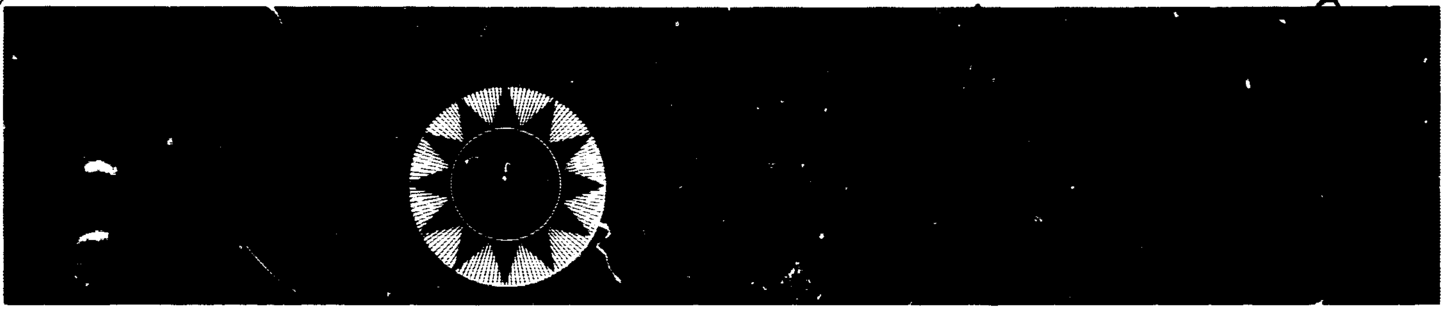

Research and Development of Silicon Solar Cells for Low Solar Intensity and Low Temperature Applications

by P. Payne

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Analysis Report

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by

Heliotek, Division of Textron, Inc.
12500 Gladstone Avenue
Sylmar, California 91342

for

AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINSTRATION

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1.0 INTRODUCTION

The purpose of this program was to obtain a solar cell design optimized for 5.0 mW/cm^2, -135°C operation as encountered in a spacecraft mission to Jupiter. During Phase I, experiments were conducted to analyze and optimize the important variables. In Phase II 500 prototype cells will be fabricated using the procedures decided upon in Phase I. This report presents an analysis and results of the investigation performed during Phase I.

In the investigation of design variables certain areas of study were assigned more importance than others. For example, the broken knee effect was stressed since it could seriously limit the output of cells at Jupiter test conditions. This was considered to be a more important area for investigation than such variables as cell thickness or cell active-surface finish and antireflection coating. Since so much time was needed for investigation of these major problem areas, no experimentation was done in some areas which were felt would result in only nominal improvements, i.e., optimization of the contact configuration for Jupiter conditions.

Where particular variables have not been investigated, state-of-the-art procedures will be used and the discussion of the optimized Jupiter cell designs will merely state the procedure.

2.0 DESIGN VARIABLE ANALYSIS

2.1 DOPANT IDENTITY AND CONCENTRATION

An N/P cell will be used. The P region will have standard boron doping. The boron concentration will be ≈ 10^{15} atoms/cm^3, i.e., 10 ohm cm resistivity. Selection of this concentration is based upon measurements performed by Heliotek which indicate that although 2 ohm cm cells (≈ 7 x 10^{15} atoms/cm^3) are 30-50 mV higher in V_{oc} at standard temperature and intensity, at Jupiter conditions they offer no advantage in V_{oc} or efficiency (see Figure 1).

2.2 DIFFUSION PROCESS

A standard phosphorous diffusion will be used to produce a P-N junction. The diffusion will be optimized with respect to cell output at Jupiter conditions and dark reverse current. In order to determine the optimum junction depth, experimental cells were fabricated with junction depths of 0.25, 0.50, 1.0, and 2.0μ; (0.50μ is a typical space cell junction depth). As expected, the short circuit current at standard AMO intensity decreased with junction depth. However, at low intensity the short circuit current was influenced more by its non-linearity characteristic as a function of temperature than the junction depth. The electrical characteristics (i.e., I-V curve shapes) of cells with a 0.25μ junction were very poor. The cells with 0.50, 1.0, and 2.0μ junctions were similar, except in the case of dark reverse current which decreased with increasing junction depth. Cells with a 2.0μ junction (produced with an 8 hour diffusion) were not significantly better than cells with 0.50 and 1.0μ junctions; consequently, in a verification experiment to evaluate larger quantities of cells, only the 0.50 and 1.0μ junction depths were investigated. At 5.0 mW/cm^2 intensity (AMO spectrum) the average I_{sc} at 28°C for cells with 1.0μ junction depth was 4.6 mA and for cells with 0.5μ junction depth was 4.8 mA. At -135°C the difference

