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

Second Quarterly Report, 1 January 1976–31 March 1976

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Westinghouse Research Laboratories
Pittsburgh, Pennsylvania

and

Dow Corning Corporation
Midland, Michigan

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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J. R. McCormick
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Contract No. 954331

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NEW TECHNOLOGY

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

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1. SUMMARY

The objective of this program, Part 2 of the Silicon Materials Task, is to develop and define purity requirements for Solar Cell Grade silicon material by evaluating the effects of metal impurities and impurity concentration on the performance of terrestrial silicon solar cells.

During this quarter the growth of all first generation doubly-doped Czochralski ingots was completed (baseline boron + Cr, Mn, Cu, Ni, Fe, Ti, V, Mg, Zn, Al, and Zr), as were 90% of the second generation ingots, several third generation ingots, and three multiply-doped (B + Cu/Mn, Cu/Cr, Mn/Cr) ingots. Qualitative mass spectroscopic analysis is complete for most of these ingots and semiquantitative results have been obtained for the Mn, Cu, Cr, Ni, Ti, and V-doped first generation crystals. In general, ingot analyses are consistent with the target impurity levels except for Ti and V, which are about 30% below the expected values, Zr which is low by a factor of two, and Mg and Zn where rapid evaporation from the melt reduces the crystal impurity content significantly. The disparity between targeted and observed impurity concentration for Ti, V, and Zr stems from the limited precision of available segregation coefficients for these elements.

All the wafers processed to solar cells exhibit relatively low dislocation densities, typically $< 10^3 \text{ cm}^{-2}$, and often below 10^2 cm^{-2} .

Etching anomalies and x-ray topographic evidence suggest that heavily-doped crystals, particularly those containing high copper content, exhibit precipitation during the post-growth cooling cycle. The ingots appear to be uniformly doped as their flat radial spreading resistance profiles indicate.

Photoconductive decay (PCD) measurements of recombination lifetime are completed for all first generation (save Mg-doped) and most second generation ingots. The lifetimes of the baseline (3 Ωcm) boron doped silicon decreases slightly during junction formation at 825°C, as has been widely noted in the literature. Similar behavior occurs for metal doped ingots which initially exhibit high lifetime in the as-grown conditions, e.g., Cu, Zr, and Ni. Generally the lifetimes of most other metal-doped ingots improve somewhat during cell processing, a result so far attributed to gettering and/or precipitation.

Solar cells have been fabricated and tested on all first, several second and a few third generation ingot wafers. The metals tend to group with respect to their effects on solar cell performance in ingots doped to the 5×10^{14} to 10^{15} atoms/cm⁻³ range: impurities causing little (Cu, Ni, and Zr), modest (Cr, Mn, Fe, and Al), and severe (V, Ti) reductions in cell efficiency. For example, the relative cell efficiencies (η doped/ η baseline) for wafers doped near 10^{15} atoms/cm⁻³ are: Cu-1.0, Ni-0.9, Zr-1.0, Cr-0.75, Mn-0.71, Al-0.78, Fe-0.53, V-0.39, and Ti-0.25. Data for Mg and Zn doped wafers are as yet too scanty for interpretation. The efficiency for the baseline boron-doped material is typically 9.5% for cells without AR coating at AM1 illumination.

Although our data are still preliminary, we note direct correlations between the PCD and OCD lifetimes of diffused wafers and the short circuit current density of the finished solar cells themselves. As wafer lifetime falls below about 1 μsec cell efficiency increasingly departs from the baseline 9.5% value. In contrast, the lifetimes

measured on as-grown wafers show little relation to cell performance, a fact attributed to the as yet unpredictable effects of cell processing on lifetime.

Because most metal dopants are relatively insoluble in silicon at low temperatures we expect, and for copper have evidence, that precipitates should be present in the solar cell wafers. Surprisingly, we have yet to note any significant harmful effects of precipitation on cell performance, behavior quite different from the degradation observed in most other silicon devices. This perhaps stems from the fact that solar cells operate at low rather than high electric field strengths.

2. INTRODUCTION

2.1 Program Objective

Our objective in Part 2 of the Silicon Materials Task (LCSSAP) is to develop and define purity requirements for solar cell grade silicon material. In a broader sense we are developing a data base which delineates the effects of various impurities and impurity levels on the performance of terrestrial silicon solar cells.

2.2 Program Approach

The basic approach we have taken is to establish, as unambiguously as possible, what concentrations of the impurities commonly found in silicon starting material (metallurgical grade silicon) can be tolerated in silicon wafers produced by (a) standard Czochralski pulling and (b) rapid sheet growth (dendritic-web) without degrading solar cell performance. Other impurities, e.g., those entering the material via a particular sheet growth process, could also be examined within the framework of our methodology as they are identified.

Briefly, the program consists in (1) establishing a matrix of those impurities which produce deep levels in silicon, (2) the growth of doubly and multiply-doped silicon Czochralski ingots and dendritic-web crystals containing a baseline boron dopant and specific impurities chosen from the matrix, (3) assessment of these crystals by a battery of chemical, microstructural, electrical and solar cell tests, (4) correlation of the impurity kind and level with crystal quality and device performance, and (5) delineation of the tolerable impurity regimes for crystal growth and useful silicon solar cell performance.

2.3 Program Personnel

This program is being conducted by a team of scientists from the Westinghouse Electric Corporation and Dow Corning Corporation whose technical responsibilities are identified below.

Westinghouse Research Laboratories

Dr. R.H. Hopkins -- Technical Manager and Dendritic Web Studies

Dr. P. Rai-Choudhury -- Device Diffusion

Mr. J.R. Davis -- Solar Cell Testing and Analysis

Dr. P.D. Blais -- Lifetime Studies, Photolithography and Metallization

Dow Corning Corporation

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

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

3. TECHNICAL PROGRESS

3.1 Impurity Matrix

As we indicated in the first quarterly report,¹ a multi-dimensional matrix involving such parameters as donor/acceptor concentration, concentration of other impurities (traps), trap species, and structural defects is required to completely define solar grade silicon. The primary aim of this program, however, is to evaluate the effect on solar cells of metal impurities not normally encountered in semiconductor grade silicon but which might be found in a low cost solar grade material. Thus, the impurities and impurity concentrations dealt with here make up the one dimensional matrix depicted in Fig. 1 and form a basis from which the effects of other parameters can be subsequently examined.

The experimental sequence is iterative with all first generation ingots (or webs) targeted at a 10^{15} atoms/cm⁻³ impurity level and later ingots grown to higher or lower impurity concentrations depending on measured solar cell performance. From the figure it is apparent that the target concentration was not achieved for every first generation ingot. The causes for this, impurity evaporation and discrepancies in published segregation coefficients, are discussed below.

Figure 1 also illustrates at a glance the general status of the ingots: grown (G), fabricated to solar cells (F), and cells tested (T). Each ingot contains from 2.5 to 7×10^{15} atoms/cm⁻³ of boron as well as the specific metal impurity.

3.2 Ingot and Web Preparation

The interaction of ingot preparation, ingot analysis, and device characterization is illustrated in Fig. 2, along with the various

Ingot Status
Concentration Range

G - Grown
F - Cell Fabricated
T - Cell Tested

Impurity Element	$< 10^{14}$	5×10^{14} To 1×10^{15}	1×10^{15} To 5×10^{15}	5×10^{15} To 1×10^{16}	$> 10^{16}$
Cr	G	G, F, T	G, F, T		
Mn	G, F, T	G, F, T	G, F, T		
Cu		G, F, T	G, F, T		G, F, T
Ni		G, F, T	G, F, T		
Fe			G, F, T		
Ti	G	G, F, T			
V	G	G, F, T			
Mg	G	G, F, T	G		
Zn	G, F, T				
Zr		G, F, T			
Al				G, F, T	

Figure 1. Status of the metal-doped ingots which form the impurity matrix for this program.

Figure 2. Flow Diagram of Ingot (or Web) Preparation and Analysis.

analytical tools used in ingot and web characterization. All ingots have been prepared using the Czochralski growth process. Nominal growth parameters are

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 cm (nominal)
Atmosphere	1 atm argon

Generally, the dopant elements were the highest purity available; their characteristics are delineated in Table 1. The last column of the table indicates the segregation coefficients used to establish the initial melt concentrations for first generation crystal growth. Within parentheses are the segregation coefficients determined from our work. In the cases of manganese, chromium, and copper, very good agreement is apparent between previously published segregation data and our information while relatively good agreement (within a factor of four) exists for nickel, titanium, vanadium, and zirconium. We could not determine k for zinc due to evaporation during growth while inadequate data so far exists to calculate k for magnesium, iron, and aluminum. It must be recognized that analytical data is constantly being collected and refined so that changes in the values shown in Table 1 may be anticipated as more information becomes available.

The status of ingot preparation/characterization is shown in Table 2. The letter designation indicates whether the ingot has been grown (G), sliced (S), analyzed (A), and processed (P) into cells. Crystal growth and slicing has been completed for thirty-one ingots with 22 of these being doped with one or more impurity elements. Analysis is essentially complete for 80 percent of the ingots. Due to the heavy load of samples for the mass spectrograph, some of the evaluation (audit) ingots (W023-00000, W025-00000) have not been analyzed. All other analysis has been completed for these ingots.

Table 1. Characteristics of Dopant Impurities

Dopant	Form	Purity %	Melting Point (C)	Temperature For 1 mm Vapor Pressure (C)	Segregation Coefficient*
Aluminum	Wire	99.99	659	1284	1.6×10^{-3} (--)
Chromium	Pellets	99.999	1900	1504	10^{-5} ($.95 \times 10^{-5}$)
Copper	Zone Refined Ingot	99.9997	1083	1628	4×10^{-4} (4×10^{-4})
Iron	Sponge/ Ingot	99.999/ 99.999	1535	1783	0.8×10^{-5} (--)
Magnesium	Ingot	99.99	651	605	$\sim 10^{-3}$ ($< 10^{-4}$)
Manganese	Flake	99.99	1244	1251	10^{-5} (1.35×10^{-5})
Nickel	Sponge/ Wire	99.999/ 99.97	1455	~ 1884	0.8×10^{-5} (3.2×10^{-5})
Titanium	Crystal	99.95	1668	~ 2500	10^{-5} ($.36 \times 10^{-5}$)
Vandium	Dendrite	99.9	2190	2550	10^{-5} ($.45 \times 10^{-5}$)
Zinc	Rod	99.999	419	487	10^{-5} (--)
Zirconium	Foil	99.99	2127	2450	10^{-5} ($.45 \times 10^{-5}$)

* The segregation coefficients shown are best values obtained from a review of the literature on impurities in silicon. The quantity in parentheses represent calculated segregation coefficients based on this work.

Table 2. Ingot Status

<u>Ingot Identification</u>	<u>Status</u>	<u>Ingot Identification</u>	<u>Status</u>
W001-00000	G,S,A,P	W017-CU002	G,S,A,P
W002-00000	G,S,A,P	W018-FE002	G,S,A,P
W003-00000	G,S,A,P	W019-CU003	G,S,A,P
W004-CR001	G,S,A,P	W020-00000	G,S
W005-MN001	G,S,A,P	W021-MG001	G,S,A
W006-NI001	G,S,A,P	W022-00000	G,S
W007-CU001	G,S,A,P	W023-00000	G,S
W008-TI001	G,S,A,P	W024-MG002	G,S,A,P
W009-V001	G,S,A,P	W025-00000	G,S
W010-NI002	G,S,A,P	W026-MN003	G,S,A,P
W011-ZR001	G,S,A,P	W027-MN/CU001	G,S,A
W012-CR002	G,S,A,P	W028-AL001	G,S, P
W013-MN002	G,S,A,P	W029-CR003	G,S,A
W014-00000	G,S,A,P	W030-CR/CU001	G,S,A
W015-ZN001	G,S,A,P	W031-CR/MN001	G,S
W016-FE001	G,S,A		

Web growth has so far run behind schedule due to delays in furnace fabrication and debugging. Some web segments about 8 mm wide by 10-20 cm long were grown targeted to a 3 Ω cm boron baseline level. The measured resistivity was about 7 Ω cm. Because the resistivity was high and the webs undersize for fabricating 1 cm x 1 cm solar cells, evaluation of this material has been held in abeyance pending improvements in the thermal geometry of the growth furnace.

3.3 Ingot Evaluation

3.3.1 Resistivity and Defect Density

The results of measurements of ingot resistivity on etch pit density are summarized in Table 3. The targeted resistivity for all samples except W023-00000 was 4 ohm-cm. Normal variation found in preparing doped crystals is ± 25 percent. The tang end values shown in Table 3 represent a position along the ingot where approximately 50 percent of the melt has been removed (50 percent pulled). Only three ingots fell significantly outside the targeted resistivity range. These were the multiply-doped ingots W027-MN/CU001, W030-CR/CU001, and W031-CR/MN001. Total impurity concentration in those ingots was approximately 2×10^{15} atoms/cm³. The resistivity of ingot W018-FE002 was also somewhat high but within the prescribed resistivity range. Ingot W023-00000 was intentionally doped to a high boron concentration to assess the effect of differing acceptor concentrations on cell performance, hence the ingots' low resistivity. Ingot W028-AL001 also exhibited low resistivity -- as expected since the second impurity, aluminum, is electrically active as an acceptor.

The etch pit density in slices taken from the seed end of the ingots ranged from 0 to 3,750 per cm². No special attempt was made to produce dislocation free ingots; however, approximately 25 percent of the ingots produced have been dislocation free on the basis of etch pit analysis. In general, significantly higher etch pit densities were

Table 3. Ingot Analysis (Resistivity, Dislocation Density, and Carbon/Oxygen Concentration)

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	4.3/96
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	-
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

encountered in tang end slices taken from ingots doped to 1×10^{15} atoms/cm³ or higher impurity concentrations.

3.3.2 Carbon and Oxygen Analysis

Only a few samples had been analyzed for carbon and oxygen content prior to this reporting period. Now all samples have been analyzed for these two impurities and the data are collected for convenience in Table 3. With a Beckman dual beam spectrophotometer the transmission spectrum of a 2 mm thick test sample is compared to that of a standard silicon sample in the spectral bands 580-635 cm⁻¹ (carbon) and 1050-1150 cm⁻¹ (oxygen). The respective absorption peaks occur at approximately 606 cm⁻¹ and 1107 cm⁻¹. The measured peak heights can be directly related to the carbon and oxygen concentrations via appropriate conversion factors.

The carbon and oxygen concentrations found in all ingots were nominal. The carbon concentrations of undoped ingots produced in the crystal pulling furnaces we use on this program typically may vary from 2.5×10^{16} atoms/cm³ to 25×10^{16} atoms/cm³ while oxygen concentrations will normally range from 50×10^{16} atoms/cm³ to 150×10^{16} atoms/cm³. No significant deviations from the above ranges were observed in the doped crystals so far grown on this program. Neither impurity concentration was sufficient to produce any crystal growth problems.

