SOLAREX

DEVELOPMENT OF A HIGH EFFICIENCY THIN SILICON SOLAR CELL

JPL CONTRACT NO. 954290

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FINAL REPORT

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TECHNICAL CONTENT STATEMENT

ABSTRACT

This report documents a highly successful program performed by Solarex for JPL/NASA-OAST in developing high-efficiency ultra-thin (40 - 60 microns) silicon solar cells for lightweight space power systems and proceeding to pilot production.

A key to the success of this program was the breakthrough development of a technology for producing ultra-thin silicon slices which are very flexible, resilient, and tolerant of moderate handling abuse. The solar cell fabrication process developed to be compatible with these slices has generated thousands of ultra-thin solar cells at a respectable yield with average AM0 conversion efficiencies of 11%, and a few experimental samples reaching efficiencies above 12%. The guiding philosophy through this stage of development was to both improve cell efficiencies and develop a cell fabrication process amenable to high manufacturing yields, so that these ultra-thin solar cells are producible and not laboratory curiosities. For example, textured surfaces were not aggressively pursued to improve optical coupling, because that would require shadow masking for the gridline pattern, which was prone to increase breakage losses in processing as compared to photolithographic gridline generation.

Experimental topics investigated were thinning technology, gaseous junction diffusion, aluminum back alloying, internal reflectance, tantalum oxide anti-reflective coating optimization, slice flexibility, handling techniques, production rate limiting steps, low temperature behavior and radiation tolerance.

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I. INTRODUCTION

This highly successful program was performed by the Solarex Corporation for the Jet Propulsion Laboratory under the auspices of NASA-OAST. It was performed over a 24 month period and resulted in very high power-to-weight ratio silicon solar cells reaching down to 30 microns thickness. The key breakthrough making such ultra-thin solar cells possible was the development of a process for producing extremely thin silicon slices while leaving the surfaces parallel, avoiding preferential perforation and not introducing stresses which would make the slices brittle. This process uses a very hot sodium hydroxide (NaOH) etch and results in ultra-thin slices of excellent flexibility and resistance to breakage in handling. This breakthrough occurred at a time when the majority of the photovoltaic community had concluded that it was not feasible to fabricate ultra-thin silicon solar cells in this thickness range.

NASA-OAST recognized the implications of this breakthrough in ultra-lightweight silicon solar cells and seized the opportunity to accelerate reduction to manufacturing practice with a Pilot Line effort in the second quarter of the second year of this program. That acceleration by NASA-OAST provided thousands of ultra-thin silicon solar cells to familiarize the photovoltaic community with the properties of these cells, their handling techniques, assembly technology adaptation and assessment of the high power-to-weight ratios that can be obtained. The fabrication technology was frozen for the Pilot Line effort at a stage which produced 50 micron thick solar cells with 11% conversion efficiencies at AM0. (These had a higher power-to-weight ratio than 75 micron cells with 12% efficiencies, and were chosen as the Pilot Line vehicle for that reason as well as for optimum flexibility.)

These ultra-thin solar cells also have improved radiation tolerance as compared to 200-250 micron silicon solar cells, since they simply do not have beginning-of-life efficiencies dependent on long minority carrier diffusion lengths in a thick slice of silicon.

Although the frozen technology employed in the Pilot Line effort produced 11% conversion efficiencies for 50-micron-thick solar cells, the laboratory efforts have resulted in 50 micron cells with AMO conversion efficiencies of up to 12.5%. Further efforts on optimizing the fabrication parameters would, no doubt, result in very reproducible conversion efficiencies in excess of 12% for cells only 50 microns thick.

II. PROGRAM DESCRIPTION

A. General

This program was initiated in September 1975 with the objective of improving process parameters which influence the performance of high-efficiency, thin silicon solar cells. Near the end of the first year of effort a breakthrough was achieved at Solarex in developing a technology to produce very flexible ultra-thin silicon slices. This in turn made possible the subsequent fabrication of extremely lightweight high efficiency solar cells only some 40 - 60 microns in thickness.

The second twelve months of this program had efforts concentrated on ultra-thin solar cells (40-60 microns in thickness). Early in 1977, at the direction of NASA-OAST and JPL a Pilot Line was set up which fabricated pilot-production quantities of these ultra-thin solar cells. After this Pilot Line effort, the remaining four months of the contract term were concentrated on further improving the efficiency of ultra-thin solar cells.

This program encompassed a wide spectrum of R&D activities from experimental n on p cell fabrication technology analysis through evaluation of thin-cell handling techniques, determination of electrical and mechanical stability, identification of production rate-limiting steps and studies of optical properties, including internal reflectance at the back interface. This effort readily achieved the initial objective of improving thin-cell process parameters and has resulted in the fabrication of thousands of high-efficiency ultra-thin solar cells for evaluation purposes.

B. Work Plan & Schedule

The schedules for the R&D efforts and the Pilot Line effort are shown on the following pages. As can be seen from these schedules, there were continuous experimental efforts on front junction formation, p+ rear layer formation, photovoltage improvement studies and interactions of process variables. Since all of these studies are related to the physical and chemical details of cell fabrication and interact with one another in affecting conversion efficiency, they were topics of continual investigation throughout the contract term. At the very beginning of this program there was a short task on optimizing the chevron gridline masks for minimum shadowing, while maintaining insignificant series resistance. There then followed a task on optimizing the anti-reflective coating, employing high-index tantalum oxide to give minimum reflectance after coverglass attachment. In addition, the effects of front surface texturing and back surface reflectance were studied, with the aim of providing maximum photon absorption paths in thin solar cells. Studies were also made of handling techniques which aid in the successful fabrication of very thin solar cells, and periodic evaluations were performed to identify production-rate-limiting steps which might hinder large-scale production of ultra-thin cells. In addition, stress testing was performed periodically to evaluate the stability of electrical and mechanical characteristics. Also, studies of techniques for determining the contact integrity of ultra-thin solar cells were performed to find non-destructive testing methods, since standard procedures usually exceed the stress limits for the silicon itself in ultra-thin cells. Finally, there was also a task on measurements and modelling to analyze the performance of these revolutionary new cells.

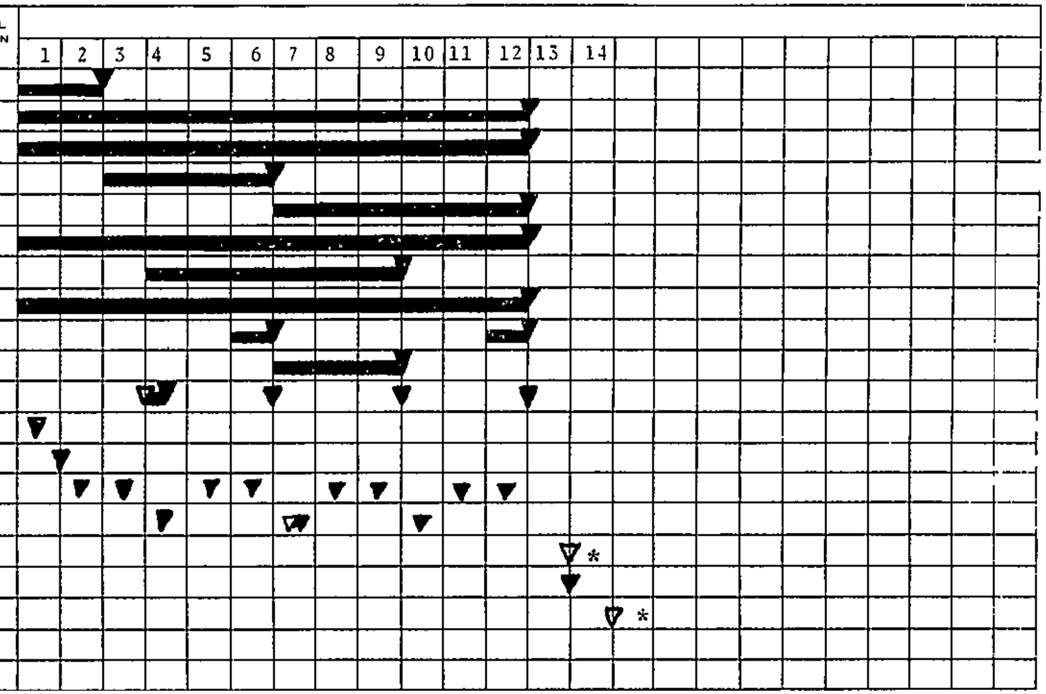
MILESTONE PROGRESS REPORT

CONTRACTOR SOLAREX CORPORATION

CONTRACT NO [illegible]

FOR PERIOD ENDING

	MILESTONES (Key Task) (1)	MILESTONES WEIGHTED % (2)	ESTIMATED % OF COMPLETION (3)	TOTAL CONTRACT ESTIMATED % OF COMPLETION (4)	TECHNICAL EVALUATION (5)
1	Gridlines				
2	Front-Junction				
	P+ Layer				
4	AR Coating				
5	Handling Techniques				
6	Photovoltage				
7	Front Texturing & Back Ref				
8	Interaction Effects				
9	Stability				
10	Production Rate-Limiting Steps				
11	Submit Cells to JPL				
12	Initial Baseline Cost Est				
13	Initial Program Plan				
14	Monthly Tech & Cost Rep				
15	Quarterly Reports				
16	Draft Final Report				
17	Oral Briefing				
18	Final Report				
19					
20					
	TOTAL CONTRACT	100%			



DELIVERIES DATE STATUS

SCHEDULE LEGEND

- SPAN TIME
- STATUS
- SCHEDULED
- COMPLETED
- RESCHEDULED
- SLIPPAGE ANTICIPATED
- ACTUAL SLIPPAGE

TECHNICAL EVALUATION SYMBOLS

- SATISFACTORY PROGRESS
- SIGNIFICANT PROBLEM
- SERIOUS PROBLEM

REMARKS * Rescheduled

Approved ____________

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MILESTONE PROGRESS REPORT

CONTRACTOR SOLAREX CORPORATION

CONTRACT NO 954290

FOR PERIOD ENDING

	MILESTONES (Key Task) (1)	MILESTONES WEIGHTED % (2)	ESTIMATED % OF COMPLETION (3)	TOTAL CONTRACT ESTIMATED % OF COMPLETION (4)	TECHNICAL EVALUATION (5)	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	Front-Junction																		
2	p⁺ Layer																		
3	Photovoltage																		
4	Interaction Effects																		
5	Front Texturing & Back Reflection																		
6	Textured Cell Structures																		
7	Measurements & Modelling																		
8	New Methods for Contact Integrity																		
9	Handling Techniques																		
10	Production Rate-Limiting Steps																		
11	Elec. & Mech. Stability Characteristics																		
12	Submit cells to JPL																		
13	Extended Baseline Cost Est																		
14	Extended Program Plan																		
15	Monthly Tech. & Cost Rep.																		
16	Quarterly Reports																		
17	Draft Final Report																		
18	Oral Briefing																		
19	Final Report																		
20																			
	TOTAL CONTRACT	100%	[redacted]																

DELIVERIES DATE STATUS

SCHEDULE LEGEND

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- COMPLETED
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- SLIPPAGE ANTICIPATED
- ACTUAL SLIPPAGE

TECHNICAL EVALUATION SYMBOLS

- SATISFACTORY PROGRESS
- SIGNIFICANT PROBLEM
- SERIOUS PROBLEM

REMARKS

Approved ____________

MILESTONE PROGRESS REPORT

CONTRACTOR SOLAREX CORPORATION

PILOT LINE PROGRAM

CONTRACT NO 954290

FOR PERIOD ENDING

	MILESTONES (Key Task) (1)	MILESTONES WEIGHTED (2)	ESTIMATED % OF COMPLETION (3)	TOTAL CONTRACT ESTIMATED % OF COMPLETION (4)	TECHNICAL EVALUATION (5)	17	18	19	20	21
1	Project Management									
2	Assemble Production Team									
3	Train additional personnel									
4	Acquire necessary equip									
5	Prepare space									
6	Install equipment									
7	Test & Upscale Production									
8	Optimize Cell Design									
9	Dev Prod Monitrg Proced's									
10	Full Scale Production									
11	Production Monitoring									
12	Complete Pilot Line Report									
13	Cell Shipments									
14	Program Plan									
15										
16										
17										
18										
19										
20										
	TOTAL CONTRACT	100%								

DELIVERIES DATE STATUS

SCHEDULE LEGEND

- SPAN TIME
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- ACTUAL SLIPPAGE

TECHNICAL EVALUATION SYMBOLS

- SATISFACTORY PROGRESS
- SIGNIFICANT PROBLEM
- SERIOUS PROBLEM

REMARKS

Approved ____________

The Pilot Line effort was carried out in conformance to a separate short-fuse schedule of its own. That schedule allowed only 2 1/2 months preparation including all phases of equipment preparation and personnel training, followed immediately by the production phase. The Pilot Line effort achieved its goal of fabricating 1000 pre-production samples and 2000 production cells within the short schedule shown following.

III. TECHNICAL DISCUSSION

A. Silicon Thinning Technology

This topic was not a scheduled format task in the contractural effort, but it was of such key importance as the breakthrough which made ultra-thin solar cell fabrication feasible that it warrants separate discussion. Prior to discovery of this thinning technology it had been very difficult and quite a hit-and-miss affair to achieve silicon slices less than a hundred microns (approximately 4 mils) in thickness which were amenable to surviving fabrication into solar cells. It was determined that a key aspect of fabricating 50 μm to 75 μm thick silicon solar cells is the technique of thinning the starting slices. The maintenance of uniform thickness across a slice is quite important for cell strength and resistance to damage in handling during processing.