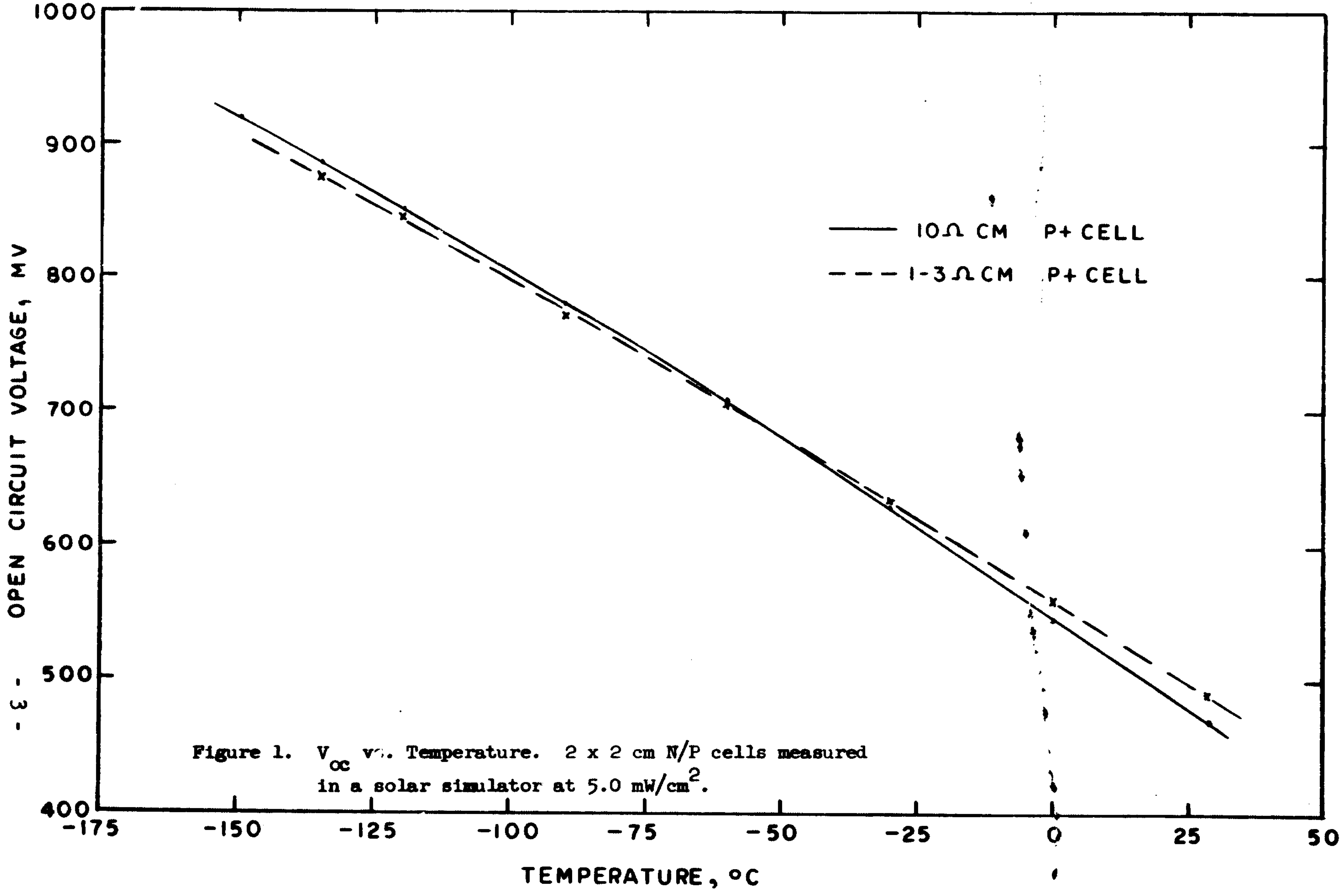

Figure 1. V_{oc} vs. Temperature. 2 x 2 cm N/P cells measured in a solar simulator at 5.0 mW/cm^2.

in I_{sc} was even less--3.93 mA average for 1.0μ junction depth cells and 3.98 mA average for 0.5μ junction depth cells. Since the dark reverse current at 0.7V for the cells with a 1.0μ junction depth was 20-25% lower than for the cells with a 0.5μ junction depth, 1.0μ was selected as the optimum junction depth.

2.3 CELL THICKNESS

As indicated in NASA/Ames Request for Proposal, the maximum average cell thickness will be 0.010".

2.4 CONTACT MATERIALS AND PROCESS OF CONTACT APPLICATION.

Standard Ti-Ag contacts will be used. In addition a P+ region will be formed on the back of the cell by the evaporation of Aℓ prior to evaporation of Ti-Ag contacts. This procedure is being used in order to eliminate a Schottky type barrier which is usually present in standard N/P production cells at low temperatures. Use of a P+ region increases the V_{oc} at low temperatures (Figure 2) and also improves the curve factor.

In selecting the contacting procedure, two basic methods were investigated: 1) a two-step evaporation with alloying of the Aℓ prior to evaporation of the Ti-Ag; and 2) a "one-step" evaporation where Aℓ, Ti, and Ag are all evaporated and the Aℓ is alloyed in the Ti-Ag contact sintering operation (performed at 605°C). The amount of Aℓ evaporated was selected on the basis of compatibility with both procedures, i.e., in the two-step evaporation procedure the dark reverse current increased with the amount of Aℓ. The alloying or sintering temperature was also selected on the basis of compatibility with both procedures; 605°, 650°, and 700°C were investigated with a two-step procedure. Alloying at 700°C resulted in very high dark reverse currents and there was no significant difference between cells with Aℓ alloyed at 605°C and 650°C. Therefore 605°C was used since a single step evaporation where Aℓ is alloyed at the same time as the Ti-Ag contacts are sintered eliminates the possibility of a 650°C temperature, which would cause sintering through the junction.