3.3.3 Metal Impurity Analysis

The primary objective of the ingot analysis effort is to establish the concentration of intentionally introduced impurities, Fig. 1, which are present in a given ingot. We anticipated that numerous second and third generation ingots would be required having impurity concentrations in the 10^{13} atoms/cm³ to 10^{14} atoms/cm³ range -- impurity concentrations which do not lend themselves to direct measurement. For this reason, a multiplicity of analytical techniques has been used to determine the impurity concentration in the more heavily doped first generation ingots (10^{15} atoms/cm³). This, we believe, will

provide a high level of confidence for predicting by means of effective segregation coefficients and growth conditions the lower impurity concentrations in the second and third generation ingots.

We have used the spark source mass spectrometer as the primary tool for ingot analysis. These measurements have been supplemented by neutron activation analysis and by the analysis of melt samples at the completion of crystal growth. The latter technique was used primarily to ascertain whether significant amounts of the impurity species was lost from the melt during growth. Due to the potential non-uniform impurity distribution across a slice taken from a doped ingot, and the inherent microscopic sampling of the mass spectrometer, multiple samples were taken from all first generation ingots to assess the uncertainties involved in these measurements. While this work is incomplete, we report below the results to date.

A second difficulty is often encountered with spark source mass spectrographic analysis -- the appearance of a few impurities (copper, titanium, and zirconium), at a concentration near their detection limit (3-10 ppba) in nearly all of the samples analyzed. We attribute the occurrence of these impurities to surface contamination of the sample at some point after crystal growth, e.g., during etching. This conclusion is based on the following observations.

1. The degree of melt contamination required to produce the observed concentrations (particularly titanium and zirconium) is well in excess of that which could be unintentionally introduced into the melt, e.g., 5 grams for titanium, 5 grams zirconium, and 0.5 grams copper.
2. Analysis of polycrystalline charge material and the resulting ingot pulled from the polycrystalline silicon gives similar concentrations, i.e., no segregation is observed.
3. In ingots intentionally doped with chromium, W004, and manganese, W005 (but with no copper), neutron activation

analysis fails to detect the existence of the copper observed by the mass spectrograph.

4. The copper detected spectrographically in unintentionally-doped samples is the same concentration at the seed and tang ends of the ingot. If the copper were incorporated during growth, one would anticipate approximately twice as much in the tang end of the ingot as in the seed end. Intentionally doped samples display this normal distribution.

Thus, we have disregarded the presence of titanium, zirconium, and copper in those ingots not intentionally doped with these elements. Where the intentional dopant is one of the above three elements at a concentration range where interference exists, further measurements are being made to develop statistically meaningful data. Simultaneously work is in progress to eliminate the Cu, Ti, and Zr surface contamination.

The analytical results for the first 31 ingots prepared for solar cell evaluation are collected in Table 4. Target impurity concentration is based on the amount of impurity added to the melt and the known segregation coefficients, Table 1. The calculated impurity concentration is derived from the measured impurity concentration in the melt at the completion of crystal growth (corrected for the volume change of the melt) and the segregation coefficients of Table 1. Tabulated in the next two columns are the mass spectrographic analyses and, where applicable, neutron activation analyses. For brevity, we use only the first three digits of the ingot designator in discussing these results below.

Generally, good agreement exists between the targeted concentration and that calculated from melt analysis, although significant differences do appear for ingots W006, W010, W011, W015, W019, and W021. The low nickel concentration in the melt of ingot W006 was caused by loss of dopant from the crucible during furnace evacuation; the nickel was in powder form. Subsequent doping with high purity

Table 4. 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	0.95	<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	1.0	1.65
W-008-TI-001	1	0.82	0.36	NA
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	Incomp
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	NA
W-017-CU-002	10	7	40	25
W-018-FE-002	2	1.6	<3	NA
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	1/1.4	1.1/2.2
W-028-AL-001	1	-	-	NA
W-029-CR-003	0.01	0.0083	<5 x 10	NA
W-030-CR/CU-001	1/1	0.82/0.75	1/1.4	0.5/2.5
W-031-CR/MN-001	1/1	0.85/0.82	1/2.5	-

1. NA indicates impurity concentration of less than 4×10^{15} atoms/cm³ which represent the limit of detection.

2. Nickel powder used as dopant. ²Dopant partially lost during furnace evacuation. Figure of 0.17×10^{15} atoms/cm³ 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 1×10^{13} atoms/cm³ for W-021 and 1×10^{14} atoms/cm³ for W-024.

nickel wire produced a significant improvement (W010). However, the calculated concentration for W010 is still lower than expected. Because of sizable discrepancy between this value and that obtained by mass spectrographic analysis, further experiments with nickel as a dopant will be conducted.

The calculated zirconium concentration, ingot W011, exceeds that added to the crucible and is obviously in error. Since only one zirconium doped ingot was prepared, additional ingots are being grown to help elucidate the source of the analytical problem.

The low zinc content of ingot W015 based on crucible remains analysis was anticipated due to the high vapor pressure of zinc at the melting point of silicon. Experimental results indicate that loss of zinc is extremely rapid and melt doping with elemental zinc is not feasible. Although magnesium was also evolved from the melt, e.g., ingot W021, the rate of volatilization was much slower than that of zinc. As indicated in Table 4, a magnesium loss of approximately 40 percent from the melt occurred during growth.

The calculated copper concentration based on analysis of crucible remains for ingot W019 is approximately two and a half times the targeted value. Good agreement has been achieved between targeted and calculated value based on analysis of crucible remains for all other copper doped ingots. Since ingot W019 represents the lowest dopant concentration, it is possible that sample contamination occurred at this relatively low impurity level. When additional copper doped ingots (less than 10^{15} atoms/cm³) are prepared, a significantly larger ingot will be grown to concentrate copper in the melt before sampling.

Mass spectrographic analysis is yet to be completed for all samples. The impurity values shown in Table 4 represent analysis of a single sample with the exception of those ingots described in Table 5. In Table 5 we have collected the data from samples for which multiple mass spectrographic analyses have been performed and an estimate of the

Table 5. Results of Multiple Mass Spectrographic
Analysis of a Single Slice

<u>Ingot Identification</u>	<u>Range of Measured Impurity Conc. (10^{15} atoms/cm³)</u>	<u>Average Impurity Concentration (10^{15} atoms/cm³)</u>
W-004-CR-001	0.8 - 1.0 (3)	0.95
W-005-MN-001	1.0 - 2.5 (4)	1.35
W-007-CU-001	0.4 - 1.5 (4)	1.0
W-008-TI-001	<5 - 0.36 (2)	0.36
W-009-V-001	0.31 (2)	0.31
W-010-NI-002	4.0 (2)	4.0
W-011-ZR-001	0.4 - 0.5 (4)	0.45

effective segregation coefficient can be made. This information will be supplemented by measurements of impurity concentration on all heavily doped ingots produced during the program. The data developed so far are very encouraging, and indicate a high probability that reliable concentrations can in fact be determined through use of the mass spectrometer with a limited number of samples. The sample size remains too small to establish a meaningful standard deviation; however, indications are that the -50, +100 percent objective for impurity determination set out at the beginning of the program can probably be realized for the majority of elements under investigation.

Mass spectrographic and neutron activation data exist for ingots doped with Mn, Cr, and Cu. Copper concentrations determined by neutron activation analyses for ingots W007, W027, and W030 were from 60 percent to 80 percent greater than the copper concentrations determined by mass spectrographic analysis, and from 65 to 250 percent of the predicted concentrations. In the case of ingot W017 the copper concentration determined by neutron activation analysis was somewhat less than that obtained by mass spectrographic analysis. Agreement for the two manganese ingots evaluated by both methods was somewhat better. The manganese concentration by neutron activation ranged from -60 to +10 percent of the manganese concentration determined by mass spectrographic analysis. A meaningful concentration was only determined for one chromium doped ingot (W030) by neutron activation analysis. The concentration is 50 percent of the chromium concentration determined by mass spectrographic analysis. The level of agreement between the neutron activation and mass spectrographic techniques is about what was anticipated at the beginning of the program. The number of samples analyzed by neutron activation analysis is yet small; as more samples are evaluated, the statistical significance of the data will be improved.

The mass spectrometer is relatively insensitive in the detection of iron due to interference from silicon for both the singly and doubly ionized iron ion. Extremely long exposures are being undertaken for

both iron-doped ingots to establish their concentrations. Growth of more heavily doped single crystal ingots is impossible due to the small segregation coefficient of iron the the consequent high melt doping level required.

No magnesium was detected spectrographically in ingots W021 and W024. We believe that the 10^{-3} value of the segregation coefficient used for magnesium is much too large. Preparation of ingots is now in progress assuming a segregation coefficient of 10^{-5} . Although analysis of the aluminum-doped ingot is incomplete, the 25 percent reduction in resistivity relative to other ingot observed for W028 corresponds to an electrically active aluminum concentration of 1×10^{15} atoms/cm³.

Since some of the analytical measurements remain incomplete and some clear differences exist between the impurity concentrations determined by various methods of analysis, we have made a best estimate of the impurity concentration in each ingot, Table 6. These values were obtained by weighing the analytical data for a particular ingot as well as data collected from other ingots doped with the same purity. Also considered were how well the segregation coefficient is known, whether the impurity is normally electrically active, the number of samples analyzed, etc. We anticipated that these values will change as additional data are collected, but the revisions in general should not be too great (i.e., -50, +100 percent).

3.4 Silicon Wafer Evaluation

3.4.1 Spreading Resistance

As the data compiled in Table 7 illustrate, the metal-doped ingots exhibit comparable resistivity homogeneity to the baseline ingots (data for the baseline material, as well as ingots W004-W007 were presented previously¹ and will not be repeated here). The possible exception to this trend is Fe-doped ingot W018 whose resistivity falls at the high end of the 3-6 Ω cm target and for which the radial variation in resistivity is largest.

Table 6. Best Estimate of Impurity Concentration

<u>Ingot Identification</u>	<u>Best Estimate of Impurity Conc. (10^{15} atoms/cm³)</u>	<u>Ingot Identification</u>	<u>Best Estimate of Impurity Conc. (10^{15} atoms/cm³)</u>
W-001-00-000	--	W-017-CU-002	10
W-002-00-000	--	W-018-FE-002	<3
W-003-00-000	--	W-019-CU-003	0.1 - 0.5
W-004-CR-001	0.95	W-020-00-000	--
W-005-MN-001	1.0	W-021-MG-001	<0.5
W-006-NI-001	0.1	W-022-00-000	--
W-007-CU-001	1.0	W-023-00-000	--
W-008-TI-001	0.36	W-024-MG-002	<0.5
W-009-V-001	0.31	W-025-00-000	--
W-010-NI-002	4.0	W-026-MN-003	0.01
W-011-ZR-001	0.45	W-027-MN/CU-001	1.0/1.0
W-012-CR-002	0.2	W-028-AL-001	--
W-013-MN-002	0.2	W-029-CR-003	0.01
W-014-00-000	--	W-030-CR/CU-001	1.0/1.0
W-015-ZN-001	.0001 - .1	W-031-CR/MN-001	1.0/1.0
W-016-FE-001	<3		

Table 7. Radial Resistivity Variations on
Transition Metal Doped and Audit Ingots

<u>Ingot No.</u>	<u>Wafer Location</u>	<u>Average Resistivity ohm-cm</u>	<u>Fractional Standard Deviation</u>
W008 Ti	seed	3.707	3.631×10^{-2}
	tang	3.668	3.467×10^{-2}
W009 V	seed	3.664	3.178×10^{-2}
	tang	3.350	2.438×10^{-2}
W010 Ni	seed	4.559	6.868×10^{-2}
	tang	5.399	5.310×10^{-2}
W011 Zr	seed	5.501	4.659×10^{-2}
	tang	4.841	7.237×10^{-2}
W012 Cr	seed	4.054	5.156×10^{-2}
	tang	4.362	4.849×10^{-2}
W013 Mn	seed	4.770	5.448×10^{-2}
	tang	3.871	5.319×10^{-2}
W014	seed	5.031	6.279×10^{-2}
	tang	3.920	5.223×10^{-2}
W015 Zn	seed	4.003	7.951×10^{-2}
	tang	4.098	5.389×10^{-2}
W016 Fe	seed	4.525	6.081×10^{-2}
	tang	4.599	6.419×10^{-2}
W017 Cu	seed	3.622	3.279×10^{-2}
	tang	3.838	6.036×10^{-2}
W018 Fe	seed	6.859	10.64×10^{-2}
	tang	5.261	14.15×10^{-2}
W019 Cu	seed	3.358	2.493×10^{-2}
	tang	3.412	2.351×10^{-2}
W020	seed	4.463	5.537×10^{-2}
	tang	4.513	4.876×10^{-2}
W022	seed	4.368	3.486×10^{-2}
	tang	3.953	3.735×10^{-2}

3.4.2 Microstructural Evaluation

Following I.D. sawing, all wafers are chemically polished, and representative slices from each ingot are Sirtl etched for five minutes to reveal their characteristic microstructural features. Unetched slices are used for x-ray topographic analysis.

Generally, the etch pit densities (EPD) of randomly selected wafers agrees within expected error with the EPD measured during ingot evaluation, Table 3. Thus, the tabulated EPD data can be considered representative of the material processed to cells. While the EPD of the wafers is well below the targeted $5 \times 10^4 \text{ cm}^{-2}$, and usually $< 10^3 \text{ cm}^{-2}$, we have noted some interesting features to the etch patterns. The more heavily-doped ingots, those containing 10^{15} metal atoms/ cm^{-3} or more, often exhibit clusters of pits, linear etch features, and shallow rounded pits. The etching response of these crystals also seems somewhat more erratic than that of the baseline material.

For example, ingot W017, doped to $4 \times 10^{16} \text{ cm}^{-3}$ copper shows, besides normal triangular etch pits, short parallel linear pit arrays, Fig. 3. The (111) x-ray topograph from this crystal, Fig. 4, illustrates the likely origin of the linear arrays, decoration of dislocations by precipitates. In the topograph the normal extinction conditions for dislocations have been modified by the precipitates which show up as strings of bright spots oriented in $\langle 110 \rangle$ directions. By comparison, the (111) topograph from V-doped ingot W009, Fig. 5, exhibits many long straight dislocation segments, sharply imaged with no apparent decoration.

The topograph from the V-doped ingot also illustrates a second point relevant to the etching experiments. While the EPD for this crystal is zero, the crystal clearly contains dislocations, albeit mostly near the wafer periphery. Because many of the dislocations are parallel to the wafer surface they aren't etched and few pits are produced. This

Figure 3. Sirtl-etched surface of a wafer from ingot W017-CU002. The heavily doped ingot exhibits short linear arrays of etch pits (arrow) as well as normal isolated triangular pits. Nomarski illumination, 100X.

