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A PROGRAM CONTINUATION TO DEVELOP PROCESSING PROCEDURES FOR ADVANCED SILICON SOLAR CELLS

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16 Abstract

The new technology such as shallow junctions, aluminum back surface fields and tantalum pentoxide (Ta_2O_5) antireflection coatings, developed on NAS3-17350 (CR-134740), coupled with the development of a chromium-palladium-silver contact system, were used to produce a 2 x 4 cm wraparound contact silicon solar cell. One thousand cells were successfully fabricated using batch processing techniques. These cells were 0.020 mm thick, with the majority (800), made from nominal ten ohm-cm silicon and the remainder from nominal thirty ohm-cm material. Unfiltered, these cells delivered a minimum AMO efficiency at 25°C of 11.5 percent and successfully passed all the normal in-process and acceptance tests required for space flight cells.

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Table of Contents

LIST OF FIGURES

List of Tables

I. SUMMARY

The new technology such as shallow junctions, aluminum back surface fields and tantalum pentoxide (Ta_2O_5) antireflection coatings developed on NAS3-17350 (NASA CR-134740), coupled with the development of a chromium-palladium-silver contact system, were used to produce a 2 x 4 cm wraparound contact silicon solar cell. To demonstrate the applicability of the processes developed, a limited production run of one thousand (1000) cells was made on the Spectrolab space cell manufacturing line using formal documented procedures.

The cells were fabricated in lot batches of ninety-six (96), which was the maximum quantity that could be produced in a single contact evaporation. These devices successfully passed all the typical in-process and acceptance tests normally mandated for space flight solar cells.

Two hundred (200) cells were made from nominal 20 ohm-cm material in order to be evaluated for potential application on the Marshall Space Flight Center program "Solar Electric Propulsion Stage" (SEPS). The remaining eight hundred (800) devices were produced from nominal 10 ohm-cm silicon. All these cells were nominal 0.020 mm thick, and without filters delivered a minimum AMO efficiency at 25°C of 11.5 percent (124.5 mW). With the exception of a very small number of 20 ohm-cm cells, the cells delivered to the NASA-Lewis Research Center had curve factors of 0.72 or higher.

II. INTRODUCTION

This program is a continuation of the efforts begun on "Development of Processing Procedures for Advanced Silicon Solar Cells", NASA CR-134740. That phase of the program demonstrated that new technology such as more shallow junctions, refined grid collector patterns, improved antireflection coatings and incorporation of the back surface field concept could be combined to produce relatively thin (0.20 mm) high output (18 mW/cm^2 AMO at 25°C) planar silicon solar cells.

Some preliminary work oriented towards wraparound contact silicon solar cells was also initiated, but the results, although encouraging (15 mW/cm^2), indicated that more intensive efforts were necessary in order to develop an advanced wraparound contact silicon solar cell. Furthermore, it had been established on a previous NASA-Lewis Research Contract (NASA CR-121021) that the space qualified titanium-palladium-silver contact system created serious difficulties in volume production of wraparound contact cells because of the relationship between titanium adherence to the silicon edge and evaporation angle.

The purpose of this contract continuation was to develop a high efficiency (11.5 percent AMO at 25°C), large (2 x 4 cm), thin (0.20 mm) wraparound contact cell that could be produced in volume and which would be capable of meeting those tests mandated for space flight planar silicon solar cells. To accomplish these goals, it was necessary to develop and qualify a new contact system that avoided the problems encountered with the titanium based system and then to make it compatible with previously developed advanced cell technology.

In general, the goals of the contract were met with respect to developing a manufacturing process since one thousand 0.20 thick 2 x 4 wraparound contact cells with a chromium-palladium-silver contact system were produced using the standard Spectrolab cell fabrication facilities.

Differences in electrical testing techniques did however indicate that the minimum efficiency goal of this program may not have been achieved in all cases for every cell, due to differences in the measurement temperature and the value established for AMO. This deviation in measured output between Spectrolab and NASA-Lewis points out the necessity for a formal exchange of standard solar cells between the two organizations so that a mutually acceptable value of cell output can be established as an initial phase of any future program. It should be pointed out that the differences observed do not imply that the processing techniques developed were not capable of achieving the program objectives.

III. CONTACT METALLIZATION SYSTEM DEVELOPMENT

In our previous work in wraparound contact silicon solar cells two significant problems were encountered; 1) poor adherence in the wraparound region of the silver-titanium-palladium contact and 2) an inferior fill factor which counterbalanced the gain in output achieved from the increase in active area. It was possible that the two problems were related, but since better fill factors had been achieved for wraparound cells made from lower resistivity (2 ohm-cm) silicon it was more likely that the latter problem involved the design of the wraparound cell itself.

The adherence problem was solved for 2 x 2 cm cells made on NASA Contract NAS3-15344 by using a two-step contacting process. The edge contact was formed initially using tooling that allowed metallization to be made at normal incidence to the cell edge. A second step was needed to deposit the front and rear surface contacts. A truly viable process suitable for large scale production had to be capable of providing all metallization in a single deposition step with only one type of tooling.

For this reason we investigated alternate metal systems which hopefully would not be as susceptible to angle of incidence effects as the conventional silver-titanium-palladium system. The key to the wraparound cell is an adherent contact. Once this was achieved, the fabrication of space qualified wraparound contact silicon solar cells would be routine, since all the technology for producing high efficiency cells was available from the first part of this program.

An investigation of the literature indicated that some work had been done on a chromium based contact system for silicon.(1) It was decided to investigate the possibility that substitution of chromium for titanium might eliminate the angle of incidence problem experienced in our previous work. An electron beam evaporation system for contact depositions was set up. This chamber used a 270° electron beam gun and had four-pocket crucible which allowed a great deal of flexibility in our choices of metal for the contact system. Preliminary tests were made using tooling from NAS3-15344 and NAS3-17350.

A. Chromium Evaluation - Adherence and Electrical

The chromium-silver contact system was characterized with respect to adherence and electrical properties. The amount of chromium was varied from zero to 3000Å keeping the subsequent silver thickness at 4.0µm. A standard 6 gridline 2 x 2 cm contact configuration was employed. The metals were evaporated from the multi-pocket crucible by electron beam heating. No attempts were made to deliberately heat the silicon solar cells during evaporation.

All contacts were tape tested using #600 Scotch Brand Tape, which exerts a much greater force on the contacts than does the standard #810 tape. (390 gms/cm vs 340 gms/cm). Those contacts with no chromium, and very thick chromium (2000Å) peeled easily. However in all cases when chromium was deposited, the failure took place at the chromium-silver interface, indicating an extremely tenacious bond between the chromium and the silicon.

Since it was planned to use a rotating substrate for the wraparound cells, it was necessary to investigate the effect of varying the angle of incidence between the source and the silicon solar cell. Cells were held in tooling formerly used to produce 2 x 2 cm wraparound cells on NAS3-15344, and the tooling was mounted at a fixed angle to the crucible. These samples showed evidence of partial peeling especially at the wraparound region of the contact.

Silicon structures with chromium only contacts were fabricated and sintered in hydrogen for a few minutes at $\sim$600°C. Visual inspection revealed that the chromium film was reduced from its former smooth and shiny metallic state to a rough and porous black deposit. Similar structures were heated in air at temperatures up to 500°C for periods of minutes. The chromium film retained its structural integrity, but the surface color changed from dark brown to a light gold, evidence that an oxide of chromium had developed. Cells were made with chromium-silver contacts and baked in air for several minutes at 500°C. Edge adherence was dramatically improved insofar as tape peel tests were concerned.

Solar cells made with no post heat treatment of the Cr-Ag contacts were electrically tested. The short circuit current and curve fill factor were similar to cells made with conventional silver-titanium contacts. The values of open circuit voltage were low, but the same behavior is observed with unsintered Ag-Ti contacted cells. When sintered in hydrogen using conventional times and temperatures the open circuit voltage of Cr-Ag cells degraded severely. Shallow junction (ρ_s = 120 ohms/□) cells were fabricated with chromium-silver contacts and heat treated in air. The cell I-V curves showed no evidence of curve factor degradation which is not typical for sintered silver-titanium contacts on shallow junctions.

A more thorough examination of the chromium based contact system was initiated based on the rather encouraging results obtained. Nominal two ohm-cm cells with chromium-silver contacts were fabricated in order to evaluate the influence of post contacting heat treatments. The diffusion schedule yielded sheet resistance values of $\sim$120 ohms/□ in keeping with the requirements of this program.

Groups of cells were heated in ambient at various temperatures and times. At a temperature of 480°C the cells attained their maximum power output within fifteen seconds, and after a period of between two and three minutes they began to show a power loss. At 400°C the same pattern was observed except it took longer to achieve maximum output ($\sim$30 sec.) and correspondingly longer (5-10 minutes) to begin to degrade. At 320°C maximum output was achieved after two minutes and there was no sign of power reduction after 30 minutes of further heating.

In all cases the main reason for power improvement after baking was an increase in open circuit voltage. The initial mode of degradation after prolonged heating was a change in cell curve factor. Further heating caused the curve fill factor to degrade more severely, and in extreme cases there was a loss in open circuit voltage. In order to understand the degradation mechanism, cells were characterized prior to heating with respect to reverse leakage, and series resistance.

Test cells were heated at 480°C in one minute intervals with the above mentioned parameters measured after each cycle. There was no significant change in reverse leakage, but there was a steady increase in cell series resistance after each heating cycle. After five minutes the cells had degraded seventeen percent from their maximum output value and the series resistance had increased from 0.1 ohm to 1.1 ohm.

The increase in series resistance is felt to be due to a reaction between the chromium and air which results in the formation of high resistance oxides of chromium at its interface with the silver contact layer. This is consistent with the previous observations made on chromium films heated in ambient.

B. Chromium Contact System - Humidity Resistance

Eleven cells contacted with chromium-silver contacts were placed in a chamber for a thirty-day temperature and humidity test. Prior to this the characteristic curve of each cell was recorded. Additional cells with both chromium-silver and titanium-silver contacts were fabricated from the same batch of cells for controls. All cells in the test were heated for one minute at 400°C to optimize their power output. The chamber was programmed to provide a temperature of 45 ± 5°C, and a relative humidity of 95 ± 5 percent for the thirty days.

After completion of this test all samples exhibited catastrophic degradation in electrical output. Short circuit current was unaffected, but the fill factor was severely reduced and in some cases there was a loss in open circuit voltage as well. Figure 1 is a typical example of a Cr-Ag cell after the thirty-day humidity test.

It can be seen that the series resistance of the test cell has increased significantly. The test results are consistent with the observations made on similar cells that were deliberately degraded by exposure to high temperature (480°C) for long periods (5-10 minutes) in air.

After electrical tests the contacts were tape peel tested using Scotch Brand #600 tape. The silver layer from both front and rear contacts was totally removed, leaving only the chromium. The chromium layer showed evidence of discoloration which is attributed to oxide formation.