The very thin cells fabricated during the first two quarters employed silicon slices which had been subjected to chemical/mechanical thinning and polishing to produce a 50 micron slice thickness. Such procedures, however, are both costly and time-consuming. Therefore, efforts were directed to establishing a simple process for chemically thinning the silicon. Attempts to employ acidic "CP" etches (nitric, hydrofluoric & acetic acid mixtures) generally resulted in non-uniform cell thicknesses, especially in localized areas.

However, it was found during the third quarter efforts that etching in 20%-40% NaOH solutions at temperatures above 100^{o}C resulted in reproducible uniformity of thickness across (100)-oriented silicon slices down to 30 microns or so in final thickness. The etching rate is approximately 4 um/minute/side for a (100) plane under such conditions, which allowed for considerable ease in trimming to the desired thickness.

It became quite apparent that the mechanical survival of slices prepared with this technique was far superior to that of slices prepared by the other methods employed, including chem/mechanical polished. In addition, uniformity of thickness across a slice is quite good (few microns) with this etching technique and is maintained even with very thin slices.

A very reproducible surface was regularly achieved which has only a fine feature "pillowed" texture, with each pillow a fraction of a micron in height. The etch rate of a few microns per minute for each side was found convenient for thickness control but not so slow as to be production rate-limiting for batch processing.

At low temperatures and/or low concentrations, the tendency is to develop preferential pyramids on the 100 plane with alkaline etches. At temperatures above 100° C, the texture appears reduced almost to a plane with features that are pillow-like; with the size and exact dimensions of such pillows dependent on the specific etch conditions. A high degree of etching reproducibility was achieved by introducing clean slices into a 20%-40% (by weight) NaOH solution when the solution has reached temperatures in the neighborhood of 105° C. Stainless steel containers were employed for the NaOH etch, with magnetic stirring. Various concentrations of etch solutions were employed with no adverse effects on the surface texture or the flexibility of the resulting slices. In fact, perfect etching was also achieved for 3-inch (7.6cm) round slices.

Several grades of NaOH were used to etch silicon slices to 50 microns. There was no apparent difference in either the etch rate, surface texture, or resulting slice flexibility.

The best grade readily available was 97.9% pure and four times as expensive as the cheapest "technical grade" for which no analysis was received or expected.

Various starting slice surface conditions have been employed in the etching experiments. These have ranged from "as-sawn" (100) to mirror-finish chem-mechanical polished (100) surfaces. A prepolished surface remains much like its original condition after a slice is reduced from 250 microns to 50 microns in a NaOH etch. Employing a slice with no smoothing treatment after sawing from the ingot results in a pillowed or quilted looking surface with each feature less than a micron or so in height. No distinct trend in solar cell performance was observed between cells made from slices with these different surface conditions, which means that the chemical polishing of the NaOH etch is apparently quite satisfactory and no other mechanical or acidic chemical polishing is required.

For some of the float zone grown silicon employed in this effort, randomly distributed surface features appeared on some slices. These consisted of either spherical-segment dents or obviously preferential square, sloped-side indentations with plane bottoms. The size of these indentations ranged up to about a half millimeter. These features did not occur on any of the Czochralski-grown silicon employed and also did not occur on many other slices from that very same ingot of float-zone silicon. It was tentatively assumed that inherent crystal defects in those few slices were the cause of the anomaly.

The NaOH etch does tend to leave a residue of microscopic particles on the silicon surface. These residue particles were not chemically identified, but were unaffected by rinsing with cold or hot deionized water. They can be removed mechanically with scrubbing or can be removed completely by other chemical treatments. The most successful residue removal was achieved by employing a 2:1 boiling mixture of sulfuric acid and hydrogen peroxide. This resulted in a very reproducible complete removal, but was relatively inconvenient. A fully satisfactory alternate residue removal method is a soak in a solution of HCL, which also eliminates the need for removing the chemically grown oxide produced by the sulfuric peroxide cleaning method.

B. Anti-reflection Coating Optimization

During this contract, efforts were directed to studying tantalum oxide anti-reflective coatings on silicon. It was found that regardless of the deposition technique employed, all films were extremely adherent and the main changes incurred related to the resulting net reflectance and the refractive index of the tantalum oxide.

The experiments performed varied the source material condition, evaporation rate, oxygen back pressure and post-deposition treatment. The means of coating evaluation consisted of reflectance measurements for films on silicon employing a Beckman DK-2A spectrophotometer with a Gier-Dunkle integrating sphere. Also, observation of reflectance and short-circuit current changes produced by overcoating the samples with silicone rubber cover-slide adhesive (medium optical index material) was used as a means to evaluate whether the anti-reflective coating's index would be high enough to provide the best optical matching for cells finally assembled with cover slides. The as-deposited reflectance was measured as a function of incident light wavelength from 400nM to 1000nM and changes with post-deposition treatment and adhesive application were observed for evaluation of overall film optical properties.

The changes in evaporant source material consisted of:

a) fresh Ta_2O_5 powder (Atomergic Chematals Co.)

b) Multiply-vacuum-melted glass from the powder.

c) Adding a back pressure of oxygen during evaporation in expectation of restoring stoichiometry after probable dissociation during evaporation.

The results of these experiments are shown in Figure 1, Figure 2 and Figure 3. These films were all electron-beam evaporated, with low background pressures before deposition. Fresh source charges of Ta_2O_5 powder produced curves of the type shown in Figure 1. The right-hand lower curve is the reflection obtained as deposited. The left-hand lower curve results after brief heating (seconds) at temperatures in excess of 350°C. The optical effect of the heating is to shorten the wavelength for quarter-wave matching, most likely due to an index of refraction increase or physical shrinkage in densification. Application of the silicone adhesive, which has a refractive index near 1.5, causes a net increase in reflectance across the silicon absorption band. This indicates a relatively low value of index of refraction for the film. These curves are very reproducible, always with an apparent film index too low for optimum optical matching of the adhesive layer and the silicon.

Figure 2 shows the set of reflectance curves measured when a background pressure of oxygen at 2×10^{-5} Torr is maintained during evaporation. Note that when the film is overcoated with the silicone the reflectance is just slightly worse over the silicon absorption band, a somewhat surprising result.

Figure 3 shows typical reflectance curves for films produced by evaporating a tantalum oxide source which has been premelted in vacuum. These films show a higher reflectance before heating and not quite as low after heating as the previous film types. However, after coating with the silicone adhesive, there is a markedly lower reflectance over the silicon absorption band. Consequently, this evaporation technique was

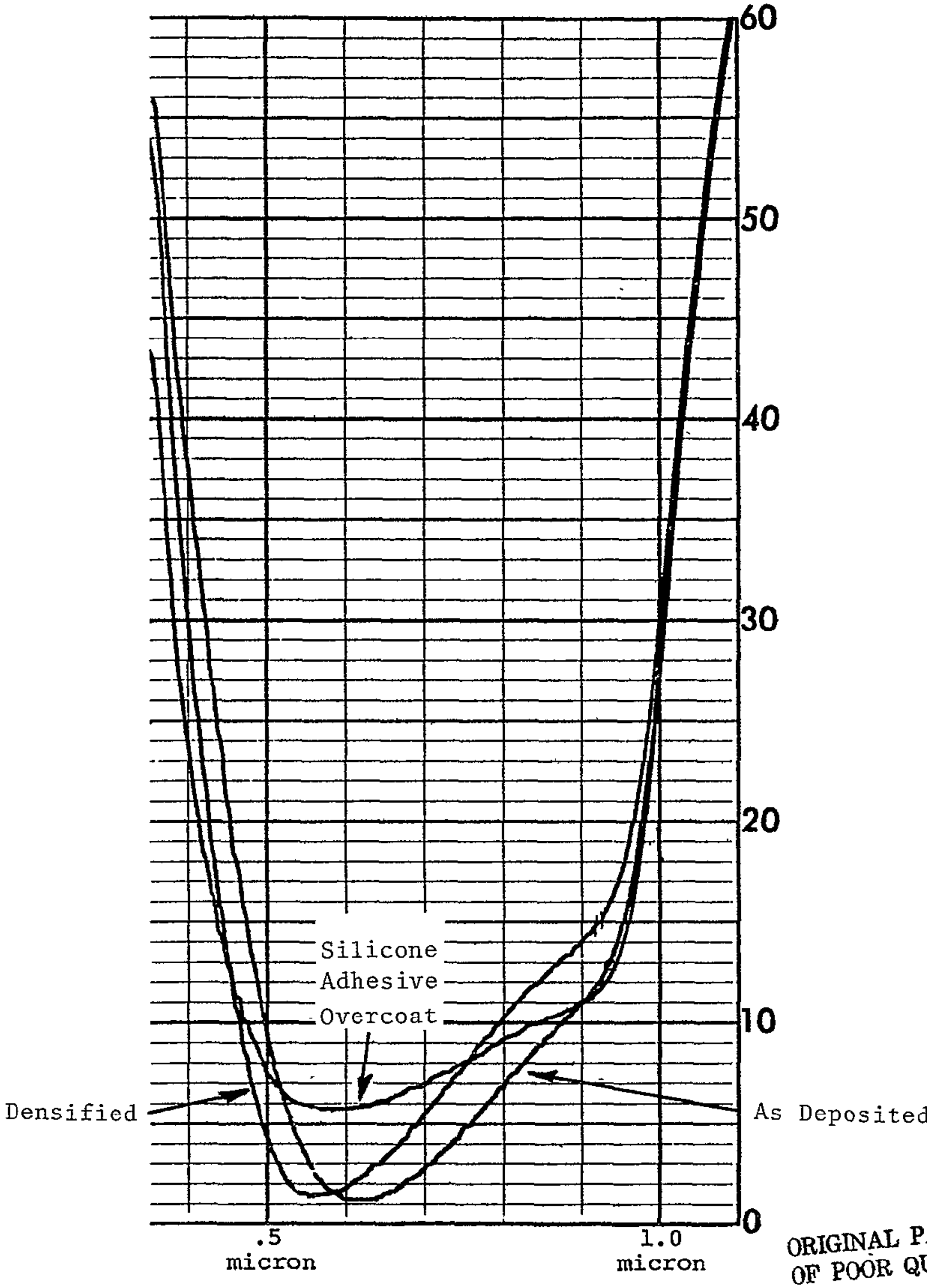


FIGURE 1. REFLECTION VS. WAVELENGTH - EVAPORATED FILM OF FRESH SOURCE $Ta_2 O_5$ POWDER.

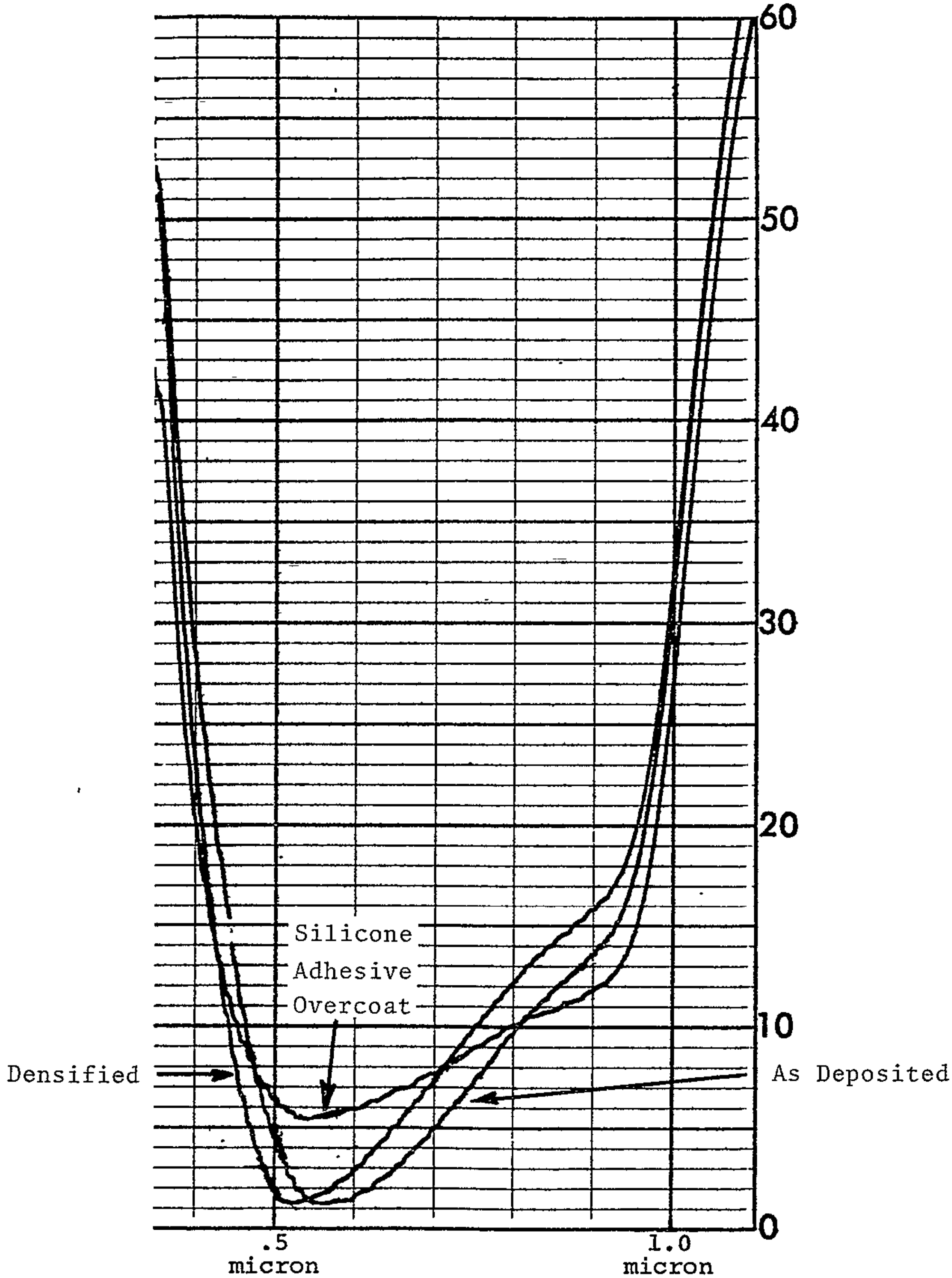


FIGURE 2. REFLECTION VS. WAVELENGTH - EVAPORATED FILM OF FRESH SOURCE $Ta_2 O_5$ POWDER WITH O_2 BACK PRESSURE.