Figure 4. (111) x-ray transmission topograph of a wafer from ingot W017-CU002. Strings of bright spot are precipitates decorating the dislocations present in the crystal. $\sim 10\times$.

Figure 5. (111) x-ray transmission topograph of a wafer from ingot W009-V001. Note the long straight and gently curving dislocation segments near the wafer center and shorter segments near the edge. (The horizontal bands are artifacts of our equipment.) $\sim 10\times$.

may lead to a low or zero EPD even when dislocations are present in the crystal. Ingot W007 on the other hand exhibits no dislocations by etching or topography.

3.4.3 Recombination Lifetimes Measured by Photoconductive Decay

The magnitude of the bulk recombination lifetime for carriers is strongly sensitive to impurities, chemical complexes and imperfections present in the silicon lattice so measurements of this parameter can be used to assess the effects of diffusion processing on silicon wafers, as well as to evaluate processed solar cells themselves. Photoconductive Decay (PCD), a well-known method for recombination lifetime measurement, was chosen for our study because of the minimal sample processing required, the relative ease of data collection and interpretation and the relevance of PCD to solar cell operation. However, several effects can cause the measured or effective lifetime τ_r' to deviate from the true bulk lifetime τ_r ; for this reason we discuss in detail below the analyses made to correct the raw lifetime data.

Measurements of Open Circuit Decay (OCD) lifetime are discussed in Section 3.5.

3.4.3.1 Raw Data Collection

The details of the measurement techniques were given in a previous report.¹ Since that time the PCD equipment has been modified to increase the maximum available test current from 10 mA to 100 mA. This provides a larger signal-to-noise ratio on lower resistivity silicon, or material with short lifetimes. The LED source was changed to a Spectronics type SE 5453-4 to increase the infrared output of the pulse light.

The apparent bulk lifetimes τ_r' we measured are summarized in Table 8. To obtain τ_r these data must be corrected for surface recombination and sample thickness.

Table 8. Summary of Uncorrected Photoconductivity
Decay Lifetime Measurements

Lot. No.	Impurity Type (Concentration, cm ⁻³)	Lifetime As-Grown $\tau_r'(\mu\text{sec})^\sigma$	Lifetime Post Diffused $\tau_r'(\mu\text{sec})^\sigma$	Ratio τ_{PD}'/τ_{AG}'
W001	Baseline	2.90 --	2.16 --	0.74
W002	Baseline	2.31 --	1.90 --	0.82
W003	Baseline	2.90 --	2.45 --	0.84
W004	Cr 1 E 15	0.14 --	0.76 0.19	5.28
W005	Mn 1.4 E 15	Note 1 --	0.25 0.04	NA
W006	Ni 1.7 E 14	2.67 0.22	2.31 --	0.87
W007	Cu 1.0 E 15	2.27 0.06	2.45 --	1.08
W008	Ti 3.6 E 14	0.80 0.22	0.58 --	0.73
W009	V 3.1 E 14	1.37 0.94	1.73 --	1.26
W010	Ni 4 E 15	2.26 0.25	2.45 --	1.08
W011	Zr 5 E 14	1.44 0.00	1.19 0.11	0.83
W012	Cr 1.8 E 14	0.14 --	1.88 0.15	13.43
W013	Mn 1.5 E 14	0.65 0.07	2.56 0.16	3.94
W014	Audit NA			
W015	Zn < 5 E 14	2.24 0.08	2.02 0.00	0.90
W016	Fe 1 E 15	0.43 --	1.88 0.29	4.34
W017	Cu 4 E 16	2.31 --	2.09 0.07	0.90
W018	Fe 2 E 15	2.09 0.65	0.65 0.07	0.31
W019	Cu 5 E 14	1.52 0.80	1.95 0.07	1.28
W020	Audit NA	2.17 0.15	2.17 0.15	1.00

Note 1. Valid lifetime measurement not possible due to insufficient trap light intensity to maintain all traps filled.

Note 2. Lifetime measurements below 0.5 μsec are dominated by decay time of pulsed LED light source.

Note 3. Dopant concentrations are preliminary measurements based mainly on crucible remains analysis and initial mass spec determinations; some data have subsequently been revised, viz. Section 3.3.

The latter correction is important since the post-diffused samples become thinner than the as-grown wafers when the N^+ region is etched off prior to lifetime measurement. This reduces the effective lifetime relative to the bulk lifetime τ_r .

With respect to the statistical variation of the data and its reliability some specific comments should be noted. First, PCD measurements on the Mn (10^{15} atoms/cm⁻³) and V (5×10^{14} atoms/cm⁻³) samples indicate a high concentration of shallow traps in the silicon. Measurements taken without the addition of a constant and intense "trap light" yield apparent lifetimes in excess of 90 μ sec. Trapping is so severe that the oscilloscope response exhibits a single time constant in marked contrast to the dual time constant normally observed with moderate trapping. Apparently, all of the minority carriers generated by the pulsed LED light source are immediately trapped and only those electrons momentarily released from the traps are observed in the conduction band. To fill the traps a 40 watt incandescent spot light (highly collimated) was focused by an f:1, 15 cm f.l. lens onto the sample. The irradiance necessary to maintain filled traps is difficult to determine, but is very near the maximum intensity available from the lamp. The intense optical radiation heats the sample, so we used a nitrogen gas jet for cooling. In some cases, thermal fluctuations in the sample caused rapid random excursions of the oscilloscope trace. Because of this and the known increase in apparent lifetime with sample temperature,² we regard as upper limits the measured lifetimes of the first generation Mn and V-doped wafers.

The standard deviation is indicated in Table 8 whenever multiple samples were tested. The normal sample size is two, but five of the average values shown represent 3 samples each. The probable error for the average value of τ_r given is equal to 0.674σ . The probable error is the largest for the V sample for the reasons cited above.

The ratio of the recombination lifetime after the phosphorus diffusion cycle to that of the as-grown material is given in the last

column of the table. In general, the lifetime of high quality material decreases during high temperature processing as widely reported in the literature while the lifetime of silicon doped with some lifetime "killing" impurities actually increases during the phosphorus diffusion cycle. Gettering and/or precipitation of the impurities are possible mechanisms for the lifetime improvement. The results of preliminary experiments designed to assess the relative contribution of each mechanism are outlined in section 3.4.5.

3.4.3.2 Corrections for Surface Recombination Velocity

The measured recombination lifetime, τ_r' , is determined by a combination of the effects of bulk recombination lifetime, τ_r , and the surface recombination velocity, s . For the purposes of analysis it is desirable that the bulk lifetime, τ_r , be obtained as a single parameter. The bulk lifetime, τ_r , is highly sensitive to impurities in the silicon, and it controls the diffusion length of the electron-hole pairs generated within a solar cell by the absorption of optical radiation. One difficulty in measuring the effective lifetime, τ_r' , is dramatically illustrated by the data taken from material with a known lifetime, Fig. 6. The measured lifetime not only deviates from the actual bulk lifetime, but it also varies with the thickness of the test specimen. The effect of sample thickness on the measurements made on baseline material during this program is shown in Fig. 7. The effective lifetime, τ_r' , varies rapidly with small changes in specimen thickness, a fact which has to be accounted for when computing τ_r .

To obtain the bulk lifetime, τ_r , we developed a rigorous mathematical correction factor based on the Shockley Model.³ By applying the model, the surface recombination velocity s was also determined. The mathematical approach involved follows below.

The general partial differential equation describing the behavior of electron minority carriers in p-type bulk silicon is

Figure 6. Effect of silicon specimen thickness on the measured value of the recombination lifetime. Material is LOPEX boron doped to 15-25 ohm-cm, (111) orientation, and a specified lifetime of 576 μ sec.

Fig. 7. Effect of silicon specimen thickness on the measurement of the uncorrected lifetime. Sample is diffused (Lot 60226) W002 baseline.

$$\begin{aligned} \frac{\partial n}{\partial t} = & L(x,y,z) - \frac{(n-n_p)}{\tau_r} - \mu_n \left(E_x \frac{\partial n}{\partial x} + E_y \frac{\partial n}{\partial y} + E_z \frac{\partial n}{\partial z} \right) \\ & + D_n \left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} + \frac{\partial^2 n}{\partial z^2} \right) \end{aligned} \quad (1)$$

where L is the generation rate due to optical radiation, $(n-n_p)$ is the deviation from thermal equilibrium, and μ_n and D_n are the electron mobility and diffusivity, respectively. Equation (1) may be simplified considerably, for the purposes of measuring the recombination lifetime by applying several reasonable constraints to the test parameters used. First, the generation rate L is zero during the transient period used to measure the recombination lifetime. Second, the ohmic contacts used to measure the conductivity modulation may be placed over the entire end of the test specimen so that the electric field is parallel to the x -axis in the illuminated volume. Alternatively, the physical length of the test specimen can be extended considerably beyond the illuminated area so that the lines of electric force become parallel in areas of chief concern. (The latter technique was used in this study.) The sole remaining electric field, E_x , is then equal to $I_t \rho / 4wd$. For these conditions, Eq. (1) reduces to

$$\frac{\partial n}{\partial t} = - \frac{n-n_p}{\tau_r} + D_n \left(\frac{\partial^2 n}{\partial x^2} + \frac{\partial^2 n}{\partial y^2} + \frac{\partial^2 n}{\partial z^2} \right) - \mu_n E_x \frac{\partial n}{\partial x} \quad (2)$$

The physical dimensions and coordinates of a standard lifetime test specimen are indicated in Fig. 8.

Figure 8. Standard coordinates and dimensioning of rectangular silicon lifetime test specimens.

Lattice discontinuities at the surface of the test specimen result in an unusually high recombination rate there compared to the bulk silicon; the so-called surface recombination velocity, s , is defined as

$$\frac{dn}{dt} = s(n-n_p) . \quad (3)$$

Minority carriers which are depleted by surface recombination produce a concentration gradient which drives the diffusion of minority carriers from the bulk silicon to the wafer surface. At the surface, equilibrium is rapidly established between the rate of recombination and the rate of diffusion. The boundary conditions at the surfaces of the sample, for a common value of surface recombination velocity, s (cm/sec) are:⁴

$$\begin{aligned} -D_n \left. \frac{\partial(\delta n)}{\partial x} \right|_{x=\pm l} &= \pm s \delta n(\pm l) \\ -D_n \left. \frac{\partial(\delta n)}{\partial y} \right|_{y=\pm w} &= \pm s \delta n(\pm w) \\ -D_n \left. \frac{\partial(\delta n)}{\partial z} \right|_{z=\pm d} &= \pm s \delta n(\pm d) \end{aligned} \quad (4)$$

where δn equals $(n-n_p)$ at the surface,

The solution to Eq. (2) for the boundary conditions imposed by Eqs. (4) is a series of eigenfunctions similar to those encountered when solving thermal problems.³ A specific solution in the series is⁴

$$\begin{aligned} n(x,y,z,t) &= G(\cos ax)(\cos by)(\cos cz) \exp(\mu E_x x/2D) \\ &\times \exp \left[\frac{1}{\tau_r} + D_n(a_i^2 + b_j^2 + c_k^2) + \frac{(\mu_n E_x)^2}{4D_n} \right] t . \end{aligned} \quad (5)$$

Substituting the boundary conditions of Eqs. (4) into Eq. (5) produces a set of transcendental equations.⁵

$$\begin{aligned}sl/D_n &= a_i l \tan(a_i l) = \epsilon_i \tan \epsilon_i \\s\omega/D_n &= b_j \omega \tan(b_j \omega) = \eta_j \tan \eta_j \\sd/D_n &= c_k d \tan(c_k d) = \zeta_k \tan \zeta_k\end{aligned}\tag{6}$$

The term on the left-hand side of Eq. (6) is readily evaluated when s is known. There exists an infinite set of ϵ_i , η_j , and ζ_k values which will satisfy the transcendental equations. The initial values for i , j , or $k = 0$ range between zero and $\pi/2$. The tangent function repeats in the first and third quadrants, so that solutions exist for the intervals $\eta\pi$ to $(\eta + 1/2)\pi$ where $\eta = 0, 1, 2, 3, \dots$. We use subscripts to denote the value of η . For the special case of $s = \infty$, the values of ϵ , η , and ζ are $\pi/2$, $3/2\pi$, $5/2\pi$, etc. for $\eta = 0, 1$, and 2 .

The total solution to Eq. (2) is an infinite series of type 5 equations with variable values of a_i , b_j , and c_k . The total specimen conductivity does not, therefore, decay with a single exponential. The higher modes (values of $i, j, k > 0$) decay more rapidly so the oscilloscope response approaches a single exponential with time. The IRE⁶ and ASTM standards⁷ on PCD Measurements include procedures to insure that the portion of the oscilloscope trace used is a single exponential (mode 0,0,0).

Normally, the initial segment of the trace is ignored to allow time for the higher modes to become negligibly small. This procedure was not practical in our work because the total transient amplitude was insufficiently great to permit accurate use of the tail segment only. We verified that this special variation in procedure produced negligible error by plotting the oscilloscope response for the high lifetime case, Fig. 9. High lifetime readings are more susceptible to errors from

Fig. 9. Plot of transient photoconductive decay voltage showing only minor errors result from neglecting the effects of the higher modes.

the higher modes since $a_i^2 + b_j^2 + c_k^2$ is significant compared to $1/\tau$. A single exponential dominates 91% of the total decay voltage. The decay time of the terminal response is only 28% greater than that of the main section. Further, note that the initial segment is devoid of any expected continuous curvature and that a zeroing error of only 34 μV is sufficient to produce the change in slope observed. From Fig. 9 we conclude that the error introduced by neglecting the effects of all the higher modes is insignificant for effective lifetimes up to 3 μsec . Lifetime correction factors can therefore be easily obtained by simply solving Eqs. (6) in the interval between 0 and $\pi/2$, when i, j , or $k = 0$.

The time dependent term in Eq. (5) can be further simplified, as previously suggested, by decreasing the electric field, E_x , so as to make the third term negligibly small. The most conservative case ($a_i^2 + b_j^2 + d_k^2 = 0$) results in the requirement

$$\frac{(\mu_n E_x)^2}{4D_n} \ll \frac{1}{\tau_r} \quad (7)$$

The electric field, E_x , is equal to $I_t(\rho/4\omega d)$ and Eq. (7) may be rewritten as

$$I_t \ll \frac{8\omega d}{\rho} \sqrt{\frac{kT}{q}} / (\mu_n \tau) \quad (8)$$

Equation (8) is plotted in Fig. 10 for convenient application. A minimum ratio of 10 should be used to determine a practical value of test current.