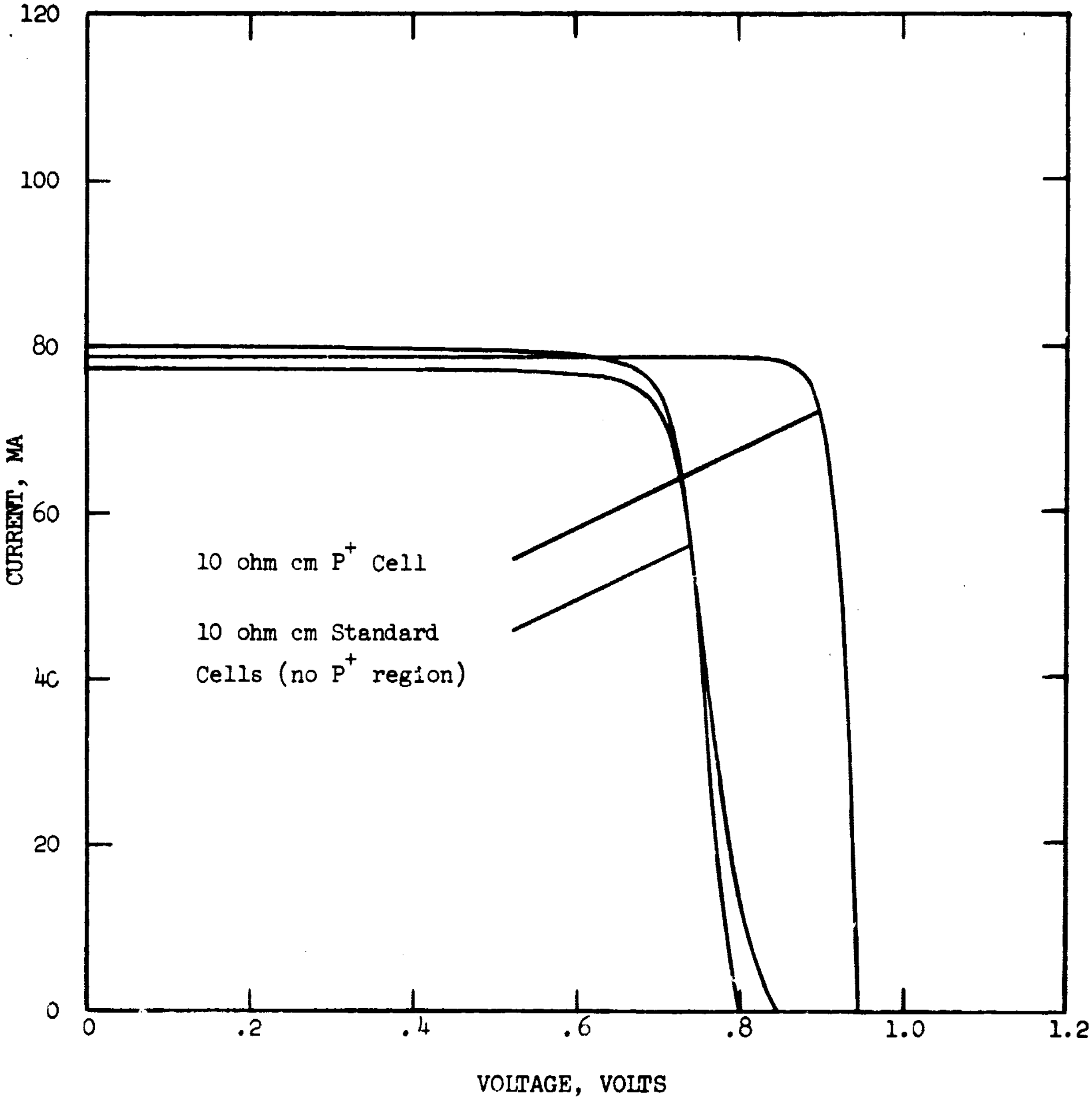

Figure 2. Comparison of 10 ohm cm P^+ Cell to Standard 10 ohm cm Cell. Measured in 100 mW/cm^2 tungsten light at -135°C.

Comparison of cells from the "one-step" and two-step evaporations showed that the high efficiency cells in each group had similar outputs; however there were more reject cells from the two-step evaporation due to I-V characteristics at low intensity and temperature as shown in Figure 3. This type of low temperature and low intensity performance was typical of cells which exhibited a very significant broken knee effect at high intensity and -135°C. Cells from the two-step evaporation were measured without sintering the Ti-Ag contacts (the Aℓ was alloyed prior to evaporation of Ti-Ag) and several of these which were similar to the cell shown in Figure 3, were sintered to determine that this was not the cause of the poor characteristics. No improvement occurred with sintering. Therefore it was concluded that the "one-step" evaporation process gave better results.

Pull tests (i.e., wires soldered to the contact and pulled perpendicular to the cell surface until failure) were performed to determine the mechanical strength of the contacts. Table I shows the data obtained for both one and two-step evaporated contacts. All the front contacts withstood more than 500 grams. The majority of the back contacts also withstood 500 grams. On those cells with less than 500 gram pull strengths, a second pull test was performed and in all cases this repeat test resulted in strengths greater than 500 grams.

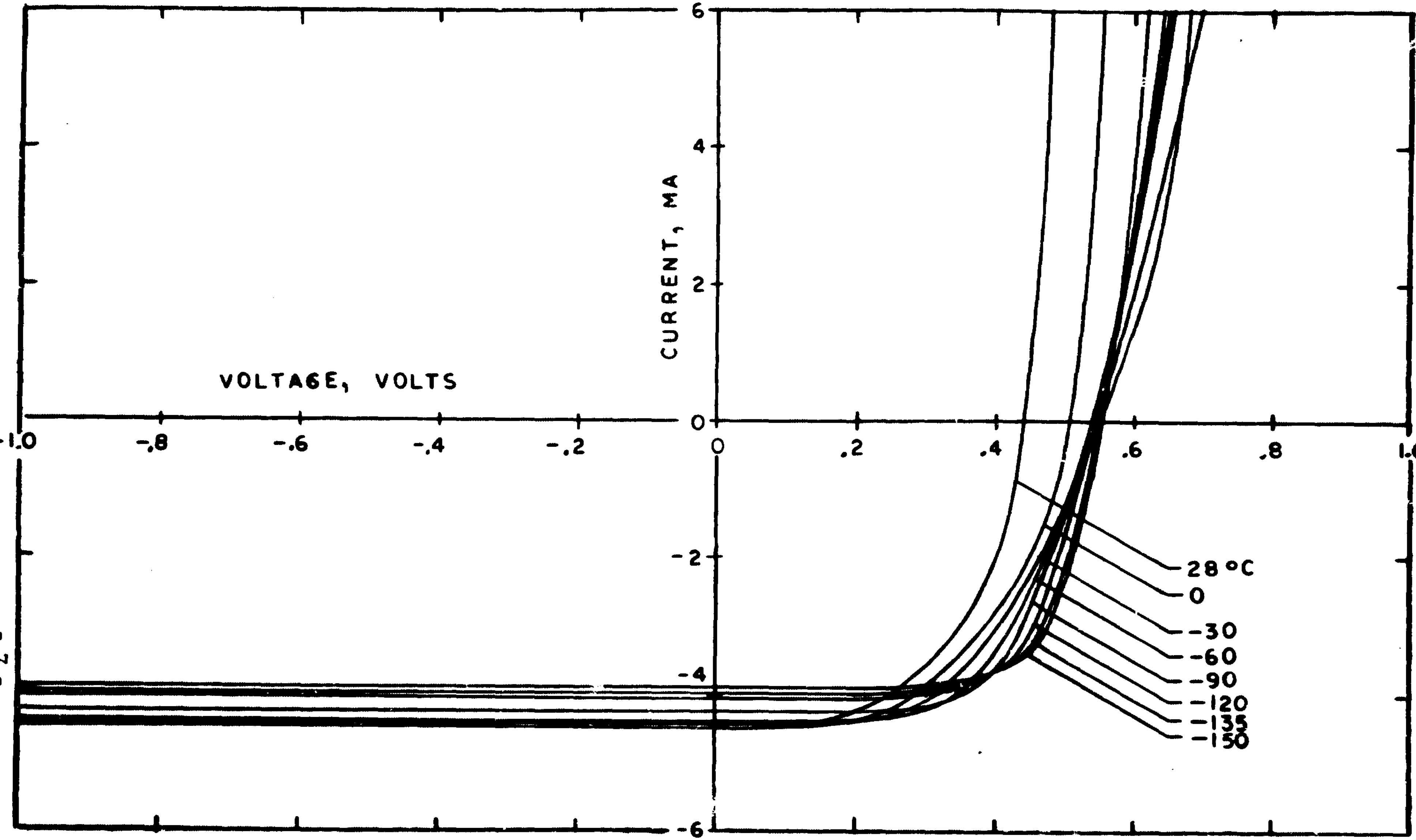

Figure 3. I-V Characteristic Curves at 5.0 mW/cm^2 of P+ cell with "Broken Knee" at High Intensity. Measured in solar simulator.