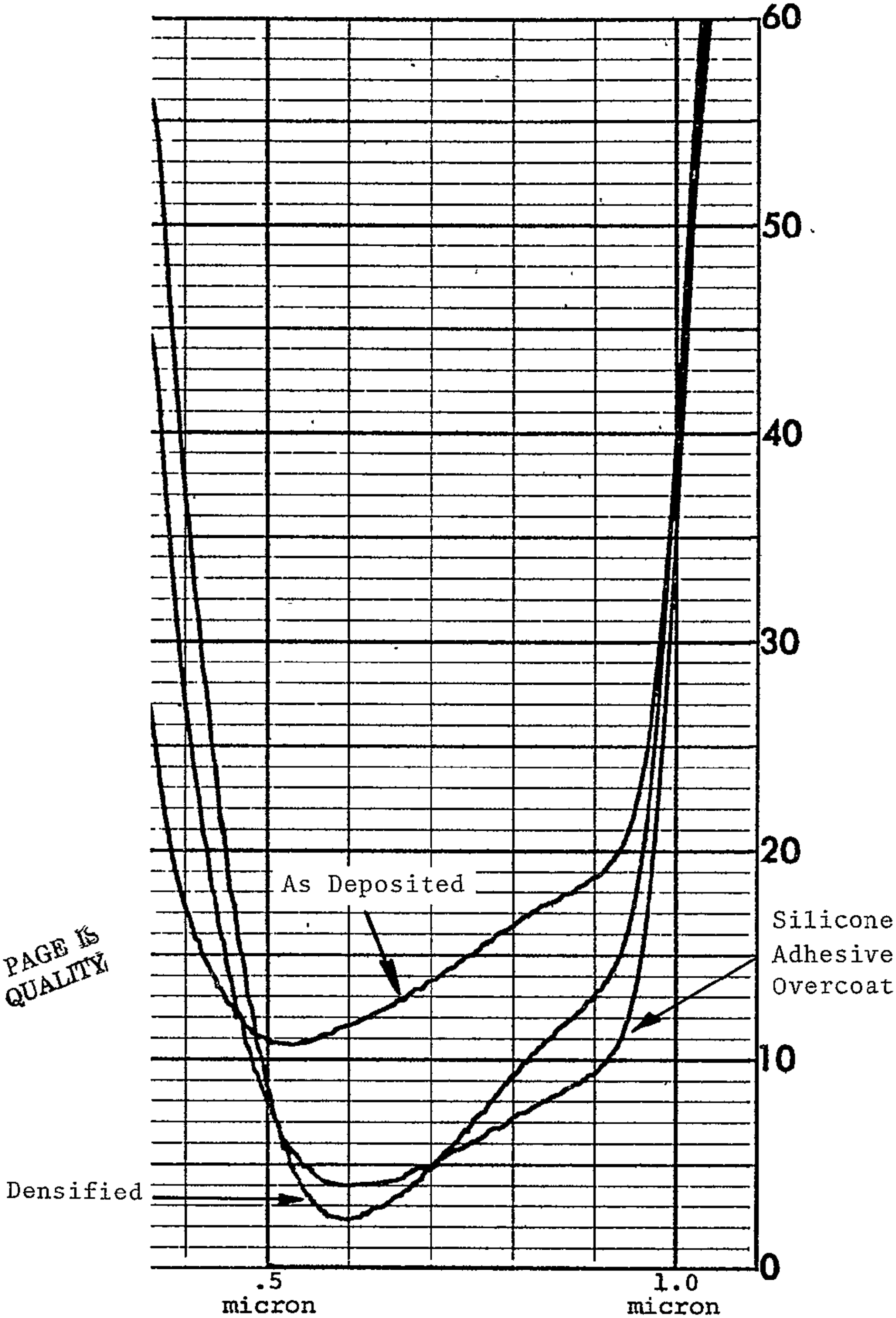


FIGURE 3. REFLECTION VS. WAVELENGTH - EVAPORATED FILM OF PRE-MELTED-SOURCE Ta_2O_5 POWDER.

employed for all subsequent experimental cells fabricated, including those samples submitted to JPL.

Some attempts were also to be made to characterize the rate of film densification as a function of the temperature of post-deposition treatment. However, the densification takes only a few seconds, which is similar to the thermal time constant of the silicon itself, so that avenue was not pursued.

In summation, films made as those in Figure 3 have a refractive index high enough to produce an excellent optical coupling in the final embodiment with cover slide attached, adhesion has been found to be excellent (even on slightly contaminated silicon surfaces) and the material is even very resistant to hydrofluoric acid. Thickness control is relatively easy, by either just observing the visible reflection passing purple, to match optimally at 550nm in the finished film after heat treatment, or by employing a quartz crystal mass monitor.

C. Internal Reflection

The purpose of this task is two-fold: first, to analyze the optical properties of the back interface for its effect on the longer wavelength end of the spectrum and, second, to attempt maximizing reflection at that interface for increasing the red response of thin solar cells.

Numerous samples were prepared on both (100) and (111) silicon slices for alloying over a range of temperatures and subsequent measurement of the internal reflection at the resulting interface. As in cell fabrication, aluminum was evaporated onto the silicon surface and then alloyed into the silicon for a given time at a particular temperature. Separate samples were used for each time and temperature.

The optical measurements were performed with the Beckman DK-2A spectrophotometer and Gier-Dunkle integrating sphere in the Solarex laboratories. The measured quantity was the net reflection at wavelengths slightly longer than the silicon absorption band. In that range the silicon is a non-absorbing window and the reflection measured is a result of both the front-surface air/silicon and the rear silicon/alloy interfaces. The reflection at the rear interface can be calculated from the measured net reflection when the properties of the front-surface interface are known. Experimentally, the front silicon surface was smooth and cleaned in a mild hydrofluoric acid solution to produce a controlled know interface prior to measurement.

The net reflection from a series of two interfaces is:

$$R = \frac{R_1 + R_2}{1 + R_1 R_2}$$

where R_1 is the reflectance of the first interface in the light path and R_2 is that of the second interface encountered in the light path. In this case, R_1 is due to the differing refractive indices of air and silicon at a wavelength of 1.3 microns. It is:

$$R_1 = \left(\frac{n_{Si} - n_{air}}{n_{Si} + n_{air}}\right)^2 = 0.31$$

The value of R_2 can thus be calculated from measured net reflection by inserting 0.31 for R_1 in the first expression above, as:

$$R_2 = \frac{R - 0.31}{1 - 0.31R}$$

Typical plots of net reflection as a function of wavelength are shown in Figure 4. Note that the reflection becomes essentially wavelength independent for wavelengths beyond 1.3 microns.

Calculated values for the silicon/alloy interface reflectance derived from measurements are shown in Figure 5 for (100) surfaces and in Figure 6 for (111) surfaces. Before alloy, R_2 was found to be in the immediate neighborhood of 0.8. After alloying, the interface reflectance decreases; most likely the mirror darkening is due to absorption in the recrystallized layer at the interface. Below the temperature of the silicon-aluminum eutectic, the sintering effect produces little disturbance of the mirror properties. However, from the eutectic up to 850°C there is a drop in reflectance to the range of 0.5 to 0.6, with a good deal of scatter from sample to sample.

For sufficiently long alloying times at temperatures of 900°C or higher, an increased reflectance reappears, although still with considerable scatter from sample to sample.

The main conclusion to be drawn is that the reflectance of the silicon/aluminum interface is high only for treatment at

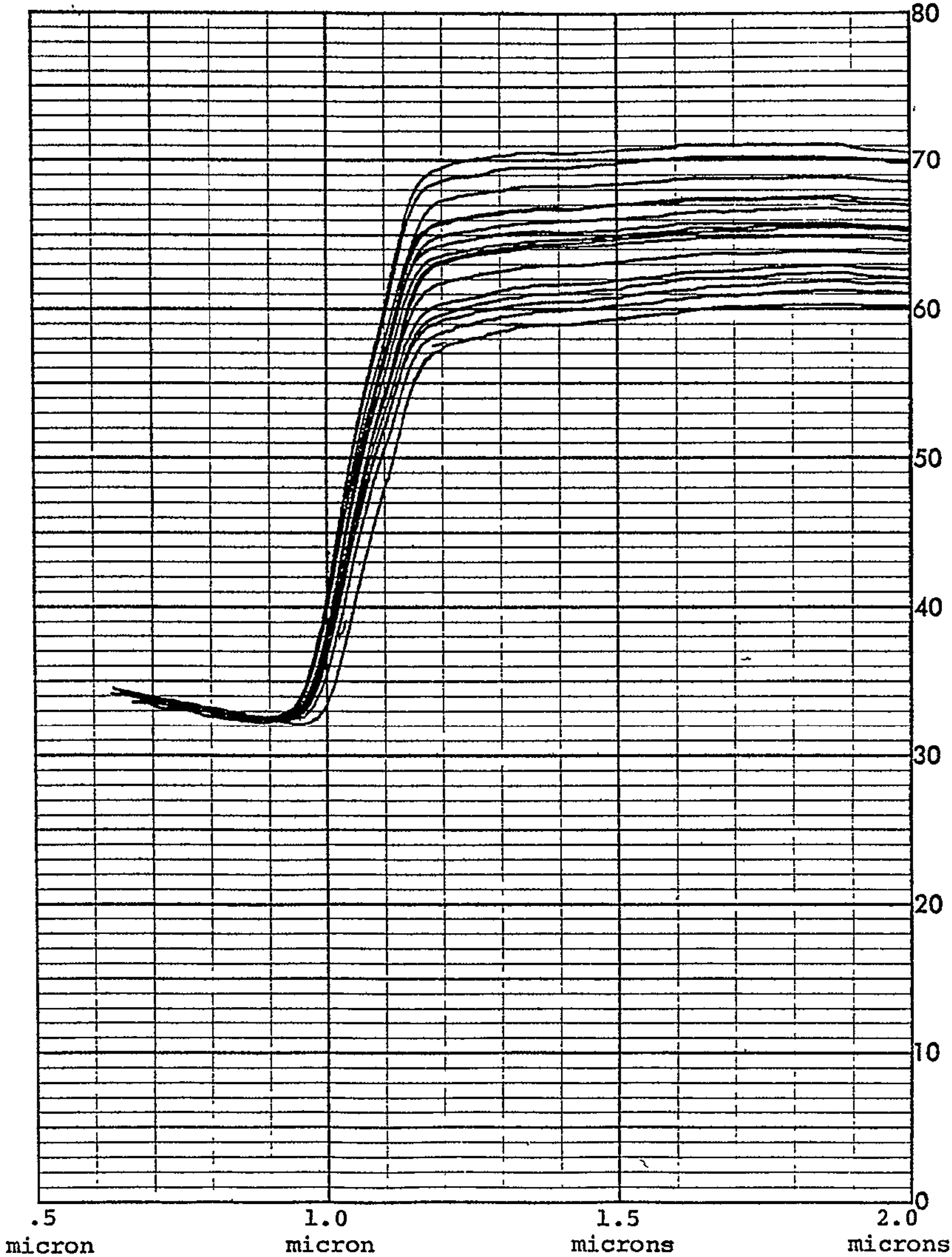
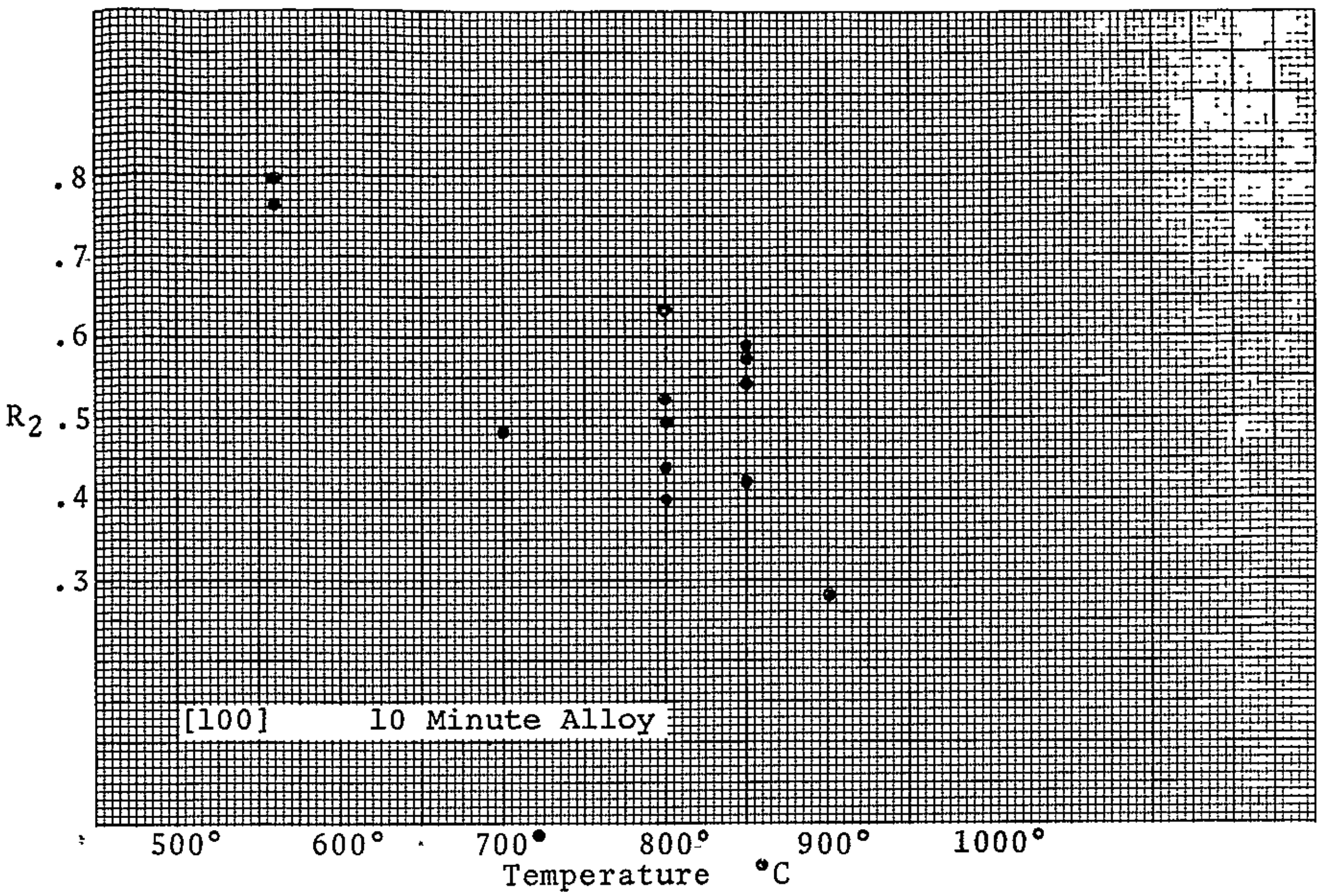