When E_x is made negligibly small by reducing I_t and the effect of all the higher modes are judged to be small by experimental verification, Eq. (5) reduces to

$$n(t) = G_o \exp\left[-\frac{1}{\tau_r} + D_n\left(\frac{\epsilon_o^2}{\ell^2} + \frac{\eta_o^2}{\omega^2} + \frac{\zeta_o^2}{d^2}\right)\right] t \quad (9)$$

Fig. 10. Critical value of test current, I_t for PCD lifetime measurements on p-type silicon with resistivity as a parameter. Cross sectional area of test sample = 0.0127 cm^2 ($w = 0.25 \text{ cm}$, $d = 1.27 \times 10^{-2} \text{ cm}$).

The effective or measured lifetime τ_r' (Table 8) is therefore related to the bulk lifetime τ_r by the relationship

$$\frac{1}{\tau_r'} = \left[\frac{1}{\tau_r} + D_n \left(\frac{\epsilon_o^2}{\ell^2} + \frac{\eta_o^2}{\omega^2} + \frac{\zeta_o^2}{d^2} \right) \right] . \quad (10)$$

By examination the first and second terms within the parentheses in Eq. (10) are much smaller than the third term and can be neglected. As an example, we may assume for the moment that $s = 1 \times 10^4$ cm/sec. The respective values of ϵ_o , η_o , and ζ_o are 1.5607, 1.5601, and 1.2567. The respective values for ϵ_o^2/ℓ^2 , η_o^2/ω^2 , and ζ_o^2/d^2 are 9.7431, 38.943, and 9791.6. The error in neglecting the terms related to ϵ_o and η_o is therefore only 0.49%. It will be shown in the following section that s in fact has a value very close to 1×10^4 cm/sec, so that Eq. (10) may be abbreviated to

$$\frac{1}{\tau_r'} = \left[\frac{1}{\tau_r} + D_n \left(\frac{\zeta_o^2}{d^2} \right) \right] \quad (11)$$

where $\zeta_o \tan \zeta_o = sd/D_n$; $0 \leq \zeta_o \leq \pi/2$

Equation (11) has been plotted in Fig. 11 as the ratio of τ_r'/τ_r with s as a parameter, and $d = 1.27 \times 10^{-2}$ cm. The effect of surface recombination velocity on the measured value of the lifetime, τ_r' , is readily apparent for $s = 1 \times 10^4$ cm/sec. For example, on our specimens a typical correction factor of 2 is required for a measured lifetime, τ_r' , of 1.0 μ sec. The standard method for controlling s is sandblasting. The assumption is then normally made that $s = \infty$ and the value of ζ_o is $\pi/2$. Equation (11) under this special condition is equal to

$$\frac{1}{\tau_r'} = \left[\frac{1}{\tau_r} + \frac{D_n \pi^2}{4d^2} \right] . \quad (12)$$

Serious errors can occur because of the assumption that $s = \infty$. Measurements during this program indicate that s is actually equal to

Fig. 11. Photoconductive decay lifetime correction factors for various values of surface recombination velocity on 0.254 mm thick p-type silicon with an electron diffusivity of 32.9 cm²/sec.

1×10^4 cm/sec for a sandblasted surface. Shockley³ has reported a value of 1×10^4 for a sandblasted germanium surface.

In practice, the standard specimen dimensions we used are $2\ell = 1$ cm, $2\omega = 0.5$ cm, and $2d = 2.54 \times 10^{-2}$ cm. Since the value of $2d$ varied slightly, the measured value was recorded for each sample and used in calculations. The specimens were etched in 20:1 (HNO_3 :HF) solution for approximately 1 minute immediately prior to PCD measurements.

3.4.3.3 Determination of Surface Recombination Velocity

One method for the direct measurement of s is suggested by Eq. (11). The magnitude of $D_n(\zeta_o^2/d^2)$ is typically $3.22 \times 10^5 \text{ sec}^{-1}$, and if the value of $1/\tau_r$ can be made much smaller than this, we can neglect it. The magnitude of ζ_o can then be obtained directly, and the surface recombination velocity is simply

$$s = \sqrt{\frac{D_n}{\tau_r}} \tan \sqrt{\frac{d^2}{\tau_r' D_n}} \quad (13)$$

Figure 6 provides the data necessary to use Eq. (13) -- τ_r is known to be 576 μsec . The value of $1/\tau_r$ is 1.74×10^2 , satisfying the requirement that $1/\tau_r \ll D_n(\zeta_o^2/d^2)$. From Fig. 6 we note that the measured or effective lifetime at $d = 1.27 \times 10^{-2}$ cm is 2.16 μsec . The electron diffusivity for 20 ohm-cm p-type silicon is approximately $47.8 \text{ cm}^2/\text{sec}$. Thus, we calculate that s equals 1.415×10^4 cm/sec. (The deviation from the theoretical value of τ_r' for large values of $h(2d)$ in Fig. 6 is due to the fact that the radiation is not constant throughout the sample. Due to the high absorption coefficient at 940 nm the effective or optical thickness is much less than the physical thickness of the specimen.)

A second method for determining s is to fit Eq. (11) to the experimentally measured variation of τ_r' with sample thickness, $2d$. A unique set of τ_r and s values are required to match the data obtained experimentally, Fig. 12. A single point fit at $\tau_r' = 1.61 \mu\text{sec}$ and

Figure 12. Experimental determination of surface recombination velocity. Theoretical curves were all computed with a bulk lifetime necessary to achieve an effective lifetime of $1.61 \mu\text{sec}$ at 0.2 mm . Measurement data are shown for diffused W001 baseline silicon.

2d = 0.020 cm was selected initially from a plot of the measured data. Three pairs of τ_r and s values were obtained which when substituted into Eq. (11) yielded the measured value, τ_r' . The three pairs of values are listed in the legend of Fig. 12. The three theoretical curves display significant changes in the slope as the value of s is changed. The slope for $s = 1 \times 10^4$ matches the experimental data very closely in the region above 1 μ sec. The experimental data were obtained from two different samples, a fact which must be appreciated when assessing the curve fit. The surface recombination velocity, s, determined by this technique is $1 \pm 0.5 \times 10^4$ cm/sec, correlating well with the value obtained from Eq. (13). We have chosen this value of s in computing the values of bulk lifetime, τ_r , from the measured effective lifetime values, τ_r' .

We note that the experimental data in Fig. 12 deviate from the theoretical curves for lifetimes less than 1.0 μ sec. The error at 0.72 μ sec is 0.14 μ sec. This deviation is experimental evidence that the decay time of the infrared LED source is too long for precise measurements below about 1.0 μ sec. Corrections for this source of error will be derived soon and reported in the next quarterly report.

3.4.3.4 Bulk Lifetime Obtained by Corrected PCD Measurements

Using Eq. (11) and $s = 1 \times 10^4$ cm/sec we corrected the effective lifetime, τ_r' values from Table 8 to yield a resulting bulk recombination lifetime, τ_r , for each specimen, Table 9. The correction factor increases rapidly for large values of τ_r' , Fig. 11, so above 10 μ sec, the computed value of the bulk lifetime becomes increasingly sensitive to small changes in the surface recombination velocity. The data in Table 9 reflects this effect, i.e., σ is large whenever τ_r is large.

As we pointed out above, data from Mn and V doped specimens are subject to large errors due to trapping. The effect is particularly serious in this instance because small changes in τ_r' near 2 to 3 μ sec produce very large errors in the computed value of τ_r . This effect

Table 9. Bulk Lifetime, τ_r , Corrected PCD Measurements

Lot No.	Impurity Type	Concentration (cm ⁻³) Note 2	Lifetime (As-Grown)		Lifetime (Diffused)	
			τ	σ	τ	σ
W001	Baseline	N/A	7.71	0.07	6.21	--
W002	Baseline	N/A	6.90	--	8.57	1.60
W003	Baseline	N/A	13.96	--	9.10	--
W004	CR001	1 x 10 ¹⁵	0.33	0.18	1.01	.30
W005	MN001	2.5 x 10 ¹⁵	Note 1	--	.32	--
W006	NI001	1.7 x 10 ¹⁴	11.27	2.70	7.88	--
W007	CU001	1.5 x 10 ¹⁵	7.38	0.23	11.10	--
W008	TI001	3.6 x 10 ¹⁴	1.95	0.47	0.71	.00
W009	V001	3.1 x 10 ¹⁴	9.74	3.46	5.00	--
W010	NI002	2 x 10 ¹⁵	8.13	2.22	9.10	--
W011	ZR001	5 x 10 ¹⁴	2.63	0.16	1.93	0.22
W012	CR002	1.8 x 10 ¹⁴	0.15	--	5.03	0.16
W013	MN002	1.5 x 10 ¹⁴	1.65	0.96	13.31	4.26
W014	Audit	N/A	7.48	0.37	8.33	0.09
W015	ZN001	1 x 10 ¹⁵ *	7.21	0.64	5.65	0.00
W016	FE001	1 x 10 ¹⁵ *	0.51	0.01	4.66	1.74
W017	CU002	4 x 10 ¹⁶	8.82	0.14	7.13	0.73
W018	FE002	2 x 10 ¹⁵ *	8.13	5.52	0.84	0.12
W019	CU003	5 x 10 ¹⁴	4.27	3.35	5.69	0.55
W020	Audit	N/A	6.99	1.70	7.30	1.39

Note 1. Lifetime measurements not possible due to extreme trap density.

Note 2. Impurity concentration measured by Mass Spec or crucible remains unless marked by * to indicate a target value.
For best estimate of impurity concentration, see Table 6.

is most pronounced for Mn and V impurities at the 10^{15} cm^{-3} and 10^{14} cm^{-3} levels respectively. The special incandescent light should be 100% effective in eliminating the effects of trapping for impurity levels less than these.

Detailed analysis of the bulk lifetime data will be postponed pending the application of secondary correction factors for the decay time of the pulsed LED light source, and the processing of additional samples. However, preliminary plots of the average short circuit current density of impurity-doped solar cells show excellent correlation with the bulk lifetime, τ_r , in column 6 of Table 9 (see Section 3.5). A correlation between these two important parameters would be predicted by solar cell theory and the apparent experimental verification of this relationship is most encouraging.

3.4.4 Diffusion Profile Studies

Ultimately characterization of the performance of a diffused solar cell requires a knowledge of the surface concentration of the device and the junction thickness. We set out to measure these parameters and the phosphorus diffusion profile by standard spreading resistance techniques. This method fails, however, because the junction is so shallow. Angle lapping and staining also were ineffective in revealing junction depth because the bevel position could not be precisely determined. Moreover, staining via HF solution and high intensity light darkens the P^+ area, not the diffused N^+ region in which we are interested. We finally determined the surface concentration and the junction profile by the incremental sheet resistance method first described by Tannenbaum.⁸

The average conductivity, $\bar{\sigma}$, of a thin sheet of removed silicon is given by,

$$\bar{\sigma} = \left(\frac{1}{\rho_{n-1}} - \frac{1}{\rho_n} \right) \frac{1}{\Delta x_n} \quad (1)$$

where ρ_{n-1} is the sheet resistivity prior to removing the n^{th} layer of silicon, and ρ_n is the sheet resistivity after etching off a thin layer of thickness Δx_n . We measured the sheet resistivity by the 4 point probe technique with a special probe whose probe spacing was 0.0625 in. The Signatone Type SP4-625-85-TC-010 head features a low pressure (85 grams weight) and tungsten carbide tips with a radius of 0.0254 cm. The probe is capable of making resistivity measurements within 0.03 μm from the junction without disturbing the junctions ability to isolate the substrate. The net donor concentration was obtained from the average conductivity, $\bar{\sigma}$ of the thin sheet via Irvin's⁹ ρ vs. N curve. Thin silicon layers of known thickness were removed from the wafer by the anodic oxidation technique. The wafers were oxidized at 25°C by anodizing them in a mixture of 100 ml tetrahydrofurfuryl alcohol, $\text{C}_5\text{H}_{10}\text{O}_2$, and 2.2 gr potassium nitrite, KNO_2 . The oxide growth rate, 35-44.5 $\text{\AA}/\text{min}$, was controlled by using a current density of approximately 6 mA/cm^2 . To improve uniformity the cell voltage was held constant for 30 minutes after the terminal voltage reached +125 volts. The oxide thickness grown under these conditions was measured, by color comparison with ellipsometrically measured standards, as 662 $\text{\AA}$ (5.30 $\text{\AA}/\text{volt}$). The silicon removed by each oxidation step was both calculated and measured to be 318 $\text{\AA}$ (2.54 $\text{\AA}/\text{volt}$).

The measured phosphorus diffusion profile for a wafer from ingot W008-TI001, Fig. 13, exhibits a surface concentration of 5×10^{20} atoms/ cm^3 and metallurgical junction depth of 0.25 microns. The anomaly in the profile evident in the figure at depths less than 0.075 μm is due to a thin $\text{Si}_x\text{N}_y\text{O}_z$ barrier film which grows on the surface during the diffusion cycle.¹⁰ The growth of these ultra-thin films less than 75 $\text{\AA}$ thick can be avoided by performing the diffusion cycle in argon rather than nitrogen. The effect of the anomaly on the performance of a solar cell is unknown. The standard solar cell diffusion cycle we use consists of 50 min. @ 825°C. The diffusion coefficient for phosphorus at 825°C

Figure 13. Phosphorus dopant profile for standard solar cell diffusion cycle.

calculated using measured profile parameters and the equation,
 $x_j = 2\sqrt{Dt} \operatorname{erfc}^{-1} (N_b/N_o)$ is $5.9 \times 10^{-15} \text{ cm}^2/\text{sec}$. This value is in close agreement with published values.

3.4.5 Gettering and Precipitation Studies

3.4.5.1 Auger Spectroscopy

Significant improvement in the recombination lifetime of chromium doped wafers following phosphorus diffusion (Table 10), and relatively small change in the lifetime of copper-doped wafers led to the suspicion that chromium might be gettered at a measurable rate while the copper present in our wafers might be electrically inactive (due to precipitation, for example). For this reason we measured by Auger electron spectroscopy elemental profiles through the depth of the phosphosilicate glass and n^+ -layers on diffused wafers from ingots W004-CR001 and W007-CU001. Some preliminary and quite interesting results are summarized here.

As might be expected in both samples, phosphorus is present throughout the regions analyzed. The unexpected result is the strong segregation of phosphorus at the glass-silicon interface. Chromium is detected below this phosphorus rich layer in the n^+ -region. The gettering process is such that chromium apparently segregates to the heavily phosphorus diffused region rather than into the glass. No copper could be detected in wafer W007, although the phosphorus profile was similar to that in the chromium doped sample. The diffusion cycle used in this study may not have been sufficient to getter the copper. This suggests the copper either precipitates or is rendered electrically inactive via some other mechanism. The clear evidence for precipitation is copper doped wafers, e.g. W017, suggests the former. We plan to examine other samples with this technique, especially those doped with manganese, heavy copper, nickel, titanium and vanadium.

