCDB

1B     22.50 .555 21.00  -8.952 1.27   .11 .779 10.29  4.55  8.60  6.30
2B     22.50 .558 21.12  -9.614 1.17   .21 .788 10.47  5.20  8.60  6.30
1C     17.00 .526 15.90  -9.414 1.15   .39 .779  7.37   .91   .29  1.76
2C     16.75 .520 15.43  -7.949 1.41   .03 .756  6.96   .65   .29  1.76
1E     17.12 .526 15.96  -8.969 1.22   .08 .779  7.42  1.04   .29  1.76
2E     16.50 .523 15.33  -8.561 1.29  -.15 .776  7.08   .91   .29  1.76
3E     17.12 .526 15.96  -8.969 1.22   .08 .779  7.42  1.04   .29  1.76
4E     16.75 .524 15.58  -8.748 1.26   .10 .773  7.18   .65   .29  1.76

AVERAGES: 60226  BASELINE  W002 00 000
       22.50 .557 21.06  -9.283 1.22   .16 .784 10.38  4.88  8.60  6.30
  STD    .00 .002   .06    .331  .05   .05 .005   .09   .33   *     *
          60226 W005MN001(1.3E15)
       16.87 .524 15.69  -8.769 1.26   .09 .773  7.24   .87   .29  1.76
  STD    .23 .002   .26    .449  .08   .16 .008   .18   .16   *     *
PERCENT OF BASELINE
       75.0 94.2  74.5   105.5   103  56.3  98.7  69.7  17.8   3.4  27.9
 STD%   1.0   .7   1.4     8.4    11 152.0   1.6   2.3   4.7    .0    .0

                                                                     MN
60108 W005MN001(1.3E15) W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP     LOG(IO) N      R    FF   EFF    OCD   PCDA  PCDB

1R*    22.50 .554 20.54  -7.538 1.57   .61 .728  9.60  5.00  8.60  6.30
1B     22.60 .550 21.18  -9.427 1.18   .17 .786 10.34   .46  8.60  6.30
2B     22.40 .550 20.82  -8.466 1.35  -.12 .777 10.12   .46  8.60  6.30
3B     22.60 .550 21.31 -10.408 1.05   .49 .791 10.40  5.20  8.60  6.30
4B     22.50 .550 20.93  -8.549 1.33  -.07 .777 10.17  3.90  8.60  6.30
5B     22.40 .550 20.92  -9.131 1.23   .31 .776 10.11  5.20  8.60  6.30
1C     17.75 .523 16.64  -9.721 1.10   .54 .780  7.66  1.04   .22  1.80
2C     17.00 .515 15.75  -8.652 1.25   .62 .756  7.00   .65   .22  1.80
3C     17.50 .520 16.31  -9.075 1.19   .49 .769  7.40  1.04   .22  1.80
4C     17.50 .520 16.31  -9.075 1.19   .49 .769  7.40   .91   .22  1.80
5C     17.50 .520 16.31  -9.075 1.19   .49 .769  7.40   .91   .22  1.80
1E     16.75 .515 15.61  -9.143 1.17   .51 .770  7.02   .78   .22  1.80
2E     17.35 .516 16.06  -8.209 1.34  -.18 .769  7.28   .91   .22  1.80
3E     16.75 .516 15.63  -9.161 1.17   .35 .775  7.08   .91   .22  1.80
4E     17.20 .516 16.11  -9.756 1.08   .77 .774  7.26   .91   .22  1.80

AVERAGES: 60108  BASELINE  W002 00 000
       22.50 .550 21.03  -9.196 1.23   .16 .781 10.23  3.04  8.60  6.30
  STD    .09 .000   .18    .704  .11   .23 .006   .12  2.16   *     *
          60108 W005MN001(1.3E15)
       17.26 .518 16.08  -9.096 1.18   .45 .770  7.28   .90   .22  1.80
  STD    .34 .003   .33    .450  .07   .25 .006   .20   .11   *     *
PERCENT OF BASELINE
       76.7 94.2  76.5   101.1    96 290.5  98.6  71.2  29.4   2.6  28.6
 STD%   1.8   .5   2.3    12.8    15 822.5   1.6   2.8  27.4    .0    .0
```

```
                                                                                       MN
60407 W013MN002 (2.6E14) BEFORE SINTER W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC   IP     LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1B      22.25 .555 20.80  -9.202 1.23    .28  .778 10.16   5.20   8.57   6.34
2B      22.50 .546 20.18  -6.152 2.02  -.79  .727  9.44   3.90   8.57   6.34
3B      22.50 .550 20.45  -6.800 1.78  -.60  .745  9.76   4.55   8.57   6.34
4B      22.60 .550 20.71  -7.207 1.65  -.65  .761 10.01   4.55   8.57   6.34
1C      22.00 .540 19.97  -6.765 1.77  -.51  .741  9.31   3.25  10.53   1.20
2C      22.00 .545 20.18  -7.347 1.60  -.51  .760  9.64   3.90  10.53   1.20
3C      22.00 .545 20.18  -7.347 1.60  -.51  .760  9.64   3.90  10.53   1.20
4C      22.25 .545 20.72  -8.601 1.31  -.15  .781 10.01   4.55  10.53   1.20
5C      22.25 .545 20.66  -8.489 1.33    .08  .770  9.88   3.90  10.53   1.20
1S      22.50 .540 20.42  -6.920 1.71  -.06  .732  9.40   3.90  10.53   1.20
2S      22.50 .545 20.94  -8.748 1.28    .23  .771  9.99   4.81  10.53   1.20
3S      22.00 .545 20.50  -8.978 1.24    .40  .769  9.76   4.55  10.53   1.20
4S      22.50 .540 20.42  -6.920 1.71  -.06  .732  9.40   3.90  10.53   1.20
1T      22.25 .545 20.89  -9.895 1.10    .59  .780 10.00   4.55  10.53   1.20
2T      22.25 .545 20.70  -8.736 1.29    .24  .770  9.88   4.55  10.53   1.20

AVERAGES: 60407  BASELINE  W002 00 000
        22.46 .550 20.53  -7.340 1.67  -.44  .753  9.84   4.55   8.57   6.34
  STD     .13 .003   .24   1.139  .29    .42  .019   .27    .46     *      *
          60407 W013MN002 (2.6E14) BEFORE SINTER
        22.23 .544 20.51  -8.068 1.45  -.02  .760  9.72   4.16  10.53   1.20
  STD     .20 .002   .29    .996  .22    .36  .017   .25    .45     *      *
PERCENT OF BASELINE
        99.0 98.8  99.9    90.1    87 194.6 101.0  98.7   91.4  122.9   18.9
 STD%    1.5  1.0   2.6    32.7    30 164.7   4.9   5.3   20.0     .1     .0

                                                                                       MN
60407A W013MN002 (2.6E14) AFTER SINTER W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC   IP     LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1B      22.60 .555 21.34 -10.230 1.08  -.04  .808 10.72   5.20   8.57   6.30
3B      22.90 .560 21.69 -11.324  .97    .82  .792 10.74   4.55   8.57   6.30
4B      22.90 .560 21.69 -11.324  .97    .82  .792 10.74   4.55   8.57   6.30
1C      22.50 .540 20.94  -8.577 1.30  -.08  .778  9.99   3.25  10.53   1.20
2C      22.00 .540 20.47  -8.491 1.32  -.22  .781  9.81   3.90  10.53   1.20
3C      22.00 .540 20.77 -10.469 1.02    .37  .797 10.01   3.90  10.53   1.20
4C      22.00 .540 20.47  -8.491 1.32  -.22  .781  9.81   4.55  10.53   1.20
5C      22.00 .540 20.47  -8.491 1.32  -.22  .781  9.81   3.90  10.53   1.20
1S      22.40 .540 20.51  -7.131 1.65  -.76  .763  9.76   3.90  10.53   1.20
2S      22.40 .540 21.06  -9.527 1.15  -.26  .804 10.28   4.81  10.53   1.20
3S      22.00 .540 20.49  -8.446 1.33  -.50  .790  9.92   4.55  10.53   1.20
4S      22.40 .540 20.75  -8.105 1.40  -.28  .774  9.90   3.90  10.53   1.20
1T      22.40 .558 21.06  -9.839 1.14    .19  .793 10.48   4.55   2.56   1.20

AVERAGES: 60407A BASELINE  W002 00 000
        22.80 .558 21.57 -10.959 1.00    .53  .797 10.73   4.77   8.57   6.30
  STD     .14 .002   .17    .516  .05    .40  .007   .01    .31     *      *
          60407A W013MN002 (2.6E14) AFTER SINTER
        22.21 .542 20.70  -8.757 1.29  -.20  .784  9.98   4.12   9.73   1.20
  STD     .21 .005   .24    .900  .16    .30  .011   .22    .45     *      *
PERCENT OF BASELINE
        97.4 97.0  95.9   120.1   129 -37.5  98.3  92.9   86.5  113.6   19.0
 STD%    1.5  1.4   1.8    12.4    24 128.1   2.3   2.2   15.6   27.9     .0
```

```
                                                                        MN
60423 W027CU-MN001 (1E15,1.3E15) W002 00 000
SOL4  1 /28/77   AM1: PO=91.60MW/CM^2  NO AR COATING

ID      ISC    VOC   IP      LOG(IO)   N      R      FF    EFF     OCD    PCDA   PCDB

1B      22.40 .550 20.84   -8.493 1.34   -.24 .782 10.18   4.16   8.57   6.34
2B      23.00 .550 20.68   -6.145 2.04  -1.06 .736  9.85   3.90   8.57   6.34
3B      23.00 .550 21.24   -7.794 1.49   -.40 .770 10.30   4.55   8.57   6.34
4B      23.00 .550 20.74   -6.153 2.04  -1.39 .748 10.00   3.90   8.57   6.34
5B      23.00 .550 21.24   -7.794 1.49   -.40 .770 10.30   4.55   8.57   6.34
1C      17.00 .510 15.66   -7.660 1.45   -.74 .769  7.06    .91    .45  22.30
2C      17.00 .510 15.66   -7.660 1.45   -.74 .769  7.06    .78    .45  22.30
3C      17.00 .510 15.66   -7.660 1.45   -.74 .769  7.06    .78    .45  22.30
4C      16.70 .510 15.50   -8.329 1.30   -.49 .780  7.02    .78    .45  22.30
5C      17.40 .510 15.96   -7.188 1.57  -1.39 .774  7.27    .91    .45  22.30
6C      16.50 .510 15.24   -8.029 1.36   -.30 .767  6.82    .65    .45  22.30
1S      17.60 .510 16.12   -7.410 1.51   -.39 .753  7.15    .91    .45  22.30
2S      17.40 .510 16.13   -8.206 1.32   -.54 .779  7.31    .91    .45  22.30
1T      16.00 .510 14.73   -7.889 1.40   -.07 .756  6.52    .65    .45  22.30
2T      16.50 .510 15.03   -7.378 1.52    .31 .732  6.51    .52    .45  22.30
3T      16.30 .510 15.20   -9.097 1.17    .32 .774  6.81    .78    .45  22.30
4T      17.00 .510 15.91   -9.299 1.13   -.01 .788  7.22    .78    .45  22.30