TABLE 1

Pull Test - 10 ohm cm N/P Cells with P+ Contact

Two-Step Evaporation

Cell No.	Front Grams Pulled	Back Grams Pulled
24-1	800	1000
24-2	1000	1000
24-3	600	1000
24-4	900	1000
24-5	1000	450 - 700
24-6	1000	500 - 700
24-7	600	1000
24-8	1000	1000
24-9	1000	250 - 700
24-10	1000	1000
One-Step Evaporation		
26-1	1000	500 - 750
26-2	1000	750
26-3	1000	1000
26-4	1000	550

2.5 CONTACT PATTERN AND GRID WIDTH

The contact will consist of bar with 6 grid lines. Both 2 and 6 grid lines have been used and at low intensity 2 grid lines are sufficient for obtaining an I-V characteristic with a good curve factor. Approximately 2% is gained in active area by using 2 grids instead of 6 grids, however, use of 2 grids makes it difficult to correlate 140 mW/cm^2 measurements to 5 mW/cm^2 measurements due to the series resistance at 140 mW/cm^2. At this point no correlation has been established between 28°C and -135°C measurements which can be used unfailingly to predict low intensity and low temperature performance from the 28°C measurements. Liebert and Hart describe a method for selecting best silicon cells for Jupiter conditions based upon the fill factor sensitivity to intensity for poor cells. "At room temperature, the percent change of fill factor with intensity between 136 and 6 mW/cm^2 increased as the efficiency at Jupiter decreased. This suggests that observation of the fill factor as the intensity is varied can be useful for sorting out the better-performing cells at Jupiter conditions without resorting to low temperature tests."[1)] However, this method does not work for cells which have a distorted knee or non-linearity of short circuit current with temperature. Both of these problems still are present on a significant percentage of the cells so testing at -135°C is necessary. If the distorted knee and short circuit current non-linearity effect can be eliminated, the method of Liebert and Hart could then be used. This would eliminate low temperature testing, but would necessitate using enough grid lines for the high intensity measurement to obtain a good fill factor.

The bar portion of the contact configuration is being reduced in order to reduce the possibility of metal extending over the cell edge and shunting the cell. This extra precaution is being taken in order to minimize the chance of having high leakage currents which are very detrimental to low light level cell performance.

2.6 CELL ACTIVE-SURFACE FINISH AND ANTIREFLECTION COATING

No investigations were done in this area. It is planned that the standard chemical polish etch and SiO antireflection coating will be used. The only precaution necessary will be to remove enough Si in the etch so as to remove all surface damage, since residual surface damage results in high dark reverse currents and once a cell is made with this defect there is no procedure which can be used to improve the shunt resistance, as in the case of etching metal off the edges.

2.7 POWER OUTPUT

The solar cell design is to be optimized for power output at Jupiter. The minimum design goal value of average cell efficiency shall be 12.8% at -135°C as stated in the Request for Proposal. Experiment 25 which was an experiment to verify both the optimum diffusion time (junction depth), and the method of contact application, indicated that the 1.0μ junction depth and a "one-step" application of Aℓ and Ti-Ag contacts was superior to a 0.50μ junction and a two-step application of the Aℓ and Ti-Ag. As shown in Table 2 the average efficiency for cells fabricated with a 1.0μ junction and a one-step evaporation (Group IV) was actually lower than for cells fabricated with a 0.50μ junction and a two-step evaporated (Group I); however 6 cells were eliminated from Group I--five due to I-V characteristic curves as shown in Figure 3 and one due to low output (4% efficiency) caused by extreme non-linearity of short circuit current (see Figure 4) while only one cell was eliminated from the average for Group IV (due to a bad broken knee).

TABLE 2

Output of P+ Cells at 5 mW/cm^2 and -135°C

Cell No.	Output, mW	Efficiency %	Average %
Group I 0.5μ junction, two-step evaporation (1)			
25-1	2.96	14.8	
25-3	2.80	14.0	
25-6	3.06	15.3	
25-25	3.06	15.3	
25-26	2.63	13.15	14.20
25-27	2.45	12.25	
25-29	2.43	12.15	
25-45	3.04	15.2	
Group II 1.0μ junction, two-step evaporation (2)			
25-8	2.83	14.15	
25-9	2.72	13.6	
25-30	2.67	13.35	13.26
25-33	2.68	13.4	
25-45	2.36	11.8	
Group III 0.5μ junction, one-step evaporation (3)			
25-13	2.72	13.6	
25-14	2.40	12.0	
25-15	2.04	10.2	
25-16	2.52	12.6	
25-17	2.55	12.75	13.28
25-35	3.23	16.15	
25-36	2.74	13.7	
25-37	2.88	14.4	
25-38	2.92	14.6	
25-39	2.56	12.8	
Group IV 1.0μ junction, one-step evaporation (4)			
25-20	2.69	13.45	
25-24	3.24	16.2	
25-40	3.03	15.15	13.50
25-41	2.90	14.5	
25-42	2.84	14.2	
25-43	2.13	10.65	
25-44	2.08	10.4	

(1) 6 cells eliminated--5 due to extreme broken knee, 1 due to low output.
(2) 3 cells eliminated due to extreme broken knee
(3) 1 cell eliminated due to extreme broken knee
(4) 1 cell eliminated due to low output