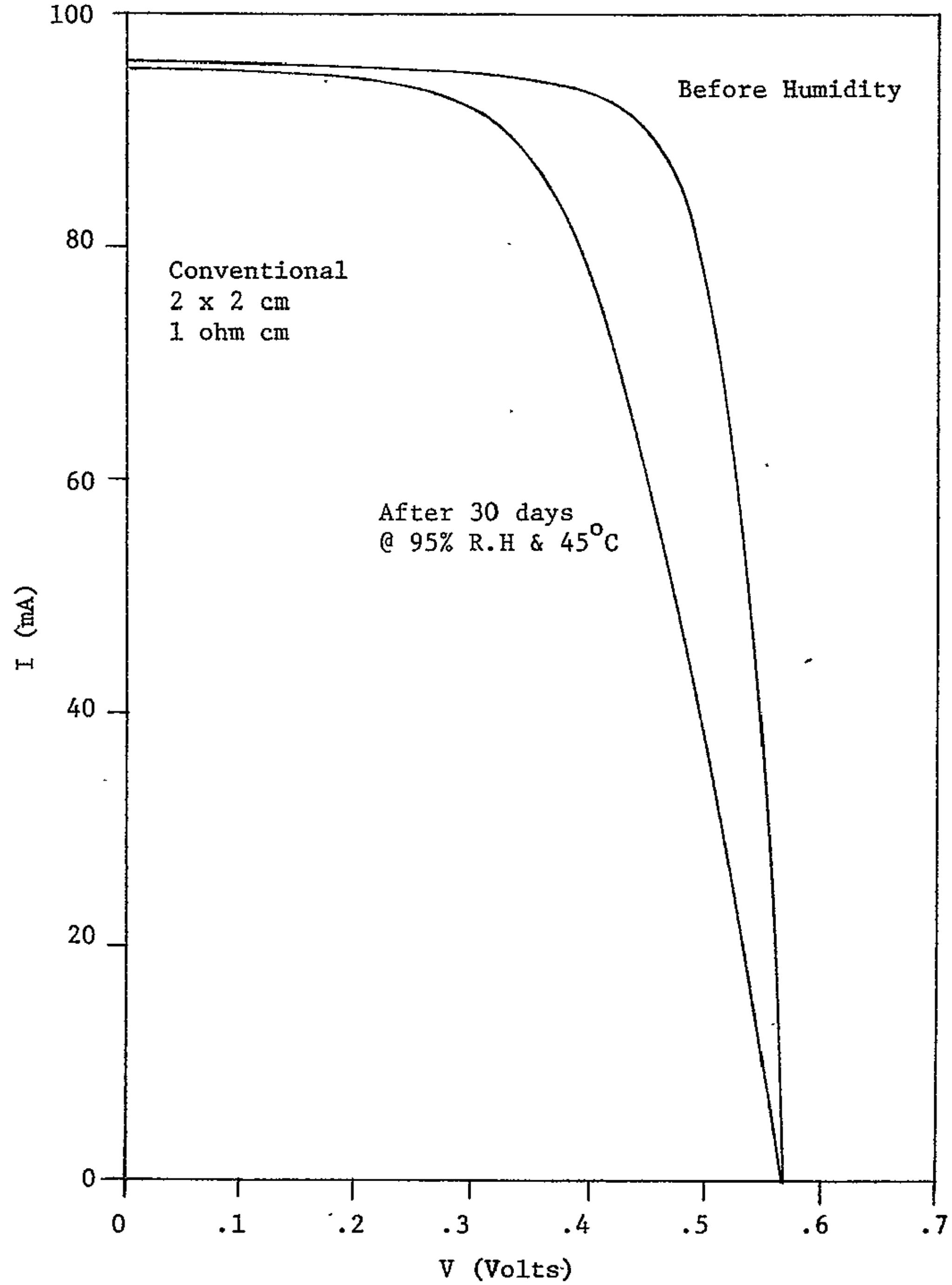


Figure 1. Cr-Ag Contact Test Sample I-V Characteristic Curves Before and After Humidity

Since all cells that underwent testing had been heat treated in air, it was decided to examine the influence of other ambients. Cells were contacted with chromium-silver and separate groups were post treated in air, helium and hydrogen, in all cases the heating cycle was six minutes at 400°C. The effective time that the cell is actually at temperature is only a small fraction of the cycle time, hence six minutes at 400°C in a furnace does not correspond to six minutes on a hotplate at the same temperature. All three groups of cells exhibited similar electrical characteristics after heating, thus arguing that it is heat rather than ambient conditions that is responsible for the formation of a low resistance ohmic contact using this particular metallization system.

These three groups of cells were placed in the humidity chamber for testing. After seven days they were removed and tested electrically. The data, presented in Table 1, show a significant difference between those cells heated in air versus the groups done in either a reducing or an inert ambient. A detailed analysis of the group 1 cells is given in Table 2. Although all cells are degrading, there is a wide variation within the group.

As has been pointed out previously the key technical problem of this program is developing a contact that adheres to the wraparound edge of the cell. Since there appears to be a significant problem with the chromium-silver system, alternate solutions to this problem were considered.

C. Alternate Contact Systems

Titanium-aluminum wraparound contact cells had been made on previous contracts. These contacts proved capable of passing the standard tape peel tests and in addition they demonstrated humidity resistance (30 days 45°C 90% R.H.). However, it remained to be seen that this contact system would be compatible with shallow junctions. Another system, Cr-Ni-Ag, was also evaluated.

Shallow junction cells (ρ_s = 120 ohms/□) with Ti-Aℓ contacts were successfully fabricated. A vitreous carbon crucible liner was used to reduce the e-gun power required to evaporate Aℓ. The electrical characteristics of these cells, I-V curves and dark reverse leakage current, were monitored before and after Ta_2O_5 A.R. coating, where the cells are heated to approximately 200°C, and then again after a post deposition air bake at 300°C. No measurable degradation in curve shape resulted from either of these relatively high temperature processes, although slight increases in leakage currents were recorded as tabulated below.

Average of 18 cell test group with Ti-Aℓ contacts	110 μA	
After A.R. coating	131 μA	(I(dark reverse @ V = 1.0V)
9 cells baked 30 sec @ 300°C	143 μA	
9 cells baked 1 min @ 300°C	200 μA	

Table 1. Humidity Test 45°C 95% RH

Ambient	I_{sc} (mA)	V_{oc} (mV)	I_{460} (mA)	Time (days)
Air	96.6	576	91.4	0
	97.2	575	75.6	7
Helium	96.8	572	90.6	0
	97.8	571	90.6	7
Hydrogen	101.2	573	94.6	0
	101.2	574	94.8	7

Table 2. Air Baked Group Humidity Test

Cell	I_{sc} (mA)	V_{oc} (mV)	I_{460} (mA)	Time (days)
1	97	573	92	0
	97	571	40	7
2	96	573	92	0
	97	571	73	7
3	96	580	90	0
	96	580	87	7
4	96	580	91	0
	97	580	89	7
5	98	576	92	0
	99	576	89	7

Increased leakage current, in this case, probably indicates shunting caused by the migration of $A\ell$ or Ti through the junction; however, the worst case value of 200μA is still negligible. Decreasing baking time to 30 sec. results in a .7% loss in short circuit current due to absorption in the A.R. coating. This loss is not offset by the improvement in curve shape attributed to 57μA less leakage current. Typical I-V curves of a cell from this test group showing the results of coating and baking are shown in Figure 2.

Two groups of solar cell test samples were fabricated, one group with chromium-nickel-silver contacts and the other with nichrome (80% Ni/ 20% Cr) - silver contacts. Following various post deposition heat treatments at 300° or 400°C in helium or hydrogen, all cells in both groups were equivalent electrically to similar cells with conventional contacts. In addition, all cells passed #600 tape pull testing both before and after heating. After seven days in humidity (65°C - 95% RH) the electrical characteristics of all of these cells degraded severely, a not surprising result since there was gross peeling front and back, when tape pull tested. Obiously, an intermediate layer of nickel does not provide the passivation obtained with palladium, nor is the nichrome alloy any more resistant to humidity effects than pure chromium.

D. Passivated Cr-Ag Contact System

Another possibility was to examine passivation of the Cr-Ag system. Cells were fabricated with chromium-palladium-silver contacts. A screening test was developed which involved subjecting the cells to steam for periods up to seven hours. These cells successfully withstood this test. Samples of Cr-Pd-Ag contacted cells were then placed in the humidity test chamber where they were monitored weekly for evidence of electrical degradation.

Six groups of cells completed 30 days of humidity testing (45°C, 95% R.H.), during which time the electrical output of each cell was measured weekly. Following the final electrical measurements, all cells were subjected to tape pull testing with #810 tape.

Of the six groups tested, five had Cr-Ag contacts. Following deposition two of these groups had been heat treated in hydrogen, two groups in air, and one in helium. The sixth group of cells has passivated Cr-Pd-Ag contacts and had been post treated in hydrogen. Data showing the average degradation in output power of each group data are tabulated below.

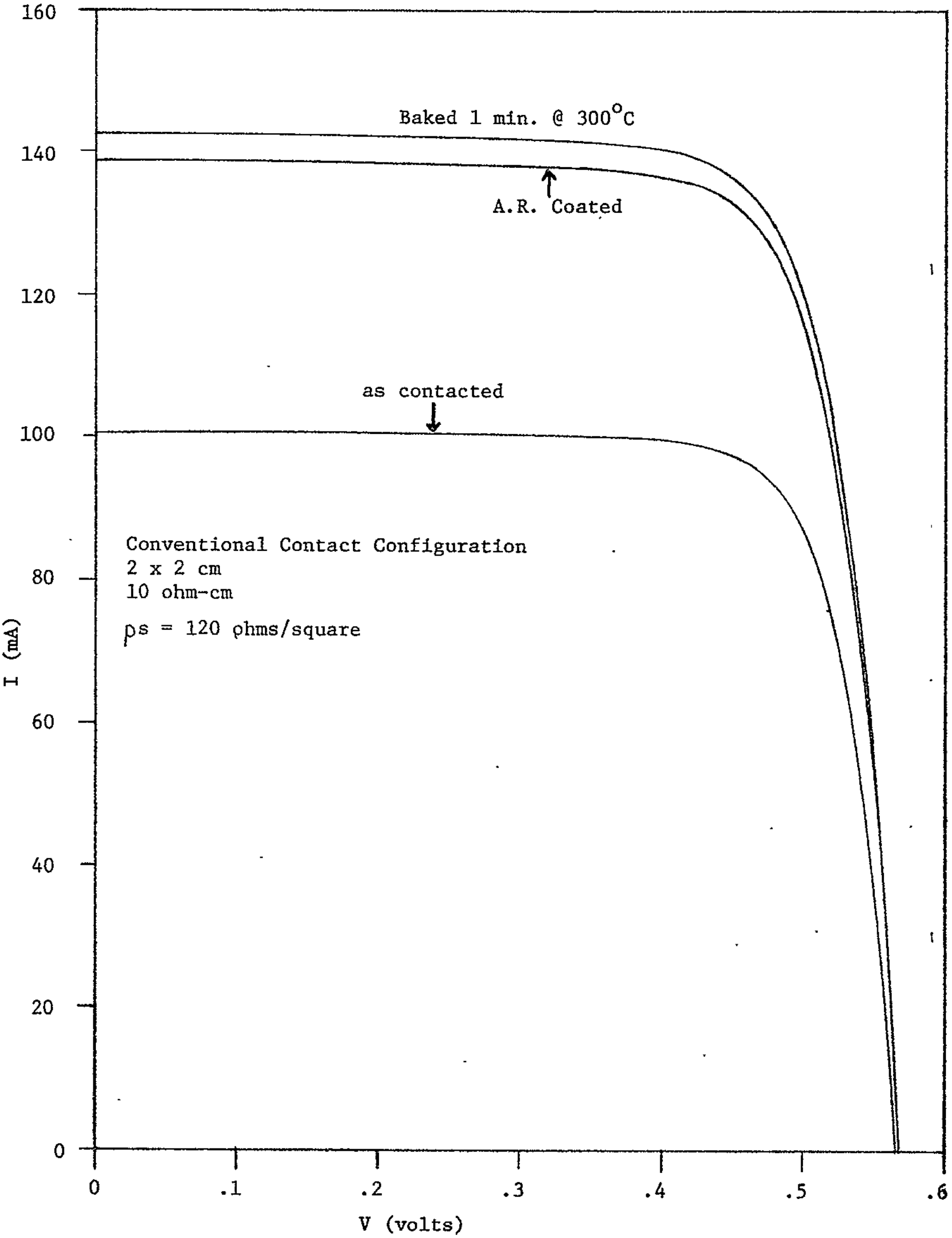


Figure 2. Ti-Aℓ Contact Test Sample I-V Characteristic Curves

Type of Cell Contact	1 Wk.	2 Wk.	3 Wk.	30 Days
Cr-Ag (air)	-17%	-26%	-26%	-29%
Cr-Ag (air)	-56%	-60%	-56%	-64%
Cr-Ag (hydrogen)	0%	-2.1%	-2.5%	-3.4%
Cr-Ag (hydrogen)	-2.7%	-3.0%	-3.8%	-10.3%
Cr-Ag (helium)	0%	-2.4%	-1.9%	-1.8%
Cr-Pd-Ag (hydrogen)	0%	0%	0%	0%

The air baked Cr-Ag groups degraded severely, a result identical to that obtained previously in the first humidity test. Changing to a non-oxidizing atmosphere during post contact deposition heat treating improved the humidity resistance of Cr-Ag contacts, and one such group, heated in helium, met the required goal of less than 2% average degradation. Figures 3 and 4 show typical before and after I-V characteristic curves of cells from the air baked group and the helium baked group respectively. In both cases, though to much different degrees, power has been lost because of the damaging effect on curve shape caused by series resistance. The passivated Cr-Pd-Ag group did not degrade measurably in this test.

When tape pull tested all the Cr-Ag contacted cells peeled extensively. In every case silver separated from a plainly visible chromium layer which remained firmly attached to the silicon. The newly exposed chromium surfaces of the air baked cells were a very definite golden color as opposed to the chromium surfaces of the helium and hydrogen baked groups which retained their original metallic appearance. There was little difference in the extent of peeling between groups. Front contacts lost 90% to 100% of their silver while back contact generally lost 15% to 25%. The Cr-Pd-Ag cells passed tape pull test with no damage. These cells were then subjected to a more severe #600 tape pull test (>390 gms/cm) which they also passed, although some slight lifting of silver along the edges of some gridlines was observed.