AVERAGES: 60423  BASELINE  W002 00 000
        22.88 .550 20.95   -7.276 1.68   -.70 .761 10.13   4.21   8.57   6.34
  STD     .24 .000   .24     .955  .30    .45 .017   .18    .29    *      *
            60423 W027CU-MN001 (1E15,1.3E15)
        16.87 .510 15.57   -7.984 1.38   -.40 .768  6.98    .78    .45  22.30
  STD     .46 .000   .42     .632  .13    .47 .014   .26    .12    *      *
PERCENT OF BASELINE
         73.7 92.7  74.3     90.3   82  143.3 100.8  68.9   18.5    5.3  351.7
 STD%     2.8   .1   2.9     24.2   24  146.2   4.1   3.8    4.3     .0     .3

                                                                        MN
60422 W026MN003 (1.3E13) W002 00 000
SOL4  1 /28/77   AM1: PO=91.60MW/CM^2  NO AR COATING

ID      ISC    VOC   IP      LOG(IO)   N      R      FF    EFF     OCD    PCDA   PCDB

1B      22.50 .555 20.61   -7.243 1.66   -.56 .759 10.02   3.90   8.57   6.30
2B      22.60 .555 21.06   -8.816 1.29    .16 .775 10.28   4.29   8.57   6.30
3B      23.00 .555 21.16   -7.609 1.55   -.24 .759 10.25   4.29   8.57   6.30
4B      22.20 .548 20.52   -7.997 1.44   -.15 .766  9.86   3.25   8.57   6.30
1C      22.50 .545 21.09   -9.556 1.15    .34 .782 10.15   4.81   9.32   5.10
2C      22.50 .545 20.95   -9.132 1.22    .82 .757  9.82   3.90   9.32   5.10
3C      22.50 .545 20.86   -8.273 1.37   -.08 .771 10.00   4.16   9.32   5.10
4C      22.50 .545 20.46   -7.009 1.70   -.10 .736  9.54   3.90   9.32   5.10
5C      22.50 .545 21.02   -9.090 1.22    .20 .779 10.10   4.55   9.32   5.10
1S      22.50 .545 20.58   -7.148 1.66   -.55 .756  9.80   3.90   9.32   5.10
2S      22.50 .545 20.58   -7.148 1.66   -.55 .756  9.80   3.25   9.32   5.10
3S      22.50 .545 19.98   -5.658 2.27  -1.32 .721  9.34   3.25   9.32   5.10
1T      22.50 .545 20.83   -8.222 1.38    .10 .763  9.90   4.55   9.32   5.10
2T      22.50 .545 20.75   -7.868 1.46   -.05 .760  9.85   3.90   9.32   5.10
3T      22.50 .545 20.75   -7.868 1.46   -.05 .760  9.85   4.55   9.32   5.10
4T*     22.50 .538 19.70   -5.198 2.53  -1.55 .702  8.99   2.21   9.32   5.10

AVERAGES: 60422  BASELINE  W002 00 000
        22.58 .553 20.84   -7.916 1.49   -.20 .765 10.10   3.93   8.57   6.30
  STD     .29 .003   .27     .584  .13    .25 .006   .17    .42    *      *
            60422 W026MN003 (1.3E13)
        22.50 .545 20.71   -7.906 1.51   -.11 .758  9.83   4.07   9.32   5.10
  STD     .00 .000   .29    1.082  .30    .53 .017   .22    .50    *      *
PERCENT OF BASELINE
         99.7 98.5  99.4    100.1  101  142.0  99.1  97.3  103.4  108.8   81.0
 STD%     1.3   .6   2.7     22.0   31  687.7   3.0   3.9   25.2     .1     .0
```

```
                                                                         MN
60511 W031CR-MN001 (1E15-1E15) W002 00 000
SOL4  1 /28/77   AM1: PO=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP     LOG(IO)  N     R     FF   EFF    OCD    PCDA   PCDB

1B     22.30 .550 20.71   -8.232 1.40  -.44 .782 10.14   4.55   8.57   6.30
2B*    22.30 .520 16.33   -2.905 6.80 -6.03 .543  6.66    .52   8.57   6.30
3B*    22.60 .500 16.06   -2.963 6.24 -3.13 .496  5.93    .26   8.57   6.30
4B     22.30 .550 21.13 -11.053   .98   .38 .805 10.44   5.20   8.57   6.30
1C     11.50 .465 10.67   -8.866 1.12   .56 .763  4.31    .39    .32    .00
2C*    12.20 .426  8.92   -3.295 5.09 -6.02 .525  2.89    .13    .32    .00
3C     12.80 .473 11.81   -7.972 1.30  -.77 .772  4.94    .13    .32    .00
4C     11.50 .465 10.73   -9.231 1.07   .23 .778  4.40    .13    .32    .00
5C     12.90 .473 11.87   -7.761 1.35  -.86 .768  4.96    .13    .32    .00
1S     12.60 .479 11.77   -9.467 1.06   .55 .776  4.95    .13    .32    .00
2S*    11.70 .445  8.73   -3.339 5.22 -8.01 .551  3.04    .13    .32    .00
3S     11.50 .470 10.70   -8.970 1.12   .18 .773  4.42    .13    .32    .00
1T     12.00 .470 11.15   -9.010 1.11   .77 .762  4.54    .13    .32    .00
2T     12.00 .470 11.15   -9.010 1.11   .77 .762  4.54    .13    .32    .00
3T*    13.20 .470 10.79   -4.137 3.47 -4.11 .627  4.12    .13    .32    .00
M1A2*  23.60 .573 21.92   -8.339 1.43  -.23 .778 11.13   5.85    .32    .00
M1A4*  23.60 .573 22.18   -9.844 1.16   .30 .789 11.29   5.20    .32    .00
C1A1*  21.40 .395 15.44   -4.794 2.11  5.92 .426  3.81    .14    .32    .00
C1A2*  22.20 .360 16.53   -5.482 1.57  5.60 .438  3.70    .14    .32    .00

AVERAGES: 60511  BASELINE  W002 00 000
       22.30 .550 20.92   -9.642 1.19  -.03 .793 10.29   4.88   8.57   6.30
  STD    .00 .000   .21    1.411  .21   .41 .011   .15    .33    *      *
            60511 W031CR-MN001 (1E15-1E15)
       12.10 .471 11.23   -8.786 1.15   .18 .769  4.63    .16    .32    .00
  STD    .56 .004   .49     .561  .10   .61 .006   .25    .09    *      *
PERCENT OF BASELINE
       54.3 85.6  53.7    108.9   97 786.4  96.9  45.0    3.3    3.7     .0
 STD%   2.5   .8   2.9     20.0   27 *****   2.2   3.2    2.1     .0     .0
                                                                         NI
61026 W047CU-NI-ZR001 (1.7E15/7.5E14/<1.5E13) W020 00 000
SOL3  1 /28/77   AM1: PO=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP     LOG(IO)  N     R     FF   EFF    OCD    PCDA   PCDB

1R*    22.50 .557 20.45   -6.974 1.75  -.10 .735  9.73    .00    .00    .00
1B.*   22.90 .556 20.55   -5.949 2.16 -1.50 .741  9.98   3.25   7.30   7.00
2B     23.00 .558 21.37   -8.418 1.37  -.16 .777 10.55   4.55   7.30   7.00
4B     22.80 .559 21.14   -8.107 1.44  -.40 .778 10.49   4.55   7.30   7.00
5B     22.90 .560 21.41   -9.032 1.27  -.04 .786 10.66   4.55   7.30   7.00
1C     21.60 .545 19.51   -6.141 2.03 -1.88 .759  9.45   1.95   2.61   3.37
2C     21.50 .545 19.99   -8.656 1.30   .19 .770  9.54   1.95   2.61   3.37
3C     21.50 .543 19.83   -7.863 1.46  -.17 .763  9.42   1.95   2.61   3.37
4C     21.70 .543 20.08   -8.119 1.41  -.15 .769  9.58   1.95   2.61   3.37
1S     21.30 .543 19.41   -6.883 1.74  -.83 .754  9.23   1.95   2.61   3.37
2S     21.50 .544 19.99   -8.533 1.32  -.03 .775  9.58   1.95   2.61   3.37
3S     21.60 .543 20.01   -8.236 1.38  -.02 .767  9.52   1.95   2.61   3.37
1T     21.20 .543 19.65   -8.283 1.37  -.07 .770  9.37   1.95   2.61   3.37
2T     21.40 .543 19.91   -8.687 1.29   .12 .773  9.50   1.95   2.61   3.37
3T     21.40 .543 19.96   -8.987 1.24   .26 .775  9.52   1.95   2.61   3.37
4T     21.60 .543 20.11   -8.852 1.26   .28 .771  9.56   1.95   2.61   3.37

AVERAGES: 61026  BASELINE  W020 00 000
       22.90 .559 21.31   -8.519 1.36  -.20 .781 10.57   4.55   7.30   7.00
  STD    .08 .001   .12     .384  .07   .15 .004   .07    .00    *      *
            61026 W047CU-NI-ZR001 (1.7E15/7.5E14/<1.5E13)
       21.48 .543 19.86   -8.113 1.44  -.21 .768  9.48   1.95   2.61   3.37
  STD    .14 .001   .22     .832  .23   .60 .006   .10    .00    *      *
PERCENT OF BASELINE
       93.8 97.2  93.2    104.8  106  94.6  98.4  89.7   42.9   35.8   48.1
 STD%   1.0   .3   1.6     14.5   23 605.0   1.3   1.6     .0     .0     .0
```

```
                                                                     NI
60114 W006NI001(5E14) W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC  IP    LOG(IO)  N      R     FF   EFF   OCD   PCDA  PCDB

1R*     22.90 .550 20.67  -6.669 1.83  -.03 .722  9.62  5.00  8.60  6.90
1B      22.75 .549 21.09  -8.432 1.35   .22 .764 10.09  5.20  8.60  6.90
2B      22.15 .549 20.38  -7.672 1.52  -.19 .759  9.76  4.55  8.60  6.90
3B      22.75 .549 21.08  -8.362 1.36   .17 .764 10.09  5.85  8.60  6.90
4B      22.30 .549 20.65  -8.274 1.38   .09 .765  9.90  5.20  8.60  6.90
1C      21.65 .535 19.84  -7.593 1.51   .24 .742  9.08  3.90  7.70 11.27
2C      21.65 .539 20.14  -8.755 1.27   .30 .768  9.48  5.20  7.70 11.27
3C      21.65 .539 19.93  -7.738 1.48  -.11 .758  9.35  3.90  7.70 11.27
4C      21.65 .539 20.14  -8.755 1.27   .30 .768  9.48  5.20  7.70 11.27
5C      21.65 .539 19.93  -7.738 1.48  -.11 .758  9.35  4.55  7.70 11.27
6C      21.65 .535 19.84  -7.593 1.51   .24 .742  9.08  3.25  7.70 11.27
1E      22.70 .545 21.12  -8.849 1.26   .47 .764 10.00  5.20  7.70 11.30
2E      22.50 .545 20.85  -8.395 1.35   .26 .762  9.88  5.20  7.70 11.30
3E      22.50 .540 20.70  -7.570 1.52  -.40 .764  9.81  5.20  7.70 11.30
4E      22.50 .545 20.85  -8.395 1.35   .26 .762  9.88  5.85  7.70 11.30
5E      22.40 .540 20.73  -8.556 1.31   .71 .749  9.58  4.55  7.70 11.30
6E      22.50 .545 20.85  -8.395 1.35   .26 .762  9.88  5.20  7.70 11.30
7E      22.00 .535 19.99  -6.467 1.86 -1.54 .765  9.52  5.20  7.70 11.30
8E      22.50 .540 20.81  -8.022 1.41  -.19 .769  9.88  5.20  7.70 11.30