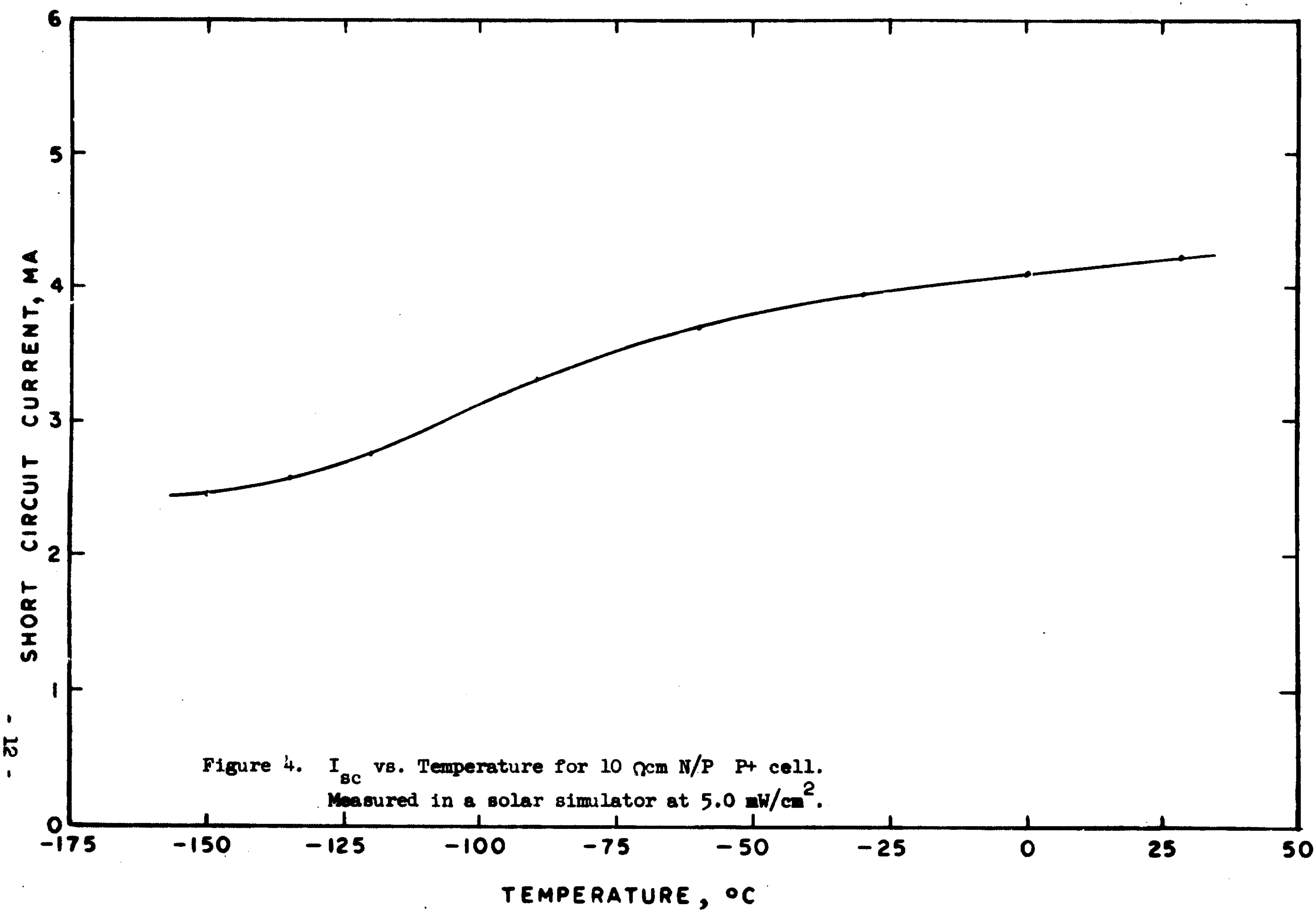

Figure 4. I_{sc} vs. Temperature for 10 Ωcm N/P P+ cell.
Measured in a solar simulator at 5.0 mW/cm^2.

The most significant factors causing low output at Jupiter conditions are the broken knee or double slope phenomenon and I_{sc} non-linearity as a function of temperature. The broken knee phenomenon has been approached both theoretically and experimentally. Application of the theory of the effects of series resistance limited regions in the cell on the I-V characteristic curve resulted in cells which simulated the effect; however, the effect was not identical.

Experiments in which the amount of Aℓ and Aℓ alloying temperature were varied indicated that these variables had no effect upon the broken knee. This, in addition to the presence of the broken knee in standard N/P cells with no P+ region provided good evidence that the broken knee effect cannot be associated with the P+ region.

It was postulated that the contacts could possibly have been the source of the problem if the sintering procedure, which has been optimized for 1 AU type cells, is firing impurities into the silicon which cause damage which is significant at 5 mW/cm^2 and -135°C, but not at 140 mW/cm^2 and 28°C. Varying the sintering time for the Ti-Ag contacts produced no effective change in the already existant double slope which occurred in cells with no sintering. It seems unlikely that the presence of just the evaporated unsintered metals could cause the double slope; therefore, the double slope should not be a contact problem.

Investigating the effect of junction depth on cell characteristics at -135°C and 5 mW/cm^2 led to an optimization based on cell output and dark reverses, but in no way shed light on the broken knee problem. This problem was present to some extent in cells with the standard junction depth as well as in cells with twice the junction depth.

Since this broken knee does not seem to be correlated to the shallow junction used on standard 1 AU N/P cells, nor the Ti-Ag contacts, nor the P+ region, it may be, as seems to be the case for short circuit current non-linearity with temperature, a problem dependent upon the properties of the bulk silicon. Investigations of P+ cells fabricated from float zone silicon (low oxygen content and high dislocation count) and Mon-X silicon (low oxygen content and low dislocation count) did not show any changes in the broken knee problem, however, of the eleven Mon-X and float zone cells measured, all exhibited a more linear dependence of I_{sc} on temperature. In Figure 5 the short circuit current vs. temperature at 5.0 mW/cm^2 in a sunlight simulator is shown for float zone and Mon-X 10 ohm cm N/P cells with a P+ contact or region. The float zone and Mon-X cells were 1 x 2 cm, rather than 2 x 2 cm, so the current scale for the 1 x 2 cm cells was doubled in order to simplify comparison. Two solid lines describe the I_{sc} vs. temperature relationship for the float zone cells with the lowest and highest coefficients and the two dashed lines describe the same limits for the Mon-X cells. The I_{sc} of the best float zone cell decreased only .37 mA or 7.9% between 28°C and -135°C. The float zone cell with the largest change in short I_{sc} between 28°C and -135°C decreased .67 mA or 14.2%. The set of curves in Figure 6 show short circuit current vs. temperature for several crucible grown P+ cells. The range in short circuit current for 23 cells is shown at both -135°C and 28°C. Curves A and C exhibit minimum fall-off in short circuit current, 10% and 13%, while curve E shows the greatest fall-off for this group of 24 cells. It was only a single cell in this particular group; however, in some groups of cells this degree of short circuit current fall-off, 1.2 - 1.5 mA or 30 - 40%, is more frequent. Curves B and D represent some of the cells which fall in between 10% and 40% change in I_{sc}. The median I_{sc} decrease for the entire group of 23 cells is about .8mA or approximately 17% change. Table 3 shows short circuit currents for 10 Mon-X and float zone cells from Expt. 26 and 23 crucible grown cells from Expt. 25. These were the cells used for the curves in Figures 5 and 6 and to obtain the median for the crucible grown cells mentioned above.