Based on the humidity test results it appeared that Cr-Ag contacts would not be suitable for this program. Even though one group of cells which had been heat treated in an inert atmosphere met the electrical performance requirement of less than 2% average degradation in power, every Cr-Ag cell tested suffered catastrophic failure when tape pulled. No other changes in the Cr-Ag deposition or heat treating processes which might improve humidity resistance were apparent at this time.

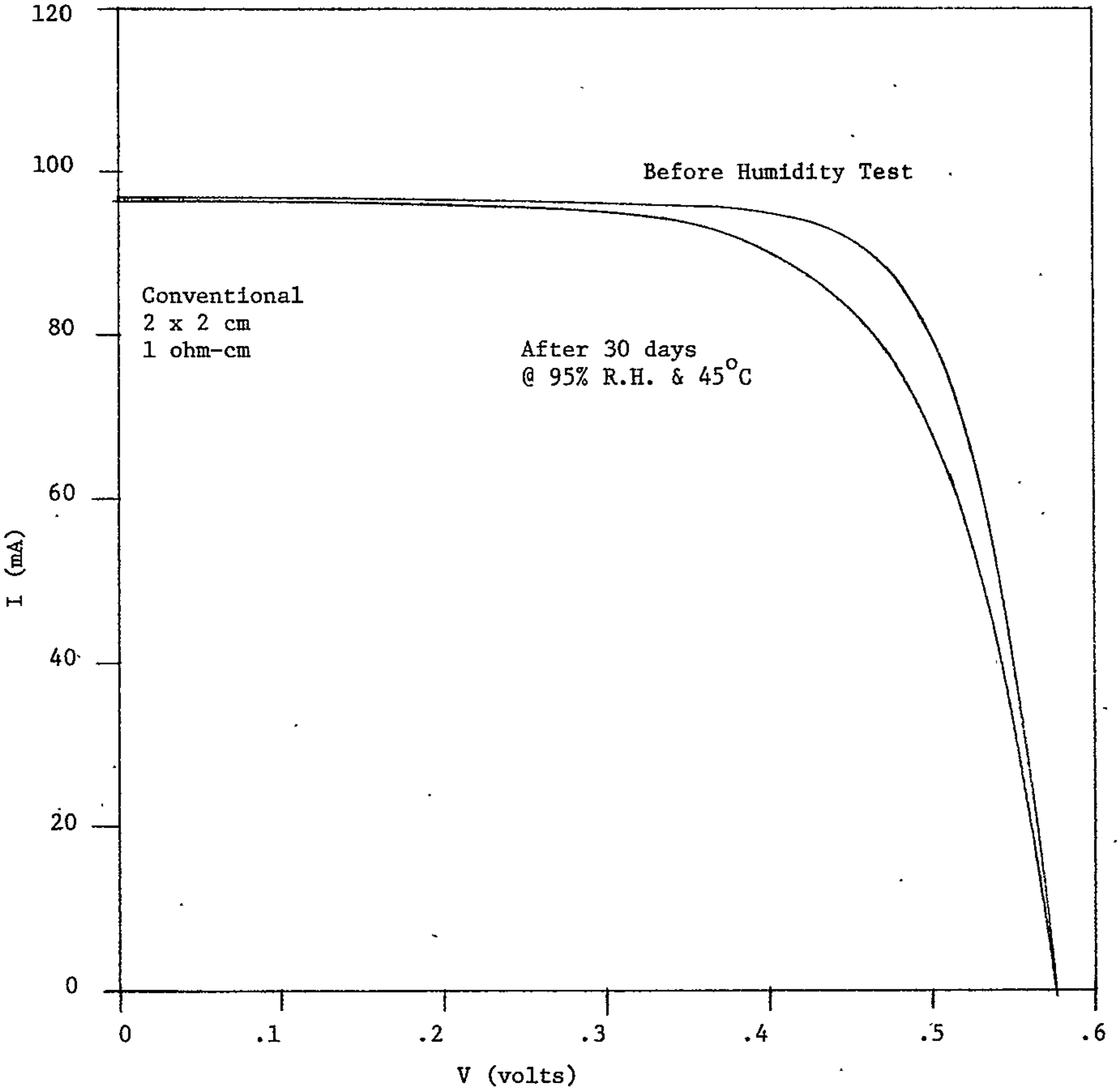


Figure 3. Air Baked Cr-Ag Contact Test Sample I-V Characteristic Curves Before and After Humidity Testing

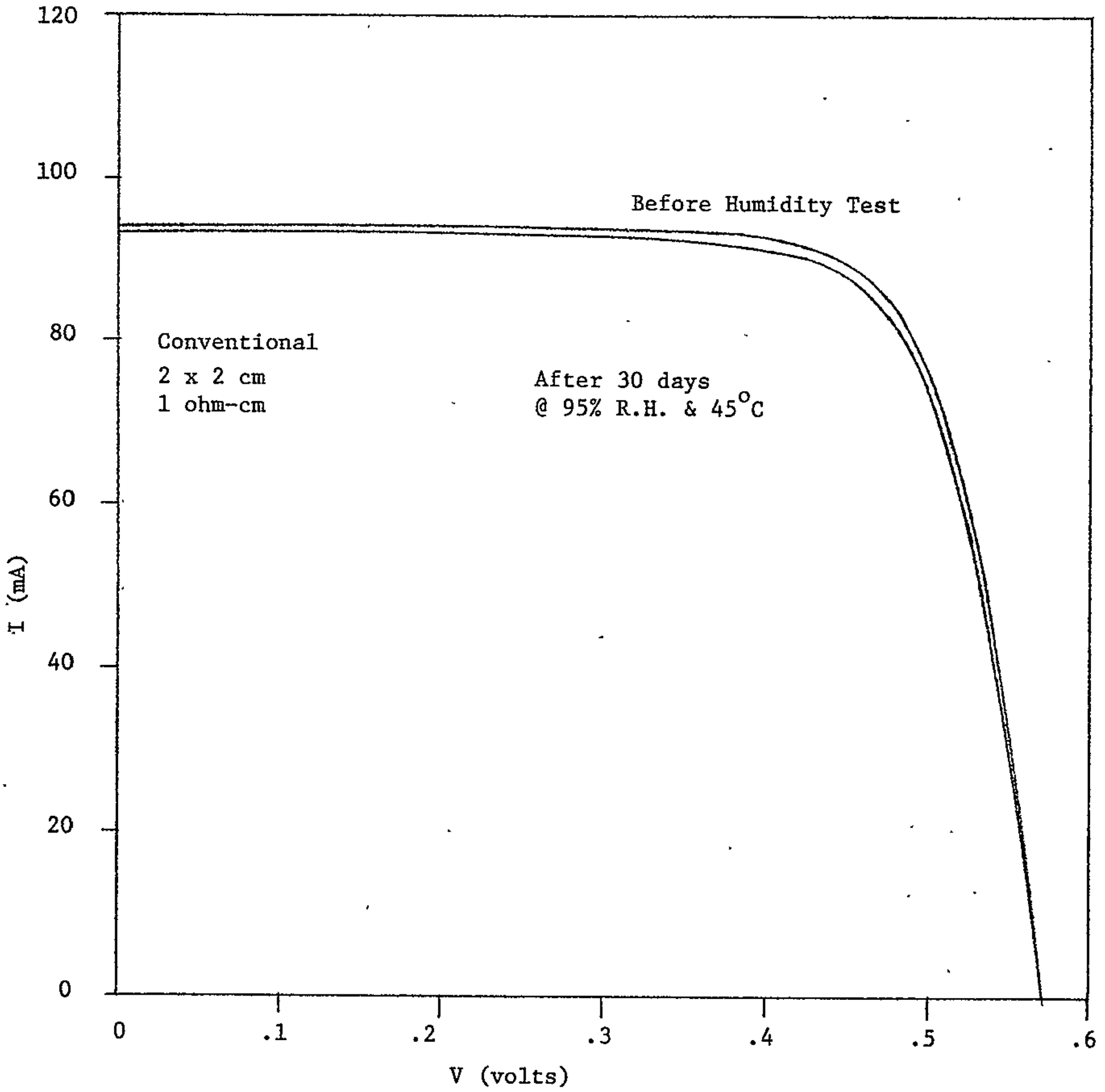


Figure 4. Helium Baked Cr-Ag Contact Test Sample I-V Characteristic Curves Before and After Humidity Testing

Based on these results it was decided to employ a chromium-palladium-silver (Cr-Pd-Ag) contact system for the fabrication of the advanced wraparound contact silicon solar cells. As a final check two groups of cells using this metallization system were subjected to an extreme humidity test run at 65°C and 95% R.H. for 30 days. One group of cells had back surface fields, the other was fabricated conventionally. Average degradation in power output at various time intervals during the test is tabulated below.

Days in Test	Avg. Degradation (%)
4	0.6
13	0.7
30	1.2

Following 30 days in humidity testing these cells were tape pull tested with no evidence of peeling. There was no noticeable difference in cell behavior between the conventional and back surface field cells during the test.

IV. CELL DESIGN

An internally written Spectrolab computer program CONTACT, based on the work of M. Wolf(2), was used to derive an optimized grid collector structure based on the electrical requirements of this contract. Preliminary data showed that for a 2 x 4 cm cell with a front spine configuration the number of grids required was between 7 and 8 per centimeter. These grids could be as narrow as .03mm. This particular configuration assumed that silver will be the predominant metal in the contact system.

In the first step, "CONTAC" was used to calculate an ideal contact configuration providing maximum cell output. In this calculation the program examined the impact of grid design on active area (current) and series resistance (curve factor) in order to maximize the output. Required input data included sheet resistance (in this case, 120 ohms/□), anticipated short circuit current density, open circuit voltage, desired test voltage, and contact thickness and resistivity.

Since ideal configurations are not always practical, i.e. grid widths less than .025mm, a second diagnostic program, OUTPUT, was also used for comparing the impact on cell output of grid configuration variables. This program was derived from the previously referenced CONTAC, and provided a first order cell I-V characteristic curve using input variables mentioned above, along with gridline number and width. In this manner more practical configurations were examined and compared to an ideal configuration.

The result of this study indicated that a best design should consist of .05mm wide grids placed to provide 15 per 2 cm length and terminating at a bar bisecting the cell along the major dimension. This configuration had the potential to provide a curve factor of .78, not including degradation due to the loss of back contact area. The front surface contribution to the cell series resistance was approximately .13 ohms. By minimizing the rear contact loss it was felt that a final curve factor of .72 minimum was achievable.

The back contact pads were configured to be 3 x 2.3mm each to decrease series resistance, thereby improving curve fill factor to the 0.72 requirement of the contract. The configuration of the cell is given in Figure 5.