AVERAGES: 60114  BASELINE  W002 00 000
        22.49 .549 20.80  -8.185 1.41   .07 .763  9.96  5.20  8.60  6.90
  STD     .27 .000   .30    .301  .07   .16 .002   .14   .46     *     *
           60114 W006NI001(5E14)
        22.11 .540 20.41  -8.059 1.42   .05 .759  9.59  4.83  7.70 11.29
  STD     .42 .004   .45    .632  .15   .52 .009   .29   .68     *     *
PERCENT OF BASELINE
        98.3 98.4  98.1   101.5   101  66.7  99.5  96.3  92.9  89.5 163.6
 STD%    3.1   .7   3.6    11.6    16 *****   1.5   4.3  22.5    .1    .3
                                                                     NI
60220 W010NI002(4E15) W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC  IP    LOG(IO)  N      R     FF   EFF   OCD   PCDA  PCDB

1R*     22.75 .553 21.07  -8.840 1.28  1.14 .740  9.85  4.55  8.42  6.30
1B.*    22.25 .545 17.97  -3.457 5.03 -6.10 .651  8.35  2.21  8.42  6.30
2B.*    23.00 .534 19.69  -4.955 2.69  -.46 .653  8.48  1.04  8.42  6.30
3B.*    22.37 .552 15.63  -2.145 **** ***** .625  8.16  3.90  8.42  6.30
4B      22.12 .552 20.17  -6.973 1.73  -.61 .751  9.70  3.25  8.42  6.30
5B.*    22.12 .552 19.85  -5.876 2.18 -1.89 .748  9.66  3.25  8.42  6.30
1C      19.37 .530 18.22 -10.445 1.01  1.05 .775  8.41  1.43  3.43  6.80
2C      19.37 .530 18.09  -9.323 1.16   .53 .772  8.38  1.30  3.43  6.80
3C      19.37 .527 17.75  -7.505 1.52  -.12 .750  8.09  1.17  3.43  6.80
4C      19.10 .527 17.70  -8.692 1.26   .70 .754  8.03  1.17  3.43  6.80
5C      19.37 .523 17.70  -7.686 1.46   .76 .727  7.79   .91  3.43  6.80
1S      19.00 .530 17.76  -9.553 1.13   .81 .768  8.18  1.43  3.43  6.80
2S      19.00 .525 17.16  -6.609 1.79  -.51 .731  7.71  1.04  3.43  6.80
3S      18.70 .530 17.35  -8.550 1.30   .22 .766  8.03  1.43  3.43  6.80
4S      19.00 .530 17.76  -9.553 1.13   .81 .768  8.18  1.43  3.43  6.80
1T      19.00 .530 17.82  -9.870 1.09   .73 .776  8.26  1.43  3.43  6.80
2T      19.00 .522 16.95  -6.078 2.00  -.70 .715  7.49   .78  3.43  6.80
3T      19.00 .530 17.82  -9.870 1.09   .73 .776  8.26  1.30  3.43  6.80

AVERAGES: 60220  BASELINE  W003 00 000
        22.12 .552 20.17  -6.973 1.73  -.61 .751  9.70  3.25  8.42  6.30
  STD     .00 .000   .00    .000  .00   .00 .000   .00   .00     *     *
           60220 W010NI002(4E15)
        19.11 .528 17.67  -8.644 1.33   .42 .756  8.07  1.24  3.43  6.80
  STD     .21 .003   .35   1.333  .30   .55 .020   .27   .22     *     *
PERCENT OF BASELINE
        86.4 95.6  87.6    76.0    77 268.9 100.7  83.2  38.0  40.7 107.9
 STD%     .9   .5   1.7    19.1    17  90.0   2.7   2.7   6.6    .0    .1
```

```
                                                                         NI
60805 W039NI003  (TWINNED)  (8E15)  W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC   IP    LOG(IO)  N     R    FF    EFF    OCD    PCDA   PCDB

1R*    22.50 .553 20.27  -6.492 1.91  -.30 .724  9.53    .00    .00    .00
1B     22.60 .558 21.03  -8.584 1.34  -.07 .778 10.37   5.46   7.30   7.00
2B*    22.20 .555 20.54  -7.968 1.47  -.40 .774 10.08   5.20   7.30   7.00
3B     22.70 .553 20.94  -7.722 1.52  -.45 .770 10.22   5.20   7.30   7.00
4B     22.60 .553 21.00  -8.384 1.37  -.26 .780 10.30   5.20   7.30   7.00
1C     21.90 .549 20.12  -7.401 1.60  -.60 .764  9.72   4.81   6.50   2.00
2C     21.80 .549 20.12  -7.765 1.50  -.43 .769  9.74   4.81   6.50   2.00
3C.*   20.80 .529 16.72  -3.777 4.21 -2.93 .607  7.07    .91   6.50   2.00
1S     22.10 .548 20.35  -7.694 1.52  -.28 .763  9.77   4.03   6.50   2.00
2S.*   22.00 .543 18.61  -4.203 3.56 -3.72 .684  8.64   3.12   6.50   2.00
3S     22.00 .546 19.79  -6.168 2.02 -1.13 .737  9.37   3.51   6.50   2.00
1T.*   20.00 .480 12.17  -6.990 1.52 15.68 .320  3.25    .13   6.50   2.00
3T.*   20.70 .517 13.89  -3.368 5.10  3.55 .416  4.70    .13   6.50   2.00
4T.*   20.60 .507 13.30  -4.155 3.43  9.48 .367  4.06    .13   6.50   2.00

AVERAGES: 60805   BASELINE  W020 00 000
       22.63 .555 20.99  -8.230 1.41  -.26 .776 10.30   5.29   7.30   7.00
  STD    .05 .002   .04    .368  .08   .15 .004   .06    .12    *      *
         60805 W039NI003  (TWINNED)   (8E15)
       21.95 .548 20.09  -7.257 1.66  -.61 .758  9.65   4.29   6.50   2.00
  STD    .11 .001   .20    .643  .21   .32 .012   .16    .55    *      *
PERCENT OF BASELINE
       97.0 98.8  95.7   111.8   118 -36.7  97.8  93.7   81.1   89.0   28.6
 STD%    .7   .6   1.1    12.1    22 338.6   2.2   2.2   12.6     .0     .0
                                                                         NI
60811 W040CR-NI001 (1E15-3.5E15)  W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC   IP    LOG(IO)  N     R    FF    EFF    OCD    PCDA   PCDB

1R*    22.50 .556 20.31  -6.639 1.86  -.14 .724  9.58    .00    .00    .00
1B     22.60 .553 20.75  -7.356 1.62  -.59 .764 10.09   4.16   7.30   7.00
2B     22.70 .555 20.99  -7.951 1.47  -.29 .770 10.26   4.94   7.30   7.00
3B     22.50 .559 20.93  -8.476 1.37  -.20 .780 10.37   4.94   7.30   7.00
4B     22.50 .556 20.91  -8.374 1.38  -.30 .781 10.33   4.94   7.30   7.00
5B     23.10 .553 21.00  -6.694 1.83  -.85 .751 10.15   3.90   7.30   7.00
1C     20.40 .531 18.61  -7.064 1.65  -.51 .749  8.58   1.30   1.35    .20
2C     20.80 .532 18.89  -6.709 1.77  -.84 .748  8.75   1.43   1.35    .20
3C     20.80 .528 18.82  -6.500 1.83  -.97 .744  8.65   1.17   1.35    .20
4C     20.40 .527 18.45  -6.479 1.84  -.98 .743  8.45   1.30   1.35    .20
5C     20.20 .519 18.01  -5.843 2.09 -1.32 .725  8.04    .65   1.35    .20
1S     20.30 .523 17.97  -5.574 2.25 -1.55 .718  8.06   1.04   1.35    .20
2S     21.50 .537 19.64  -7.077 1.66  -.64 .755  9.22   1.95   1.35    .20
3S     21.50 .534 19.61  -7.020 1.67  -.51 .749  9.10   1.69   1.35    .20
1T     18.50 .501 16.48  -5.994 1.96  -.85 .715  7.01    .39   1.35    .20
2T     17.80 .493 15.85  -6.074 1.90  -.58 .709  6.58    .26   1.35    .20
3T     17.40 .488 15.49  -6.108 1.87  -.44 .706  6.34    .26   1.35    .20
4T     16.70 .485 14.97  -6.460 1.73  -.23 .714  6.12    .26   1.35    .20

AVERAGES: 60811   BASELINE  W020 00 000
       22.68 .555 20.92  -7.770 1.53  -.45 .769 10.24   4.58   7.30   7.00
  STD    .22 .002   .09    .667  .17   .24 .011   .11    .45    *      *
         60811 W040CR-NI001 (1E15-3.5E15)
       19.69 .517 17.73  -6.408 1.85  -.79 .731  7.91    .98   1.35    .20
  STD   1.58 .018  1.55    .478  .17   .36 .018  1.06    .57    *      *
PERCENT OF BASELINE
       86.8 93.0  84.8   117.5   121  23.7  95.1  77.2   21.3   18.5    2.9
 STD%   7.9  3.7   7.8    13.8    26 221.4   3.7  11.2   15.8     .0     .0
```

```
                                                                      NI
60809 W041CR-CU-NI001 (8E14-1.7E15-3E15) W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC    VOC   IP     LOG(IO)  N      R      FF    EFF    OCD    PCDA   PCDB

1R*      22.50 .553 20.30   -6.577 1.87   -.23 .725   9.54    .00    .00    .00
2B       23.10 .553 21.53   -8.666 1.31   -.19 .784  10.59   5.20    .00    .00
3B.*     22.60 .548 20.20   -5.845 2.18 -1.38 .732   9.59   3.25    .00    .00
4B       22.70 .552 21.07   -8.204 1.41   -.37 .779  10.33   4.81    .00    .00
5B       22.90 .552 21.21   -8.046 1.44   -.39 .776  10.38   4.94    .00    .00
1C       19.30 .503 16.73   -5.066 2.51 -1.55 .685   7.03    .65    .43    .20
2C       20.80 .527 18.74   -6.297 1.91 -1.01 .737   8.55   1.30    .43    .20
3C       19.00 .507 16.84   -5.725 2.12 -1.20 .713   7.26    .52    .43    .20
4C.*     20.20 .505 14.93   -2.911 6.79 -7.81 .562   6.07    .26    .43    .20
1S       19.30 .509 16.84   -5.135 2.49 -1.96 .701   7.28    .52    .43    .20
2S       20.50 .523 18.32   -5.948 2.05 -1.23 .728   8.26    .91    .43    .20
3S       20.30 .518 17.61   -4.887 2.71 -2.41 .700   7.79    .78    .43    .20
1T       18.20 .495 15.73   -5.081 2.47 -1.35 .677   6.45    .39    .43    .20
2T       17.70 .502 15.66   -5.779 2.08   -.93 .704   6.62    .39    .43    .20
3T       17.70 .498 15.53   -5.464 2.24 -1.33 .698   6.51    .52    .43    .20
4T       16.90 .496 14.94   -5.859 2.03   -.66 .699   6.20    .52    .43    .20