FIGURE 4. NET REFLECTION AS A FUNCTION OF WAVELENGTH



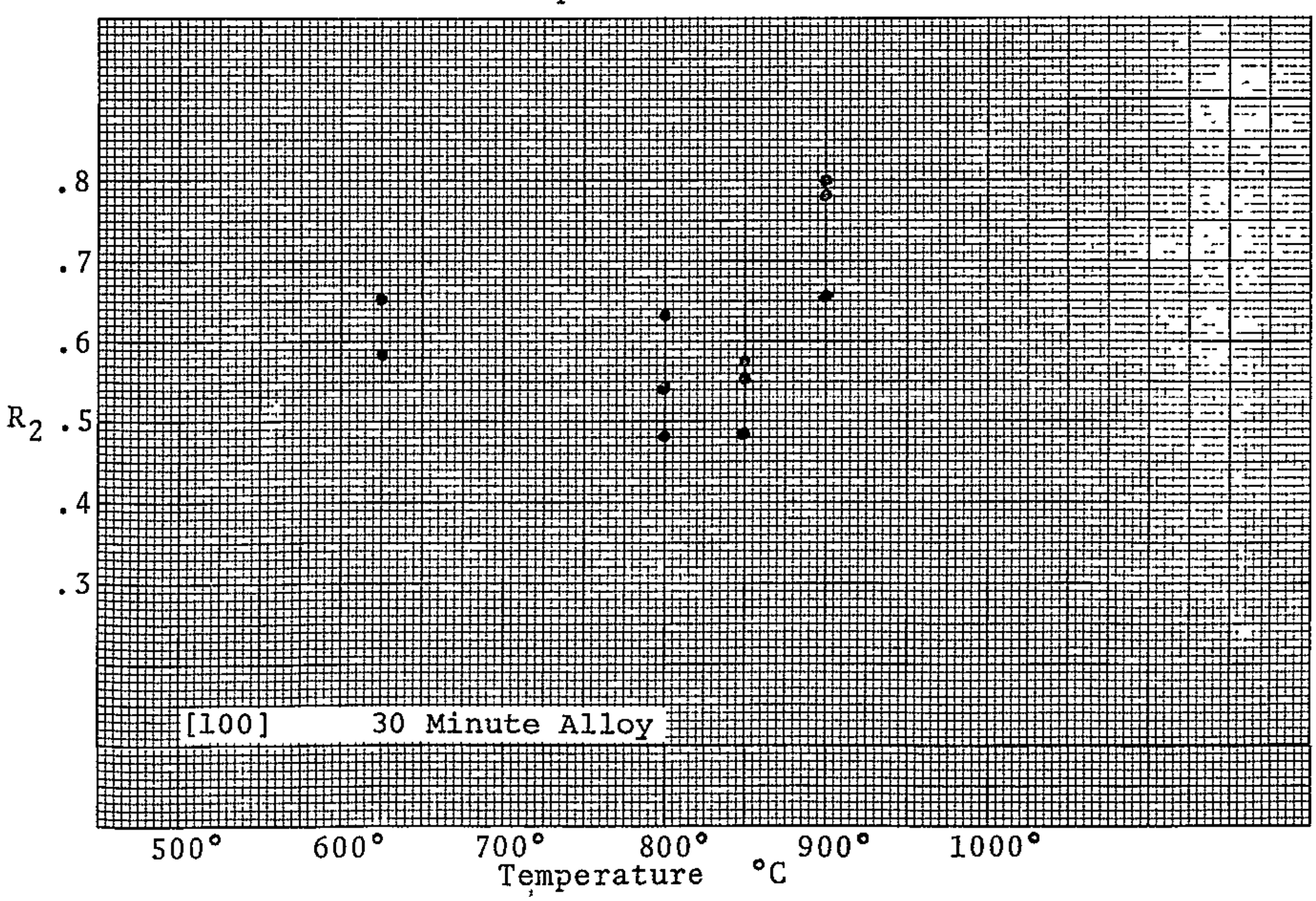
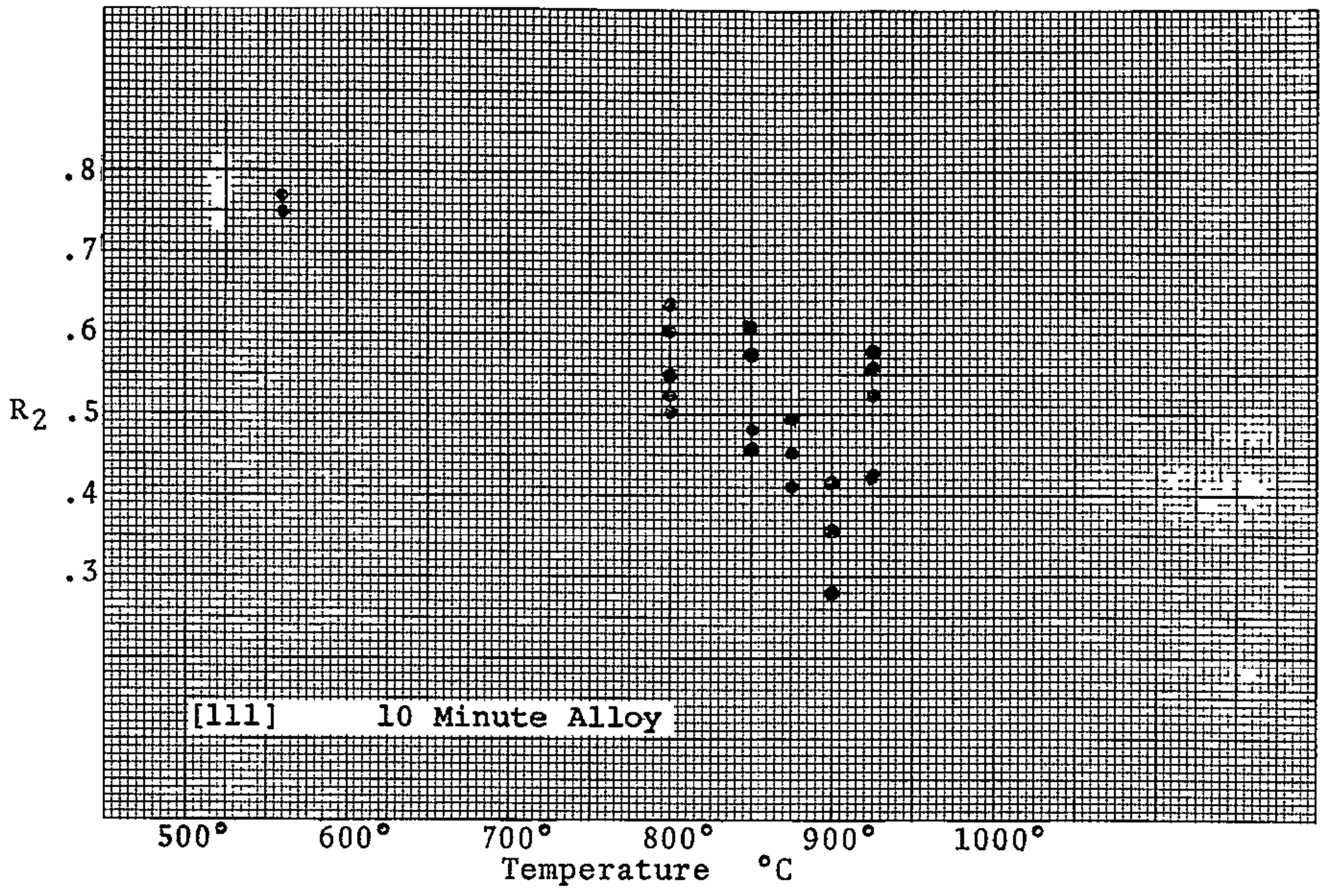


FIGURE 5. REFLECTION OF Si Al INTERFACE (R_2) VS. ALLOY TEMPERATURE



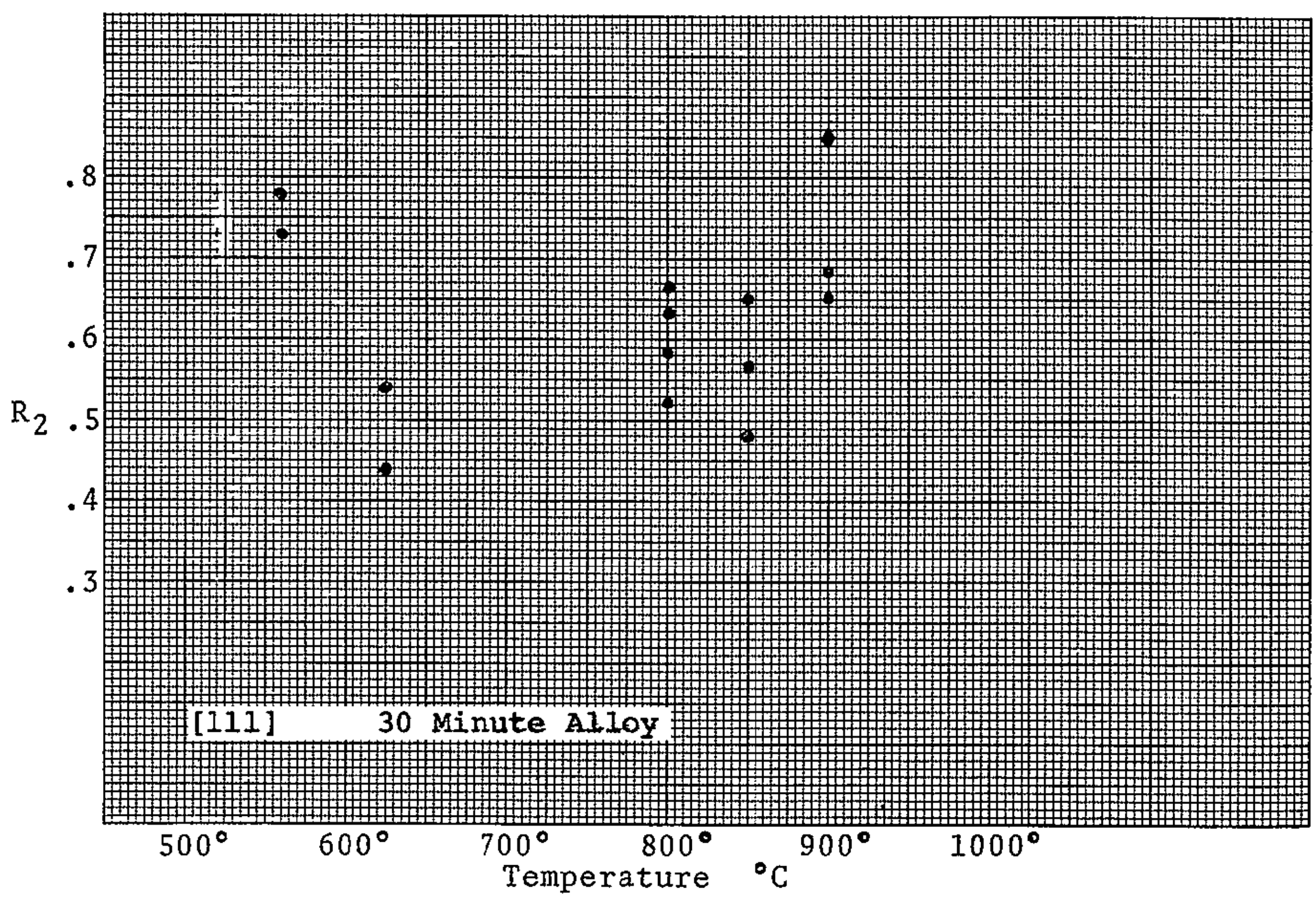


FIGURE 6. REFLECTION OF Si Al INTERFACE (R_2) VS. ALLOY TEMPERATURE

temperatures below the eutectic or long alloying above optimum phosphorus diffusion temperatures. Otherwise, a reflectance in the neighborhood of 50 - 60% will result.

These reflectance experiments indicate that utilization of high internal reflectance would require a process with avoidance of the silicon-aluminum eutectic after aluminum application or other different process techniques to utilize a high (900°C +) temperature alloy.

For verification of the effect of high optical reflectance at the silicon/alloy interface, a small quantity of cells were fabricated with a 925°C alloy. Employing such a high alloy temperature ruined the short wavelength response and power output, but the red component of the short-circuit current increased by over 10mA for 2cm x 2cm sample cells which were 200 microns thick.