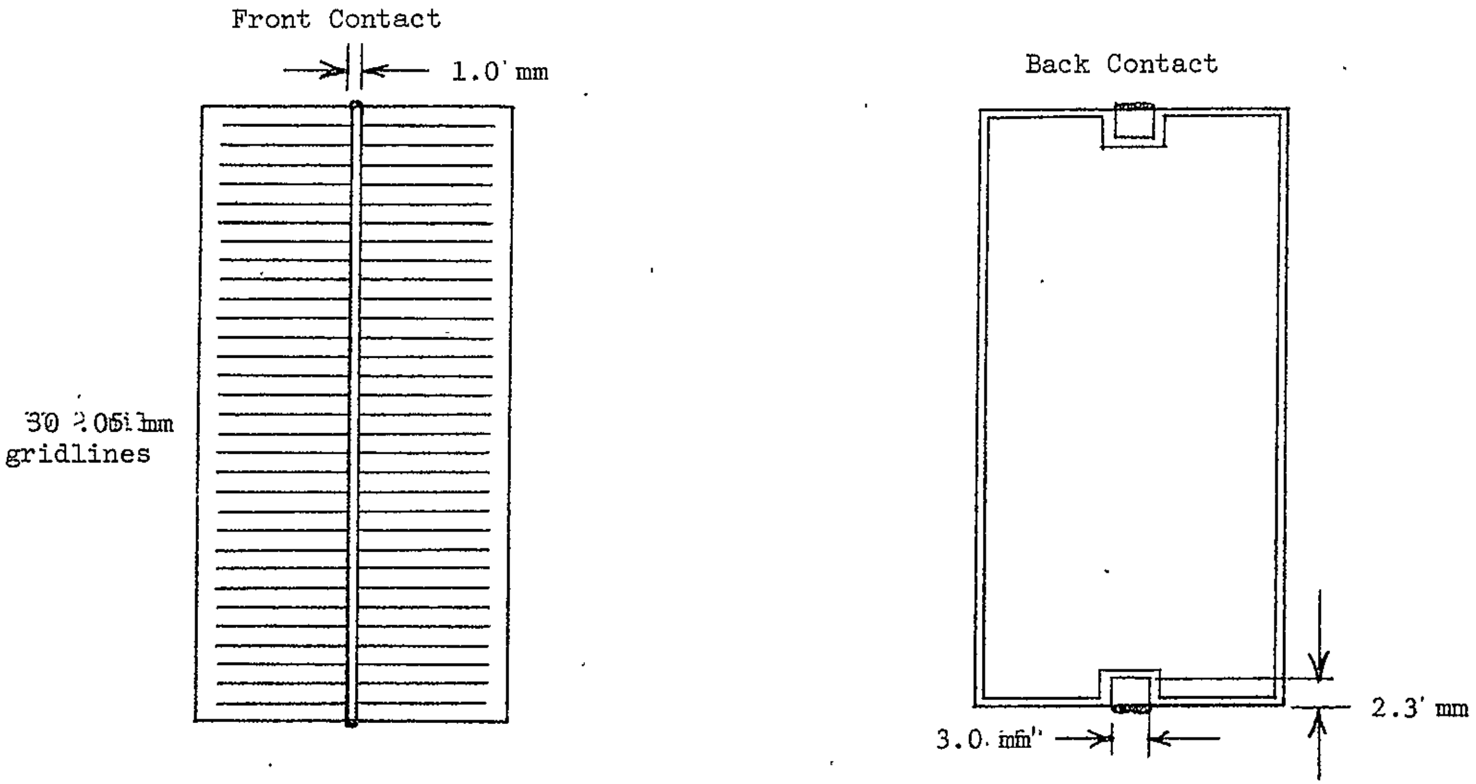


FIGURE 5. WRAPAROUND CONTACT CONFIGURATION

V. PRODUCTION EQUIPMENT

In order to meet the batch lot requirements of this contract, namely at least fifty (50) 2 x 4 cm wraparound contact solar cells per lot, it was necessary to employ production line equipment. In certain cases, such as contact evaporation, existing facilities could be directly used. For the aluminum deposition it was necessary to design and build a holding fixture that could provide uniform aluminum coverage for eighty (80) cells in a single evaporation. The tantalum pentoxide antireflection coating required the construction of modified cell holders to avoid covering the main current carrying front spine with AR materials.

A. Production Evaporator

Spectrolab's latest production evaporator was evaluated for the pilot line phase of this program. Unlike conventional coaters, this evaporator, Airco Temescal Model VV-400 employs dynamic rather than static fixturing. The substrate holder is a drum, and as it rotates, each cell is exposed to the evaporating metal. This method of evaporation, properly tooled, can deposit metal on the edges of wraparound cells in a uniform fashion, thus eliminating the need for a separate evaporation to coat the cell edges.

Wraparound cells contacted with titanium-silver have been made using this coater, but the adherence of the edge contact was substandard because a great majority of the metallization was deposited at non-normal incidence angles. For the preliminary checkout, dummy wafers of both 2 x 2 and 2 x 4 cm silicon were used with their appropriate wraparound tooling, full edge coverage in the 2 x 2 case and a narrow strip in the 2 x 4 cm configuration.

Both chromium and silver were evaporated from a water cooled crucible using electron beam heating. Because the system is rotating, the condensation rate of both metals was extremely high, $\sim$150 Å/sec for chromium and $\sim$500Å/sec for silver. The contact system consisted of a layer of approximately 500 Å of chromium followed by 2 μm of silver. In actual production, the silver thickness was between 4 and 6 μm.

The adherence on the chromium-silver contacts was similar to the previous results reported, poor edge adherence prior to heating. However after heat treatment in ambient, the edge contacts were extremely tenacious, showing no evidence of peeling when tested with #600 Scotch Brand adhesive. From these preliminary tests we concluded that the new contact evaporator could be successfully employed during the pilot production phase of this effort.

A group of 2 x 4 wraparound contact cells were then fabricated using the rotating drum evaporator to deposit chromium-palladium-silver contacts. The cells were nominal two ohm-cm, 0.30mm thick with sheet resistance value of 120 ohms/□, but they did not have back surface fields. After AR coating with Ta_2O_5 they averaged slightly higher than twelve percent efficiency under AMO test conditions (25°C). These cells were electrically equivalent to similar cells made with conventional titanium-palladium-silver contacts.

The cells were measured before and after testing with Scotch Brand #810 tape. No peeling of the contacts was observed, and there was no change in electrical output. A typical I-V characteristic curve is shown in Figure 6. Other test samples (wafers only) were contacted in another deposition run and tested with Scotch Brand #600 tape, which has a greater adhesion value (390 gms/cm vs. 340 gms/cm). Repeated testing showed no apparent contact peeling, either on the surface or the edges of the cells.

Based on these results, tooling to allow ninety-six (96) cells per pumpdown to be contacted was procured. Figure 7 shows the coater fully loaded for a wraparound contact deposition run.

B. BSF Tooling

The back surface field process required that one side of the silicon wafer be coated with relatively thick aluminum which acts as an acceptor source. For a conventional BSF cell this is accomplished by placing the parts on a plate and depositing aluminum from a heated filament source.

The wraparound cell requires that only certain portions of the back surface be coated with aluminum. Thus the parts must be mounted in special tooling to achieve the desired pattern. This reduces the number of parts that can be coated in a single deposition run.

For this reason we initiated an experimental investigation to determine the feasibility of obtaining a back surface field using thick film aluminum paste deposited selectively by silk screen printing. This technique had already been developed successfully for deep junction etched surface cells.(3) Preliminary work, however, indicated that contaminating elements in the same commercially available paste (such as Englehardt #3113 aluminum molecular bonding ink) created a condition that was incompatible with the extremely shallow junctions required for this program.

Efforts were therefore concentrated on improving the technique for evaporating aluminum using conventional resistance heated filament sources. New tooling was designed and fabricated to allow eighty 2 x 4 cm cells to be aluminized in a single pumpdown. This tooling is a patterned metal shell consisting of seven plates, each holding eight cells, and four plates, holding six cells each, that fits completely around the filament coils, which are centered along its major axis. The parts are mounted in metal masks and fixed to the shell.

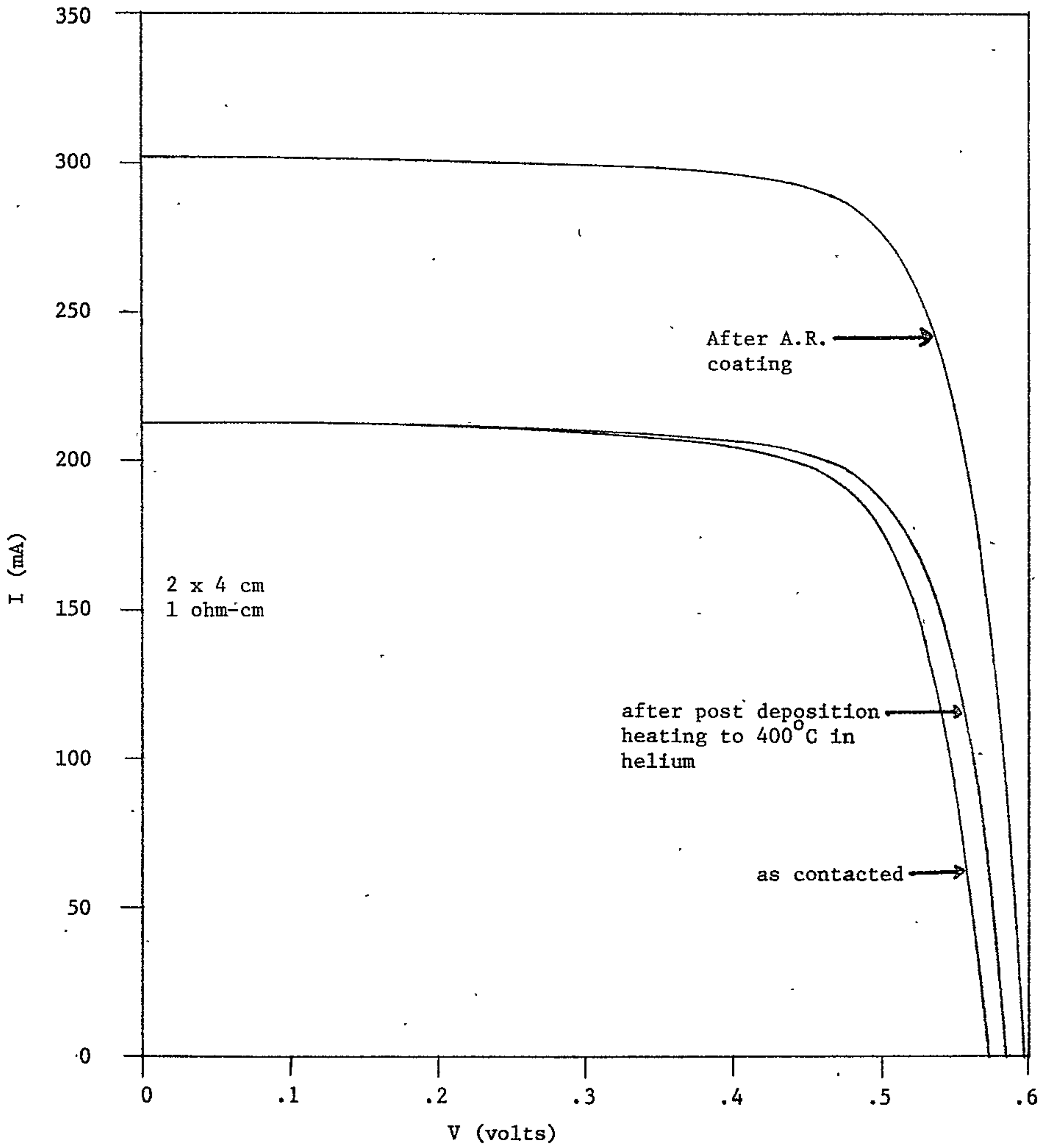


Figure 6. Wraparound Cr-Pd-Ag Contact Test Sample I-V Characteristic Curves

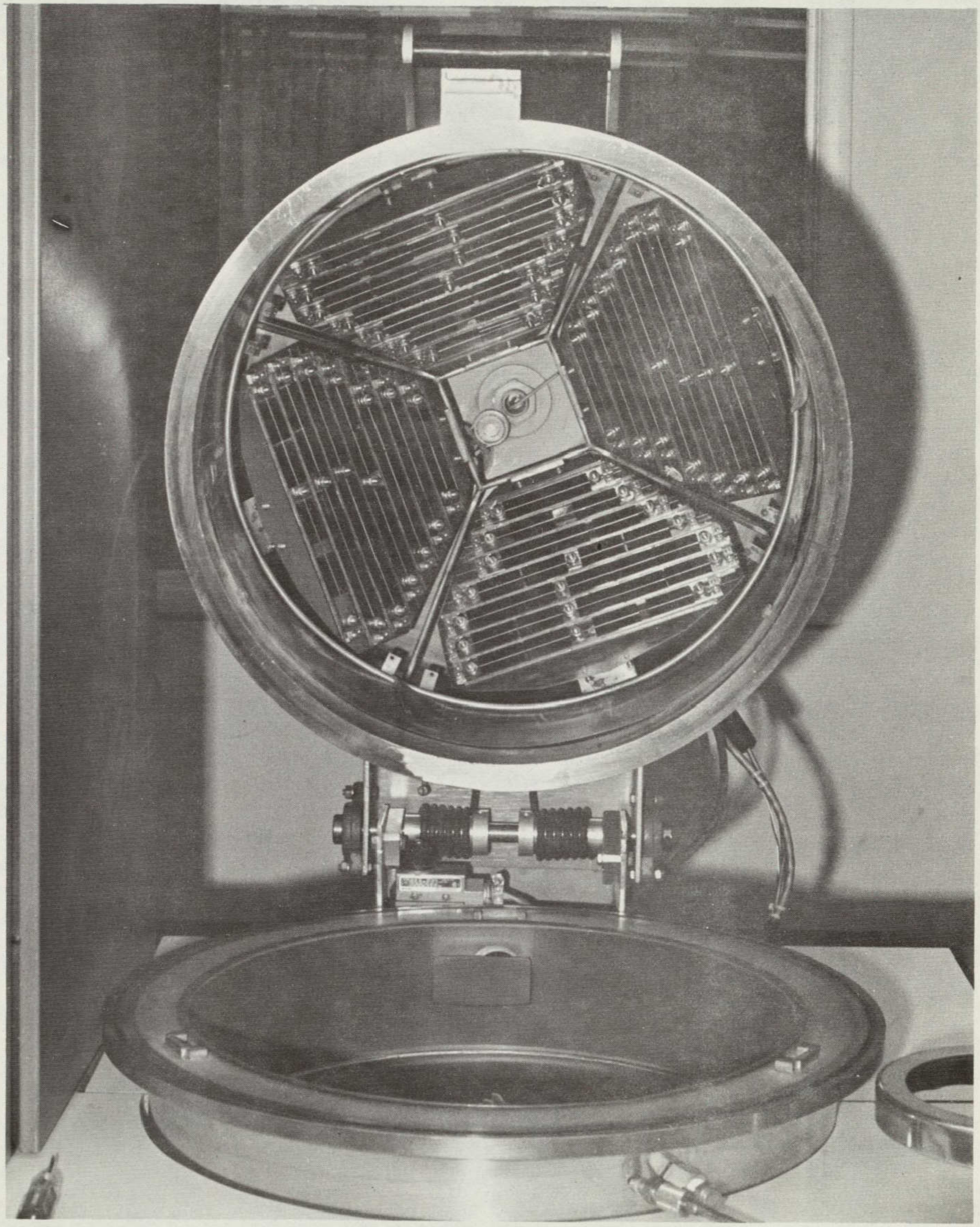


Figure 7. Rotating Substrate Contact Evaporator with Wraparound Cell Tooling

This tooling was fitted into an 18" vacuum system (see Figure 8).