AVERAGES: 60809  BASELINE  W020 00 000
         22.90 .552 21.27   -8.305 1.39   -.31 .780  10.43   4.98    .00    .00
  STD      .16 .000   .19     .263  .05    .09 .003    .11    .16     *      *
            60809 W041CR-CU-NI001 (8E14-1.7E15-3E15)
         18.97 .508 16.69   -5.524 2.26 -1.36 .704   7.19    .65    .43    .20
  STD     1.26 .011  1.19     .443  .25    .48 .017    .75    .27     *      *
PERCENT OF BASELINE
          82.8 91.9  78.5    133.5   163 *****  90.3   69.0   13.0 ***** *****
 STD%      6.1  2.0   6.4      7.6    25 322.5   2.6    8.1    5.9 ***** *****
                                                                      TI
60908 W051CU/TI001 (1.7E15/3.6E14) W002 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC    VOC   IP     LOG(IO)  N      R      FF    EFF    OCD    PCDA   PCDB

1R*      22.50 .553 20.30   -6.469 1.92   -.57 .732   9.63    .00    .00    .00
1B       22.90 .560 21.35   -8.842 1.30    .09 .778  10.55   4.29   8.57   6.34
2B       22.60 .557 20.53   -6.648 1.86   -.91 .750   9.99   3.90   8.57   6.34
3B       21.00 .552 19.58   -8.797 1.30   -.08 .782   9.58   1.95   8.57   6.34
4B       22.80 .558 20.97   -7.489 1.59   -.49 .764  10.28   4.16   8.57   6.34
1C       13.90 .467 12.75   -7.748 1.32    .04 .748   5.13    .10   1.57    .50
2C       13.70 .464 12.47   -7.260 1.44   -.16 .738   4.96    .10   1.57    .50
3C       13.80 .465 12.63   -7.573 1.36   -.17 .748   5.07    .10   1.57    .50
4C       14.00 .465 12.70   -6.983 1.51   -.55 .738   5.08    .10   1.57    .50
5C       13.90 .464 12.67   -7.305 1.42   -.22 .741   5.05    .10   1.57    .50
1S       13.80 .460 12.33   -6.164 1.79 -1.40 .725   4.87    .10   1.57    .50
2S       14.00 .466 12.84   -7.778 1.31    .06 .748   5.16    .10   1.57    .50
1T       13.70 .464 12.50   -7.309 1.42   -.47 .747   5.02    .10   1.57    .50
2T       13.70 .464 12.32   -6.352 1.73 -1.65 .739   4.97    .10   1.57    .50
3T       13.70 .464 12.45   -6.991 1.51   -.84 .745   5.01    .10   1.57    .50
4T*      13.30 .523 10.98   -4.134 3.87 -5.89 .651   4.79   1.95   1.57    .50

AVERAGES: 60908  BASELINE  W002 00 000
         22.33 .557 20.61   -7.944 1.51   -.34 .768  10.10   3.58   8.57   6.34
  STD      .77 .003   .66     .925  .23    .39 .012    .36    .95     *      *
            60908 W051CU/TI001 (1.7E15/3.6E14)
         13.82 .464 12.57   -7.146 1.48   -.53 .742   5.03    .10   1.57    .50
  STD      .12 .002   .17     .515  .15    .56 .007    .08    .00     *      *
PERCENT OF BASELINE
          61.9 83.4  61.0    110.0    98  44.9  96.5   49.8    2.8   18.3    7.9
 STD%      2.7   .8   2.8     17.7    27 520.8   2.4    2.6     .7     .0     .0
```

```
                                                                              TI
60914 W048TI004 (3.6E11) W002 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC   IP     LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*     22.50 .555 20.59   -7.402 1.61    .03 .744   9.82    .00    .00    .00
1B.*    23.70 .558 21.22   -5.870 2.20 -1.38 .736  10.29   3.25   8.57   6.34
2B      23.10 .556 20.79   -6.096 2.08 -1.33 .743  10.09   3.25   8.57   6.34
3B.*    22.90 .554 20.60   -6.035 2.11 -1.49 .745  10.00   3.25   8.57   6.34
4B      22.80 .558 21.08   -7.923 1.48  -.33 .771  10.37   4.29   8.57   6.34
5B      23.00 .558 21.50   -9.020 1.26  -.06 .787  10.68   5.20   8.57   6.34
1C      22.70 .552 20.82   -7.217 1.65  -.78 .766  10.15   3.64   5.09   4.30
2C      22.70 .552 20.98   -7.835 1.49  -.49 .774  10.26   4.29   5.09   4.30
3C*     22.90 .541 18.41   -3.302 5.41 -7.19 .660   8.65   1.95   5.09   4.30
4C      22.90 .550 20.74   -6.374 1.94 -1.31 .754  10.05   3.90   5.09   4.30
1S      22.50 .551 20.56   -6.882 1.76 -1.09 .765  10.03   3.90   5.09   4.30
2S      22.70 .550 20.65   -6.736 1.80  -.83 .751   9.92   3.38   5.09   4.30
3S      22.80 .551 21.07   -7.855 1.48  -.38 .771  10.24   3.90   5.09   4.30
1T      22.70 .551 21.04   -8.137 1.42  -.32 .776  10.27   4.16   5.09   4.30
2T      22.70 .552 21.20   -8.973 1.26   .01 .783  10.38   4.16   5.09   4.30
3T      22.80 .551 21.07   -7.855 1.48  -.38 .771  10.24   4.29   5.09   4.30
4T      22.40 .549 20.75   -8.117 1.42  -.23 .772  10.04   4.03   5.09   4.30

AVERAGES: 60914  BASELINE  W002 00 000
        22.97 .557 21.12   -7.680 1.61  -.57 .767  10.38   4.25   8.57   6.34
  STD     .12 .001   .29    1.206  .35   .55 .018    .24    .80     *      *
          60914 W048TI004 (3.6E11)
        22.69 .551 20.89   -7.598 1.57  -.58 .768  10.16   3.97   5.09   4.30
  STD     .14 .001   .20     .744  .20   .39 .009    .14    .27     *      *
PERCENT OF BASELINE
        98.8 98.8  98.9    101.1   98  98.3 100.2   97.9   93.4   59.4   67.8
 STD%    1.1   .3   2.3     26.7   36 230.6   3.6    3.6   25.2     .0     .0
                                                                              TI
61020 W050TI-V001 (3.6E11/4E11)  W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC   IP     LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*     22.50 .557 20.64   -7.745 1.53    .46 .739   9.79    .00    .00    .00
1B      23.20 .562 21.64   -8.844 1.30    .01 .781  10.76   5.20   7.30   6.99
2B      23.30 .563 21.83   -9.382 1.21    .19 .785  10.89   5.46   7.30   6.99
3B      23.60 .560 21.78   -7.790 1.52   -.34 .768  10.74   4.94   7.30   6.99
4B      23.30 .560 21.75   -8.943 1.28    .09 .780  10.76   4.94   7.30   6.99
5B      23.60 .561 22.03   -8.918 1.29    .06 .781  10.93   5.20   7.30   6.99
1C      20.60 .527 18.78   -6.927 1.68   -.77 .753   8.65    .78   1.07   1.06
2C      20.30 .526 18.69   -7.662 1.47   -.38 .763   8.62    .78   1.07   1.06
3C*     20.00 .501 15.59   -3.692 4.19  -1.54 .561   5.94    .26   1.07   1.06
4C      20.40 .525 18.88   -8.167 1.35   -.12 .768   8.70    .78   1.07   1.06
5C      20.40 .525 18.70   -7.309 1.56   -.56 .759   8.60    .78   1.07   1.06
1S      20.00 .524 18.36   -7.379 1.54   -.63 .763   8.45    .78   1.07   1.06
2S      20.20 .525 18.67   -7.977 1.40   -.34 .771   8.64    .78   1.07   1.06
3S      20.50 .526 18.96   -8.052 1.38   -.20 .768   8.76    .91   1.07   1.06
1T      20.40 .526 18.74   -7.526 1.51   -.41 .761   8.63    .91   1.07   1.06
2T      20.50 .525 18.95   -8.040 1.38   -.20 .768   8.74    .78   1.07   1.06
3T      20.20 .524 18.63   -7.804 1.43   -.32 .765   8.57    .78   1.07   1.06
4T      20.20 .523 18.54   -7.425 1.52   -.52 .761   8.50    .78   1.07   1.06

AVERAGES: 61020  BASELINE  W020 00 000
        23.40 .561 21.81   -8.775 1.32    .00 .779  10.82   5.15   7.30   6.99
  STD     .17 .001   .13     .527  .10    .18 .006    .08    .19     *      *
          61020 W050TI-V001 (3.6E11/4E11)
        20.34 .525 18.72   -7.661 1.48   -.41 .764   8.62    .80   1.07   1.06
  STD     .17 .001   .17     .368  .09    .19 .005    .09    .05     *      *
PERCENT OF BASELINE
        86.9 93.6  85.8    112.7  112 *****  98.1   79.7   15.6   14.7   15.2
 STD%    1.3   .4   1.3      9.7   16 *****   1.3    1.4    1.6     .0     .0
```

```
                                                                         TI
61019 W045CR-FE-TI001 (6.5E14-4.3E14-6E13)  W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC    VOC  IP     LOG(IO)  N      R     FF    EFF    OCD     PCDA   PCDB

1R*      22.50 .555 20.44   -6.975 1.74   -.03 .732   9.67    .00     .00    .00
1B       22.50 .544 19.23   -4.564 3.12 -2.30 .679   8.79   1.56    7.30   6.99
2B       22.70 .554 21.04   -8.117 1.43   -.35 .777 10.33   5.20    7.30   6.99
3B       22.70 .555 21.04   -8.163 1.42   -.28 .775 10.33   4.55    7.30   6.99
4B       22.80 .555 21.01   -7.605 1.55   -.55 .770 10.30   4.29    7.30   6.99
5B       22.70 .553 20.99   -7.815 1.50   -.56 .776 10.30   4.29    7.30   6.99
1C       15.50 .484 14.21   -7.652 1.38   -.07 .749   5.94    .13     .99    .15
2C       16.20 .486 14.91   -8.004 1.31    .23 .751   6.25    .13     .99    .15
3C       16.20 .490 14.83   -7.400 1.46   -.48 .754   6.33    .13     .99    .15
4C       15.70 .478 14.07   -6.162 1.83 -1.42 .731   5.80    .13     .99    .15
5C       15.80 .481 14.39   -7.090 1.52   -.63 .747   6.01    .13     .99    .15
1S       15.60 .480 14.11   -6.641 1.66 -1.01 .741   5.86    .13     .99    .15
2S       16.10 .487 14.71   -7.267 1.49   -.55 .751   6.23    .13     .99    .15
3S       16.20 .489 14.83   -7.388 1.46   -.48 .753   6.31    .13     .99    .15
1T       16.30 .487 14.95   -7.675 1.38   -.02 .749   6.29    .13     .99    .15
2T       16.30 .487 14.95   -7.675 1.38   -.02 .749   6.29    .13     .99    .15
3T       16.20 .486 14.90   -7.818 1.35   -.14 .756   6.30    .13     .99    .15
4T       16.20 .487 14.83   -7.470 1.43   -.24 .749   6.25    .13     .99    .15