3.4.5.2 Transmission Electron Microscopy

Samples from baseline ingot W002, ingot W007, and ingot W008 have been thinned by chemical jet etching. The latter samples were heat treated at 550°C for 50 hours to stimulate precipitation. The initial results were inconclusive since the jet etching technique which thins from only one side of the sample leaves a residue of surface artifacts which hinder interpretation. We are now thinning samples by ion milling which has the secondary advantage that larger electron transparent regions can be developed for viewing.

3.5 Solar Cell Characterization and Analysis

3.5.1 Cell Characteristics

We fabricated solar cells on wafers from 18 ingots representing 11 metallic additives (at one or more concentrations) within the basic 3 Ω -cm boron doped silicon. All the electrical measurement data have been loaded into a computer file and analyzed with several specially written programs. The data, compiled in toto in the Appendix and in summary form below, Table 10, were obtained via a three point fit of the photovoltaic I-V curve to a single exponential model. We used forward bias dark current measurements to obtain the resistive term. This method provides an excellent fit to the I-V curve at the maximum power point but deviates somewhat from the curve elsewhere. More recently we have developed a method for cell analysis based on a four point fit to the illuminated I-V data which provides good agreement over the entire characteristic curve. This improved method will be implemented as soon as the data base is augmented to include the additional data points. The new program will also provide information on standard deviations from the test data, a parameter not calculated in the present routine.

From the data, Table 10, some general trends in cell performance with impurity content emerge. These trends are graphically depicted in

Table 10. Summary of Solar Cell Characteristics

<u>Ingot ID</u>	<u>V_{OC} (V)</u>	<u>I_{SC} (ma)</u>	<u>V_P</u>	<u>I_P</u>	<u>I_O</u>	<u>n</u>	<u>FF</u>	<u>n(%)</u>	<u>τ (μsec)</u>
CU 017	.5355	21.64	.4332	19.71	9.27E-08	1.628	.7369	8.54	2.281
Base 003	.5484	22.55	.4469	20.65	6.26E-08	1.582	.7462	9.23	3.250
CU 007	.5497	22.71	.4560	21.05	1.51E-08	1.380	.7692	9.60	3.683
Base 002	.5506	22.83	.4536	21.07	3.62E-08	1.462	.7602	9.56	3.952
CU 019	.5395	21.95	.4451	20.26	8.61E-08	1.424	.7618	9.02	4.043
Base 003	.5500	22.00	.4554	20.38	5.79E-09	1.396	.7668	9.28	4.550
CR 004	.5250	18.37	.4243	16.68	1.33E-06	1.646	.7349	7.09	.923
Base 002	.5590	22.27	.4606	20.55	2.32E-08	1.479	.7606	9.47	4.082
CR 012	.5454	21.59	.4371	19.52	2.78E-07	1.780	.7247	8.54	2.305
Base 002	.5537	22.27	.4475	20.27	1.35E-07	1.699	.7356	9.07	3.250
MN 005	.5242	16.87	.4362	15.68	3.46E-09	1.279	.7731	6.84	.867
Base 002	.5565	22.50	.4673	21.03	1.06E-09	1.259	.7847	9.83	4.875
MN 013	.5405	22.20	.4539	20.74	1.87E-09	1.225	.7847	9.42	4.121
Base 002	.5583	22.80	.4707	21.36	1.03E-09	1.224	.7897	10.05	4.767
MN 026	.5450	22.50	.4484	20.74	3.07E-08	1.461	.7585	9.30	4.065
Base 002	.5533	22.58	.4572	20.88	8.76E-09	1.426	.7645	9.55	3.933
NI 010	.5278	19.11	.4330	17.58	4.39E-08	1.448	.7547	7.61	1.235
Base 003	.5470	22.37	.4278	19.77	4.17E-06	2.157	.6919	8.46	2.730
NI 006	.5401	22.11	.4445	20.39	1.66E-08	1.440	.7590	9.06	4.829
Base 002	.5490	22.49	.4532	20.78	8.70E-09	1.428	.7630	9.42	5.200

Table 10 (continued)

<u>Ingot ID</u>	<u>V_{OC}(V)</u>	<u>I_{SC}(ma)</u>	<u>V_P</u>	<u>I_P</u>	<u>I_O</u>	<u>n</u>	<u>FF</u>	<u>η(%)</u>	<u>τ(μsec)</u>
ZR 011	.5451	22.07	.4528	20.47	9.93E-09	1.353	.7707	9.27	3.553
Base 003	.5494	22.45	.4479	20.56	5.27E-08	1.579	.7468	9.21	3.198
V 009	.4668	10.21	.3862	9.45	4.58E-09	1.194	.7658	3.65	.282
Base 003	.5544	22.46	.4570	20.73	2.01E-08	1.463	.7609	9.48	3.952
TI 008	.4375	7.70	.3440	6.84	1.29E-06	1.658	.6985	2.36	.190
Base 003	.5574	22.72	.4571	20.91	1.86E-08	1.525	.7547	9.56	4.030
FE 018	.4929	14.25	.3877	12.69	7.14E-07	1.835	.7004	4.92	.279
Base 003	.5545	22.00	.4560	20.28	2.45E-08	1.488	.7581	9.25	4.160
MG 024	.5406	22.48	.4529	20.98	2.48E-09	1.250	.7815	9.50	4.562
Base 002	.5450	22.68	.4584	21.21	9.02E-10	1.216	.7868	9.72	4.875
ZN 015	.5377	22.11	.4435	20.43	1.44E-08	1.410	.7619	9.06	3.714
Base 002	.5400	21.53	.4502	20.02	3.74E-09	1.299	.7755	9.02	3.575
AL 028	.5269	17.93	.4369	16.62	5.17E-09	1.324	.7686	7.26	1.219
Base 002	.5400	22.69	.4436	20.89	4.54E-08	1.466	.7566	9.27	4.290
Audit 014	.5537	22.25	.4586	20.61	1.46E-08	1.407	.7670	9.45	4.095
Base 002	.5580	22.38	.4703	20.96	5.38E-10	1.223	.7894	9.86	4.550

Fig. 14, which illustrates how relative solar cell efficiency (n doped wafer/ n baseline wafer diffused concurrently) with the type and concentration of metal impurity. For impurity concentrations in the 10^{14} to 10^{15} atoms/cm⁻³ range, the metals tend to group with respect to their impact on cell performance: little degradation -- Cu, Ni, and Zr; modest degradation -- Cr, Mn, Fe, and Al; and severe degradation -- Ti and V. Data for Mg and Zn are too scanty to evaluate their effects yet. Most striking are the behavior of Cu and Ti. Even at the heaviest doping level 4×10^{16} atoms/cm⁻³, copper hardly reduces cell efficiency compared to baseline material. Even small amounts of titanium, however, drastically reduce cell output. For those other metals where multiple concentrations have been evaluated, cell performance tends to improve with decreasing metal content. Note, for example, the data for Cr and Mn in particular where relative cell efficiency increases from about 70% to over 90% as the impurity level is reduced from 10^{15} to about 10^{14} atoms/cm³.

3.5.2 Cell Analysis

Although our solar cell and lifetime results must still be considered preliminary, as we pointed out in the foregoing sections, we have noted a correlation between cell behavior and carrier lifetime. The trends are illustrated in Figs. 15 and 16, where short circuit current density is plotted against log lifetime (from both OCD and PCD measurements). For comparison Fig. 17 depicts how lifetime influences short circuit current density in a solar cell subjected to increasing doses of electron irradiation. The post-processing data, Fig. 15, for photo-decay and open-circuit voltage decay lifetimes are qualitatively in agreement with the behavior of Fig. 17. The most important feature of these data is the fact that a good correlation is obtained with cell performance. The precise correlation function cannot be deduced without knowing the distribution and character of the recombination centers through the cell. It should also be noted that

Figure 14. Variation in solar cell performance with metal doping.
No AR coatings, AML quartz-iodine illumination.

Figure 15. The variation in short circuit current density of finished solar cells as a function of the PCD and OCD lifetimes of the diffused material. The unmarked data points are from audit and baseline ingot wafers.

Figure 16. The variation in short circuit current density for finished solar cells with the PCD lifetime of the as-grown materials. The dashed curve is data for the diffused material taken from Fig. 15.

Figure 17. The variation in short circuit current density with lifetime for cells fabricated from 10 Ω cm, boron-doped silicon tested under the conditions specified. The lifetime of the cells was adjusted by electron irradiation. Data from Ref. 11.

the difference between OCVD and photodecay decay curves is due in part to differences in the carrier injection profiles of the two methods and also to the non-negligible decay time of the LED. Mathematical correction for these effects should provide closer agreement between the two methods.

Contrary to the correspondence of lifetime and cell performance for processed wafers, Fig. 15, no clear correlation exists between cell performance and lifetimes measured on as-grown wafers, Fig. 16. The lack of correlation illustrates the profound and yet unpredictable effect of processing on the recombination centers associated with the metal contaminants. In general, lifetime might be expected to increase during processing for material containing contaminants since heat treatment permits the metal atoms to cluster or precipitate at dislocations or surfaces. This is apparently true for some but not all impurities. Predicting the process effects for specific impurities requires information on solubilities, diffusion constants and electrical behavior, which is not now available.

One feature of our results seems fertile for speculation. We expect nearly all the metal additives to exhibit significant precipitation at room temperature. However, considering the behavior of copper, nickel, and zirconium the effect of precipitates appears to be negligible or at least slight. This is rather unexpected result considering that precipitates of these metals are disastrous in other semiconductor devices. It seems reasonable to suppose that one essential difference is that solar cells operate with very low electric field strengths as compared, for example, to rectifiers. Clearly, this area requires additional study to confirm this surmise.

4. CONCLUSIONS

Our data aren't yet complete enough to draw detailed or firm conclusions; however, the trends we observe seem plausible. First, not all metal impurities produce the same effects on silicon solar cells. Some, like copper, behave as though they were not present at all while others like titanium produce dramatic efficiency reductions in a cell even when present in small amounts. To a first order this can be understood on the basis of relative gettering and precipitation rates. For those impurities which do reduce cell efficiency, reducing the impurity content improves cell performance. Take chromium and manganese, for example. In each case, cell efficiency recovers to over 90% of the baseline material as the impurity content is reduced from about 10^{15} to about 10^{14} atoms/cm⁻³.

Lifetime and solar cell short circuit current appear correlated as one would expect on theoretical grounds. The correlation, however, seems to hold only for processed (diffused) material, not for the as-grown, impurity-doped wafers. We can understand this on the basis that the diffusion heat treatment may drastically modify the impurity distribution and electrical activity, both of which influence lifetime and hence cell performance. Thus, it seems important to recognize that sample history is important when attempting to predict cell performance from lifetime measurements on starting material.

Finally, we find that the effect of impurities on solar cells may be quite different from that normally associated with other silicon devices. For example, precipitates though present in solar cells are not necessarily harmful. This may be a consequence of the low field nature of the cell. This result suggests that some caution be exercised when extrapolating the effects of specific impurities on other silicon devices to predict the performance of a solar cell.

5. PROGRAM STATUS

5.1 Present Status

All elements are on or ahead of schedule save the Web studies, Fig. 18.

During this quarter we have:

- Completed the growth of all first generation ingots.
- Completed growth of nearly all second generation ingots.
- Initiated the growth of third generation and multiply-doped ingots.
- Initiated the growth of baseline dendritic web crystals.
- Completed semi-quantitative mass spectroscopy of Cr, Mn, Cu, Ti, V, Ni, and Zr-doped first generation ingots.
- Completed C, O analysis of all ingots grown to date.
- Completed qualitative mass spectroscopic evaluation, microstructural evaluation, and spreading resistance on first 20 ingots grown.
- Measured the photoconductive decay lifetimes of the first twenty ingots grown.
- Fabricated and tested solar cells on 18 ingots representing 11 different metal impurity dopants.
- Initiated Auger and transmission electron microscopy studies of precipitation and gettering in solar cells.

5.2 Future Activity

During the next quarter we expect to:

- Complete the growth of second and third generation ingots.
- Complete the growth of baseline web material.
- Complete semi-quantitative analyses on heavily doped ingots.
- Continue microstructural and spreading resistance evaluation of all ingots.

- Complete solar cell and lifetime measurements of all second and most third generation ingots.
- Initiate solar cell and lifetime measurements on multiply-doped ingots.
- Continue studies of precipitation and gettering.

Figure 18. Experimental Program Schedule

6. REFERENCES

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7. APPENDIX

PHOTOVOLTAIC CHARACTERISTICS OF SOLAR CELLS UNDER AM1-EQUIVALENT QUARTZ-IODINE ILLUMINATION

Test Conditions: No anti-reflective coatings, cell area = 1 cm^2 and
illumination = 100 mw/cm^2 .

Key to Abbreviations:

R	--	calibrated reference devices
C	--	wafers from ingot center
T	--	wafers from tang end
S	--	wafers from seed end
E or N	--	end
*	--	item deleted from average

Note: Some data (Cu, Mn, Cr) are reruns with slightly different grid structure, or reruns designed to assess the effects of sintering treatments (Al, Mn). The data are grouped by impurity as in Table 10.