C. AR Coating Tooling

New tooling was constructed for applying the tantalum pentoxide antireflection coating to large quantities of wraparound cells. A spring loaded hold-down bar running down the ohmic allowed complete Ta_2O_5 coverage while minimizing the handling required. The fixturing was capable of holding a maximum of 108 cells. (See Figure 9.)

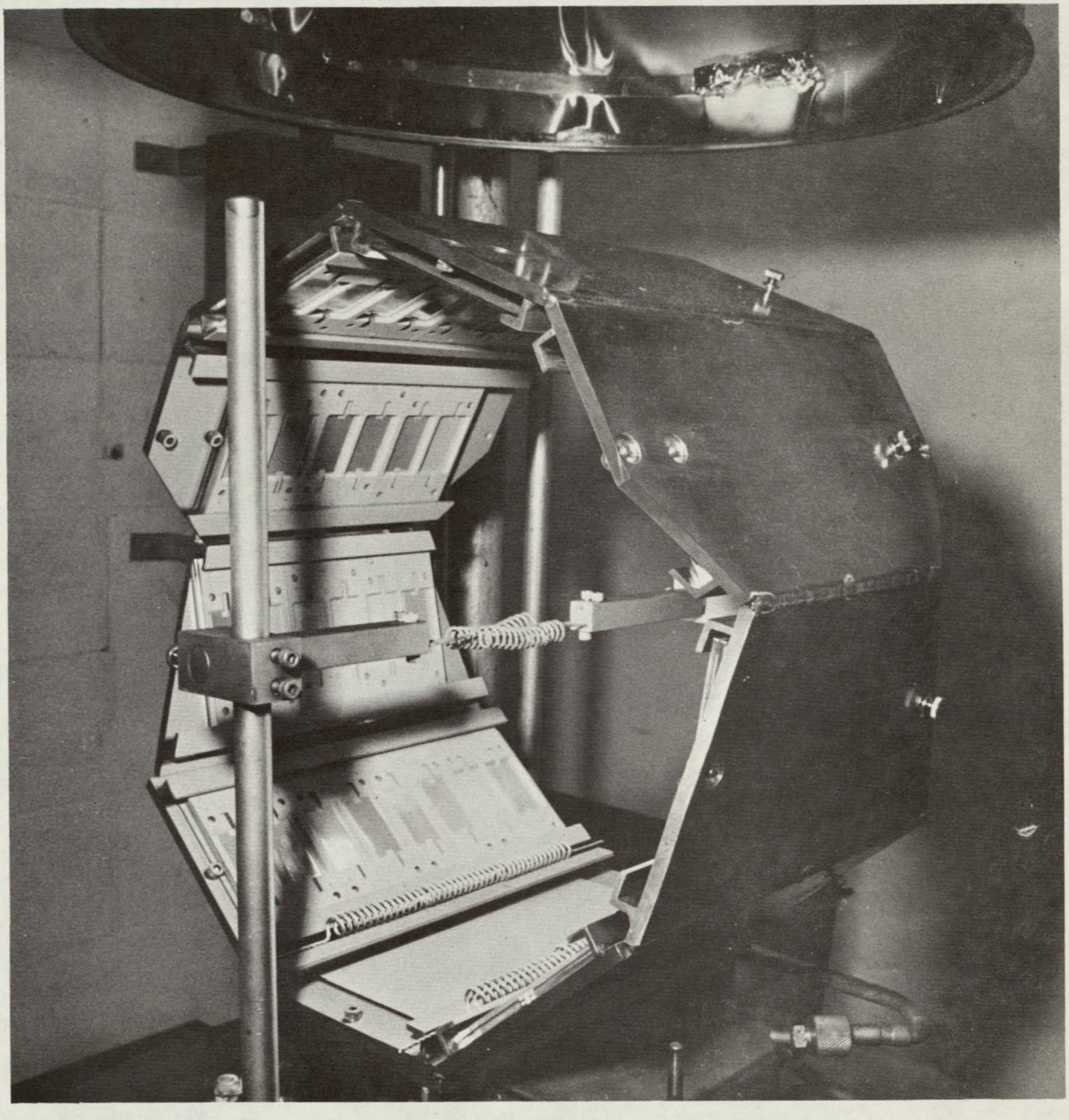
D. Electrical Test Fixturing

A new electrical test fixture was designed and built for this program which provides parallel N-contact current and voltage probes at both N-contact pads as shown in Figure 10a. This arrangement differed from the previous test fixture used which had a single current probe at one N-pad and a single voltage probe at the opposite N-pad, as is shown in Figure 10b. The P-contact probes are similar for both cases.

An improvement in curve shape was expected with the new fixture since current would now flow in both directions through the main ohmic bar, thus reducing the IR loss associated with the series resistance of the ohmic bar. Surprisingly, however, load current readings obtained with the new fixture were actually 3% lower at maximum power compared to values obtained with the previous fixture. Further investigation led to the following explanation. Consider the solar cell equivalent circuit shown in Figure 11a. This model, which represents measurement with the new fixture includes the series resistance of the front ohmic bar as a separate component of the total series resistance and since only half the total current must flow through each half of the bar, this component can be reduced, in effect, to the total series resistance of the bar divided by two.

On the other hand, Figure 11b illustrates the situation encountered with the previous test fixture. Even though the ohmic bar series resistance component is doubled, since all current must now flow through the entire length of the bar to one contact pad, the corresponding voltage is measured at a point which does not reflect this loss. Thus, for any given current, a higher corresponding voltage and, in turn, a higher power output is recorded. For any practical application, the actual power output obtainable from a wraparound cell of the type being considered here can be measured only in accordance with the circuit model illustrated in Figure 11a, that is, with the new test fixture. All electrical test measurements made in connection with the production phase of this program were taken with this fixture.

Figure 8. Aluminum Deposition Tooling for Wraparound Cells



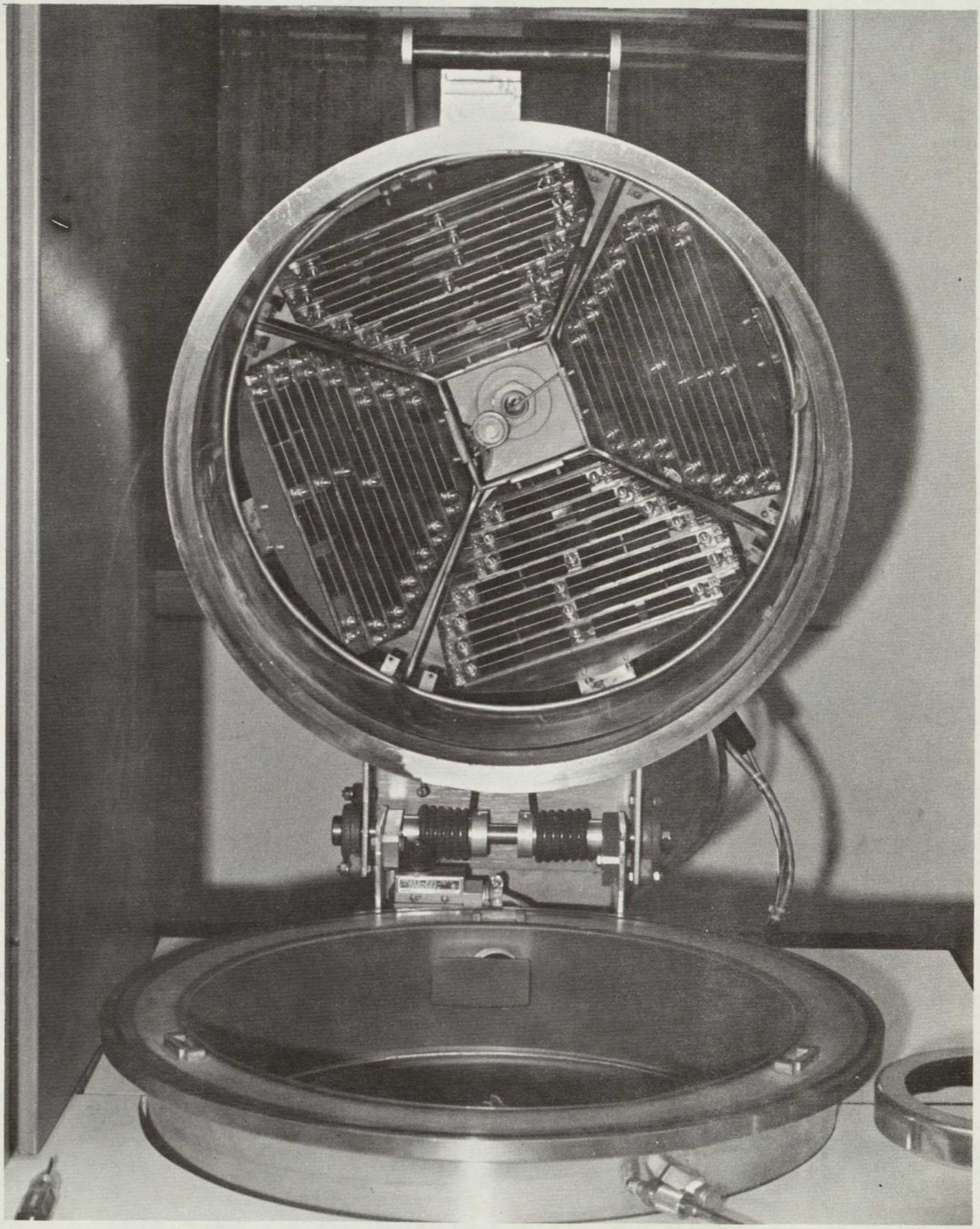
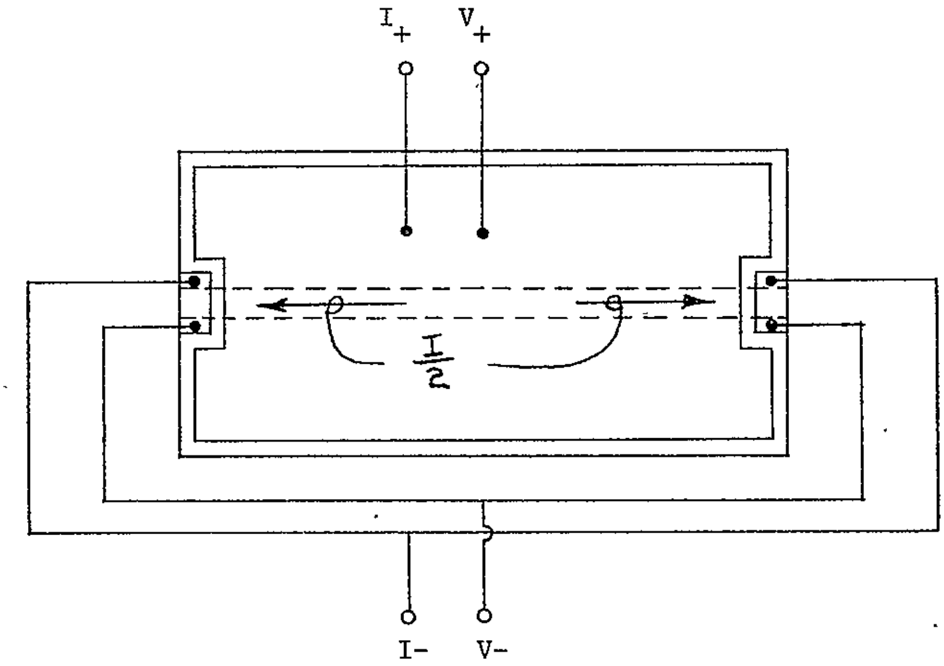
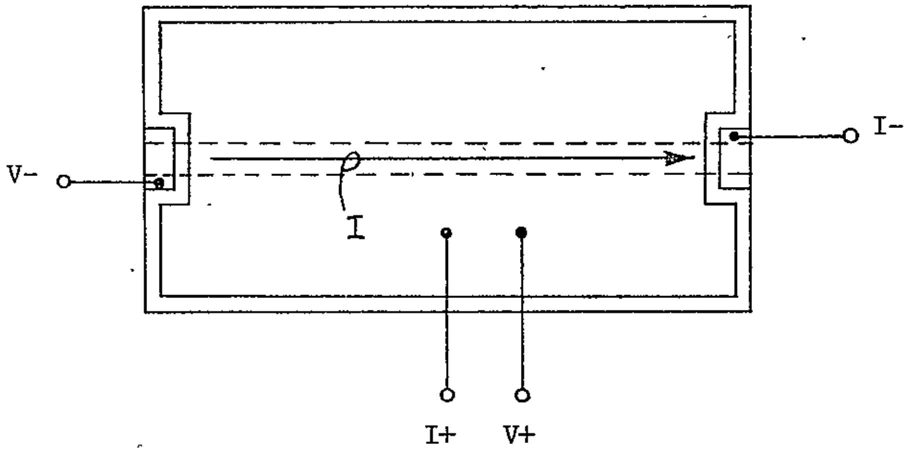