AVERAGES: 61019  BASELINE  W020 00 000
         22.73 .554 21.02   -7.925 1.48   -.44 .774 10.32   4.58    7.30   6.99
  STD      .05 .001   .02     .228  .05    .13 .003    .01    .37     *      *
             61019 W045CR-FE-TI001 (6.5E14-4.3E14-6E13)
         16.52 .490 14.99   -7.139 1.60   -.55 .743   6.36    .24    1.48    .68
  STD     1.75 .016  1.26     .883  .46    .66 .020    .72    .38     *      *
PERCENT OF BASELINE
         72.7 88.4   71.3    109.9   108   73.9  96.0   61.6    5.2   20.2    9.7
 STD%     7.8  3.0    6.1     14.1    36  232.1   2.9    7.1    9.4   23.0   26.1
                                                                         TI
60205 W008TI001(3.6E14) W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC    VOC  IP     LOG(IO)  N      R     FF    EFF    OCD     PCDA   PCDB

1R*      22.70 .555 20.85   -7.855 1.49    .47 .741   9.88   4.55    8.60   6.90
1B       22.80 .558 20.77   -6.747 1.83   -.99 .757 10.19   3.90    2.45  11.30
2B       22.80 .558 20.77   -6.747 1.83   -.99 .757 10.19   3.90    2.45  11.30
3B       22.80 .558 20.77   -6.747 1.83   -.99 .757 10.19   3.90    2.45  11.30
4B       22.60 .555 20.46   -6.391 1.95 -1.22 .751   9.96   3.90    2.45  11.30
5B       22.60 .558 20.68   -7.062 1.72   -.85 .763 10.18   4.55    2.45  11.30
1C.*      7.80 .428  6.23   -4.129 3.53 -6.61 .601   2.12    .20     .58   2.00
2C.*      7.80 .430  6.43   -4.576 2.91 -4.30 .625   2.22    .26     .58   2.00
3C        7.80 .446  7.17   -8.297 1.20    .59 .748   2.75    .26     .58   2.00
4C.*      7.60 .420  5.81   -3.815 4.12 -6.95 .556   1.88    .16     .58   2.00
5C        7.80 .438  6.85   -6.140 1.81   -.27 .683   2.47    .26     .58   2.00
1S        7.80 .445  7.11   -7.574 1.36   -.24 .739   2.71    .07     .58   2.00
2S        7.70 .445  6.90   -6.608 1.65 -1.61 .722   2.62    .14     .58   2.00
3S.*      7.60 .429  6.04   -4.084 3.64 -7.10 .597   2.06    .20     .58   2.00
4S.*      7.70 .445  6.59   -5.012 2.56 -6.17 .686   2.48    .20     .58   2.00
1T.*      7.60 .438  6.22   -4.256 3.42 -9.27 .643   2.26    .26     .58   2.00
3T        7.60 .443  6.89   -7.261 1.44   -.63 .734   2.61    .21     .58   2.00
4T        7.60 .443  6.89   -7.261 1.44   -.63 .734   2.61    .08     .58   2.00

AVERAGES: 60205  BASELINE  W003 00 000
         22.72 .557 20.69   -6.739 1.83 -1.01 .757 10.14   4.03    2.45  11.30
  STD      .10 .001   .12     .213  .07    .12 .004    .09    .26     *      *
             60205 W008TI001(3.6E14)
          7.72 .443  6.97   -7.190 1.49   -.47 .727   2.63    .17     .58   2.00
  STD      .09 .003   .12     .686  .20    .65 .021    .09    .08     *      *
PERCENT OF BASELINE
         34.0 79.5   33.7     93.3    81  154.0  96.0   25.9    4.2   23.7   17.7
 STD%      .5   .6     .8     13.9    15   77.7   3.3    1.1    2.4     .0     .0
```

```
                                                                      TI
60608 W033TI002 (3.6E12) W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP    LOG(IO)  N     R    FF    EFF   OCD   PCDA  PCDB

1B     22.50 .555 21.29 -10.648 1.03   .17 .807 10.65  5.20  8.42 11.60
2B     22.25 .555 20.77  -8.964 1.27   .07 .781 10.20  4.55  8.42 11.60
3B     22.50 .555 21.02  -8.816 1.29  -.33 .792 10.46  4.55  8.42 11.60
4B     22.00 .555 20.66  -9.694 1.15   .24 .789 10.18  4.94  8.42 11.60
5B     22.25 .555 20.77  -8.964 1.27   .07 .781 10.20  4.29  8.42 11.60
1C     19.80 .535 18.60  -9.703 1.12   .06 .795  8.90  1.95  2.88  3.10
2C     20.20 .544 18.41  -7.003 1.71  -.61 .750  8.71  1.69  2.88  3.10
3C     19.60 .535 18.47 -10.313 1.04   .39 .794  8.80  2.21  2.88  3.10
4C     19.40 .535 18.09  -9.040 1.22   .33 .773  8.49  1.95  2.88  3.10
5C     19.60 .535 18.47 -10.313 1.04   .39 .794  8.80  2.34  2.88  3.10
1S     19.00 .534 17.94 -10.740  .99   .73 .790  8.48  2.21  2.88  3.10
2S     19.20 .534 18.01  -9.766 1.11   .48 .782  8.48  1.95  2.88  3.10
3S     19.20 .534 18.01  -9.766 1.11   .48 .782  8.48  2.21  2.88  3.10
1T     19.30 .537 17.96  -8.543 1.31  -.29 .782  8.57  1.95  2.88  3.10
2T     18.90 .537 17.65  -9.128 1.21   .15 .780  8.38  1.69  2.88  3.10
3T     19.60 .537 18.33  -9.153 1.20  -.03 .787  8.76  1.95  2.88  3.10
4T     19.60 .537 18.33  -9.153 1.20  -.03 .787  8.76  2.08  2.88  3.10

AVERAGES: 60608  BASELINE  W003 00 000
       22.30 .555 20.90  -9.417 1.20   .04 .790 10.34  4.71  8.42 11.60
  STD    .19 .000   .23    .688  .10   .20 .009   .19   .32    *     *
          60608 W033TI002 (3.6E12)
       19.45 .536 18.19  -9.385 1.19   .17 .783  8.63  2.02  2.88  3.10
  STD    .35 .003   .27    .941  .18   .36 .012   .17   .19    *     *
PERCENT OF BASELINE
       87.2 96.6  87.0    100.3    99 383.2  99.1  83.5  42.8  34.2  26.7
 STD%   2.3   .5   2.3     18.0    24 *****   2.7   3.2   7.4    .0    .0
                                                                      TI
60721 W037ZR-TI001 (1.5E13-3.6F14)  W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP    LOG(IO)  N     R    FF    EFF   OCD   PCDA  PCDB

1R*    22.50 .556 20.28  -6.519 1.91  -.30 .725  9.59   .00   .00   .00
1B     22.70 .556 20.99  -7.902 1.48  -.38 .772 10.30  5.20  7.30  7.00
2B     22.70 .556 20.91  -7.507 1.58  -.70 .772 10.31  5.20  7.30  7.00
3B     22.60 .554 20.91  -7.925 1.47  -.45 .775 10.26  5.20  7.30  7.00
4B     23.10 .554 21.26  -7.529 1.57  -.52 .767 10.38  4.55  7.30  7.00
5B     23.00 .555 21.34  -8.201 1.41  -.32 .778 10.50  5.20  7.30  7.00
1C     13.90 .465 12.33  -6.197 1.79  -.06 .695  4.75   .13   .42   .50
2C     13.80 .464 12.25  -6.260 1.76   .07 .695  4.70   .13   .42   .50
3C     14.00 .463 12.40  -6.169 1.79  -.01 .693  4.75   .13   .42   .50
1S     13.30 .463 11.91  -6.667 1.61   .40 .703  4.58   .13   .42   .50
2S     13.90 .464 12.33  -6.188 1.79  -.06 .695  4.74   .13   .42   .50
3S     13.90 .463 12.27  -5.972 1.88  -.33 .691  4.70   .13   .42   .50
1T     13.80 .462 12.24  -6.199 1.78  -.10 .696  4.69   .13   .42   .50
2T     12.90 .456 10.99  -4.840 2.58 -2.65 .667  4.15   .13   .42   .50
3T     13.70 .458 11.96  -5.662 2.01  -.44 .677  4.49   .13   .42   .50
4T     13.50 .461 11.98  -6.256 1.76   .10 .693  4.56   .13   .42   .50

AVERAGES: 60721  BASELINE  W020 00 000
       22.82 .555 21.08  -7.813 1.50  -.47 .773 10.35  5.07  7.30  7.00
  STD    .19 .001   .18    .263  .06   .13 .004   .08   .26    *     *
          60721 W037ZR-TI001 (1.5E13-3.6E14)
       13.67 .462 12.07  -6.041 1.88  -.31 .690  4.61   .13   .42   .50
  STD    .33 .003   .39    .465  .25   .81 .010   .18   .00    *     *
PERCENT OF BASELINE
       59.9 83.2  57.2    122.7   125 134.8  89.3  44.6   2.6   5.8   7.1
 STDZ   1.9   .6   2.4      8.8    23 236.5   1.7   2.1    .1    .0    .0
```

```
                                                                          TI
60820 W042TI003 (7E13)   W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC    VOC   IP     LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*     22.50 .555 20.37  -6.775 1.81  -.11 .728  9.62   .00    .00    .00
1B      22.90 .555 21.06  -7.486 1.59  -.46 .763 10.26  4.16   7.30   7.00
2B      22.30 .559 20.58  -7.812 1.52  -.33 .768 10.12  4.16   7.30   7.00
3B.*    22.60 .555 20.23  -5.899 2.18 -1.38 .734  9.74  4.16   7.30   7.00
4B      22.80 .556 20.99  -7.577 1.56  -.44 .765 10.26  4.55   7.30   7.00
5B      22.80 .555 21.13  -8.187 1.42  -.17 .772 10.33  4.55   7.30   7.00
1C      16.20 .493 14.15  -5.458 2.25 -1.12 .688  5.81  1.20    .71    .80
2C      16.10 .495 14.25  -5.993 1.97  -.35 .696  5.87  1.20    .71    .80
3C      16.30 .496 14.73  -6.987 1.59   .33 .718  6.14  1.20    .71    .80
4C      16.30 .495 14.53  -6.248 1.85  -.28 .706  6.02  1.20    .71    .80
5C.*    16.30 .486 12.85  -3.484 4.76 -6.53 .613  5.13  1.20    .71    .80
1S      16.60 .494 14.53  -5.532 2.20  -.92 .688  5.97   .26    .71    .80
2S      16.70 .493 14.73  -5.810 2.04  -.63 .696  6.06   .13    .71    .80
3S      16.60 .495 14.69  -5.923 2.00  -.57 .699  6.08   .13    .71    .80
1T      16.40 .492 14.43  -5.740 2.08  -.63 .691  5.90   .13    .71    .80
2T      16.20 .493 14.24  -5.657 2.13  -.90 .693  5.86   .13    .71    .80
3T      16.40 .493 14.48  -5.839 2.03  -.60 .696  5.95   .13    .71    .80
4T      16.50 .492 14.42  -5.515 2.20  -.81 .684  5.87   .13    .71    .80

AVERAGES: 60820  BASELINE  W020 00 000
        22.70 .556 20.94  -7.766 1.52  -.35 .767 10.24  4.36   7.30   7.00
  STD     .23 .002   .21    .271  .07   .12 .003   .08   .19    *      *
            60820 W042TI003 (7E13)
        16.39 .494 14.47  -5.882 2.03  -.59 .696  5.96   .53    .71    .80
  STD     .18 .001   .19    .414  .18   .37 .009   .10   .51    *      *
PERCENT OF BASELINE
        72.2 88.8  69.1   124.3   134  32.2  90.7  58.2  12.2    9.7   11.4
 STD%    1.6   .5   1.6     8.2    18 198.1   1.6   1.4  12.7     .0     .0
```