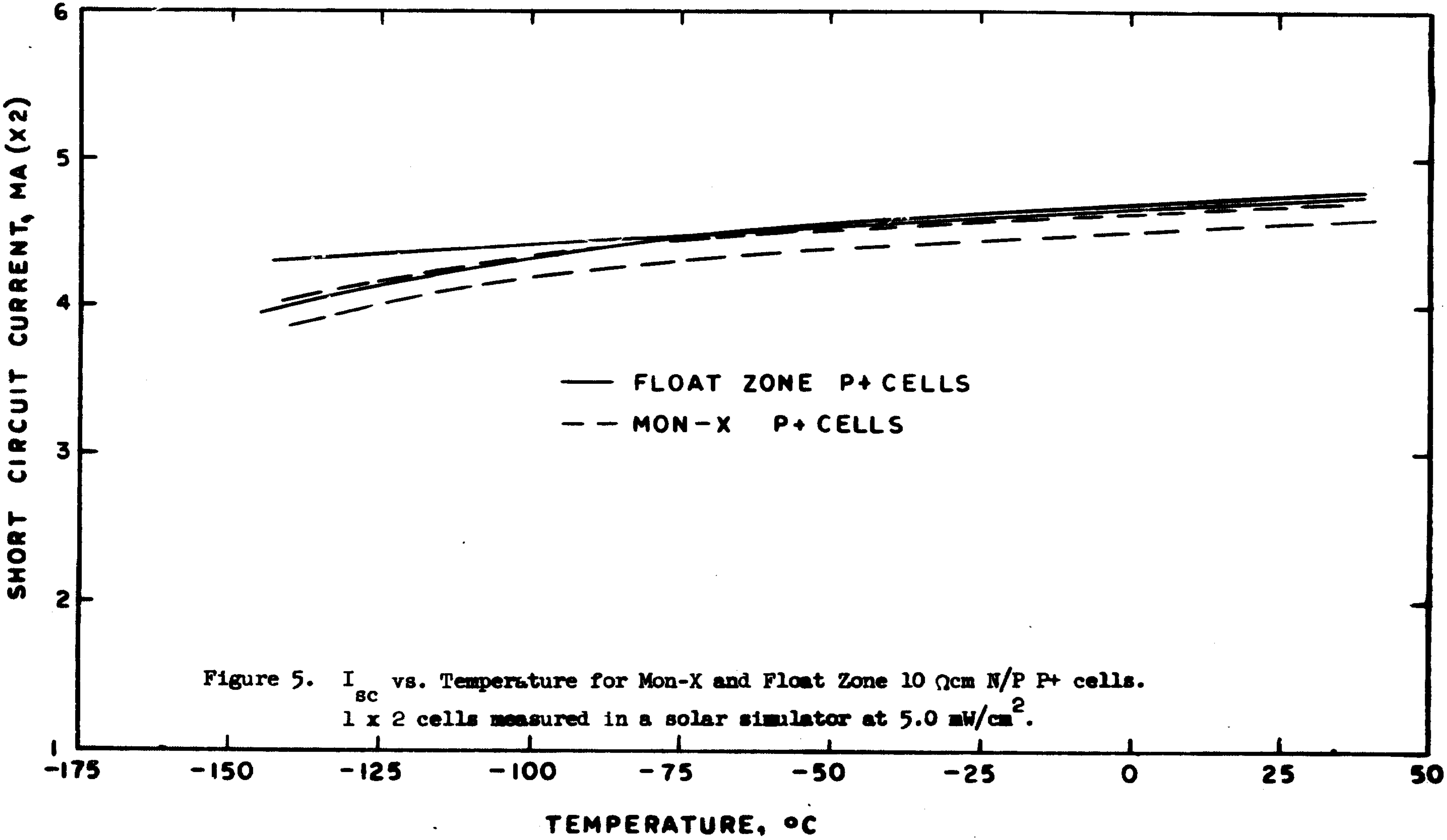

Figure 5. I_{sc} vs. Temperature for Mon-X and Float Zone 10 Ωcm N/P P+ cells.
1 x 2 cells measured in a solar simulator at 5.0 mW/cm^2.