D. Diffusion Optimization

Throughout this program there was a continuous effort on optimizing the front junction diffusion process. It involved the use of both phosphorus and arsenic from different source compositions (PH_3, $POCl_3$, AsH_3) both alone and in combination, changed in gas compositions and flow rates, and variations of time-temperature schedules. The resulting solar cells were evaluated in terms of maximum output power under AM0 illumination (P_{max}), open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), short-wavelength short-circuit current component (I_{SC} Blue), long-wavelength short-circuit current component (I_{SC} Red) and I-V curve fill factor (F).

In general, it was determined that employing phosphine diffusion (PH_3) produced the highest efficiency cells, while phosphorus oxychloride produced slightly lower efficiencies and combination diffusions with arsenic (as AsH_3) have not as yet produced significant improvements in cell performance. (Arsenic alone requires elevated diffusion temperatures for attainment of reasonable lateral sheet resistance which degrade other parameters.) A long series of experiments was performed to evaluate the effects that the temperature of phosphorus diffusion has on the performance of ultra-thin silicon solar cells. Quantities of cells were processed at each experimental temperature to assure a sample large enough so that extraneous effects from individual cell faults could be weeded out of the resulting performance characteristics, without reducing confidence in the results. Czochralski-grown slices were employed.

The silicon surface preparation was soon standardized to common NaOH thinning etch, hydrochloric acid cleaning, followed by a water rinse, a hydrofluoric acid etch and a rinse in de-ionized water, in order to remove any variables from deposits on residual oxides. The diffusion employed argon carrier gas and phosphine as the source of phosphorus. Early in the program diffusions were performed on 250 micron slices isochronally over a temperature range spanning 750°C to 900°C. Near the end of the first year emphasis in diffusion experimentation shifted to 50 micron slices and a higher temperature range.

The results of the diffusion experiments for cells of conventional thickness showed an onset of loss in short-wavelength photocurrent at 830-840°C, but a steady climb in open-circuit voltage past these diffusion temperatures, so that the maximum in peak output power did not occur until approximately 870°C. Experimentation with isochromal diffusion of 50 micron slices as a function of temperature produced the parameters for 2cm x 2cm solar cells shown* in Figures 7,8, and 9, where both mean values and measured limits are indicated.

It is to be noted that there is a decline in short-circuit current for longer wavelengths commencing for diffusion temperatures above 850°C, and for shorter wavelengths at temperatures above 860°C. The long wavelength short-circuit current was measured by inserting a Corning No. 2408 long-pass filter 3mm in thickness between the cell being measured and the incident AM0 light beam, while the short-wavelength short-circuit current was obtained by inserting a Corning No. 9788 short-pass filter 5mm in thickness in the incident AM0 light beam. The decline of the long-wavelength component indicates diminishing bulk minority carrier lifetime in these thin cells commencing at diffusion temperatures above 850°C. The fall in short-wavelength response follows the expected behavior with increasing junction depth at higher temperatures, while the values achieved at 850-865°C are equal to the best achieved for cells of conventional thickness at slightly lower temperatures.

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*Without cover slides, but with tantalum oxide coatings.

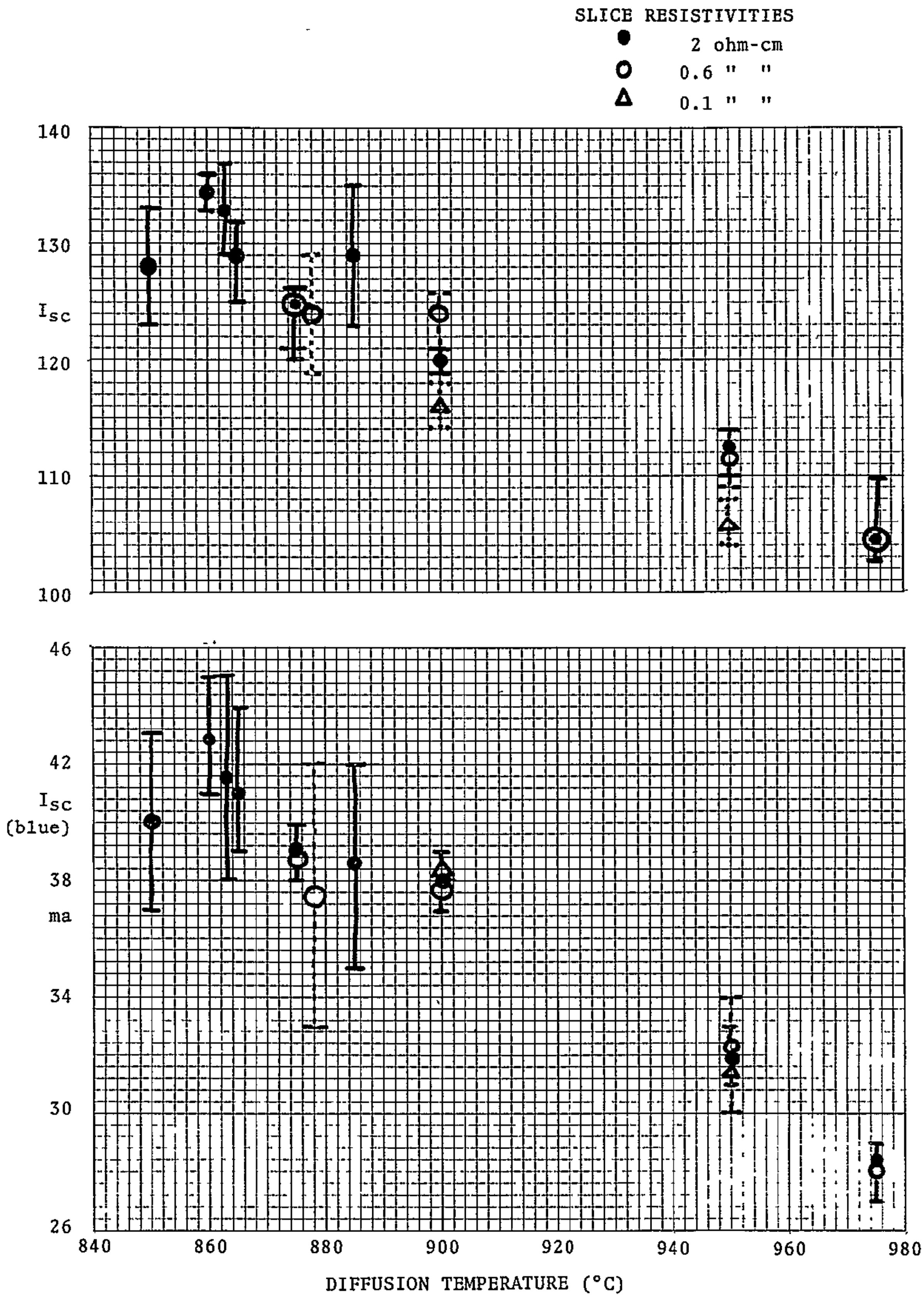


FIGURE 7. Short-circuit current and its short-wavelength component vs. diffusion temperature.

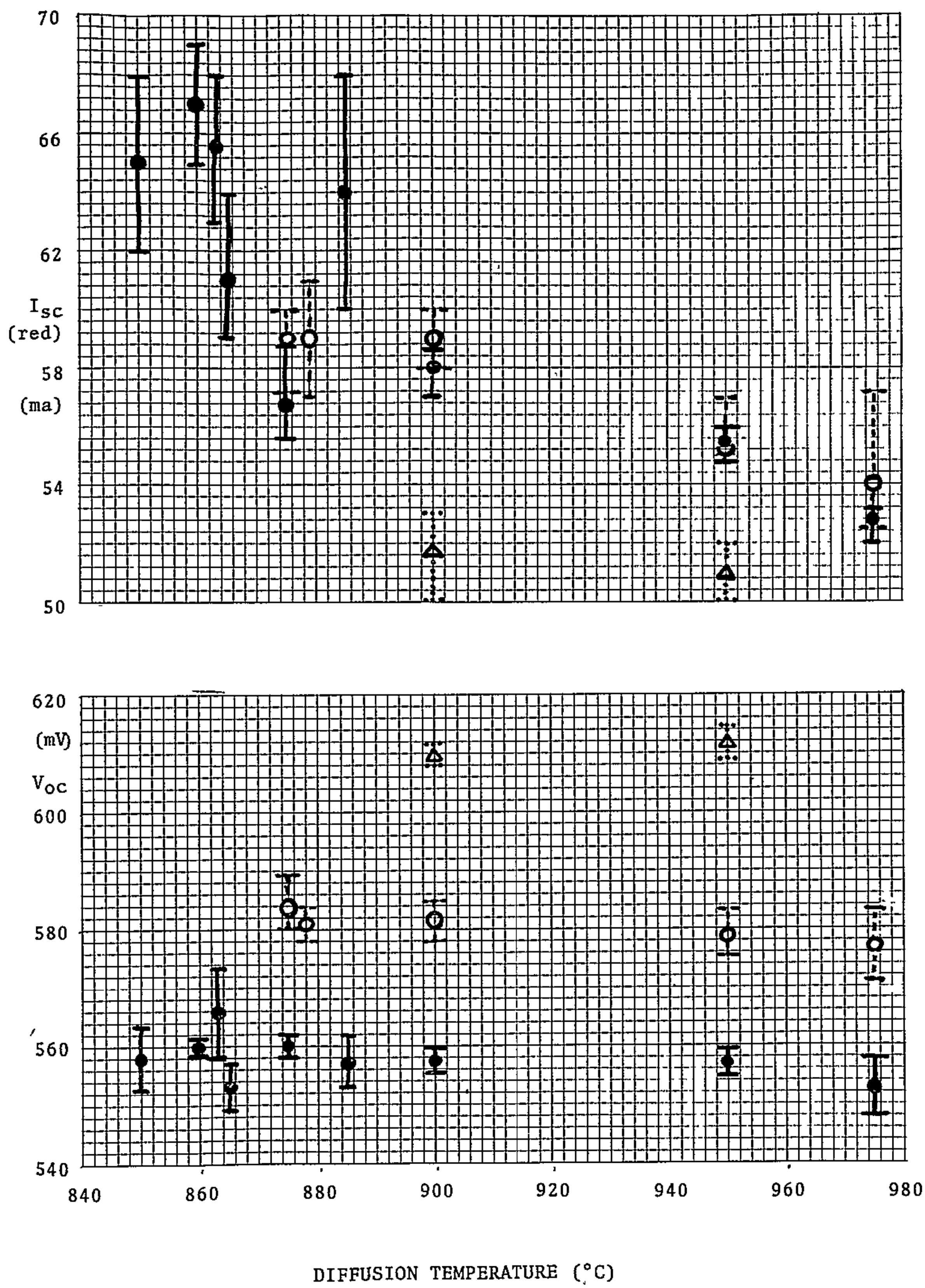


FIGURE 8. Behavior of red current and voltage vs. diffusion temperature.

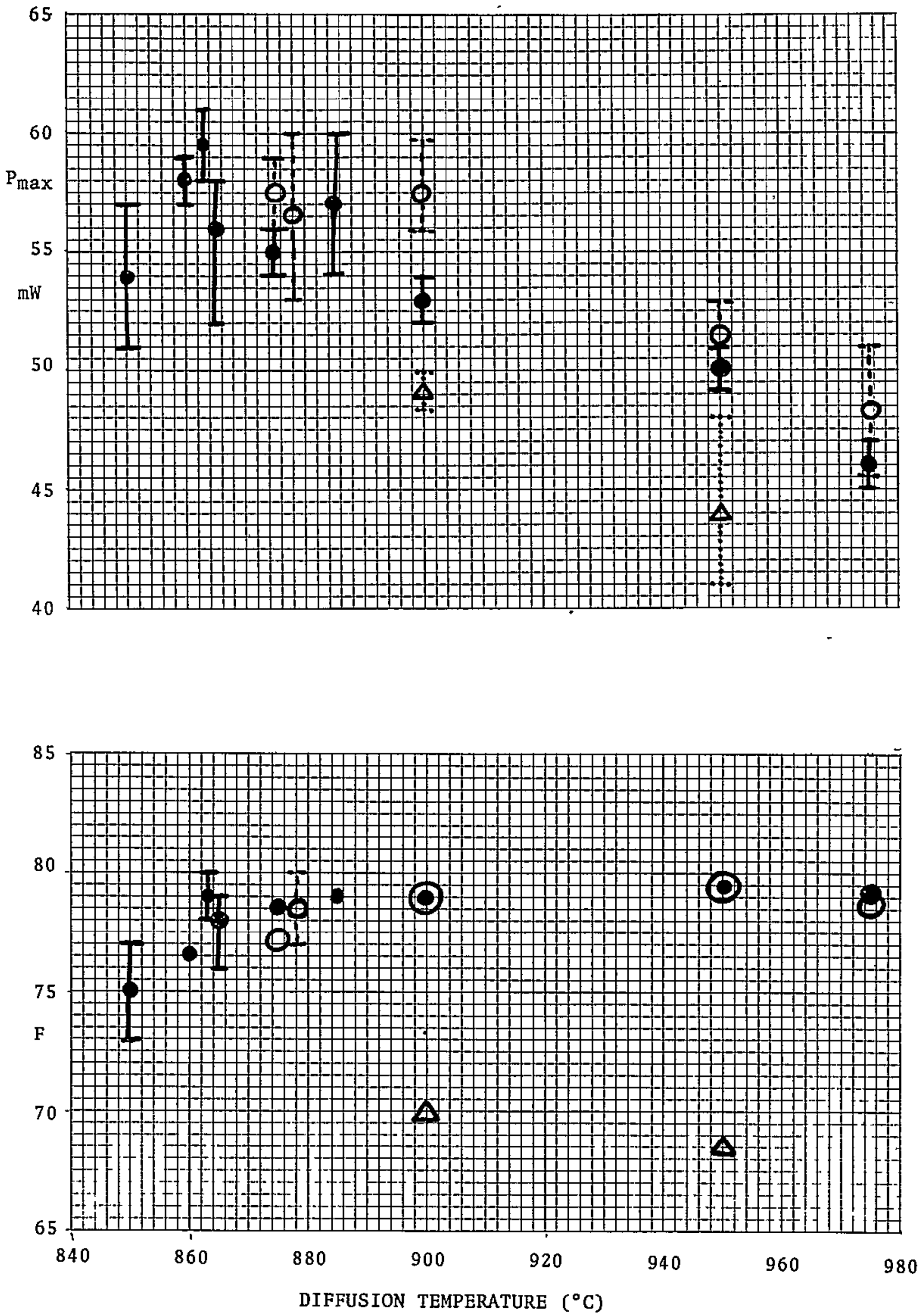


FIGURE 9. Maximum power and fill factor vs.diffusion temperature.