Figure 9. Ta_2O_5 AR Coating Tooling for Wraparound Cells

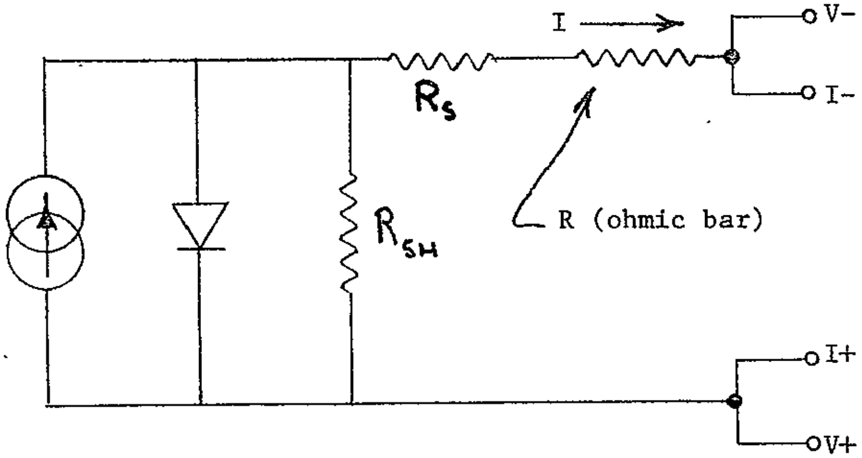


a. New Fixture

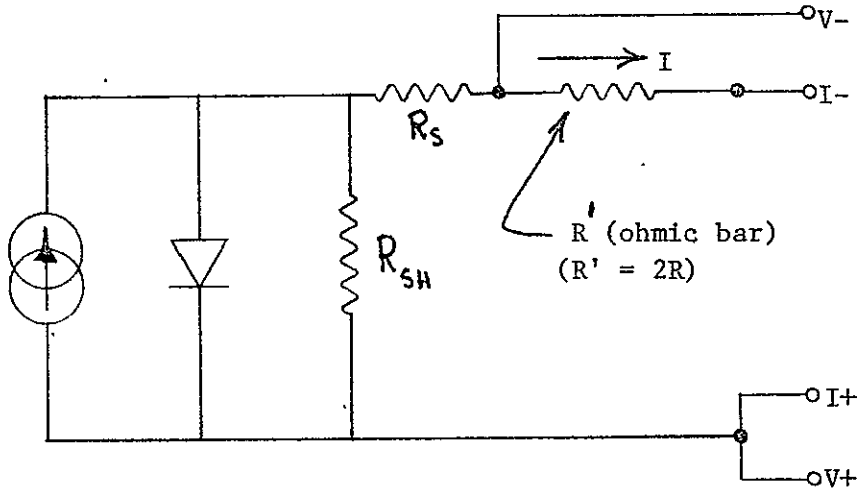


b. Old Fixture

Figure 10. Electrical Test Probe Attachment



a. New Fixture



b. Old Fixture

Wraparound Cell

Figure 11. Equivalent Circuit Models Including Test Fixture Affects

VI. PROCESS INTEGRATION

Procedures had already been established for fabricating cells of the type proposed for this program using conventional Ti-Pd-Ag contacts. In order to test these procedures with another contact system, Cr-Pd-Ag, solar cell test samples were fabricated in the prescribed manner with the exception of contact deposition and post deposition heat treatment.

These cells were 0.20mm 2 x 2 cm, 10 ohm-cm with $\rho_s = 120$ and a back surface field. Contacts were applied through an 18 gridline bimetallic mask, the optimum design for a shallow junction cell with a conventional contact configuration, and the cells were then heated to 400°C in helium. A Ta_2O_5 AR coating was applied to the front surface and the cells were again heated, this time in air at 300°C, to reduce absorption in the AR coating.

The electrical output of these completed cells was equivalent to that obtained with conventional contacts, the best cells being 12.6% efficient. A number of these cells had reduced open circuit voltage. This same effect is also seen with conventional contacts, however, and can be attributed to improper formation of the back surface field, a process not impacted by contacts. One of the better I-V curves is shown in Figure 12.

A. Contacts

Following this, six sets of evaporation mask tooling, sufficient to contact 12 cells per deposition run, were received and accepted as conforming to released drawings. Using this tooling complete process integration was demonstrated by the fabrication of a lot of 12 shallow junction 2 x 4 cm, 0.20mm thick, 10 ohm-cm, P+ wraparound cells with Cr-Pd-Ag contacts. Contact definition on these cells was consistent with other bimetallic mask results. The dimensions of the back surface contacts and front ohmic bar were within 0.05mm of the masks themselves. A substantial amount of contact material was evident at the wraparound edges. Gridline width averaged .08-.10mm, somewhat wider than the .05mm mask openings. This increase is caused by metal overspray in areas where the mask is raised slightly above the surface of the cell, the result of decreasing cell thickness toward the edges of the cells, (pillowing), which is caused by the etching used to remove work damage in the saw-cut silicon blank.

Six of these twelve cells were completed in strict accordance with the procedures called out on the lot traveler developed for this program. When tested, five of the six completed cells met the electrical requirements of 11.5 percent efficiency and 0.72 minimum curve fill factor. The sixth cell was excessively shunted. The efficiencies of the five acceptable cells ranged from 11.5% to 12.3% and averaged 11.9%. Curve fill factors ranged from .746 to .754 and averaged .749. The I-V characteristic curve of the best cell of these five is shown in Figure 13.