```
                                                                          TI
60823 W043FE-TI001 (5.6E14-6E13)   W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC    VOC   IP     LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*     22.50 .555 20.28  -6.544 1.89  -.21 .723  9.55   .00    .00    .00
1B      23.00 .556 21.20  -7.668 1.54  -.42 .767 10.38  4.16   7.30   7.00
2B      22.80 .555 21.05  -7.800 1.51  -.40 .770 10.31  4.94   7.30   7.00
3B      22.70 .555 20.57  -6.474 1.92 -1.06 .749  9.98  3.90   7.30   7.00
4B      22.80 .554 20.58  -6.247 2.01 -1.27 .747  9.98  4.81   7.30   7.00
5B      23.50 .555 21.73  -7.981 1.46  -.24 .770 10.62  4.55   7.30   7.00
1C      16.10 .493 14.40  -6.353 1.81  -.35 .712  5.98   .13    .50    .90
2C      15.90 .490 14.29  -6.678 1.68   .12 .712  5.87   .13    .50    .90
3C      16.20 .487 14.34  -5.983 1.94  -.42 .698  5.82   .13    .50    .90
4C      16.30 .488 14.36  -5.797 2.03  -.51 .691  5.81   .13    .50    .90
5C      16.00 .481 13.86  -5.199 2.36 -1.48 .681  5.54   .13    .50    .90
1S      16.30 .490 14.10  -5.137 2.44 -1.58 .680  5.74   .13    .50    .90
2S      16.20 .489 14.16  -5.464 2.22 -1.16 .689  5.78   .13    .50    .90
3S      16.20 .486 13.74  -4.665 2.82 -2.27 .661  5.50   .13    .50    .90
1T      16.00 .484 14.25  -6.238 1.82  -.21 .704  5.76   .13    .50    .90
2T      16.10 .484 14.30  -6.125 1.87  -.28 .700  5.77   .13    .50    .90
3T      16.20 .488 14.42  -6.200 1.85  -.27 .704  5.88   .13    .50    .90
4T      16.20 .488 14.37  -6.037 1.92  -.46 .701  5.86   .13    .50    .90

AVERAGES: 60823  BASELINE  W020 00 000
        22.96 .555 21.03  -7.234 1.69  -.68 .761 10.25  4.47   7.30   7.00
  STD     .29 .001   .43    .724  .23   .41 .010   .25   .39    *      *
            60823 W043FE-TI001 (5.6E14-6E13)
        16.14 .487 14.22  -5.823 2.06  -.74 .694  5.78   .13    .50    .90
  STD     .12 .003   .21    .564  .32   .68 .014   .13   .00    *      *
PERCENT OF BASELINE
        70.3 87.8  67.6   119.5   122  90.8  91.3  56.4   2.9    6.8   12.9
 STD%    1.4   .7   2.4    16.6    38 227.2   3.2   2.6    .3     .0     .0
```

```
                                                                        V
60902 W046FE-V001 (5.6E14-7E13) W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC    VOC   IP     LOG(I0)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*     22.50 .555 20.54   -7.237 1.66   -.04 .741  9.79    .00    .00    .00
1B      22.60 .558 21.13   -9.001 1.27   -.15 .790 10.53   4.42   7.30   7.00
2B      22.80 .560 21.47  -10.118 1.10    .31 .793 10.71   5.20   7.30   7.00
3B      22.70 .558 21.27   -9.440 1.20    .22 .785 10.52   4.16   7.30   7.00
4B      22.80 .559 21.47  -10.103 1.10    .31 .793 10.69   4.94   7.30   7.00
5B      22.80 .556 21.19   -8.446 1.36   -.10 .776 10.40   4.16   7.30   7.00
1C*      9.90 .480  8.15   -4.280 3.52  -6.38 .640  3.22    .10    .15    .15
2C      18.00 .499 16.83   -9.299 1.10    .24 .780  7.41    .65    .15    .15
3C      17.50 .496 15.85   -6.537 1.73  -1.33 .750  6.88    .65    .15    .15
4C      17.40 .496 15.89   -7.037 1.57  -1.02 .759  6.93    .65    .15    .15
5C      17.40 .493 15.93   -7.379 1.47   -.48 .755  6.85    .65    .15    .15
1S      17.70 .498 16.40   -8.284 1.27   -.19 .771  7.19    .39    .15    .15
2S      17.50 .498 16.21   -8.202 1.29   -.31 .773  7.12    .39    .15    .15
3S      17.60 .495 16.21   -7.710 1.39   -.55 .767  7.07    .52    .15    .15
1T      17.80 .500 16.52   -8.516 1.23    .06 .769  7.24    .52    .15    .15
2T      17.10 .497 15.62   -6.984 1.59  -1.31 .765  6.88    .52    .15    .15
3T      17.20 .496 15.66   -6.808 1.64  -1.32 .759  6.85    .52    .15    .15
4T      17.10 .496 15.83   -8.240 1.28   -.14 .769  6.89    .52    .15    .15

AVERAGES: 60902  BASELINE  W020 00 000
        22.74 .558 21.31   -9.422 1.21    .12 .787 10.57   4.58   7.30   7.00
  STD     .08 .001   .14     .645  .10    .20 .007   .12    .42    *      *
          60902 W046FE-V001 (5.6E14-7E13)
        17.48 .497 16.09   -7.727 1.42   -.58 .765  7.03    .54    .15    .15
  STD     .27 .002   .36     .815  .19    .55 .008   .18    .09    *      *
PERCENT OF BASELINE
        76.9 89.0  75.5    118.0   117 *****  97.2  66.5   11.9    2.1    2.1
 STD%    1.5   .5   2.2     14.9    27 *****   1.9   2.5    3.3     .0     .0
                                                                        V
61020 W050TI-V001 (3.6E11/4E11)  W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC    VOC   IP     LOG(I0)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*     22.50 .557 20.64   -7.745 1.53    .46 .739  9.79    .00    .00    .00
1B      23.20 .562 21.64   -8.844 1.30    .01 .781 10.76   5.20   7.30   6.99
2B      23.30 .563 21.83   -9.382 1.21    .19 .785 10.89   5.46   7.30   6.99
3B      23.60 .560 21.78   -7.790 1.52   -.34 .768 10.74   4.94   7.30   6.99
4B      23.30 .560 21.75   -8.943 1.28    .09 .780 10.76   4.94   7.30   6.99
5B      23.60 .561 22.03   -8.918 1.29    .06 .781 10.93   5.20   7.30   6.99
1C      20.60 .527 18.78   -6.927 1.68   -.77 .753  8.65    .78   1.07   1.06
2C      20.30 .526 18.69   -7.662 1.47   -.38 .763  8.62    .78   1.07   1.06
3C*     20.00 .501 15.59   -3.692 4.19  -1.54 .561  5.94    .26   1.07   1.06
4C      20.40 .525 18.88   -8.167 1.35   -.12 .768  8.70    .78   1.07   1.06
5C      20.40 .525 18.70   -7.309 1.56   -.56 .759  8.60    .78   1.07   1.06
1S      20.00 .524 18.36   -7.379 1.54   -.63 .763  8.45    .78   1.07   1.06
2S      20.20 .525 18.67   -7.977 1.40   -.34 .771  8.64    .78   1.07   1.06
3S      20.50 .526 18.96   -8.052 1.38   -.20 .768  8.76    .91   1.07   1.06
1T      20.40 .526 18.74   -7.526 1.51   -.41 .761  8.63    .91   1.07   1.06
2T      20.50 .525 18.95   -8.040 1.38   -.20 .768  8.74    .78   1.07   1.06
3T      20.20 .524 18.63   -7.804 1.43   -.32 .765  8.57    .78   1.07   1.06
4T      20.20 .523 18.54   -7.425 1.52   -.52 .761  8.50    .78   1.07   1.06

AVERAGES: 61020  BASELINE  W020 00 000
        23.40 .561 21.81   -8.775 1.32    .00 .779 10.82   5.15   7.30   6.99
  STD     .17 .001   .13     .527  .10    .18 .006   .08    .19    *      *
          61020 W050TI-V001 (3.6E11/4E11)
        20.34 .525 18.72   -7.661 1.48   -.41 .764  8.62    .80   1.07   1.06
  STD     .17 .001   .17     .368  .09    .19 .005   .09    .05    *      *
PERCENT OF BASELINE
        86.9 93.6  85.8    112.7   112 *****  98.1  79.7   15.6   14.7   15.2
 STD%    1.3   .4   1.3      9.7    16 *****   1.3   1.4    1.6     .0     .0
```

```
                                                                          V
61022 W049V003 (4E11) W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC  IP    LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*     22.50 .555 20.54  -7.331 1.63    .20 .736   9.72    .00    .00    .00
1B.*    22.30 .553 18.40  -3.477 5.04 -7.99 .703   9.17   2.60   7.30   7.00
2B*     22.50 .548 18.01  -3.378 5.27 -6.18 .641   8.35   1.82   7.30   7.00
3B*     22.30 .549 18.28  -3.515 4.91 -6.83 .680   8.80   2.08   7.30   7.00
4B      22.40 .556 20.61  -7.434 1.61   -.70 .769  10.13   3.51   7.30   7.00
1C.*    22.20 .543 17.92  -3.286 5.52 -8.24 .675   8.61   1.82   4.33   3.68
2C*     22.00 .537 17.28  -3.403 5.12 -4.48 .599   7.49   1.17   4.32   3.68
3C      22.20 .549 19.88  -5.765 2.23 -1.96 .745   9.61   2.86   4.32   3.68
4C      22.40 .549 19.99  -5.619 2.31 -2.07 .742   9.65   3.25   4.32   3.68
5C      22.40 .549 20.80  -8.382 1.36   -.15 .776  10.09   3.25   4.32   3.68
1S      22.40 .551 20.81  -8.406 1.36   -.15 .776  10.13   3.25   4.32   3.68
2S*     22.10 .537 17.65  -3.369 5.21 -6.16 .638   8.00   1.30   4.32   3.68
3S.*    22.30 .549 19.58  -4.951 2.78 -3.16 .734   9.50   2.99   4.32   3.68
1T      22.40 .549 20.45  -6.951 1.73   -.79 .757   9.85   3.12   4.32   3.68
2T      22.40 .550 20.58  -7.418 1.59   -.56 .764   9.96   3.12   4.32   3.68
3T.*    22.30 .541 17.98  -3.345 5.31 -7.26 .663   8.46   1.56   4.32   3.68
4T.*    22.20 .546 18.70  -3.844 4.16 -6.17 .712   9.13   2.34   4.32   3.68

AVERAGES: 61022  BASELINE  W020 00 000
        22.40 .556 20.61  -7.434 1.61   -.70 .769  10.13   3.51   7.30   7.00
  STD     .00 .000   .00    .000  .00    .00 .000    .00    .00    *      *
             61022 W049V003 (4E11)
        22.37 .550 20.42  -7.090 1.76   -.95 .760   9.88   3.14   4.32   3.68
  STD     .07 .001   .37   1.114  .38    .79 .013    .20    .14    *      *
PERCENT OF BASELINE
        99.9 98.8  99.1   104.6  110   64.8  98.8   97.5   89.5   59.2   52.6
 STD%     .3   .1   1.8    15.0   24  112.3   1.7    2.0    4.0     .0     .0