The maximum in peak output power for 2 ohm-cm cells was found to occur for diffusion temperatures in the neighborhood of 860°C, due to some improvement in open-circuit voltage between 850°C and 860°C before the decline in short-circuit current becomes dominant. The further improvement in curve full factor beyond 860°C diffusion temperatures is not sufficient to counteract the current decrease.

Contrary to the usual nearly constant peak power as a function of slice resistivity usually observed for 200-250 micron cells in the range of 0.5-2 ohm-cm, a slight net improvement in cell efficiency due to the increase in V_{OC} was observed for cells made from 0.6 ohm-cm slices as compared to 2 ohm-cm material. This is most likely due to the fact that ultra-thin cells do not depend on the extremely long minority carrier diffusion lengths necessary for maintaining I_{SC} (Red) in thick high-efficiency cells, since they do not have the additional generation volume. At 0.1 ohm-cm, however, the additional bulk disturbance of heavier doping became apparent in reduced long-wavelength response, and the power fell.

Further study to find the optimum base material slice resistivity, including tolerance to radiation, other types of interactions with the cell processing technology, etc., is certainly warranted for these ultra-thin cells.

E. Czochralski vs. Float Zone Silicon

The starting silicon material employed for cell fabrication in this program was picked from both Czochralski-grown and float-zone ingots. This was done so that any differences in device performance could be evaluated. However, we must say that no differences could be discerned in the initial electrical performance for the very thin cells fabricated, other than a very slight trend toward better fill factors with the Float-Zone silicon.

F. Aluminum Deposition & P^+ Alloy Schedule

1. Aluminum Thickness

The thickness of the deposited aluminum film used as the alloy source for forming the p^+ back surface was varied from 1000 Å to 10,000 Å. It was found that there is a large drop in the resulting cell performance upon using deposited films of less than 2000 Å in thickness. On the other hand, there is only a marginal electrical performance improvement with increasing aluminum film thickness between approximately 2000 Å and 10,000 Å. Also, two other limitations become apparent for aluminum films thicker than 4000 Å on these very thin cells. Near an 8000 Å film thickness the aluminum begins to form lumps and balls upon alloying, which not only produce difficulties in handling and contacting, but also stress the silicon so violently as to dimple the front surface on cooling. Above a 4000 Å film thickness, the whole cell curls after alloying and becomes more susceptible to breakage.

Upon consideration of these factors, it was decided to employ a few thousand Å of aluminum film thickness for the very thin (under 80 μm) silicon solar cells. This thickness is probably near optimum, but further study of interactions with other fabrication parameters should be performed in the future.

2. P^+ Alloy Schedule

Experimentation was done with aluminum alloying temperature to determine its effect on resulting electrical performance for very thin cells. It was found that there is a slight improvement in the photocurrent at longer wavelengths with increasing alloying temperature for ultra-thin cells. All of the alloy variation experiments were done on 1.75 ohm-cm float-zone silicon from the same ingot.

Figure 10 is a plot of both the ranges and mean values of the longer wavelength short-circuit currents for groups of cells alloyed at temperatures from 700°C to 800°C. The filter employed passes wavelengths longer than 560nm and was the same as employed for the data presented in previous sections above. Both the alloying temperature and time were varied for the experimental runs. As can be seen from the figure, there is a trend toward increasing the red component of the photocurrent with increasing alloying temperature, and also a trend to lowering the red component with increasing time in the alloying furnace. It is apparent that short alloying cycles at higher temperatures produce improvement in cell performance, since the open-circuit voltage and fill factors were unaffected, as can be seen from the additional data in Table I. As discussed in section C above, however, increasing alloying temperatures produce a reduction in optical reflectance at the alloy interface, and at temperatures in the range of the phosphorus diffusion commences to degrade the short-wavelength response.

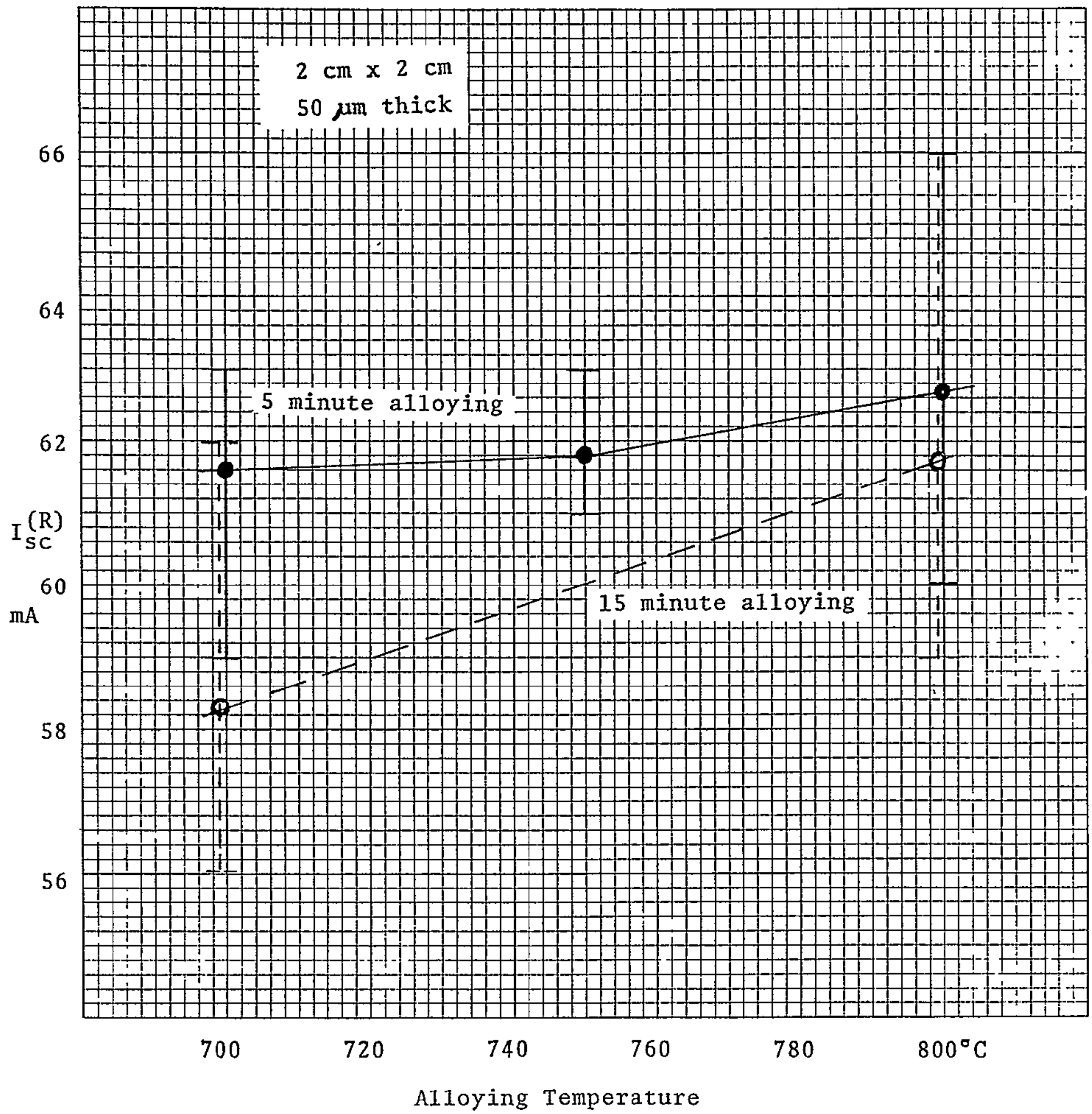


Figure 10. Effect of alloying temperature and time on the red component of the short-circuit current.

TABLE I

Exp't.#	T(alloy)	t(min)	V_{oc}(mV)	I_{sc}(red)(mA)	F	P_{max}(mW)
67	700°C	5	547-555	59-63	.77-.79	54-58
67	750°C	5	550-557	61-63	.76-.77	53-58
67	800°C	5	552-561	60-66	.77-.78	56-58
67	700°C	15	550-558	56-62	.77-.79	52-57
67	800°C	15	550-556	59-66	.77-.80	54-58

Cell performance data for alloy temperature and time variations. Measured for fifty 2cm x 2cm cells without coverslides at 25°C, with thicknesses from 55 μm to 65 μm.

G. Power Output vs. Thickness

Reduction in solar cell thickness from the conventional 200-250 micron range down to the neighborhood of 50 microns reduces the minority-carrier generation volume for the long-wavelength end of the silicon absorption band. In addition, the closer proximity of the back contact to the front junction accentuates the effect of minority carrier recombination in the neighborhood of the back contact on reducing both the open-circuit voltage under illumination and the collection of minority carriers generated by intermediate to long-wavelengths. Despite these deleterious possibilities the ultra-thin silicon solar cells fabricated in this program retained most of the photovoltaic conversion efficiency achieved with similarly fabricated high-efficiency cells of conventional thickness. Figure 11 shows the peak power at AM0 for 2cm x 2cm cells of 2 ohm-cm and various thicknesses fabricated during this program. These cells were measured at 25°C without covers and are smooth-surface cells with tantalum oxide anti-reflection coatings. The improving efficiencies achieved during this program as shown in the figure resulted largely from experimentation on optimizing the technology for diffusion and improved p^+ formation. The improvement over initial results achieved by the time just prior to freezing the technology utilized in the Pilot Line effort was further advanced for small quantities of experimental cells also shown in the figure as the latest results.

Figure 11 shows the output power over a wide thickness range and the improvements wrought by experimentation with the cell technology. The Pilot Line portion of this program, on the other hand, provided data for output power as a function of thickness for cells processed nearly identically in quantity. Figure 12 shows the AM0 power as a function of thickness (limited by the

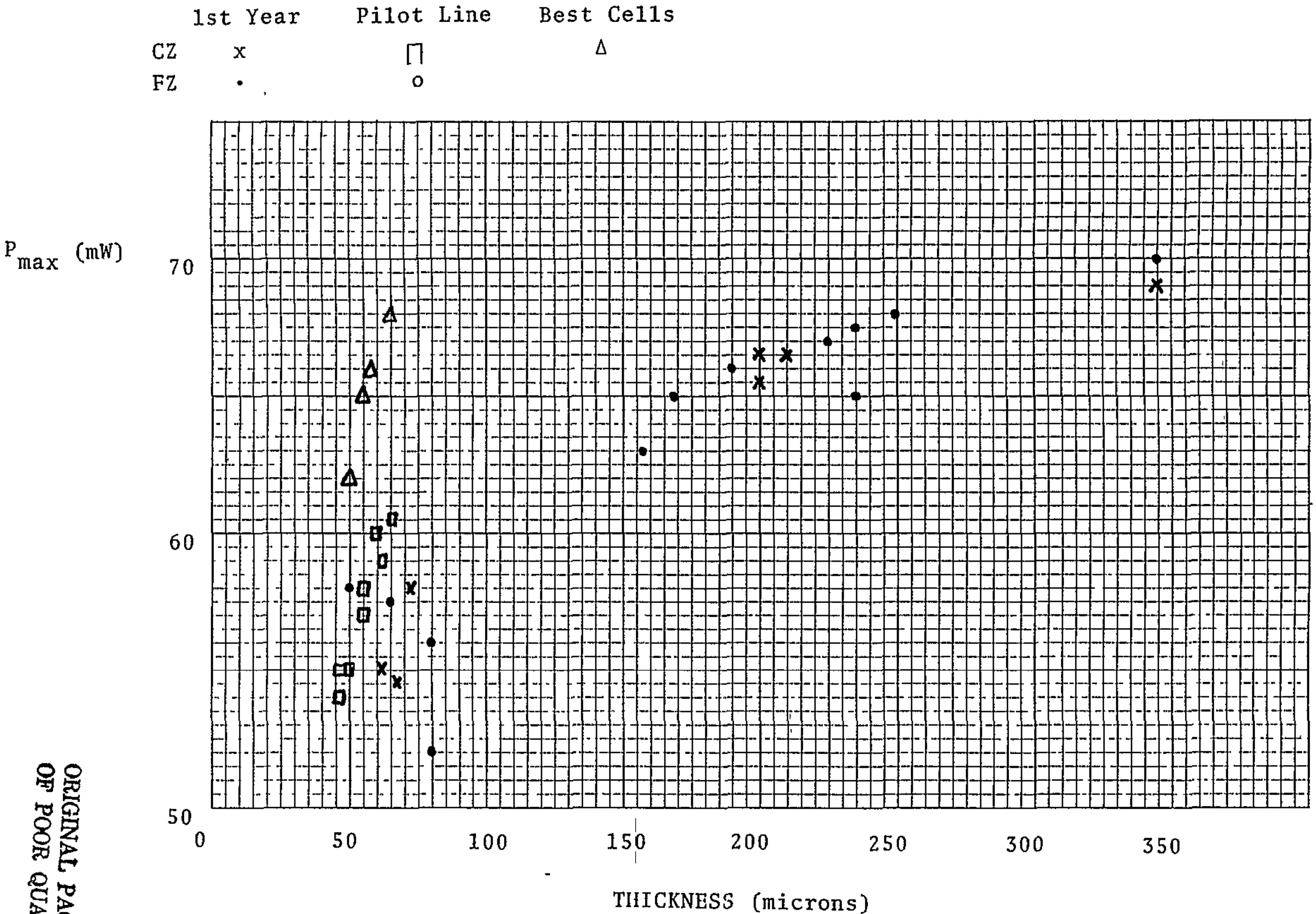


FIGURE 11. OUTPUT POWER AT AMO AND 25°C FOR 2CM X 2CM CELLS AS A FUNCTION OF THICKNESS (WITHOUT COVERSLIDES).