60316 W017CU002(4E16) W003 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5500	22.75	.4452	20.74	6.77E-08	1.662	.7378	9.23	3.250
2B	.5500	22.25	.4417	20.16	1.34E-07	1.759	.7278	8.91	3.250
3B	.5500	22.75	.4554	21.07	6.04E-09	1.397	.7668	9.59	3.250
4B	.5420	22.25	.4368	20.21	9.96E-08	1.692	.7321	8.83	1.950
5B	.5500	22.75	.4554	21.07	6.04E-09	1.397	.7668	9.59	4.550
1C	.5320	21.75	.4288	19.76	9.58E-08	1.659	.7323	8.47	1.950
2C	.5370	22.20	.4334	20.19	8.63E-08	1.658	.7341	8.75	2.600
3C	.5300	21.74	.4239	19.63	1.88E-07	1.748	.7223	8.32	1.950
4C	.5320	22.00	.4315	20.08	5.35E-08	1.583	.7405	8.67	2.210
5C	.5320	21.75	.4297	19.80	7.82E-08	1.632	.7352	8.51	2.210
1S	.5320	21.60	.4300	19.67	7.32E-08	1.625	.7360	8.46	2.210
2S	.5350	21.60	.4259	19.44	2.73E-07	1.825	.7163	8.28	1.950
3S	.5400	21.60	.4397	19.78	3.58E-08	1.560	.7455	8.70	2.860
1T	.5400	21.25	.4350	19.30	9.98E-08	1.693	.7315	8.39	2.210
2T	.5400	21.25	.4404	19.48	2.99E-08	1.542	.7476	8.58	2.470
3T	.5400	21.25	.4465	19.66	6.63E-09	1.386	.7651	8.78	2.470

AVERAGES: 60316 BASELINE W003 00 000

.5484	22.55	.4469	20.65	6.26E-08	1.582	.7462	9.23	3.250
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60316 W017CU002(4E16)

.5355	21.64	.4332	19.71	9.27E-08	1.628	.7369	8.54	2.281
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PERCENT CHANGE

-2.36	-4.06	-3.07	-4.56	48.20	2.95	-1.25	-7.52	-29.82
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60204 W007CU001(1.5E15) W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1R*	.5470	22.62	.4413	20.57	9.13E-08	1.694	.7336	9.08	4.550
1B	.5520	22.87	.4435	20.73	1.34E-07	1.763	.7282	9.19	3.900
2B	.5450	22.30	.4439	20.42	3.59E-08	1.571	.7459	9.06	3.900
3B	.5520	22.87	.4613	21.31	1.86E-09	1.301	.7786	9.83	4.550
4B	.5520	23.25	.4636	21.73	9.37E-10	1.247	.7849	10.07	5.200
5B	.5520	22.87	.4559	21.15	8.10E-09	1.429	.7637	9.64	2.210
1C	.5520	22.75	.4654	21.31	5.16E-10	1.206	.7899	9.92	2.600
2C	.5470	22.75	.4428	20.74	6.73E-08	1.653	.7379	9.18	4.550
3C	.5520	22.75	.4654	21.31	5.16E-10	1.206	.7899	9.92	3.900
4C	.5520	22.75	.4654	21.31	5.16E-10	1.206	.7899	9.92	3.250
5C	.5470	22.75	.4466	20.87	2.90E-08	1.550	.7489	9.32	4.550
1S*	.5470	22.62	.3850	17.76	1.26E-04	4.048	.5528	6.84	1.950
2S	.5470	22.75	.4543	21.11	4.12E-09	1.355	.7707	9.59	3.250
3S*	.5400	22.75	.4307	20.50	2.45E-07	1.815	.7189	8.83	1.560
1E*	.5500	22.62	.4422	20.51	1.24E-07	1.746	.7292	9.07	4.550
1T	.5500	22.62	.4497	20.77	2.51E-08	1.543	.7506	9.34	3.900
2T	.5500	22.62	.4603	21.10	1.50E-09	1.280	.7804	9.71	4.160
3T	.5500	22.62	.4546	20.92	7.47E-09	1.417	.7645	9.51	2.990

AVERAGES: 60204 BASELINE W002 00 000

.5506	22.83	.4536	21.07	3.62E-08	1.462	.7602	9.56	3.952
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60204 W007CU001(1.5E15)

.5497	22.71	.4560	21.05	1.51E-08	1.380	.7692	9.60	3.683
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PERCENT CHANGE

-.17	-.55	.53	-.08	-58.27	-5.65	1.18	.43	-6.80
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60120 W007CU001(1.5E15) W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1R*	.5570	22.60	.4433	20.33	2.92E-07	1.903	.7159	9.01	7.000
2B	.5500	22.30	.4552	20.65	6.12E-09	1.400	.7664	9.40	.000
3B	.5450	22.30	.4534	20.72	3.19E-09	1.330	.7730	9.39	.000
4B	.5500	22.60	.4606	21.09	1.36E-09	1.272	.7813	9.71	.000
1C	.5500	22.50	.4622	21.04	8.23E-10	1.235	.7858	9.72	.000
2C	.5500	22.60	.4567	20.97	4.20E-09	1.365	.7705	9.58	.000
3C	.5500	22.60	.4606	21.09	1.36E-09	1.272	.7813	9.71	.000
4C	.5450	22.50	.4527	20.88	4.03E-09	1.349	.7709	9.45	.000
5C	.5450	22.40	.4577	20.94	8.96E-10	1.231	.7849	9.58	.000
6C	.5450	22.50	.4477	20.73	1.47E-08	1.472	.7568	9.28	.000
1E	.5450	22.50	.4563	20.99	1.42E-09	1.264	.7810	9.58	.000
2E	.5450	22.40	.4489	20.67	1.10E-08	1.443	.7601	9.28	.000
3E	.5500	22.50	.4600	20.98	1.61E-09	1.286	.7797	9.65	.000
4E	.5460	22.50	.4481	20.71	1.66E-08	1.487	.7554	9.28	.000
5E	.5470	22.50	.4570	20.96	1.88E-09	1.291	.7782	9.58	.000
6E	.5420	21.75	.4476	20.11	7.76E-09	1.404	.7636	9.00	.000

AVERAGES: 60120 BASELINE W002 00 000

.5483	22.40	.4564	20.82	3.56E-09	1.334	.7736	9.50	.000
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60120 W007CU001(1.5E15)

.5467	22.44	.4546	20.84	5.53E-09	1.342	.7724	9.47	.000
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PERCENT CHANGE

-.30	.17	-.39	.10	55.20	.55	-.16	-.29	-.00
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60323 W019CU003(2E14) W003 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1R*	.5500	22.50	.4421	20.40	1.27E-07	1.750	.7287	9.02	5.000
3B	.5500	22.00	.4554	20.38	5.79E-09	1.396	.7668	9.28	4.550
1C	.5400	22.00	.4359	20.01	8.39E-08	1.665	.7344	8.72	3.510
2C	.5400	22.00	.4541	20.58	7.40E-10	1.207	.7865	9.34	4.550
3C	.5400	21.75	.4496	20.22	2.85E-09	1.311	.7739	9.09	3.510
1S	.5400	22.40	.4522	20.90	1.34E-09	1.248	.7814	9.45	4.160
2S	.5400	22.00	.4541	20.58	7.40E-10	1.207	.7865	9.34	5.200
3S	.5400	22.00	.4541	20.58	7.40E-10	1.207	.7865	9.34	3.900
4S	.5400	22.00	.4473	20.38	5.57E-09	1.367	.7673	9.12	3.900
1T	.5400	22.30	.4333	20.19	1.46E-07	1.740	.7266	8.75	3.900
2T	.5400	22.00	.4492	20.44	3.26E-09	1.321	.7728	9.18	4.160
3T	.5350	21.00	.4211	18.72	6.16E-07	1.972	.7018	7.88	3.640

AVERAGES: 60323 BASELINE W003 00 000

.5500	22.00	.4554	20.38	5.79E-09	1.396	.7668	9.28	4.550
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60323 W019CU003(2E14)

.5395	21.95	.4451	20.26	8.61E-08	1.424	.7618	9.02	4.043
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PERCENT CHANGE

-1.91	-.25	-2.26	-.57	1386.56	2.02	-.66	-2.76	-11.14
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60225A W004CR001(1E15) W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	FFF	TAU
1B	.5590	22.20	.4665	20.67	2.13E-09	1.330	.7769	9.64	3.900
2B	.5590	22.20	.4513	20.19	8.49E-08	1.724	.7344	9.11	3.900
3B	.5590	22.20	.4621	20.54	7.04E-09	1.437	.7649	9.49	4.550
4B	.5590	22.20	.4582	20.42	1.86E-08	1.536	.7539	9.36	3.900
5B	.5590	22.55	.4650	20.95	3.33E-09	1.367	.7728	9.74	4.160
2C	.5250	18.75	.4179	16.87	2.40E-07	1.792	.7161	7.05	.910
3C	.5250	18.00	.4355	16.69	3.76E-09	1.313	.7692	7.27	.910
4C	.5250	18.50	.4304	17.02	1.52E-08	1.441	.7541	7.32	1.300
5C	.5190	18.65	.3995	16.29	2.34E-06	2.222	.6725	6.51	.520
1S	.5150	18.50	.4342	17.33	4.10E-10	1.124	.7900	7.53	1.170
2S	.5300	18.15	.4381	16.79	5.83E-09	1.363	.7647	7.36	1.170
3S	.5300	18.15	.3960	15.38	1.06E-05	2.738	.6334	6.09	.260
4S	.5300	18.75	.4347	17.25	1.49E-08	1.451	.7546	7.50	1.170
1I	.5230	18.25	.4238	16.65	4.95E-08	1.569	.7391	7.05	.910
2I	.5280	18.00	.4331	16.57	1.39E-08	1.443	.7549	7.17	.910
3I*	.2630	18.00	.1677	11.64	1.08E-03	3.527	.4121	1.95	.010

AVERAGES: 60225A BASELINE W002 00 000

.5590	22.27	.4606	20.55	2.32E-08	1.479	.7606	9.47	4.082	
60225A W004CR001(1E15)									
.5250	18.37	.4243	16.68	1.33E-06	-1.646	.7349	7.09	.923	
PERCENT CHANGE									
-6.08	-17.51	-7.88	-18.83	5632.82	11.29	-3.38	-25.17	-77.39	

60105 W004CR001(1E15) W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	FFF	TAU
1B	.5560	22.37	.4527	20.48	3.72E-08	1.607	.7455	9.27	4.530
2B*	.5540	19.85	.4534	18.24	1.96E-08	1.541	.7520	8.27	2.860
3B	.5570	22.70	.4561	20.86	2.14E-08	1.544	.7525	9.51	3.900
4B	.5570	22.37	.4607	20.70	6.73E-09	1.427	.7655	9.54	3.900
1C	.5250	17.25	.4273	15.79	3.01E-08	1.523	.7449	6.75	.910
2C	.5300	17.50	.4316	16.02	2.87E-08	1.530	.7457	6.92	1.040
3C	.5200	14.90	.4034	13.11	1.17E-06	2.116	.6826	5.29	.780
4C	.5300	18.37	.4327	16.85	2.36E-08	1.503	.7487	7.29	1.170
5C	.5200	16.12	.4080	14.33	5.98E-07	1.960	.6975	5.85	.910
6C	.5350	18.90	.4377	17.37	1.86E-08	1.488	.7520	7.60	1.000
1F	.5340	18.00	.4359	16.51	2.31E-08	1.514	.7487	7.20	1.040
2F	.5340	18.75	.4284	16.97	1.26E-07	1.725	.7262	7.27	1.040
3E	.5340	18.75	.4326	17.10	5.13E-08	1.603	.7389	7.40	.910

AVERAGES: 60105 BASELINE W002 00 000

.5567	22.48	.4565	20.68	2.18E-08	1.526	.7545	9.44	4.110	
60105 W004CR001(1E15)									
.5291	17.62	.4264	16.01	2.30E-07	1.662	.7317	6.84	.978	
PERCENT CHANGE									
-4.95	-21.64	-6.59	-22.61	954.80	8.94	-3.02	-27.56	-76.21	

60225 W012CR002(1.8E15) W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5550	22.75	.4484	20.71	8.11E-08	1.702	.7354	9.28	3.900
2B*	.5460	19.00	.4274	16.86	8.26E-07	2.091	.6944	7.20	2.210
3B	.5550	22.25	.4560	20.50	1.43E-08	1.497	.7570	9.35	3.250
4B	.5510	21.82	.4380	19.61	3.10E-07	1.899	.7143	8.59	2.600
5B*	.5510	20.10	.4571	18.64	4.22E-09	1.378	.7692	8.52	3.900
1C	.5430	21.75	.4364	19.72	1.24E-07	1.730	.7286	8.60	2.600
2C	.5500	21.50	.4552	19.91	5.93E-09	1.401	.7664	9.06	3.250
3C	.5460	21.75	.4428	19.85	5.42E-08	1.628	.7402	8.79	2.600
4C	.5460	21.75	.4399	19.76	9.86E-08	1.707	.7319	8.69	2.210
5C	.5460	21.50	.4396	19.52	1.04E-07	1.716	.7309	8.58	2.210
1E*	.5350	21.50	.4175	19.02	1.14E-06	2.090	.6906	7.94	.130
2E	.5460	22.00	.4271	19.50	1.01E-06	2.103	.6934	8.33	1.950
3E	.5500	21.63	.4417	19.60	1.30E-07	1.759	.7278	8.66	2.990
4E	.5500	22.00	.4434	19.99	9.54E-08	1.713	.7325	8.86	3.120
5F	.5500	21.87	.4346	19.56	4.88E-07	1.975	.7067	8.50	2.210
6E	.5370	21.00	.4239	18.76	5.06E-07	1.942	.7053	7.95	1.040
7E	.5350	20.75	.4231	18.57	4.37E-07	1.911	.7077	7.86	1.170

AVERAGES: 60225 BASELINE W002 00 000

.5537 22.27 .4475 20.27 1.35E-07 1.699 .7356 9.07 3.250

60225 W012CR002(1.8E15)

.5454 21.59 .4371 19.52 2.78E-07 1.780 .7247 8.54 2.305

PERCENT CHANGE

-1.50 -3.06 -2.32 -3.70 105.54 4.77 -1.48 -5.93 -29.09

60108 W005MN001(2.5F15) W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1R*	.5540	22.50	.4447	20.38	1.43E-07	1.781	.7270	9.06	5.000
1B	.5500	22.60	.4626	21.14	7.22E-10	1.226	.7869	9.78	.455
2B	.5500	22.40	.4588	20.85	2.29E-09	1.314	.7764	9.56	.455
3B	.5500	22.60	.4650	21.21	3.30E-10	1.172	.7934	9.86	5.200
4B	.5500	22.50	.4589	20.94	2.24E-09	1.312	.7766	9.61	3.900
5B	.5500	22.40	.4558	20.76	5.34E-09	1.387	.7679	9.46	2.000
1C	.5230	17.75	.4366	16.53	1.64E-09	1.242	.7773	7.22	1.040
2C	.5150	17.00	.4212	15.61	1.83E-08	1.441	.7510	6.57	.650
3C	.5200	17.50	.4303	16.20	4.97E-09	1.327	.7660	6.97	1.040
4C	.5200	17.50	.4303	16.20	4.97E-09	1.327	.7660	6.97	.910
5C	.5200	17.50	.4303	16.20	4.97E-09	1.327	.7660	6.97	.910
1F	.5150	16.75	.4261	15.51	4.77E-09	1.314	.7660	6.61	.780
2F	.5160	17.35	.4284	16.10	3.33E-09	1.283	.7702	6.89	.910
3E	.5160	16.75	.4291	15.56	2.56E-09	1.265	.7724	6.68	.910
4E	.5160	17.20	.4275	15.94	4.15E-09	1.303	.7677	6.81	.910

AVERAGES: 60108 BASELINE W002 00 000

.5500 22.50 .4602 20.98 2.18E-09 1.282 .7802 9.66 2.402

60108 W005MN001(2.5F15)

.5179 17.26 .4289 15.98 5.51E-09 1.314 .7670 6.86 .896

PERCENT CHANGE

-5.84 -23.31 -6.81 -23.82 152.45 2.49 -1.70 -29.00 -62.72

60226 W005MN001(2.5E15) W002 00 000

ID	VOC	ISC	VF	IP	IO	N	FF	FFF	TAU
1H	.5550	22.50	.4642	20.98	1.60E-09	1.297	.7797	9.74	4.550
2E	.5580	22.50	.4704	21.08	5.25E-10	1.221	.7896	9.91	5.200
1C	.5260	17.00	.4392	15.83	1.52E-09	1.247	.7776	6.95	.910
2C	.5200	16.75	.4268	15.42	1.22E-08	1.415	.7556	6.58	.650
1E	.5260	17.12	.4395	15.95	1.40E-09	1.240	.7784	7.01	1.040
2E	.5230	16.50	.4362	15.35	1.72E-09	1.251	.7762	6.70	.910
3E	.5260	17.12	.4395	15.95	1.40E-09	1.240	.7784	7.01	1.040
4E	.5240	16.75	.4358	15.56	2.50E-09	1.282	.7726	6.78	.650