                                                                          V
60206 W009V001(4E14)  W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID      ISC   VOC  IP    LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*     22.75 .553 20.86  -7.725 1.52    .43 .739   9.83   4.55   1.90   6.90
1B      22.50 .555 20.89  -8.240 1.41   -.41 .782  10.32   5.20   8.42  11.60
2B      22.50 .555 20.86  -8.167 1.42   -.31 .776  10.25   3.90   8.42  11.60
3B      22.20 .552 20.25  -7.256 1.65    .05 .738   9.57   2.86   8.42  11.60
4B      22.60 .555 20.74  -7.501 1.58   -.19 .754  10.00   3.90   8.42  11.60
5B      22.50 .555 20.65  -7.403 1.61   -.40 .758  10.02   3.90   8.42  11.60
1C      10.20 .467  9.47  -8.743 1.16   -.11 .773   3.89    .20   2.17    .40
2C      10.20 .467  9.47  -8.743 1.16   -.11 .773   3.89    .26   2.17    .40
3C      10.20 .467  9.47  -8.743 1.16   -.11 .773   3.89    .39   2.17    .40
4C      10.20 .467  9.47  -8.743 1.16   -.11 .773   3.89    .26   2.17    .40
5C      10.20 .467  9.47  -8.743 1.16   -.11 .773   3.89    .26   2.17    .40
1S      10.25 .465  9.47  -8.486 1.20    .44 .757   3.81    .33   2.17    .40
2S      10.25 .469  9.55  -9.236 1.08    .38 .775   3.94    .26   2.17    .40
3S      10.25 .469  9.55  -9.236 1.08    .38 .775   3.94    .26   2.17    .40
1T      10.20 .465  9.35  -7.757 1.35   -.32 .751   3.77    .26   2.17    .40
2T      10.20 .468  9.52  -9.455 1.05    .73 .772   3.90    .39   2.17    .40
3T      10.20 .468  9.52  -9.455 1.05    .73 .772   3.90    .26   2.17    .40
4T      10.20 .462  9.46  -8.907 1.12    .89 .758   3.78    .26   2.17    .40

AVERAGES: 60206  BASELINE  W003 00 000
        22.46 .554 20.68  -7.713 1.53   -.25 .762  10.03   3.95   8.42  11.60
  STD     .14 .001   .23    .408  .10    .17 .016    .26    .74    *      *
             60206 W009V001(4E14)
        10.21 .467  9.48  -8.854 1.14    .22 .769   3.88    .28   2.17    .40
  STD     .02 .002   .05    .449  .08    .40 .008    .06    .06    *      *
PERCENT OF BASELINE
        45.5 84.2  45.8    85.2   74  288.9 100.9   38.6    7.1   25.8    3.4
 STD%     .4   .5    .8    12.2   10  327.9   3.1    1.6    3.0     .0     .0
```

```
                                                                    V
60609 W035V002 (4E12) W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP    LOG(IO)  N     R     FF   EFF   OCD   PCDA  PCDB

1B     23.25 .554 21.95 -10.270 1.07   .06 .805 10.96  5.46  8.42 11.60
2B     22.50 .554 21.10  -9.485 1.18   .15 .788 10.39  5.20  8.42 11.60
3B     22.50 .554 21.10  -9.485 1.18   .15 .788 10.39  5.20  8.42 11.60
4B     22.50 .554 21.10  -9.485 1.18   .15 .788 10.39  5.20  8.42 11.60
1C     18.30 .525 17.19  -9.843 1.08   .28 .790  8.02  1.30  1.45  1.16
2C*    18.20 .489 13.77  -3.304 5.18 -4.34 .555  5.22   .20  1.45  1.16
3C     18.00 .523 16.90  -9.877 1.07   .44 .786  7.82  1.04  1.45  1.16
4C     18.00 .523 16.90  -9.877 1.07   .44 .786  7.82  1.30  1.45  1.16
1S     18.20 .516 16.92  -8.630 1.25   .01 .774  7.69  1.30  1.45  1.20
2S     18.60 .521 17.36  -9.013 1.19   .10 .779  7.99  1.04  1.45  1.20
3S     18.60 .521 17.36  -9.013 1.19   .10 .779  7.99  1.30  1.45  1.20
1T     18.00 .525 16.91  -9.891 1.08   .33 .789  7.89  1.30  1.45  1.20
2T     18.00 .525 16.91  -9.891 1.08   .33 .789  7.89  1.30  1.45  1.20
3T     18.00 .525 16.91  -9.891 1.08   .33 .789  7.89  1.30  1.45  1.20
4T     18.00 .525 16.91  -9.891 1.08   .33 .789  7.89  1.30  1.45  1.20

AVERAGES: 60609  BASELINE  W003 00 000
       22.69 .554 21.31  -9.681 1.15   .13 .792 10.53  5.27  8.42 11.60
  STD    .32 .000   .37    .340  .05   .04 .007   .25   .11   *     *
         60609 W035V002 (4E12)
       18.17 .523 17.03  -9.582 1.12   .27 .785  7.89  1.25  1.45  1.19
  STD    .24 .003   .18    .466  .06   .14 .005   .09   .10   *     *
PERCENT OF BASELINE
       80.1 94.4  79.9   101.0   97 208.7  99.1  74.9  23.7  17.2  10.2
 STD%   2.2   .5   2.3     8.5   10 207.2   1.6   2.7   2.5    .0    .2
                                                                    ZN
60424 W015ZN001 (<1E12) W002 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC  IP    LOG(IO)  N     R     FF   EFF   OCD   PCDA  PCDB

1B     21.75 .540 20.28  -8.656 1.29  -.28 .786  9.77  3.90  8.57  6.30
2B     21.75 .540 20.28  -8.656 1.29  -.28 .786  9.77  3.90  8.57  6.30
3B     21.10 .540 19.35  -7.315 1.60  -.64 .762  9.19  3.25  8.57  6.30
4B     21.50 .540 19.90  -8.171 1.39  -.08 .768  9.42  3.25  8.57  6.30
1C     21.80 .540 20.04  -7.468 1.55  -.54 .765  9.52  3.90  5.28  7.20
2C     22.10 .540 20.58  -8.563 1.31  -.24 .783  9.88  4.55  5.28  7.20
3C*    21.70 .527 17.94  -3.836 4.05 -4.44 .662  8.01  1.95  5.28  7.20
4C     22.10 .540 20.32  -7.684 1.50  -.08 .755  9.53  3.90  5.28  7.20
1S     22.30 .540 20.44  -7.161 1.64  -.84 .766  9.76  3.90  5.28  7.20
2S*    19.50 .537 17.40  -5.794 2.20 -1.78 .732  8.11  3.25  5.28  7.20
1T     22.10 .530 19.93  -6.271 1.92 -1.11 .742  9.20  2.60  5.28  7.20
2T     22.20 .534 20.10  -6.511 1.84  -.85 .744  9.32  3.25  5.28  7.20
3T     22.20 .540 20.45  -7.577 1.52  -.57 .770  9.76  3.90  5.28  7.20
A201*  22.20 .540 20.80  -9.326 1.18   .04 .789 10.00  4.81  2.17 *****
A202*  22.20 .540 20.49  -7.714 1.49  -.57 .773  9.81  4.55  2.17 *****
A203*  22.20 .540 20.49  -7.714 1.49  -.57 .773  9.81  4.55  2.17 *****
A221*  22.20 .530 19.76  -5.515 2.29 -2.14 .740  9.21  3.25 40.00 *****
A223*  22.20 .530 20.32  -7.034 1.65  -.94 .766  9.53  3.25 40.00 *****

AVERAGES: 60424  BASELINE  W002 00 000
       21.53 .540 19.95  -8.199 1.39  -.32 .776  9.54  3.58  8.57  6.30
  STD    .27 .000   .38    .547  .13   .20 .011   .25   .33   *     *
         60424 W015ZN001 (<1E12)
       22.11 .538 20.27  -7.319 1.61  -.60 .761  9.57  3.71  5.28  7.20
  STD    .15 .004   .23    .712  .19   .34 .013   .23   .57   *     *
PERCENT OF BASELINE
      102.7 99.6 101.6   110.7  116  11.9  98.1 100.3 103.9  61.6 114.3
 STD%   2.0   .7   3.1    15.2   26 290.2   3.1   5.1  26.9    .0    .1
```

```
                                                                            ZR
61026 W047CU-NI-ZR001 (1.7E15/7.5E14/<1.5E13) W020 00 000
SOL3  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC    VOC   IP     LOG(IO)  N       R     FF     EFF    OCD    PCDA   PCDB

1R*      22.50 .557 20.45   -6.974 1.75   -.10 .735   9.73    .00    .00    .00
1B.*     22.90 .556 20.55   -5.949 2.16  -1.50 .741   9.98   3.25   7.30   7.00
2B       23.00 .558 21.37   -8.418 1.37   -.16 .777  10.55   4.55   7.30   7.00
4B       22.80 .559 21.14   -8.107 1.44   -.40 .778  10.49   4.55   7.30   7.00
5B       22.90 .560 21.41   -9.032 1.27   -.04 .786  10.66   4.55   7.30   7.00
1C       21.60 .545 19.51   -6.141 2.03  -1.88 .759   9.45   1.95   2.61   3.37
2C       21.50 .545 19.99   -8.656 1.30    .19 .770   9.54   1.95   2.61   3.37
3C       21.50 .543 19.83   -7.863 1.46   -.17 .763   9.42   1.95   2.61   3.37
4C       21.70 .543 20.08   -8.119 1.41   -.15 .769   9.58   1.95   2.61   3.37
1S       21.30 .543 19.41   -6.883 1.74   -.83 .754   9.23   1.95   2.61   3.37
2S       21.50 .544 19.99   -8.533 1.32   -.03 .775   9.58   1.95   2.61   3.37
3S       21.60 .543 20.01   -8.236 1.38   -.02 .767   9.52   1.95   2.61   3.37
1T       21.20 .543 19.65   -8.283 1.37   -.07 .770   9.37   1.95   2.61   3.37
2T       21.40 .543 19.91   -8.687 1.29    .12 .773   9.50   1.95   2.61   3.37
3T       21.40 .543 19.96   -8.987 1.24    .26 .775   9.52   1.95   2.61   3.37
4T       21.60 .543 20.11   -8.852 1.26    .28 .771   9.56   1.95   2.61   3.37

AVERAGES: 61026  BASELINE  W020 00 000
         22.90 .559 21.31   -8.519 1.36   -.20 .781  10.57   4.55   7.30   7.00
  STD      .08 .001   .12     .384  .07    .15 .004    .07    .00    *      *
            61026 W047CU-NI-ZR001 (1.7E15/7.5E14/<1.5E13)
         21.48 .543 19.86   -8.113 1.44   -.21 .768   9.48   1.95   2.61   3.37
  STD      .14 .001   .22     .832  .23    .60 .006    .10    .00    *      *
PERCENT OF BASELINE
          93.8 97.2  93.2    104.8  106   94.6  98.4   89.7   42.9   35.8   48.1
 STD%      1.0   .3   1.6     14.5   23  605.0   1.3    1.6     .0     .0     .0

                                                                            ZR
60221 W011ZR001(<1.5E13) W003 00 000
SOL4  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID       ISC    VOC   IP     LOG(IO)  N       R     FF     EFF    OCD    PCDA   PCDB