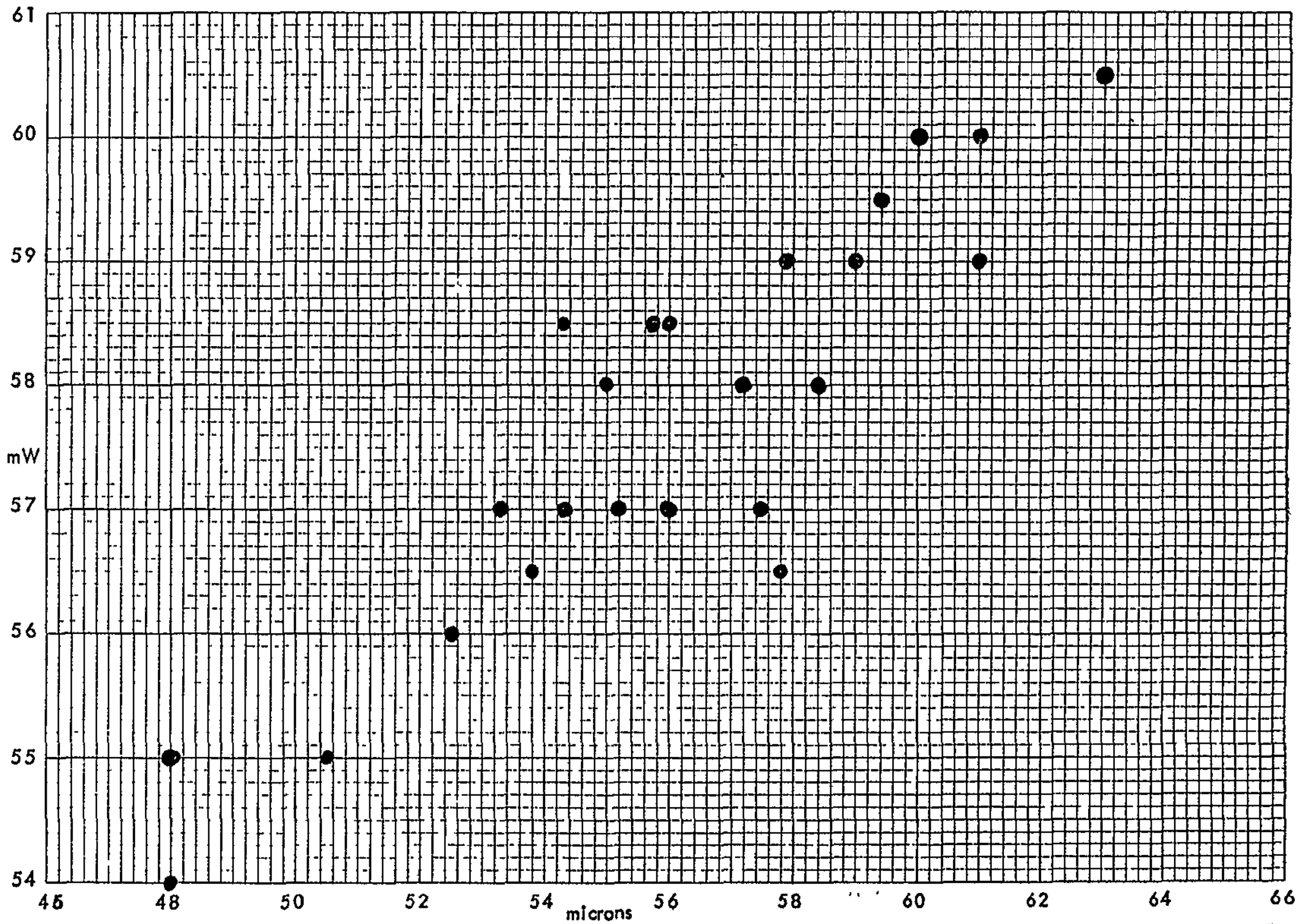


FIGURE 12. PEAK OUTPUT POWER AT AM0 FOR UNCOVERED 2CM X 2CM PILOT LINE CELLS OF THICKNESS IN THE NEIGHBORHOOD OF 50 MICRONS AT 25°C.(WITHOUT COVERSLIDES)

tolerance range in the Pilot Line program) for a quantity of cells picked at random from those which passed Final Q.C. It should be noted that there is a fairly strong dependence of output power on cell thickness in this range. Consequently, comparison to other thin cells must be scrupulously viewed in terms or actual thicknesses, lest one conclude that an unexpectedly high or low cell efficiency is process related. A 65mW 2cm x 2cm cell 75 microns thick would fit the same trend as shown in Figure 12 but have a worse power-to-weight ratio than 58 mW at 55 microns thickness. Improving the minority carrier lifetime in the p^+ region at the rear of the cell raises the power at any given thickness and decreases the rate of change with thickness.

H. Excess Forward Current & Low-Temperature Behavior

The application of very thin silicon solar cells to interplanetory missons which can experience multiples of 1AU provokes interest in how the junction forward voltage varies as a function of injected current density. An ideal forward characteristic has the form:

$$I = I_0 \exp(\frac{qV}{kT} - 1)$$

Crystal damage, resulting electronically active defect centers, mid-gap states from undesirable impurities and imperfect edge finishing modify the ideal characteristic to:

$$I = I_1 + I_2 = I_{01} \exp (\frac{qV}{n_1 kT} - 1) + I_{02} \exp (\frac{qV}{n_2 kT} - 1)$$

where the values of n are greater than unity (n_2 is nearly unity) and the values of I_0 are larger than in the ideal case. The most common effect on a solar cell is to reduce the junction forward voltage at low injection current densities (where I_1 is dominant) from the ideal case and consequently the output voltage of the cell at low light levels. One of the physical factors affecting the junction forward characteristic is residual work damage from sawing slices out of ingots. In general, very thin cells are etched more than thicker cells and thereby have their junctions at a position in the slice which is further from the original sawed surface. Consequently, they tend to have more ideal forward characteristics than thick cells simply because there is less chance of residual work damage in the resulting slice. In addition, of course, there are a myriad of other factors which require a sophisticated approach to their control. These include such topics as impurity solubilities, interfacial segregation, crystal stresses, slice flexure during high temperature furnance treatment, etc., which are a topic of continuing study.

The present status of typical ultra-thin solar cell junction characteristics from this program is demonstrated in Figure 13. The two samples in the plot are from different experimental groups and the lot-to-lot variation in the I_1 component is apparent. We are working on this area and think I_1 will be brought under control in the near future.

Figure 14 is a plot which shows the low temperature behavior of a cell having a lower I_1 component as for the lower curve in Figure 13. Here the importance of controlling the I_1 component of the junction injection current becomes obvious. On missons reaching multiples of of 1 AU both the incident light intensity and the cell temperature will drop. In order to fully realize the benefit of higher voltages expected at lower temperatures the cell's I_1 component must not intersect the I_2 component at current densities greater than a fraction of the short circuit current produced at the decreased incident intensity. The cell characteristics shown in Figure 14 have an intercept of the I_1 and I_2 components at approximately 1.3% of the 1 AU AM0 short circuit current even at -100°C. The rise in the intercept current level occurs because I_2 is controlled by the silicon bandgap energy, while I_1 has a considerably smaller activation energy and therefore changes less as the temperature is decreased. The lower I_1 is, the better the maintenance of the fill factor and the better the improvement of operating voltage to help compensate for decreasing I_{sc} at multiples of 1 AU.

Figure 15 shows the illuminated I-V characteristics at 25°C and -100°C for 5% of AM0 1 AU incident intensity of a thin cell from the same group as in Figure 14. It can be seen that these cells have an I_1 component of injection current low enough to maintain their fill factors at low intensities. The efficiency at 25°C for 5% sun is only 8.3%, but that is an artificial laboratory condition.

Figure 13. Dark forward characteristics of two current representative thin solar cells.

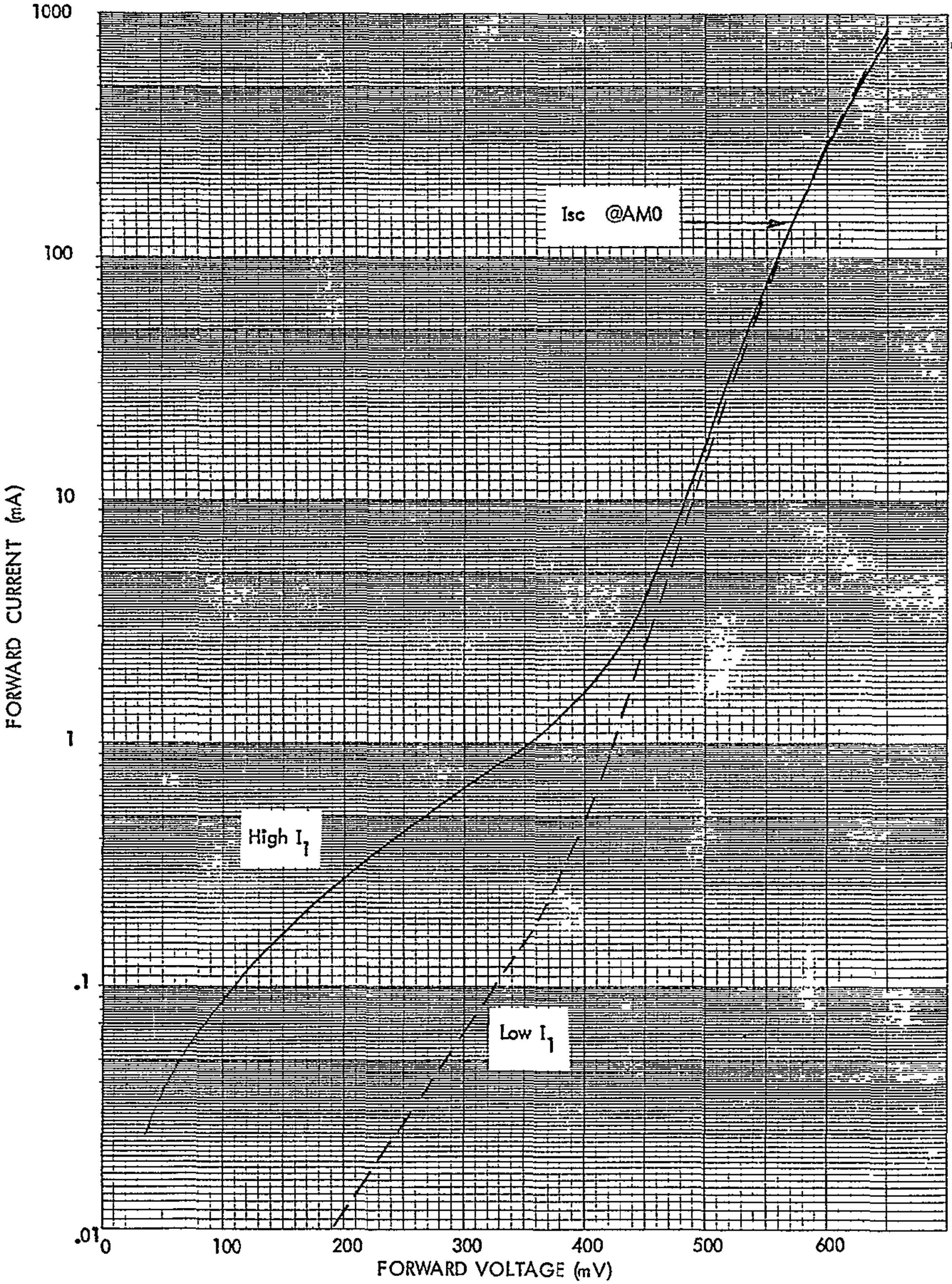


Figure 14. Effect of low temperature on the junction forward I-V characteristic for the thin cell of the lower curve in Figure 2.