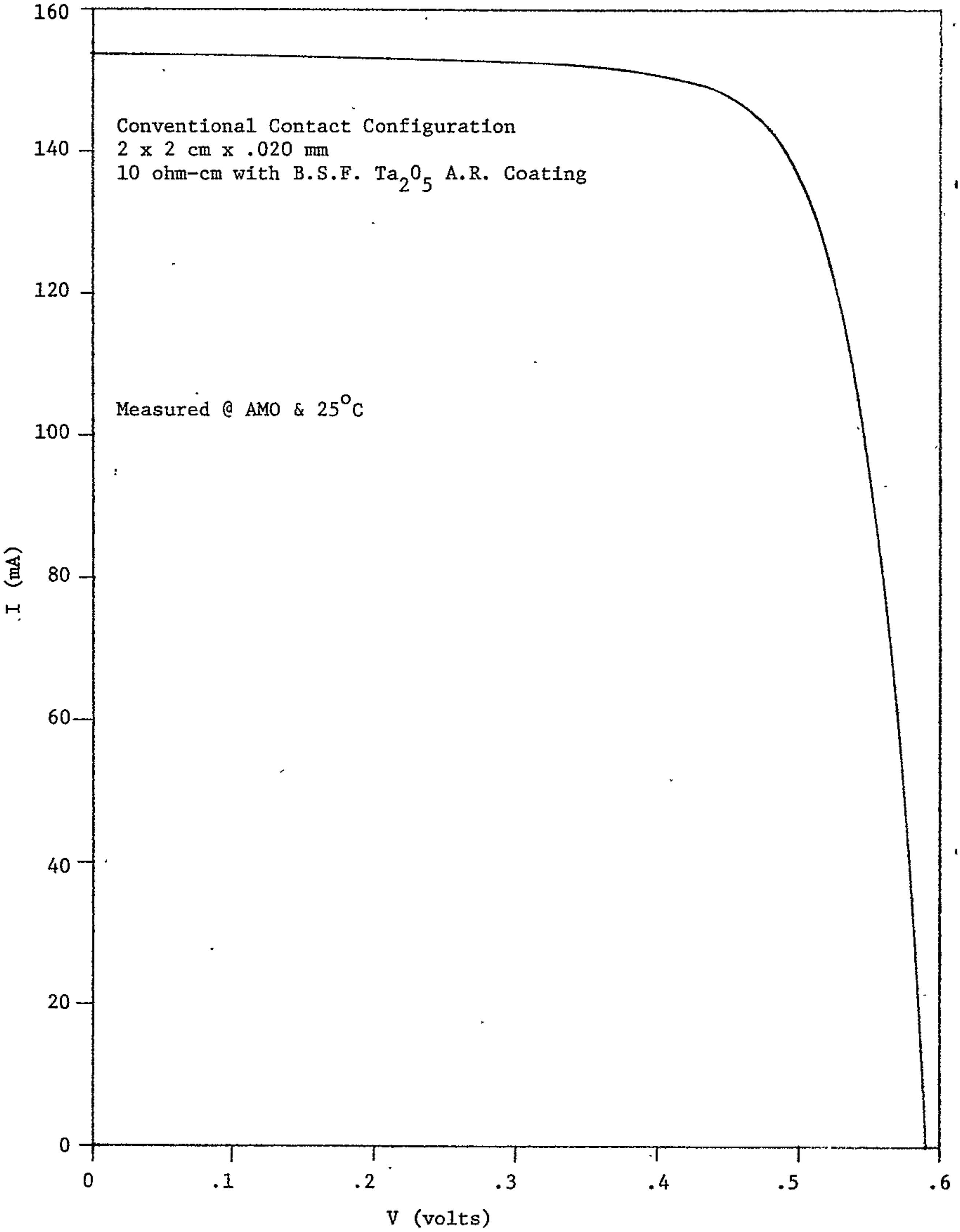


Figure 12. Cr-Pd-Ag Contact Test Sample I-V Characteristic Curve

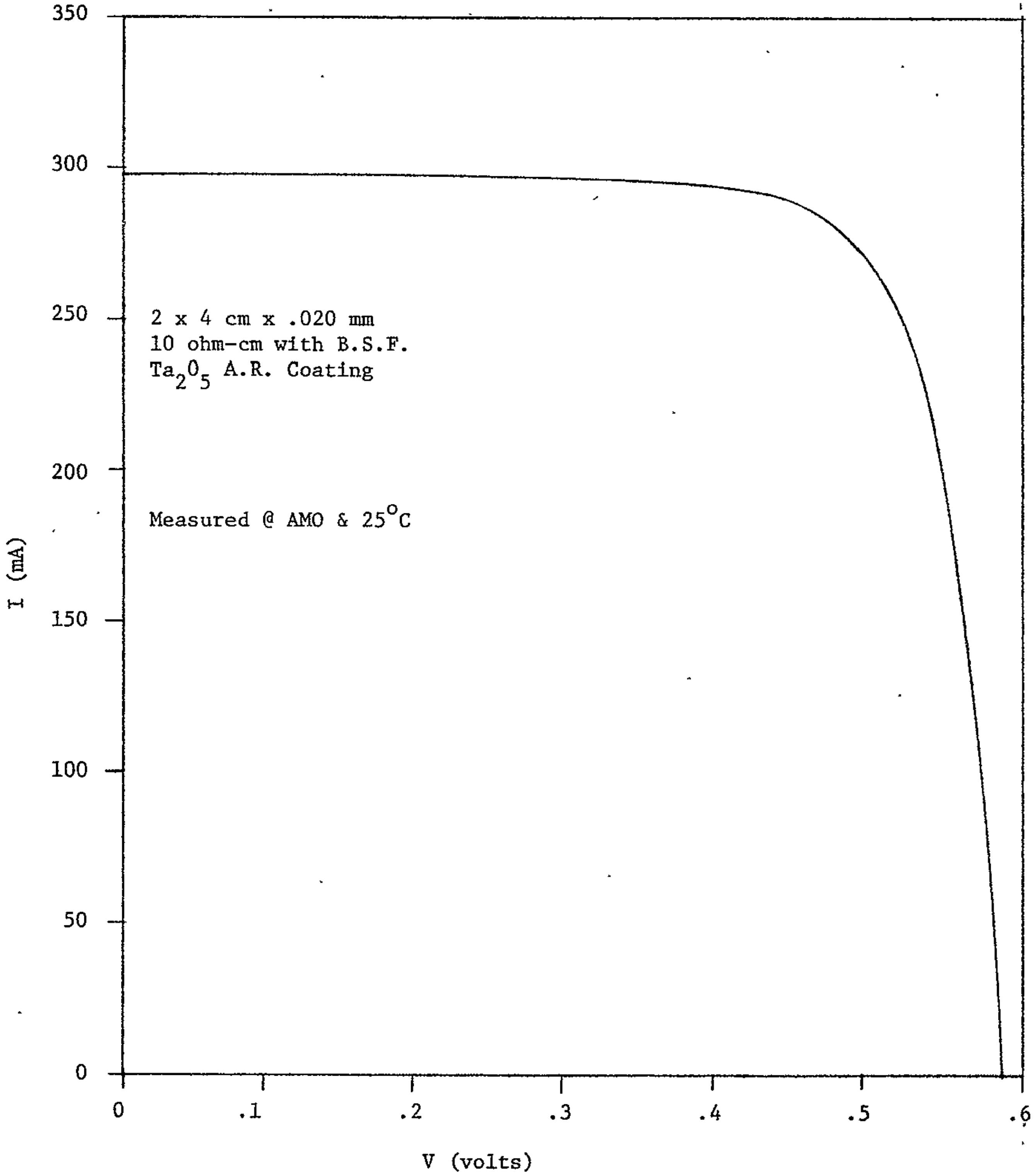


Figure 13. 12.3% Efficient Wraparound Cell I-V Characteristic Curve

These cells fabricated in the first tooling evaluation test lot that were electrically acceptable were subjected to a contact peel testing using Scotch Brand #810 tape. This was followed by a thermal cycle test, 10 complete cycles between -196°C and +100°C. No measurable degradation in output power was seen. These same cells were then placed in an accelerated humidity test (65°C-95% RH) for five days. When tape tested, partial peeling of the front ohmic bar was observed.

Subsequent investigation revealed that the cause of this failure was the presence of a thin and porous underlayer of silver which had been deposited on portions of the front ohmic bar area prior to the deposition of either chromium or palladium. The sequence used for this run deposited Cr-Pd-Ag on the back side of the cell, then the masks were flipped to repeat the sequence on the front side.

During the first sequence the relatively wide openings provided for the edge contacts allowed a small amount of each metal to reach the front side of the cell. Since the great majority of this metal was silver, the subsequent initial chromium bonding layer did not interact with the silicon surface, thus causing the failure.

In order to solve this problem the deposition sequence was altered so that chromium only was deposited on one side, then the other, followed by palladium and then silver. Samples made in this manner were tested using Scotch Brand #600 tape, with no failures. This was followed by an accelerated humidity test (65°C, 95% RH) for nine days. No contact peeling occurred when these cells were subsequently tape tested with #600 Scotch Brand tape.

B. Back Surface Field

Once the volume tooling for depositing aluminum on the 2 x 4 wraparound cells was completed and installed an investigation was initiated to determine the optimum aluminum thickness for this program. A number of test groups were fabricated (6 or 12 cells per group) with various amounts of aluminum. All other process steps were held constant. The resulting electrical data are summarized below. The values of percent yield given represent the number of finished cells in each group which satisfy the minimum electrical requirements (11.5% AMO efficiency and .72 CFF) of this contract divided by the number of cells started in that group.

Aℓ Thickness (microns)	$\overline{V_{oc}}$ (v)	$\overline{I_{sc}}$ (mA)	$\overline{P_{max}}$ (mW)	$\overline{\text{Efficiency}}$ %	$\overline{\text{CFF}}$	$\overline{\text{Yield}}$ %
1	.577	285	123	11.3	.75	0
3	.591	289	128	11.9	.75	100
7	.582	291	126	11.6	.74	83
9	.589	294	127	11.7	.73	75
12	.586	295	125	11.5	.72	50

These data indicate several trends. Short circuit current increased continuously with increasing aluminum thickness. Open circuit voltage was nearly constant for aluminum deposition thicknesses of three microns or greater The CFF showed a drop with increasing aluminum thickness which resulted in reduced conversion efficiencies for these groups. The reduction in yield was due to line losses (cell breakage) in the case of very thick aluminum. This is not unexpected since the relatively thin silicon can be significantly stressed during the aluminum BSF processing. The maximum yield was obtained for a deposition thickness of approximately three microns, which was not consistent with previous observations that at least five microns of aluminum is necessary for an optimized BSF effort. Another observation that had significance was the fact that in the three micron case the resulting sample surface was relatively smooth and uniform which would tend to make interconnecting by welding much more reliable.

All test samples fabricated during the aluminum thickness experiments discussed above were contacted in the rotating drum evaporator with Cr-Pd-Ag contacts deposited in the modified sequence described in the last monthly narrative. Following electrical testing each cell was tape pull tested with #810 tape (including edge contacts). No peeling was observed and when retested electrically no degradation was recorded. A random sample was selected from these cells and placed in accelerated humidity testing (65°C, 95% RH). After 8 days each cell was tape pulled again with #810 tape (including edges) and again no peeling was observed.

The average output power of these 14 cells after humidity and tape pull was slightly improved, probably due to measurement error. Unfortunately, one of the 14 cells had degraded 5.5%, slightly higher than the specified single cell maximum allowable degradation of 5%. The curve shape degradation of this cell was probably caused by increased series resistance rather than shunting since V_{oc} remained constant. Careful visual inspection of this cell did not reveal any possible cause for this failure. All contact areas seemed intact. Since the remaining 13 cells in this test group showed no degradation whatsoever, no major problem was anticipated.

VII. PILOT PRODUCTION

Once all of the individual process steps required to fabricate the 2 x 4 cm wraparound contact cells had been successfully demonstrated, formal documentation was initiated. Figure 14 is the Process Flow Chart derived for this phase of the program. It charts the critical fabrication and inspection points for cell processing as well as the required testing sequence mandated for these parts.

A. Test Requirements

The current-voltage characteristics of ten cells picked at random from each batch were measured under equivalent outer space illumination at a temperature of 25 ± 2°C. The source of illumination was a Spectrosun® Mark III xenon solar simulator whose light level was set using a transfer cell directly calibrated to a balloon flown standard cell. The short circuit current, open circuit voltage, and maximum power output were determined, and the fill factor and efficiency calculated using 135.3 mW/cm^2 as the value of the solar constant. Measurements were made on the cells without coverglasses.

The remaining cells in each lot had short circuit current, open circuit voltage and current at a fixed load (470 mV) recorded. From these data it was possible to eliminate those cells that did not meet the minimum efficiency (11.5 percent) or minimum fill factor (0.72) values.

Following this initial test, all acceptable cells were tested for adherence using Scotch Brand 810 tape. The tape was applied to the contacted edge or edges of the cell as well as to the top and bottom surfaces. Following the tape test, the cells were retested at a fixed load voltage. The batch of cells would be rejected if the average electrical degradation of the cells exceeded two percent. Individual cells were rejected if they showed electrical degradation equal to or greater than five percent following tape testing.

Five cells from each batch were then rubbed using a Pink Pearl eraser for 20 strokes with a force of 20 ounces. Peeling of the coating from more than 10% of the area of any cell would be cause for rejection of the entire batch.

Ten coated cells from each batch of cells were then picked at random and subjected to storage at 40°C and 90% relative humidity for a period of 30 days. The cells were then tape tested once more. Average degradation in electrical performance exceeding two percent, or degradation of any cell by more than five percent would be cause for rejection of the batch.

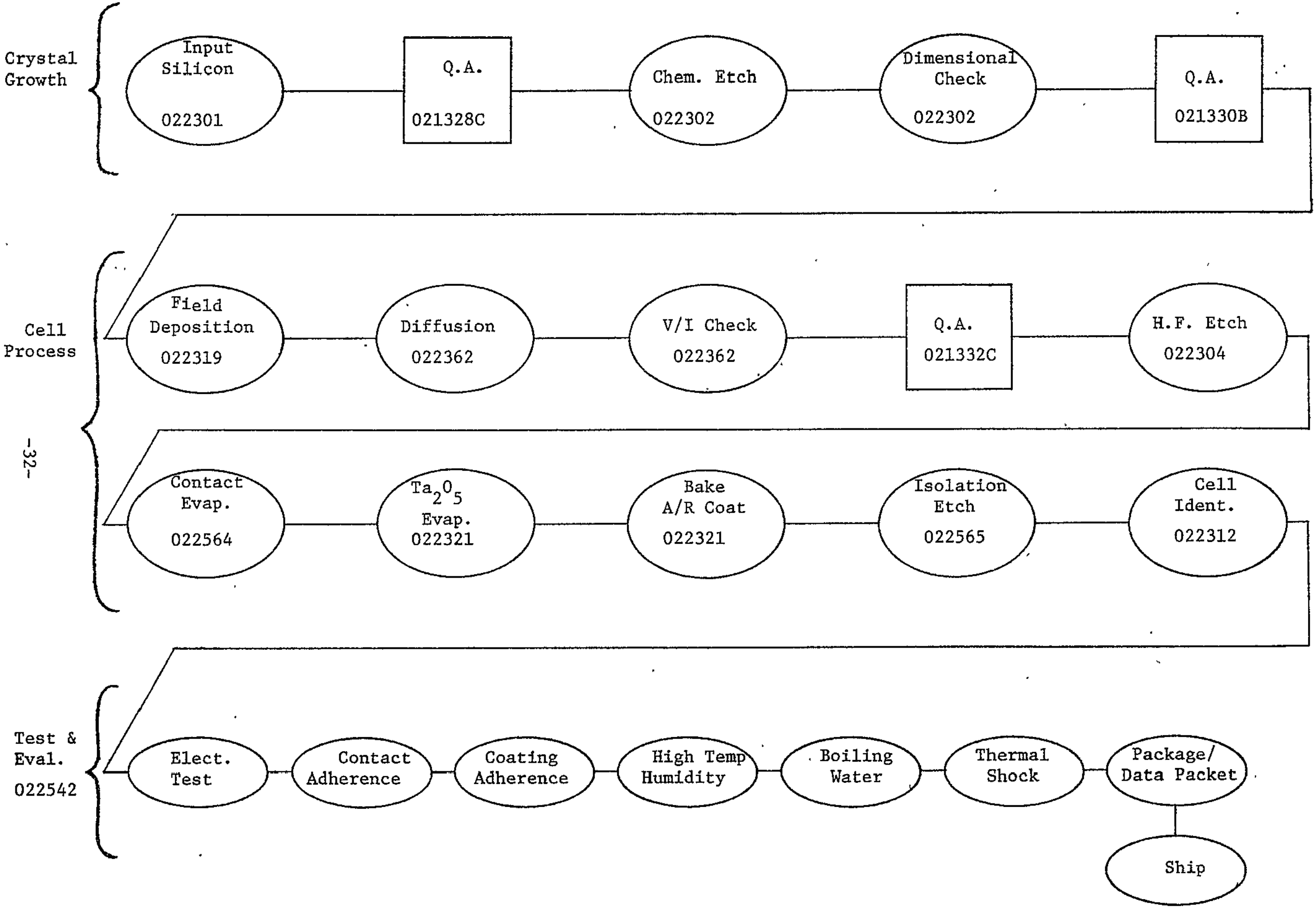


Figure 14. Process Flow Chart for Wraparound Contact Solar Cells

Ten coated cells from each batch were then suspended for thirty minutes in boiling deionized water after which they were dried and subjected to tape testing. Once again, the same conditions for rejection were imposed on the lot batch.

The final test took five coated cells from each batch which were subjected to 10 temperature cycles at a maximum thermal rate of approximately 90°C/minute between the extremes of -196°C ± 10°C and 100°C ± 10°C. The solar cells remained at the extremes for a minimum of 2 minutes. Following this, the cells were electrically tested. Average degradation in electrical performance of more than two percent, or degradation of any cell by more than five percent would result in rejection of the batch.

B. Test Results

Originally it had been planned to produce one thousand ten ohm-cm wraparound contact solar cells. However, upon direction from the Technical Monitor, two hundred of these cells were made from higher resistivity (15-30 ohm-cm) silicon in order to support the "The Solar Cell Selection and Characterization" phase of the SEPS program (NAS8-31670). This change had minimal impact upon the outcome of the program, although a very small percentage of the higher resistivity cells did not meet the 0.72 fill factor requirement. Since the slight reduction in fill factor for these cells had no influence on the study, they were included in the two hundred deliverable cells.