1B       22.50 .550 20.46   -6.751 1.80   -.76 .749   9.81   3.90   8.42  11.60
2B       22.37 .552 20.68   -7.922 1.47   -.36 .772  10.08   4.55   8.42  11.60
3B       22.37 .550 20.22   -6.516 1.89   -.63 .736   9.58   2.99   8.42  11.60
4B       22.50 .550 20.46   -6.751 1.80   -.76 .749   9.81   1.95   8.42  11.60
5B       22.50 .545 20.24   -6.332 1.94   -.57 .727   9.43   2.60   8.42  11.60
1C       22.00 .545 20.70   -9.858 1.11    .13 .795  10.08   3.90   1.08   2.60
2C       22.00 .545 20.18   -7.375 1.59   -.43 .758   9.61   3.25   1.08   2.60
3C       21.75 .542 19.96   -7.507 1.55   -.21 .754   9.41   2.21   1.08   2.60
4C       21.75 .542 19.84   -7.259 1.62    .05 .738   9.20   1.95   1.08   2.60
5C       22.00 .545 20.46   -8.640 1.30    .08 .773   9.81   3.90   1.08   2.60
1S       22.37 .540 20.68   -8.051 1.41   -.05 .764   9.76   3.29   1.08   2.60
2S       22.37 .547 20.93   -9.224 1.21    .15 .783  10.14   3.90   1.08   2.60
3S       22.25 .540 20.22   -6.565 1.84  -1.24 .758   9.64   3.64   1.08   2.60
4S       22.37 .540 20.56   -7.371 1.58   -.70 .768   9.81   3.90   1.08   2.60
1T       22.50 .550 21.21  -10.403 1.05    .54 .790  10.33   4.55   1.30   2.60
2T       21.50 .550 20.14   -9.454 1.18    .29 .783   9.79   3.90   1.30   2.60
3T       22.00 .550 20.48   -8.742 1.30    .16 .773   9.89   3.90   1.30   2.60
4T       22.00 .550 20.52   -8.970 1.26    .24 .775   9.92   3.90   1.30   2.60

AVERAGES: 60221  BASELINE  W003 00 000
         22.45 .549 20.41   -6.855 1.78   -.62 .747   9.74   3.20   8.42  11.60
  STD      .06 .002   .17     .557  .16    .15 .015    .22    .93    *      *
            60221 W011ZR001(<1.5E13)
         22.07 .545 20.45   -8.417 1.38   -.08 .770   9.80   3.55   1.15   2.60
  STD      .28 .004   .37    1.114  .22    .45 .015    .29    .70    *      *
PERCENT OF BASELINE
          98.3 99.2 100.2     77.2   78  187.7 103.2  100.6  111.1   13.6   22.4
 STD%      1.5  1.1   2.7     27.5   21   93.9   4.2    5.3   60.4    1.2     .0
```

```
                                                                    ZR
60714 W036ZR002 (2.5E13)  W025 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC   IP     LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*    22.60 .554 20.35   -6.467 1.92   -.29 .723   9.57    .00    .00    .00
1B     22.20 .549 20.42   -7.490 1.57   -.53 .765   9.86   5.20  12.74   7.60
2B     22.40 .549 20.57   -7.385 1.60   -.54 .763   9.92   5.20  12.74   7.60
3B     22.50 .547 20.61   -7.185 1.65   -.68 .761   9.91   4.16  12.74   7.60
4B     22.50 .548 20.47   -6.766 1.79   -.81 .751   9.80   5.20  12.74   7.60
5B     22.80 .549 21.04   -7.794 1.49   -.30 .767  10.15   5.20  12.74   7.60
1C     19.90 .531 18.09   -6.922 1.70   -.44 .741   8.29   1.30    .97   1.20
2C     20.10 .529 18.20   -6.740 1.75   -.41 .734   8.26   1.30    .97   1.20
3C     20.20 .527 18.24   -6.595 1.80   -.46 .731   8.23   1.04    .97   1.20
4C     20.30 .523 17.79   -5.503 2.29   -.66 .687   7.72   1.04    .97   1.20
5C     20.00 .528 18.05   -6.545 1.82   -.57 .732   8.17   1.04    .97   1.20
1S     19.90 .531 17.94   -6.519 1.84   -.48 .728   8.13   1.04    .97   1.20
2S     20.10 .532 18.32   -7.136 1.63   -.26 .743   8.40   1.17    .97   1.20
3S     20.30 .526 17.95   -5.617 2.24  -1.22 .710   8.02   1.04    .97   1.20
1T     19.70 .528 17.78   -6.505 1.84   -.70 .734   8.07   1.04    .97   1.20
2T     20.20 .529 18.29   -6.664 1.78   -.60 .738   8.33   1.04    .97   1.20
3T     20.00 .527 17.98   -6.305 1.91   -.84 .730   8.14   1.04    .97   1.20

AVERAGES: 60714  BASELINE  W025 00 000
       22.48 .548 20.62   -7.324 1.62   -.57 .761   9.93   4.99  12.74   7.60
  STD    .19 .001   .22     .341  .10    .17 .005    .12    .42     *      *
            60714 W036ZR002 (2.5E13)
       20.06 .528 18.06   -6.459 1.87   -.60 .728   8.16   1.10    .97   1.20
  STD    .18 .002   .18     .474  .20    .25 .015    .18    .10     *      *
PERCENT OF BASELINE
       89.3 96.3  87.6    111.8   116   94.1  95.6  82.2   22.0    7.6   15.8
 STD%   1.6   .6   1.8     10.9    20   86.7   2.7   2.8    4.0     .0     .0
                                                                    ZR
60721 W037ZR-TI001 (1.5E13-3.6E14)  W020 00 000
SOL5  1 /28/77   AM1: P0=91.60MW/CM^2  NO AR COATING

ID     ISC   VOC   IP     LOG(IO)  N      R     FF    EFF    OCD    PCDA   PCDB

1R*    22.50 .556 20.28   -6.519 1.91   -.30 .725   9.59    .00    .00    .00
1B     22.70 .556 20.99   -7.902 1.48   -.38 .772  10.30   5.20   7.30   7.00
2B     22.70 .556 20.91   -7.507 1.58   -.70 .772  10.31   5.20   7.30   7.00
3B     22.60 .554 20.91   -7.925 1.47   -.45 .775  10.26   5.20   7.30   7.00
4B     23.10 .554 21.26   -7.529 1.57   -.52 .767  10.38   4.55   7.30   7.00
5B     23.00 .555 21.34   -8.201 1.41   -.32 .778  10.50   5.20   7.30   7.00
1C     13.90 .465 12.33   -6.197 1.79   -.06 .695   4.75    .13    .42    .50
2C     13.80 .464 12.25   -6.260 1.76    .07 .695   4.70    .13    .42    .50
3C     14.00 .463 12.40   -6.169 1.79   -.01 .693   4.75    .13    .42    .50
1S     13.30 .463 11.91   -6.667 1.61    .40 .703   4.58    .13    .42    .50
2S     13.90 .464 12.33   -6.188 1.79   -.06 .695   4.74    .13    .42    .50
3S     13.90 .463 12.27   -5.972 1.88   -.33 .691   4.70    .13    .42    .50
1T     13.80 .462 12.24   -6.199 1.78   -.10 .696   4.69    .13    .42    .50
2T     12.90 .456 10.99   -4.840 2.58  -2.65 .667   4.15    .13    .42    .50
3T     13.70 .458 11.96   -5.662 2.01   -.44 .677   4.49    .13    .42    .50
4T     13.50 .461 11.98   -6.256 1.76    .10 .693   4.56    .13    .42    .50

AVERAGES: 60721  BASELINE  W020 00 000
       22.82 .555 21.08   -7.813 1.50   -.47 .773  10.35   5.07   7.30   7.00
  STD    .19 .001   .18     .263  .06    .13 .004    .08    .26     *      *
            60721 W037ZR-TI001 (1.5E13-3.6E14)
       13.67 .462 12.07   -6.041 1.88   -.31 .690   4.61    .13    .42    .50
  STD    .33 .003   .39     .465  .25    .81 .010    .18    .00     *      *
PERCENT OF BASELINE
       59.9 83.2  57.2    122.7   125  134.8  89.3  44.6    2.6    5.8    7.1
 STD%   1.9   .6   2.4      8.8    23  236.5   1.7   2.1     .1     .0     .0
```

APPENDIX 5

Impurity Build-Up Equations

1. Sequential Melt Replenishment

Consider a crystal being grown from a melt having a uniform distribution of impurities save perhaps in a boundary layer at the growing interface. As the crystal is grown, the melt volume decreases from its initial value, V_O, to $(1 - g)V_o$. If solute is rejected by the growing crystal with an effective distribution coefficient k, then the normal freeze equation predicts the solute concentration in the liquid to be

$$C_\ell = C_\ell^1(1 - g)^{k-1} \qquad \text{(A-1)}$$

where C_ℓ^1 is the initial liquid concentration. The total amount of impurity in the liquid is then

$$Q = (1 - g)V_o\, C_\ell \qquad \text{(A-2)}$$

$$= V_o C_\ell^1 (1 - g)^k \qquad \text{(A-3)}$$

Let $p = (1 - g)^k$ so that

$$Q = V_o C_\ell^1 p \; . \qquad \text{(A-3a)}$$

Now replenish the melt to its original volume, V_o, with a volume $V_o g$ of feed stock of solute concentration C_o. The total impurity content is now

$$Q = V_o C_\ell^1 p + V_o g C_o \qquad \text{(A-4)}$$

or

$$C_\ell = C_\ell^1 p + g C_o \; . \qquad \text{(A-5)}$$

Let n be the number of pulls. At the start of the nth pull, we have

$$n = 1 \qquad C_\ell^{\,i}(1) = C_o$$

$$n = 2 \qquad C_\ell^{\,i}(2) = C_o(p + g)$$

$$n = 3 \qquad C_\ell^{\,i}(3) = C_o \{p^2 + pg + g\}$$

$$\vdots$$

$$n = n \qquad C_\ell^{\,i}(n) = C_o \{p^{n-1} + g(p^{n-2} + \ldots + 1)\} \tag{A-6}$$

$$\text{or} \qquad C_\ell^{\,i}(n) = C_o \left\{p^{n-1} + g \left[\frac{p^{n-1} - 1}{p - 1}\right]\right\} \tag{A-7}$$

2. Continuous Melt Replenishment

In the case of continuous melt replenishment, the melt volume is invariant at V_o. As a volume of crystal dV_c is grown from the melt, an equal volume of feed stock material is added. The change in impurity content in the melt is then

$$V_o dC_\ell = (C_o - kC_\ell)dV_c \ . \tag{A-8}$$

Integration with the initial condition that $C_\ell = C_o$ when $V_c = 0$ gives

$$\frac{C_\ell}{C_o} = \frac{1}{k}\left[1 - (1-k)\ \exp\left(-\frac{kV_c}{V_o}\right)\right] \tag{A-9}$$

if $\frac{kV_c}{V_o}$ is much less than unity, Eq. (A-9) is approximated by

$$\frac{C_\ell}{C_o} \simeq \left[1 + (1-k)\ \frac{V_c}{V_o}\right] \tag{A-10}$$

$$\simeq \left[1 + \frac{V_c}{V_o}\right] \ . \tag{A-10a}$$