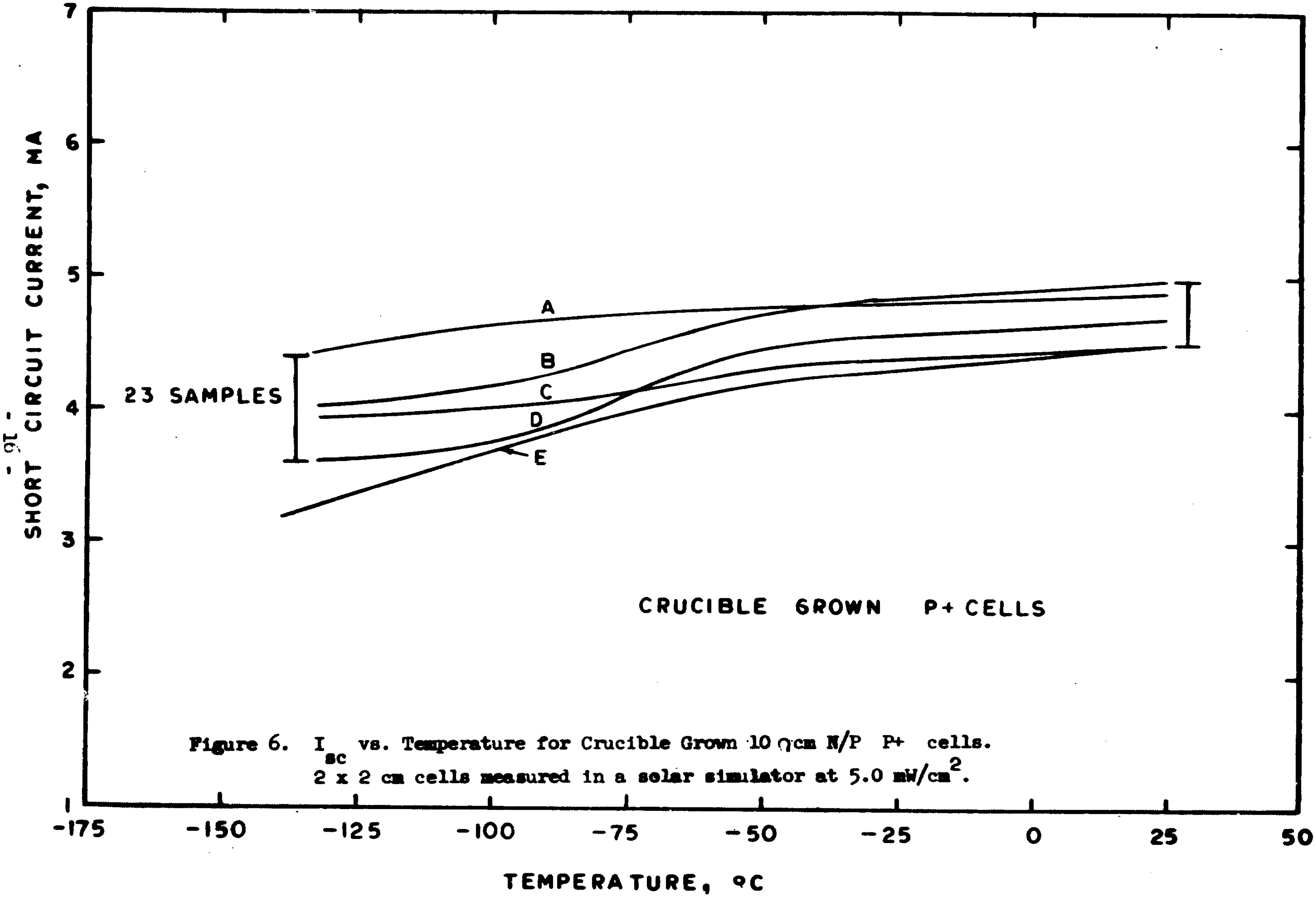

Figure 6. I_{sc} vs. Temperature for Crucible Grown 10 Ωcm N/P P+ cells.
2 x 2 cm cells measured in a solar simulator at 5.0 mW/cm^2.

The only difference between the Mon-X and float zone silicon and the crucible grown silicon besides oxygen content was the crystal orientation which was <100> for the crucible grown silicon and <111> for the Mon-X and float zone silicon. The orientation is not believed to be the important variable with respect to linearity of the I_{sc} vs. temperature relationship since some of the <100> crucible grown cells also exhibited only a 10% change in I_{sc}. This improvement in the I_{sc} thermal relationship for the crucible grown silicon is believed to be related to an impurity that is present. One theory proposed is that it might be a function of oxygen content. The broken knee problem was still observed in the float zone and Mon-X cells, so this effect could not be correlated to material type. Although extensive studies with float zone silicons were not able to be performed in the time available, it was noted that cells with no broken knee present had some of the highest efficiencies yet obtained. The cells shown in Figure 7 are float zone cells ranging from 15.2% to 16.8% efficiency at Jupiter test conditions.

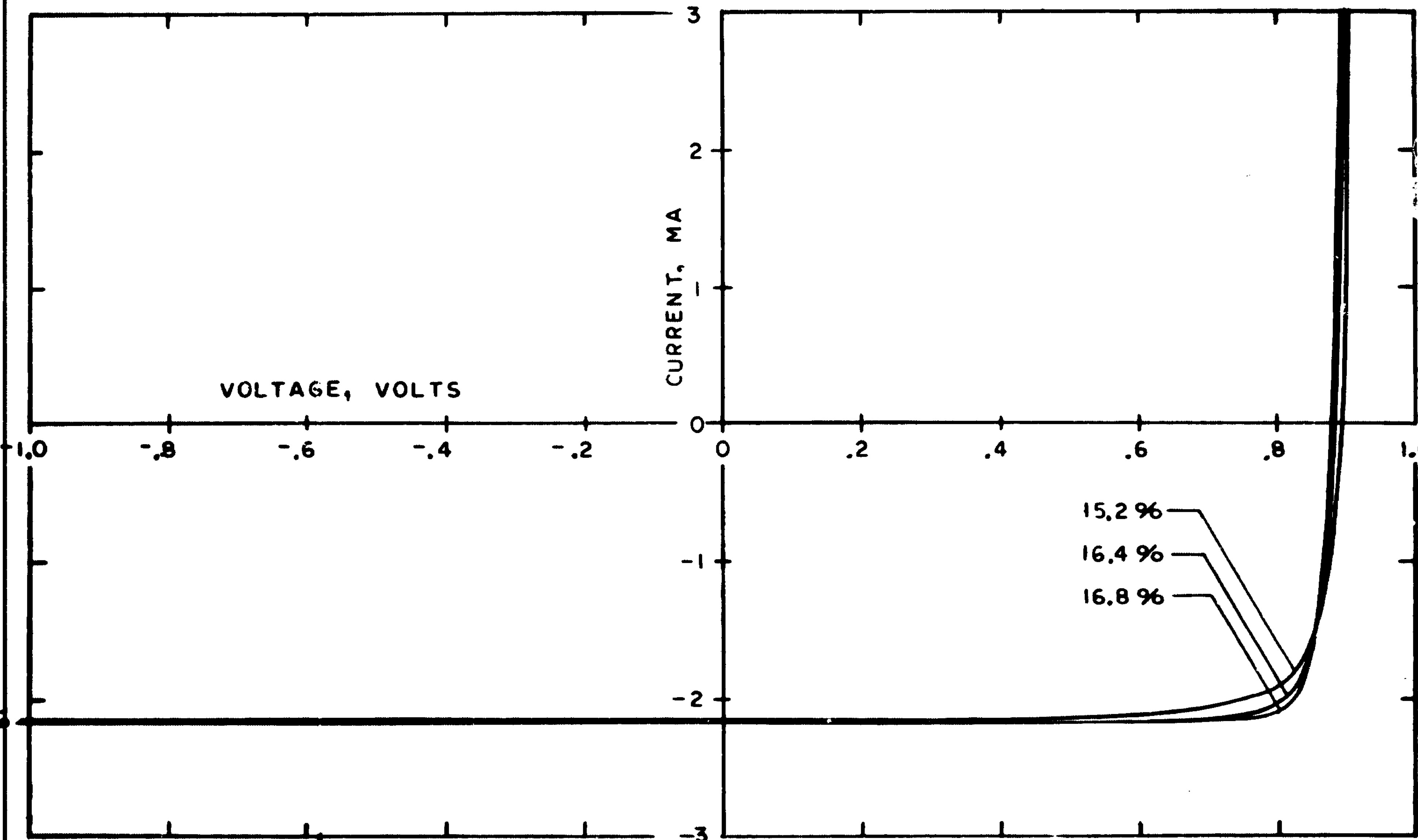

Figure 7. I-V Characteristic Curves of High Effeciency Float Zone 10 Ωcm N/P P+ cells. 1 x 2 cm cells measured in a solar simulator at 5.0 mW/cm^2 and -135°C.