AVERAGES: 60226 BASELINE W002 00 000

.5565	22.50	.4673	21.03	1.06E-09	1.259	.7847	9.83	4.875	
60226 W005MN001(2.5E15)									
.5242	16.87	.4362	15.68	3.46E-09	1.279	.7731	6.84	.867	
PERCENT CHANGE									
-5.81	-25.01	-6.66	-25.44	225.48	1.59	-1.47	-30.40	-82.22	

60422 W026MN003 (8.9E12) W002 00 000

ID	VOC	ISC	VF	IP	IO	N	FF	FFF	TAU
1B	.5550	22.50	.4563	20.74	1.37E-08	1.491	.7577	9.46	3.900
2B	.5550	22.60	.4626	21.02	2.60E-09	1.336	.7752	9.72	4.290
3B	.5550	23.00	.4567	21.21	1.24E-08	1.479	.7590	9.69	4.290
4B	.5480	22.20	.4534	20.55	6.35E-09	1.399	.7660	9.32	3.250
1C	.5450	22.50	.4570	21.01	1.12E-09	1.247	.7830	9.60	4.810
2C	.5450	22.50	.4475	20.72	1.56E-08	1.478	.7562	9.27	3.900
3C	.5450	22.50	.4527	20.88	4.03E-09	1.349	.7709	9.45	4.160
4C	.5450	22.50	.4406	20.49	7.55E-08	1.663	.7362	9.03	3.900
5C	.5450	22.50	.4555	20.97	1.77E-09	1.282	.7788	9.55	4.550
1S	.5450	22.50	.4475	20.72	1.56E-08	1.478	.7562	9.27	3.900
2S	.5450	22.50	.4475	20.72	1.56E-08	1.478	.7562	9.27	3.250
3S	.5450	22.50	.4364	20.34	1.77E-07	1.783	.7238	8.88	3.250
1T	.5450	22.50	.4500	20.80	8.26E-09	1.415	.7634	9.36	4.550
2T	.5450	22.50	.4487	20.76	1.15E-08	1.447	.7596	9.31	3.900
3T	.5450	22.50	.4487	20.76	1.15E-08	1.447	.7596	9.31	4.550
4T*	.5380	22.50	.4261	20.16	4.27E-07	1.903	.7095	8.59	2.210

AVERAGES: 60422 BASELINE W002 00 000

.5533	22.58	.4572	20.88	8.76E-09	1.426	.7645	9.55	3.933	
60422 W026MN003 (8.9E12)									
.5450	22.50	.4484	20.74	3.07E-08	1.461	.7585	9.30	4.065	
PERCENT CHANGE									
-1.49	-.33	-1.94	-.66	249.95	2.40	-.78	-2.59	3.38	

0407 W013MN002 (1.5E14) BEFORE SINTER W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5550	22.25	.4640	20.74	1.68E-09	1.302	.7792	9.62	5.200
2B	.5460	22.50	.4387	20.40	1.30E-07	1.741	.7284	8.95	3.900
3B	.5500	22.50	.4479	20.60	3.72E-08	1.589	.7456	9.23	4.550
4B	.5500	22.60	.4532	20.86	1.07E-08	1.453	.7605	9.45	4.550
1C	.5400	22.00	.4386	20.10	4.74E-08	1.592	.7422	8.82	3.250
2C	.5450	22.00	.4488	20.30	1.08E-08	1.443	.7600	9.11	3.900
3C	.5450	22.00	.4488	20.30	1.08E-08	1.443	.7600	9.11	3.900
4C	.5450	22.25	.4560	20.75	1.49E-09	1.269	.7803	9.46	4.550
5C	.5450	22.25	.4524	20.64	4.25E-09	1.355	.7702	9.34	3.900
1S	.5400	22.50	.4350	20.44	1.03E-07	1.690	.7317	8.89	3.900
2S	.5450	22.50	.4527	20.88	4.03E-09	1.349	.7709	9.45	4.810
3S	.5450	22.00	.4522	20.40	4.48E-09	1.361	.7696	9.23	4.550
4S	.5400	22.50	.4350	20.44	1.03E-07	1.690	.7317	8.89	3.900
1T	.5450	22.25	.4560	20.75	1.49E-09	1.269	.7803	9.46	4.550
2T	.5450	22.25	.4524	20.64	4.25E-09	1.355	.7702	9.34	4.550

AVERAGES: 60407 BASELINE W002 00 000

.5503	22.46	.4509	20.65	4.50E-08	1.521	.7534	9.31	4.550
60407 W013MN002 (1.5E14) BEFORE SINTER								
.5436	22.23	.4480	20.51	2.69E-08	1.438	.7606	9.19	4.160
PERCENT CHANGE								
-1.20	-1.05	-.65	-.65	-40.31	-5.49	.96	-1.30	-8.57

60407A W013MN002 (1.5E14) AFTER SINTER W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5550	22.60	.4748	21.35	4.45E-11	1.065	.8083	10.14	5.200
3B	.5600	22.90	.4686	21.36	1.53E-09	1.304	.7804	10.01	4.550
4B	.5600	22.90	.4686	21.36	1.53E-09	1.304	.7804	10.01	4.550
1C	.5400	22.50	.4510	20.96	1.98E-09	1.278	.7778	9.45	3.250
2C	.5400	22.00	.4519	20.52	1.46E-09	1.257	.7804	9.27	3.900
3C	.5400	22.00	.4580	20.68	1.94E-10	1.120	.7974	9.47	3.900
4C	.5400	22.00	.4519	20.52	1.46E-09	1.257	.7804	9.27	4.550
5C	.5400	22.00	.4519	20.52	1.46E-09	1.257	.7804	9.27	3.900
1S	.5400	22.40	.4458	20.71	8.34E-09	1.403	.7632	9.23	3.900
2S	.5400	22.40	.4600	21.11	9.42E-11	1.077	.8030	9.71	4.810
3S	.5400	22.00	.4548	20.60	5.79E-10	1.190	.7886	9.37	4.550
4S	.5400	22.40	.4495	20.82	2.97E-09	1.312	.7738	9.36	3.900
1T	.5450	22.30	.4637	21.01	1.14E-10	1.098	.8015	9.74	4.550

AVERAGES: 60407A BASELINE W002 00 000

.5583	22.80	.4707	21.36	1.03E-09	1.224	.7397	10.05	4.767
60407A W013MN002 (1.5E14) AFTER SINTER								
.5405	22.20	.4539	20.74	1.87E-09	1.225	.7847	9.42	4.121
PERCENT CHANGE								
-3.19	-2.63	-3.57	-2.86	80.31	.06	-.64	-6.33	-13.55

60220 W010NI002(2E15) W003 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1R*	.5530	22.75	.4479	20.75	6.33E-08	1.663	.7387	9.29	4.550
1B	.5450	22.25	.4186	19.40	3.16E-06	2.366	.6697	8.12	2.210
2B	.5340	23.00	.4063	19.87	5.53E-06	2.464	.6572	8.07	1.040
3B	.5520	22.37	.4132	19.00	1.21E-05	2.822	.6357	7.85	3.900
4B	.5520	22.12	.4514	20.31	2.41E-08	1.546	.7508	9.17	3.250
5B	.5520	22.12	.4497	20.26	3.45E-08	1.588	.7463	9.11	3.250
1C	.5300	19.37	.4400	17.97	3.64E-09	1.316	.7704	7.91	1.430
2C	.5300	19.37	.4400	17.97	3.64E-09	1.316	.7704	7.91	1.300
3C	.5270	19.37	.4307	17.78	2.19E-08	1.480	.7503	7.66	1.170
4C	.5270	19.10	.4306	17.53	2.26E-08	1.485	.7498	7.55	1.170
5C	.5230	19.37	.4177	17.47	1.89E-07	1.743	.7205	7.30	.910
1S	.5300	19.00	.4380	17.57	6.33E-09	1.367	.7643	7.70	1.430
2S	.5250	19.00	.4238	17.28	7.30E-08	1.619	.7342	7.32	1.040
3S	.5300	18.70	.4382	17.30	5.85E-09	1.361	.7651	7.58	1.430
4S	.5300	19.00	.4380	17.57	6.33E-09	1.367	.7643	7.70	1.430
1T	.5300	19.00	.4411	17.66	2.61E-09	1.290	.7735	7.79	1.430
2T	.5220	19.00	.4168	17.14	1.89E-07	1.743	.7201	7.14	.780
3T	.5300	19.00	.4411	17.66	2.61E-09	1.290	.7735	7.79	1.300

AVERAGES: 60220 BASELINE W003 00 000

.5470 22.37 .4278 19.77 4.17E-06 2.157 .6919 8.46 2.730

60220 W010NI002(2E15)

.5278 19.11 .4330 17.58 4.39E-08 1.448 .7547 7.61 1.235

PERCENT CHANGE

-3.50 -14.60 1.21 -11.08 -98.95 -32.87 9.07 -10.07 -54.76

60114 W006NI001(1.7E14) W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1R*	.5500	22.90	.4399	20.68	1.98E-07	1.815	.7223	9.10	5.000
1B	.5490	22.75	.4536	21.04	7.72E-09	1.417	.7641	9.54	5.200
2B	.5490	22.15	.4517	20.43	1.23E-08	1.466	.7587	9.23	4.550
3B	.5490	22.75	.4536	21.04	7.72E-09	1.417	.7641	9.54	5.850
4B	.5490	22.30	.4539	20.63	7.04E-09	1.411	.7649	9.36	5.200
1C	.5350	21.65	.4339	19.76	5.31E-08	1.593	.7404	8.58	3.900
2C	.5390	21.65	.4466	20.06	5.24E-09	1.361	.7677	8.96	5.200
3C	.5390	21.65	.4432	19.96	1.29E-08	1.446	.7579	8.84	3.900
4C	.5390	21.65	.4466	20.06	5.24E-09	1.361	.7677	8.96	5.200
5C	.5390	21.65	.4432	19.96	1.29E-08	1.446	.7579	8.84	4.550
6C	.5350	21.65	.4339	19.76	5.31E-08	1.593	.7404	8.58	3.250
1E	.5450	22.70	.4502	20.99	7.92E-09	1.410	.7638	9.45	5.200
2E	.5450	22.50	.4494	20.78	9.75E-09	1.431	.7615	9.34	5.200
3E	.5400	22.50	.4462	20.81	7.66E-09	1.395	.7641	9.28	5.200
4E	.5450	22.50	.4494	20.78	9.75E-09	1.431	.7615	9.34	5.850
5E	.5400	22.40	.4401	20.52	3.39E-08	1.550	.7466	9.03	4.550
6E	.5450	22.50	.4494	20.78	9.75E-09	1.431	.7615	9.34	5.200
7E	.5350	22.00	.4428	20.37	6.13E-09	1.363	.7662	9.02	5.200
8E	.5400	22.50	.4477	20.86	4.98E-09	1.355	.7687	9.34	5.200

AVERAGES: 60114 BASELINE W002 00 000

.5490 22.49 .4532 20.78 8.70E-09 1.428 .7630 9.42 5.200

60114 W006NI001(1.7E14)

.5401 22.11 .4445 20.39 1.66E-08 1.440 .7590 9.06 4.829

PERCENT CHANGE

-1.63 -1.69 -1.93 -1.90 90.66 .87 -.52 -3.78 -7.14

60221 W0112R001(5E14) W003 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5500	22.50	.4491	20.64	2.81E-08	1.556	.7491	9.27	3.900
2B	.5520	22.37	.4584	20.76	4.05E-09	1.368	.7707	9.52	4.550
3B	.5500	22.37	.4448	20.38	7.30E-08	1.675	.7366	9.06	2.990
4B	.5500	22.50	.4491	20.64	2.81E-08	1.556	.7491	9.27	1.950
5B	.5450	22.50	.4379	20.40	1.30E-07	1.738	.7284	8.93	2.600
1C	.5450	22.00	.4616	20.67	2.39E-10	1.143	.7957	9.54	3.900
2C	.5450	22.00	.4482	20.28	1.28E-08	1.460	.7583	9.09	3.250
3C	.5420	21.75	.4445	20.01	1.70E-08	1.483	.7547	8.90	2.210
4C	.5420	21.75	.4388	19.83	6.35E-08	1.636	.7381	8.70	1.950
5C	.5450	22.00	.4536	20.45	3.02E-09	1.326	.7735	9.27	3.900
1S	.5400	22.37	.4462	20.69	7.63E-09	1.395	.7641	9.23	3.290
2S	.5470	22.37	.4589	20.90	1.04E-09	1.246	.7836	9.59	3.900
3S	.5400	22.25	.4445	20.52	1.17E-08	1.437	.7592	9.12	3.640
4S	.5400	22.37	.4476	20.73	5.13E-09	1.358	.7683	9.28	3.900
1T	.5500	22.50	.4644	21.10	4.07E-10	1.187	.7917	9.80	4.550
2T	.5500	21.50	.4614	20.08	1.01E-09	1.254	.7836	9.27	3.900
3T	.5500	22.00	.4577	20.44	3.11E-09	1.341	.7732	9.36	3.900
4T	.5500	22.00	.4585	20.47	2.48E-09	1.322	.7754	9.38	3.900