The cells were fabricated in batches of ninety-six (96) and each batch was tested in accordance with the requirements described in VII-A of this report. With the exception of aluminum deposition and isolation etching, which required special work stations, all processing was done in the Spectrolab solar cell production department, and in most cases production personnel were utilized.

Three 96 cell lots of 15-30 ohm-cm wraparound cells successfully completed all required testing and 200 cells, with AMO efficiencies greater than 11.5%, were shipped to NASA-Lewis along with appropriate data packets. Some pertinent test data for these lots is tabulated below.

Average Power Degradation

Lot #	Boil	Humidity	Thermal Cycle
12	.7%	0%	.8%
13	1.0%	.9%	1.2%
14	.6%	0%	.7%

In all cases the average degradation was less than the 2% maximum specified, with no single cell degradation greater than 1.5%, again less than the maximum allowable value of 5%. Similar good results were recorded for the tape pull test, as well as the AR abrasion test.

Figure 15 shows the percentage of cells tested which met the minimum efficiency requirement of 11.5 percent. It should be pointed out that lots 16 and 17 were rework lots, the former containing 72 starting cell blanks and the latter, 48. Although technically lot 17 did not meet the lot batch requirement, economic constraints and material availability forced this situation. Both lots, although smaller than the first fifteen lots, did go through all the required tests.

Figure 16 shows the efficiency distribution of all the ten ohm-cm cells prior to environmental testing, and provides the same data for the nominal twenty ohm-cm cells. Virtually every 10 ohm-cm cell with greater than 11.5% efficiency met the minimum fill factor requirement of 0.72. A typical value of 0.74 was obtained. All but 25 of the 217 nominal 20 ohm-cm cells with better than 11.5% efficiency also met this minimum requirement. These higher resistivity cells had a typical fill factor of 0.73. The lower value reflects the increased series resistance due to the loss of back contact area. An increased short circuit current compensated for this fill factor loss, however, so that average power output was slightly higher than the 10 ohm-cm case.

The front surface, back surface and wraparound edges of each cell were tape pull tested using Scotch Brand #810 tape. Out of over 1500 cells tested, only a few showed any evidence of peeling, limited in those cases to small spots at random locations. No peeling was observed at any edge contact, an impressive result considering the volume of cells tested. When retested electrically, the average power degradation of all cells was less than 0.5% and no single cell degradation greater than three percent was recorded. There were no lot failures based on the specifified allowable values of two percent average degradation and no single cell degradation greater than five percent.

There were no lot failures due to the coating adherence test. This was as expected since tantalum pentoxide has been used in standard production of space qualified cells for nearly two years. The humidity test did not influence contact integrity, no peeling was observed after tape testing. The amount of electrical degradation observed averaged less than 0.5 percent. The highest electrical degradation seen on any cell exposed to this test was 1.5 percent, well below the allowable 5 percent.

The boiling water test resulted in an overall average electrical degradation for all cells tested of 0.4 percent with 1.5 percent electrical degradation being the maximum observed for any cell. Once again, this is not unexpected in light of the humidity test results reported. Thermal cycling test results were very similar, average electrical degradation from lot to lot ranged from zero to 1.2 percent with the maximum single cell electrical degradation for any lot being of the order of 1.5 percent.

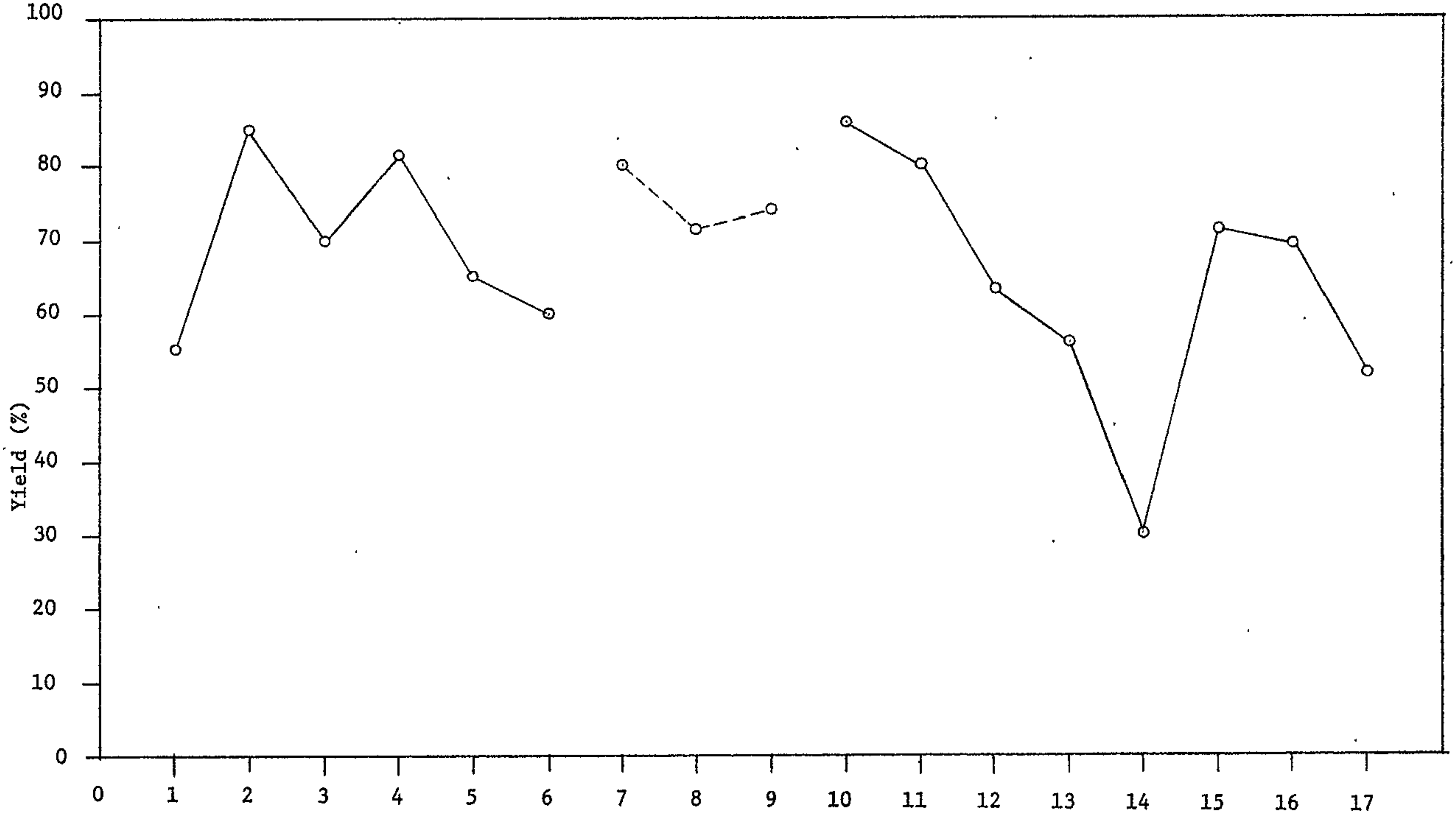


Figure 15. Electrical Yield of Each Wraparound Cell Lot

-------- 20 ohm-cm
———— 10 ohm-cm

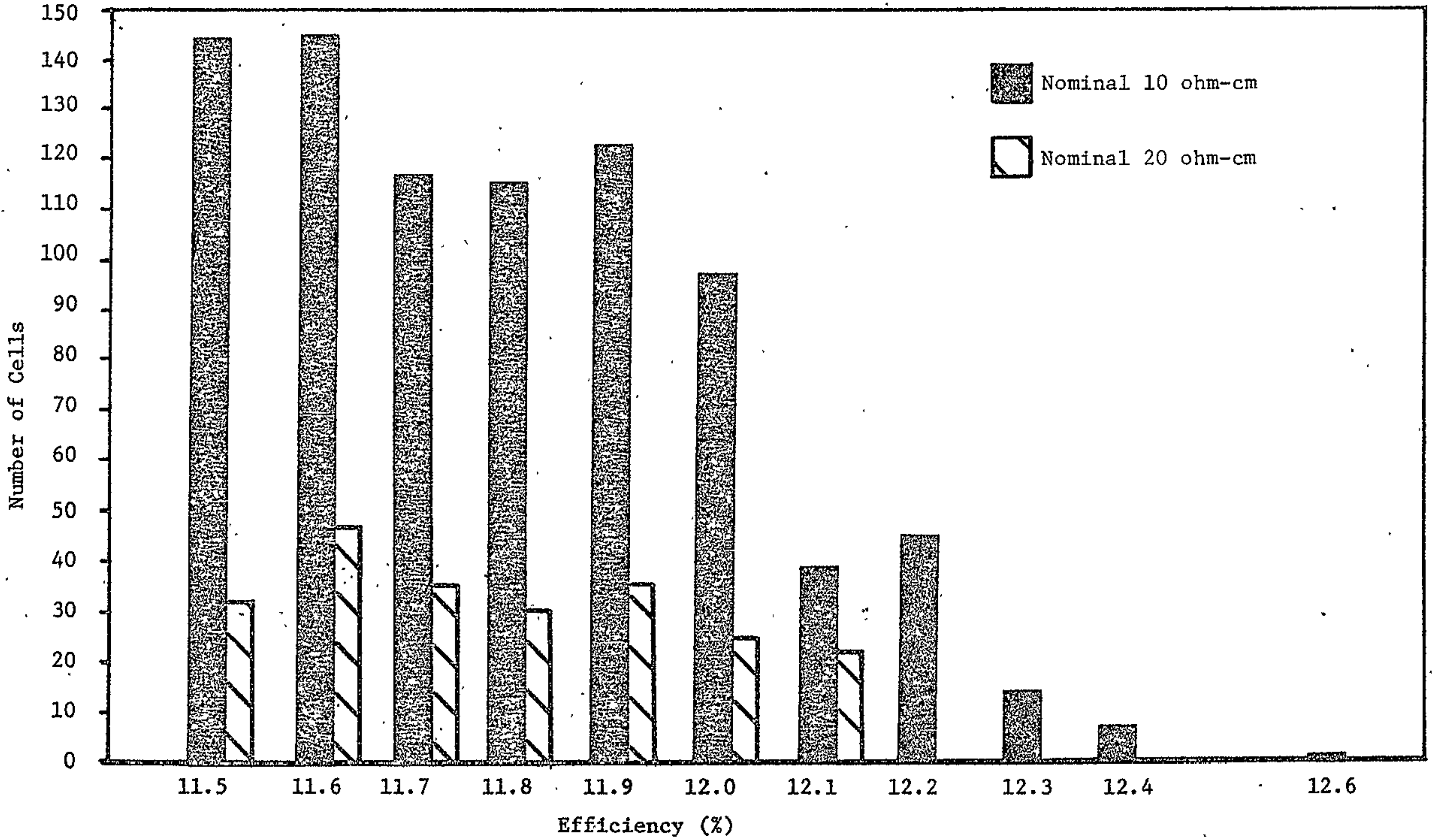


Figure 16. Efficiency Distribution of Wraparound Cells

VIII RECOMMENDATIONS

This contract has demonstrated that thin (0.020 mm) large area (2 x 4 cm) silicon wraparound solar cells can be fabricated in a production environment. In addition, these cells have shown the capability of passing the stringent tests required for space qualified devices.

The main area for improvement in these devices involves eliminating the design compromises that were necessitated to produce useful cells. The cells delivered on this contract, although technically described as high efficiency, do not yet equal the power output per unit area of conventionally configured cells. In principle, the wraparound contact cell should deliver more power since the front junction collector bar is located on the rear surface. In fact, it has been necessary to place a spine configuration on the front surface in order to eliminate poor cell curve factor due to edge imperfections.

The second difficulty is the lack of freedom in locating the junction collectors on the rear surface. The amount of rear surface given up to these collectors must be minimized in order to reduce series resistance, thus constraining the interconnect design.

Both problems could be either solved or substantially relieved by investigating the concept of dielectric isolation. This would eliminate the problems of edge defect shunting, thus allowing elimination of the front spine with a resultant increase in active area. By employing isolation on the rear surface, it would be possible to completely cover the rear surface with an ohmic contact thus eliminating series resistance. The wraparound contact could then be brought around and located upon the isolation layer thus allowing complete freedom with respect to both location and dimensions of the junction contact.

Another aspect of new technology that should be investigated with respect to wraparound cells is selective etch technology, which is capable of providing an additional five to seven percent increase in output power. There might be problems incorporating selective etch technology and dielectric isolation sinse surface finish may be an important parameter for successful dielectric isolation, but the potential gain makes such an effort an attractive proposition.

Finally, as mentioned previously, it is strongly recommended that in any future programs, agreement between NASA-Lewis and the contractor with regards to AMO measurements be established as part of the initial phase of the contract. This can be accomplished by correlation of cell samples between the two organizations' respective simulators.

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