TABLE 3

I_{sc} Of Cells At 5.0 mW/cm^2

	CELL NO.	28°C	-135°C	ΔI_{sc}	Δ%
FLOAT ZONE CELLS.					
	26-1	4.70	4.30	.40	8.5
	26-2	4.82	4.40	.42	8.7
	26-8	4.72	4.35	.37	7.8
	26-18	4.75	4.08	.67	7.1
	26-19	4.77	4.18	.59	14.0
	26-20	4.82	4.20	.62	12.8
MON-X CELLS.					
	26-9	4.60	3.92	.78	19.4
	26-11	4.85	4.20	.65	13.4
	26-12	4.60	4.00	.60	13.1
	26-13	4.65	4.05	.60	12.8
CRUCIBLE GROWN CELLS.					
	25-1	4.55	3.77	.78	17.2
	25-2	4.50	3.25	1.25	27.8
	25-3	4.60	3.80	.80	16.4
	25-4	4.48	3.90	.58	12.9
	25-5	4.5	3.60	.90	20.0
	25-6	4.70	4.13	.57	12.1
	25-25	4.70	4.03	.67	14.3
	25-26	4.78	3.93	.85	17.8
	25-27	4.70	3.80	.90	19.2
	25-29	4.80	4.02	.78	16.3
	25-45	4.80	4.02	.78	16.3
	25-47	4.75	4.18	.57	12.0
	25-48	4.70	4.18	.52	11.1
	25-46	4.83	4.03	.80	16.6
	25-13	4.80	4.10	.70	14.6
	25-14	4.60	3.70	.90	19.6
	25-15	4.70	3.60	1.10	23.4
	25-16	4.80	3.80	1.00	20.8
	25-17	4.80	3.90	.90	18.7
	25-35	4.90	4.40	.50	10.2
	25-36	5.00	3.90	1.10	22.0
	25-37	4.70	4.00	.70	14.9
	25-38	5.00	4.00	1.00	20.0
	25-39	4.90	4.0	.90	18.4
	25-53	4.88	4.27	.61	11.9

2.8 VOLTAGE-CURRENT CURVE

At -135°C and 5.0 mW/cm^2 the cells with good power outputs have correspondingly good fill factors - .74 - .89. Those with broken knees and low efficiencies have lower fill factors.

2.9 ENVIRONMENTAL EFFECTS

In an accelerated humidity test (65°C, 95% relative humidity) P+ cells with approximately 0.5 mils of solder withstand 60 hours exposure with no degradation. Heliotek's experience with standard N/P cells has shown that if cells can withstand 3 days at 65°C, 95% relative humidity, they will also be able to withstand 30 days at 45°C and 90% relative humidity. Using this as a basis, (since the 30 day test was not performed) the Jupiter cells are not expected to degrade after 30 days at 45°C, 90% relative humidity.

2.10 MAGNETIC CHARACTERISTICS

Aluminum, the only new material used, has no magnetic properties, therefore, the P+ cell for Jupiter, like standard solar cells, should have no magnetic properties.

2.11 WEIGHT

The average cell weight will be .300 grams which corresponds to an average thickness of .010". With this thickness average cell efficiencies of 13% can be obtained.

2.12 SIZE

Larger area cells would reduce cost, testing, and handling, however, they have not been investigated during this program since this is a minor change in cell design and only the more significant variables were able to be investigated. Therefore 2 x 2 cm cells will be used.

2.13 COVER GLASS

According to the RFP .006" fused silica coverglasses will be used for the Jupiter cell design.

2.14 INTERCONNECT FEASIBILITY

Cells will have the contacts covered with a thin layer (about 0.5 mil) of solder to provide humidity resistance. Standard techniques can be used for interconnections and as demonstrated by the pull test data presented in Section 2.4, the contacts will endure state-of-the-art pull-strength tests.

2.15 RELIABILITY PREDICTION ESTIMATE

The limited environmentals tests, contact pull tests and measurements performed indicate that the cell design selected meet the requirements specified for standard production space qualified N/P cells. Therefore, the reliability of this Jupiter cell design should in all respects be comparable to current production cells.

3.0 ALTERNATE DESIGNS CONSIDERATIONS

The work done so far on various types of P+ cells seems to indicate that oxygen content is an important variable with respect to linearity of the I_{sc} as a function of temperature. This is an important area to pursue as an alternate design since non-linear fall-off in I_{sc} and the broken knee problem are the most serious obstacles to overcome in fabricating high efficiency (15-16%) cells for Jupiter conditions. As long as either problem is present, there is going to be some difficulty in obtaining uniformly high output cells.. The measurements which have been done indicate that float zone rather than crucible grown silicon may have to be used in order to fully optimize cell I_{sc} at -135°C.

The dimensions of the bar on the N contact are being decreased in order to move the contact from near the cell edge to minimize leakage current and increase the active area to some extent. If a "zero gap" contact is needed then edge etching to remove the metal on the junction edge becomes a necessity. This would require tighter cell dimensions tolorances and extra fabrication steps.

More active area can be achieved by decreasing the number of grid lines in future designs, but at the present it is desireable to have good cell characterestics at high intensity for correlation measurement purposes.

Pd could be added to the front and back contacts to obtain a solderless humidity resistant cell for this application.

All the investigation during this program has been done on N/P cells. Radiation analyses conducted by Dr. R. J. Debs NASA/Ames have indicated that P/N solar cells, though they are more seriously damaged by electron irradiation than N/P solar cells at room temperature, show less damage at -135°C. Whether or not a P/N cell should be considered and selected would depend upon the significance of this radiation resistance difference, the level of radiation encountered on a Jupiter mission and the output advantage obtained with a P/N cell.

4.0 SUMMARY OF DESIGN SELECTED

The solar cell design selected from this study to be fabricated for a Jupiter mission will have the following characteristics and will utilize the fabrication procedures described. A crucible grown 10 ohm N/P cell with a boron-doped P region and a 1.0μ deep junction will be used. Al and Ti-Ag will be applied in a "one-step" evaporation to form a P+ contact on the back of the cell. A 6-grid configuration with a modified bar to reduce the possibility of high leakage currents has been selected for the front contact. The contacts will be sintered and solder covered (approximately 0.5 mil thick) using standard production procedures. Since the source of the broken knee problem has not been established and the problem has not been eliminated, the efficiency of these cells are expected to range from 11-15% with an average around 13%. Without the broken knee, this range would probably be from 13.0 to 16.5%.

The following are areas (not listed in order of importance) which have not been investigated or need further investigation and should be considered in future design activity:

1. P/N cells
2. Source of the broken knee
3. Float zone N/P P+ cells and the effects of oxygen content on low temperature I_{sc}
4. Optimization of grid configuration
5. Effect of resistivity (2 and 10 ohm cm cells have looked at but a comprehensive study of the effects of resistivity has not been made).
6. Effect of impurities on cell characteristics at low temperature and intensity.

References

1. Liebert, Curt H. and Hart, Jr., Russell E., "Solar-Cell Performance at Low Temperature and Simulated Solar Intensities", NASA TN D-5547, 1969.