AVERAGES: 60221 BASELINE W003 00 000

.5494 22.45 .4479 20.56 5.27E-08 1.579 .7468 9.21 3.198

60221 W0112R001(5E14)

.5451 22.07 .4528 20.47 9.93E-09 1.353 .7707 9.27 3.553

PERCENT CHANGE

-.79 -1.70 1.09 -.43 -81.17 -14.30 3.21 .66 11.10

60206 W009V001(3.1E14) W003 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1R*	.5530	22.75	.4479	20.75	6.33E-08	1.663	.7387	9.29	4.550
1B	.5550	22.50	.4642	20.98	1.60E-09	1.297	.7797	9.74	5.200
2B	.5550	22.50	.4625	20.93	2.65E-09	1.338	.7750	9.68	3.900
3B	.5520	22.20	.4470	20.24	6.37E-08	1.664	.7383	9.05	2.860
4B	.5550	22.60	.4549	20.79	1.89E-08	1.525	.7539	9.46	3.900
5B	.5550	22.50	.4563	20.74	1.37E-08	1.491	.7577	9.46	3.900
1C	.4670	10.20	.3889	9.48	1.32E-09	1.133	.7741	3.69	.195
2C	.4670	10.20	.3889	9.48	1.32E-09	1.133	.7741	3.69	.260
3C	.4670	10.20	.3889	9.48	1.32E-09	1.133	.7741	3.69	.390
4C	.4670	10.20	.3889	9.48	1.32E-09	1.133	.7741	3.69	.260
5C	.4670	10.20	.3889	9.48	1.32E-09	1.133	.7741	3.69	.260
1S	.4650	10.25	.3805	9.42	1.05E-08	1.297	.7516	3.58	.325
2S	.4690	10.25	.3896	9.51	1.78E-09	1.159	.7711	3.71	.260
3S	.4690	10.25	.3896	9.51	1.78E-09	1.159	.7711	3.71	.260
1T	.4650	10.20	.3793	9.35	1.43E-08	1.327	.7476	3.55	.260
2T	.4680	10.20	.3869	9.44	3.25E-09	1.203	.7649	3.65	.390
3T	.4680	10.20	.3869	9.44	3.25E-09	1.203	.7649	3.65	.260
4T	.4620	10.20	.3770	9.35	1.35E-08	1.313	.7484	3.53	.260

AVERAGES: 60206 BASELINE W003 00 000

.5544 22.46 .4570 20.73 2.01E-08 1.463 .7609 9.48 3.952

60206 W009V001(3.1E14)

.4668 10.21 .3862 9.45 4.58E-09 1.194 .7658 3.65 .282

PERCENT CHANGE

-15.81 -54.53 -15.49 -54.41 -77.19 -18.41 .64 -61.48 -92.87

60205 W008TI001(3.6E14) W003 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1R*	.5550	22.70	.4504	20.73	5.27E-08	1.645	.7412	9.34	4.550
1B	.5580	22.80	.4576	20.98	1.79E-08	1.526	.7547	9.60	3.900
2B	.5580	22.80	.4576	20.98	1.79E-08	1.526	.7547	9.60	3.900
3B	.5580	22.80	.4576	20.98	1.79E-08	1.526	.7547	9.60	3.900
4B	.5550	22.60	.4531	20.73	2.85E-08	1.571	.7489	9.39	3.900
5B	.5580	22.60	.4597	20.86	1.07E-08	1.474	.7604	9.59	4.550
1C	.4280	7.80	.3250	6.73	2.06E-06	1.998	.6548	2.19	.195
2C	.4300	7.80	.3284	6.76	1.53E-06	1.938	.6620	2.22	.260
3C	.4460	7.80	.3628	7.14	1.45E-08	1.300	.7441	2.59	.260
4C	.4200	7.60	.3092	6.33	8.55E-06	2.379	.6134	1.96	.156
5C	.4380	7.80	.3404	6.88	5.44E-07	1.760	.6851	2.34	.260
1S	.4450	7.80	.3612	7.12	1.81E-08	1.319	.7412	2.57	.065
2S	.4450	7.70	.3589	7.00	3.21E-08	1.382	.7331	2.51	.143
3S	.4290	7.60	.3248	6.53	2.34E-06	2.041	.6508	2.12	.195
4S	.4450	7.70	.3553	6.95	7.58E-08	1.485	.7203	2.47	.195
1T	.4380	7.60	.3443	6.77	2.47E-07	1.630	.6999	2.33	.260
3T	.4430	7.60	.3588	6.93	2.16E-08	1.334	.7385	2.49	.208
4T	.4430	7.60	.3588	6.93	2.16E-08	1.334	.7385	2.49	.078

AVERAGES: 60205 BASELINE W003 00 000

.5574 22.72 .4571 20.91 1.86E-08 1.525 .7547 9.56 4.030

60205 W008TI001(3.6E14)

.4375 7.70 .3440 6.84 1.29E-06 1.658 .6985 2.36 .190

PERCENT CHANGE

-21.51 -66.11 -24.75 -67.29 6838.85 8.74 -7.45 -75.35 -95.30

60317 W018FE002(1.5E15) W003 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5560	22.00	.4599	20.36	6.45E-09	1.422	.7657	9.37	4.550
2B	.5560	22.00	.4599	20.36	6.45E-09	1.422	.7657	9.37	4.550
3B	.5560	22.00	.4599	20.36	6.45E-09	1.422	.7657	9.37	4.550
4B	.5500	22.00	.4443	20.02	7.87E-08	1.687	.7352	8.90	2.990
1C	.4900	14.30	.3765	12.47	1.99E-06	2.123	.6701	4.70	.260
2C	.5000	14.30	.4015	12.95	8.88E-08	1.604	.7274	5.20	.260
3C	.4900	14.30	.3803	12.59	1.08E-06	1.985	.6834	4.79	.260
4C	.4900	14.30	.3803	12.59	1.08E-06	1.985	.6834	4.79	.260
5C	.5000	14.30	.4015	12.95	8.88E-08	1.604	.7274	5.20	.390
1S	.4900	14.25	.3871	12.74	3.24E-07	1.763	.7063	4.93	.260
2S	.4900	14.00	.3866	12.50	3.51E-07	1.779	.7046	4.83	.260

AVFRAGES: 60317 BASELINE W003 00 000

.5545 22.00 .4560 20.28 2.45E-08 1.488 .7581 9.25 4.160

60317 W018FE002(1.5E15)

.4929 14.25 .3877 12.69 7.14E-07 1.835 .7004 4.92 .279

PERCENT CHANGE

-11.12 -35.23 -14.99 -37.44 2812.74 23.30 -7.61 -46.80 -93.30

60421 W024MG002 (1E14) W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5450	23.00	.4606	21.58	3.55E-10	1.165	.7930	9.94	5.200
2B	.5450	22.60	.4603	21.20	3.85E-10	1.172	.7922	9.76	5.200
3B	.5450	22.60	.4571	21.11	1.10E-09	1.245	.7832	9.65	4.550
4B	.5450	22.50	.4555	20.97	1.77E-09	1.282	.7788	9.55	4.550
1C	.5450	22.60	.4579	21.13	8.59E-10	1.227	.7854	9.67	4.940
2C	.5450	22.60	.4579	21.13	8.59E-10	1.227	.7854	9.67	5.200
3C	.5450	22.40	.4540	20.83	2.77E-09	1.318	.7745	9.45	4.940
4C	.5450	22.50	.4594	21.08	5.21E-10	1.192	.7897	9.68	4.550
5C	.5450	22.60	.4579	21.13	8.59E-10	1.227	.7854	9.67	4.160
1S	.5350	22.30	.4454	20.73	2.94E-09	1.299	.7739	9.23	4.160
2S	.5350	22.50	.4462	20.94	2.35E-09	1.280	.7762	9.34	4.160
3S	.5320	22.60	.4372	20.83	1.41E-08	1.432	.7573	9.11	3.380
1T	.5400	22.30	.4535	20.84	8.75E-10	1.218	.7851	9.45	4.940
2T	.5400	22.60	.4584	21.26	1.70E-10	1.110	.7987	9.75	5.200
3T	.5400	22.30	.4535	20.84	8.75E-10	1.218	.7851	9.45	4.550

AVERAGES: 60421 BASELINE W002 00 000

.5450	22.68	.4584	21.21	9.02E-10	1.216	.7868	9.72	4.875	
60421 W024MG002 (1E14)									
.5406	22.48	.4529	20.98	2.48E-09	1.250	.7815	9.50	4.562	
PERCENT CHANGE									
-.80	-.85	-1.21	-1.12	174.33	2.80	-.67	-2.30	-6.42	

60424 W0152N001 (<5E14) W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5400	21.75	.4538	20.34	7.84E-10	1.212	.7858	9.23	3.900
2B	.5400	21.75	.4538	20.34	7.84E-10	1.212	.7858	9.23	3.900
3B	.5400	21.10	.4457	19.50	8.13E-09	1.406	.7628	8.69	3.250
4B	.5400	21.50	.4474	19.92	5.25E-09	1.364	.7677	8.91	3.250
1C	.5400	21.80	.4464	20.17	6.91E-09	1.388	.7649	9.00	3.900
2C	.5400	22.10	.4527	20.63	1.15E-09	1.238	.7827	9.34	4.550
3C*	.5270	21.70	.4109	19.18	1.23E-06	2.073	.6892	7.88	1.950
4C	.5400	22.10	.4431	20.34	1.63E-08	1.471	.7554	9.02	3.900
1S	.5400	22.30	.4470	20.65	6.17E-09	1.375	.7664	9.23	3.900
2S*	.5370	19.50	.4344	17.77	6.08E-08	1.629	.7372	7.72	3.250
1T	.5300	22.10	.4322	20.25	3.17E-08	1.515	.7474	8.75	2.600
2T	.5340	22.20	.4352	20.34	3.39E-08	1.533	.7466	8.85	3.250
3T	.5400	22.20	.4431	20.59	4.48E-09	1.347	.7696	9.23	3.900
A201	.5400	22.20	.4549	20.79	5.54E-10	1.186	.7890	9.46	4.810
A202	.5400	22.20	.4494	20.63	3.11E-09	1.316	.7733	9.27	4.550
A203	.5400	22.20	.4494	20.63	3.11E-09	1.316	.7733	9.27	4.550
A221	.5300	22.20	.4323	20.35	3.09E-08	1.512	.7478	8.80	3.250
A222	.5400	22.50	.4510	20.96	1.98E-09	1.278	.7778	9.45	3.900
A223	.5400	22.50	.4392	20.58	4.23E-08	1.575	.7439	9.04	3.250

AVERAGES: 60424 BASELINE W002 00 000

.5400	21.53	.4502	20.02	3.74E-09	1.299	.7755	9.02	3.575	
60424 W0152N001 (<5E14)									
.5377	22.11	.4435	20.43	1.44E-08	1.410	.7619	9.06	3.714	
PERCENT CHANGE									
-.42	2.74	-1.48	2.00	284.16	8.56	-1.77	.49	3.90	

60409 W028AL001 (1E15) BEFORE SINTER W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5540	22.75	.4561	20.99	1.17E-08	1.471	.7596	9.57	4.550
2B	.5540	22.75	.4561	20.99	1.17E-08	1.471	.7596	9.57	4.550
3B	.5540	22.40	.4612	20.82	3.03E-09	1.347	.7737	9.60	4.160
4B	.5470	22.75	.4415	20.69	8.89E-08	1.689	.7340	9.13	3.900
1C	.5370	17.50	.4447	16.21	4.54E-09	1.362	.7670	7.21	1.300
2C	.5300	17.50	.4298	15.97	4.41E-08	1.581	.7401	6.86	.910
3C	.5350	18.50	.4324	16.85	6.25E-08	1.633	.7360	7.28	1.040
4C	.5390	18.25	.4501	17.00	1.62E-09	1.277	.7777	7.65	1.300
1S	.5390	18.35	.4486	17.05	2.51E-09	1.312	.7735	7.65	1.300
2S	.5390	18.35	.4428	16.90	1.21E-08	1.457	.7567	7.48	1.300
3S	.5390	18.35	.4486	17.05	2.51E-09	1.312	.7735	7.65	1.300
4S	.5390	18.35	.4486	17.05	2.51E-09	1.312	.7735	7.65	1.300

AVERAGES: 60409 BASELINE W002 00 000

.5523	22.66	.4537	20.87	2.88E-08	1.495	.7567	9.47	4.290
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60409 W028AL001 (1E15) BEFORE SINTER

.5371	18.14	.4432	16.76	1.66E-08	1.406	.7623	7.43	1.219
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PERCENT CHANGE

-2.74	-19.94	-2.32	-19.70	-42.53	-5.96	.73	-21.54	-71.59
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60409A W028AL001 (1E15) AFTER SINTER W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5400	22.50	.4330	20.36	1.54E-07	1.746	.7258	8.82	4.550
2B	.5400	22.75	.4480	21.10	4.71E-09	1.350	.7694	9.45	4.550
3B	.5400	22.75	.4512	21.20	1.87E-09	1.273	.7784	9.56	4.160
4B	.5400	22.75	.4421	20.91	2.13E-08	1.496	.7526	9.25	3.900
1C	.5250	17.00	.4408	15.89	7.08E-10	1.188	.7847	7.00	1.300
2C	.5200	17.00	.4272	15.66	1.11E-08	1.404	.7568	6.69	.910
3C	.5300	18.00	.4398	16.70	3.54E-09	1.320	.7698	7.34	1.040
4C	.5350	18.40	.4431	17.04	4.71E-09	1.356	.7672	7.55	1.300
1S	.5300	18.25	.4429	17.00	1.47E-09	1.248	.7786	7.53	1.300
2S	.5250	18.25	.4329	16.85	7.90E-09	1.378	.7615	7.30	1.300
3S	.5250	18.25	.4329	16.85	7.90E-09	1.378	.7615	7.30	1.300
4S	.5250	18.30	.4353	16.96	4.05E-09	1.318	.7687	7.38	1.300

AVERAGES: 60409A BASELINE W002 00 000

.5400	22.69	.4436	20.89	4.54E-08	1.466	.7566	9.27	4.290
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60409A W028AL001 (1E15) AFTER SINTER

.5269	17.93	.4369	16.62	5.17E-09	1.324	.7686	7.26	1.219
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PERCENT CHANGE

-2.43	-20.96	-1.52	-20.44	-88.61	-9.72	1.59	-21.66	-71.59
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60301 W01400000(AUDIT) W002 00 000

ID	VOC	ISC	VP	IP	IO	N	FF	EFF	TAU
1B	.5580	22.25	.4702	20.84	5.50E-10	1.225	.7891	9.80	4.550
2B	.5580	22.50	.4704	21.08	5.25E-10	1.221	.7896	9.91	4.550
1C	.5550	22.25	.4560	20.50	1.43E-08	1.497	.7570	9.35	4.290
2C	.5550	22.50	.4642	20.98	1.60E-09	1.297	.7797	9.74	4.420
3C	.5550	22.50	.4642	20.98	1.60E-09	1.297	.7797	9.74	4.420
1N	.5570	22.25	.4648	20.71	2.16E-09	1.327	.7769	9.63	4.290
2N*	.4850	21.50	.3249	15.53	4.54E-04	4.808	.4837	5.04	.130
3N	.5480	22.00	.4437	20.06	6.39E-08	1.653	.7381	8.90	3.250
4N	.5520	22.00	.4584	20.42	4.00E-09	1.368	.7707	9.36	3.900

AVERAGES: 60301 BASELINE W002 00 000

.5580	22.38	.4703	20.96	5.38E-10	1.223	.7894	9.86	4.550
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60301 W01400000(AUDIT)

.5537	22.25	.4586	20.61	1.46E-08	1.407	.7670	9.45	4.095
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PERCENT CHANGE

-.78	-.56	-2.49	-1.68	2613.26	14.98	-2.83	-4.10	-10.00
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