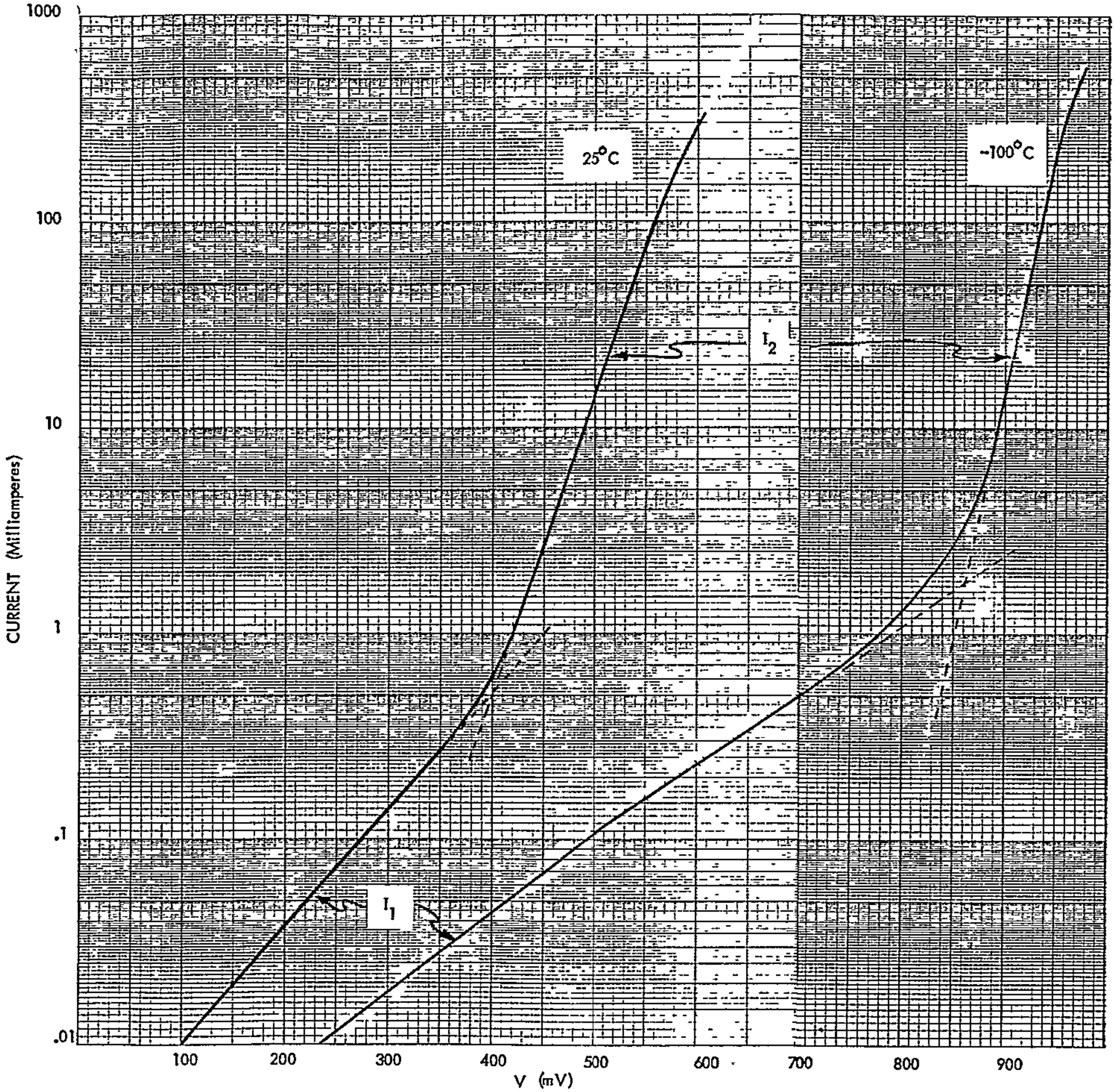
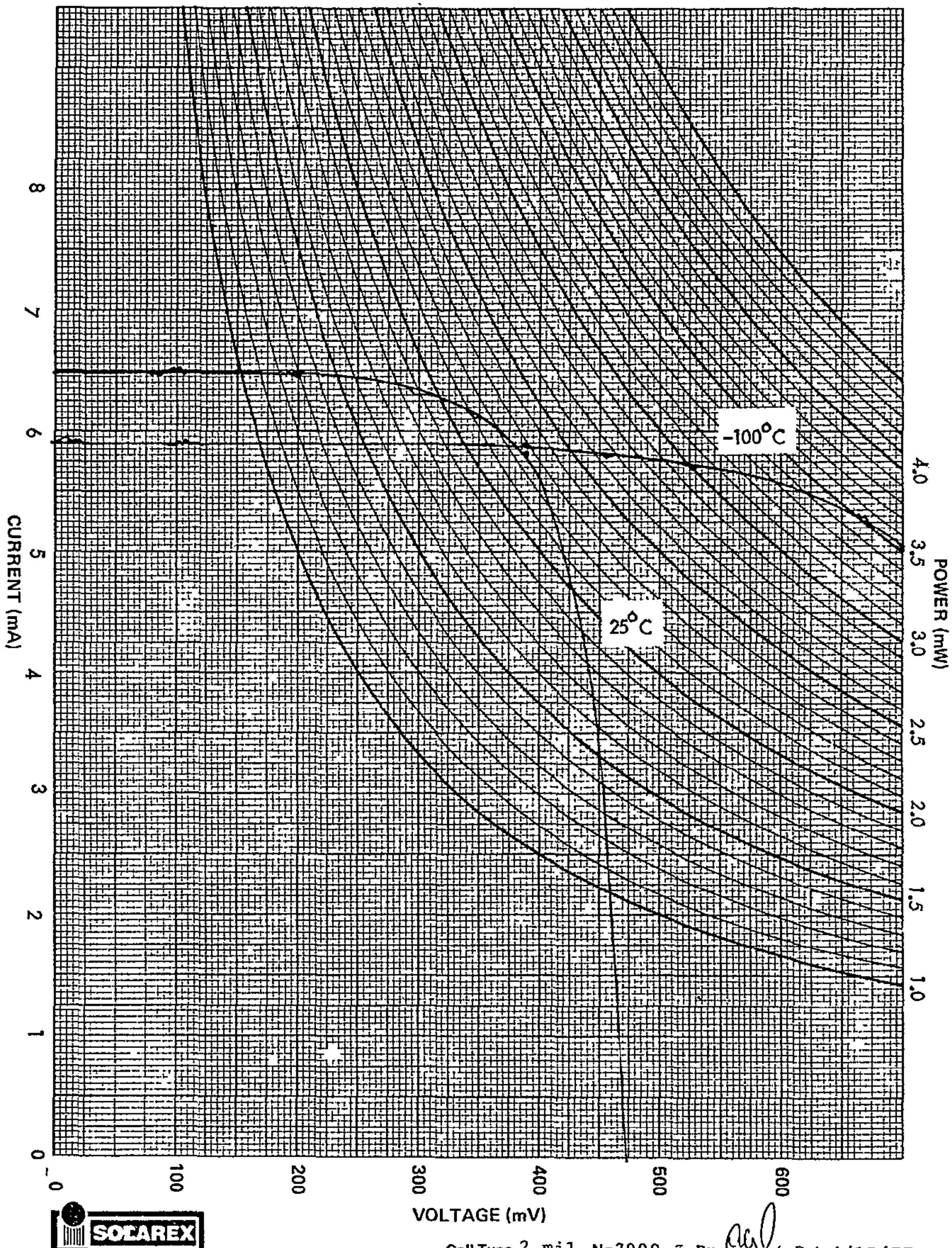


Figure 15. Low light level I-V characteristic of a 50 micron 2cm x 2cm cell for 5% of AM0 1AU illumination.



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In space, the cell temperature drop at low light levels improves the voltage and recovers the efficiency. This cell's efficiency at 5% sun and -100°C is 13%. The low-temperature, low-current efficiencies can be kept quite high with these cells and probably can be improved further.

During this program measurements made on samples at JPL were reported which showed a collapse of cell I-V characteristics at temperatures in the neighborhood of -100°C for a few samples. Subsequently, measurements were made to -120°C at Solarex on a large quantity of ultra-thin cells to find the cause of the observed effect. However, the effect was not observed in any of the measurements made at Solarex and the temperature chamber measurements were halted after a couple of weeks. The conclusion drawn was that some few of the sample cells sent to JPL were somehow under-sintered and had non-ohmic contacts at low temperatures, or gridline adhesion failed at the low temperatures. Since measurements at JPL on cells of other manufacture also showed a small incidence of the collapse at very low temperatures, it would be advantageous to develop some type of low-temperature screening methodology for any cells destined for operation at low temperature on interplanetary missions, as suggested by JPL.

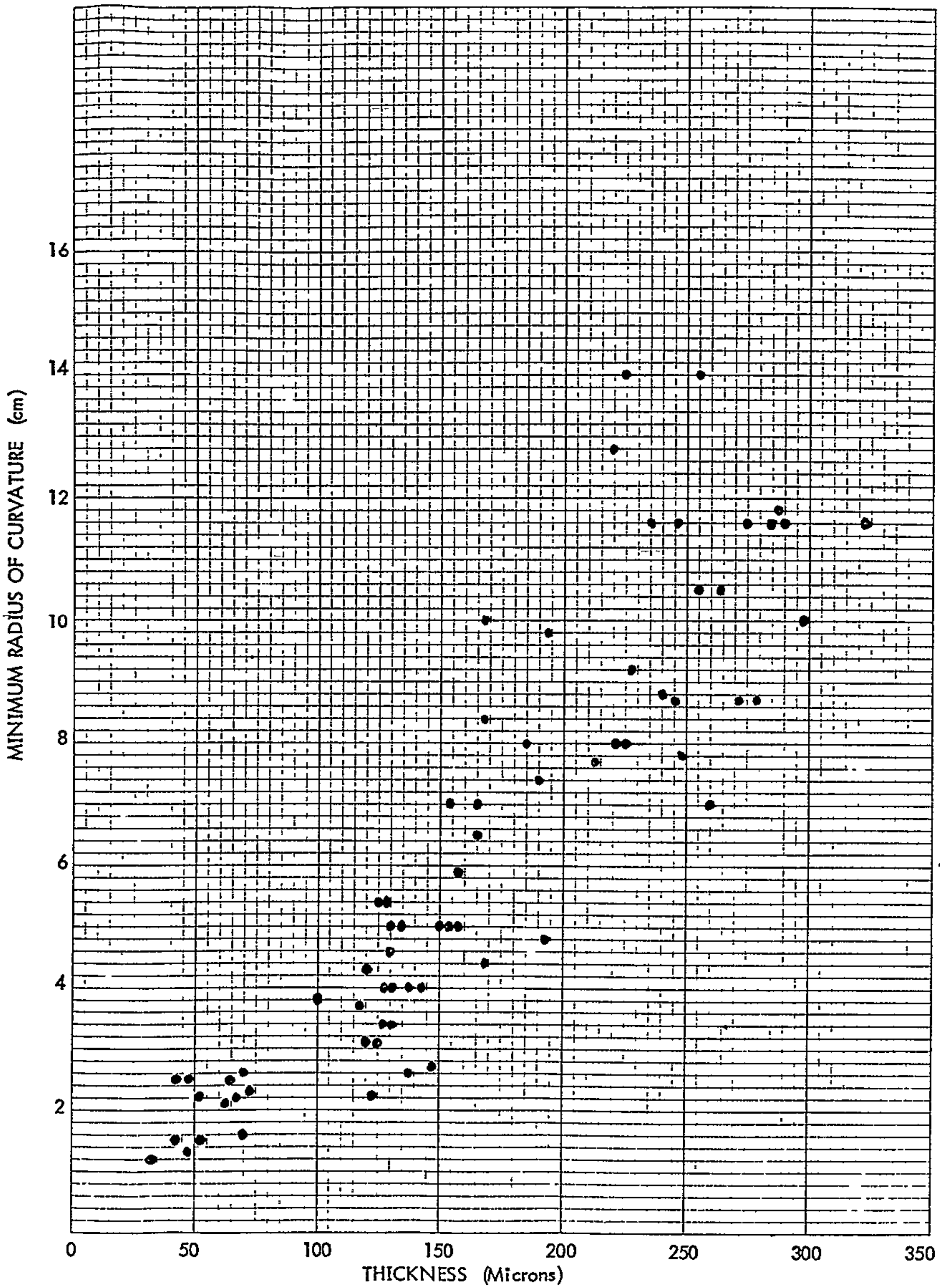
I. Flexibility & Fracture Limits

It was observed that very thin silicon slices are considerably more resistant to breakage in handling than was originally expected. This mechanical durability appears to be attributable to two factors, which are the inherent low mass per unit area and the flexibility of the silicon slice. The low mass per unit area reduces forces due to acceleration on the thin cells and thereby lowers the stresses produced by handling. The flexibility of very thin silicon slices and the cells fabricated from them allows them to deflect under mechanical stress without damage.

In order to quantify the flexibility of thin silicon solar cells we devised a static bending apparatus during this program. Both silicon slices and completed solar cells were flexed cylindrically until they reached their strain limit and fractured. The radius of curvature was measured down to the point of fracture for each slice or cell. The measurements were repeated for various silicon thicknesses and the resulting radius of curvature attained at fracture was plotted as a function of silicon thickness, as shown in Figure 16, for this case of static displacement. The limiting curvature for the best cases reached a ratio of curvature radius to silicon thickness of 200:1. The great majority of cells under 150 microns (6 mils) attain a 400:1 ratio of radius to thickness. Specifically, this means that the great majority of cells 50 microns thick can be deflected to a 2 centimeter radius of curvature. If there is interest in rolling up cells to this radius, a simple coaxial press with the desired curvature could be employed to sort out those few cells with mechanical defects which would fracture prematurely.

The differences observed in handling durability between very thin cells and, say, cells 150 microns thick, are apparently due also to the difference in mass per unit area, which sets the

Figure 16. Radius of curvature at fracture vs. cell thickness.



stress under acceleration. The measurements reported in Figure 16 are strictly for the case of static deflection and do not reflect the difference in the dynamic case.

These measurements do relate to one important consequence of flexibility as a function of thickness. Large ultra-lightweight arrays made from thin cells can be rolled up onto quite small drums for launch configuration without damaging the cells.

J. Stability Tests

Determinations of the stability of cell electrical and mechanical characteristics were performed during the program on 50 um thick cells as called for in the contract schedule. No discernable changes occurred for 50 hour thermal soaks at 150-160°C, which was the first type of test. The second type of test was the thermal shock produced by putting the thin solar cells in liquid nitrogen (-196°C) and rapidly transferring them to boiling de-ionized water at 100°C for five (5) complete cycles. When the solar cells are put into the liquid nitrogen they quickly curl cylindrically to a radius of some few centimeters. This behavior is not surprising since the test cells were not supported and mainly consist of a layer of 8 um of silver on some 42 μm of silicon. The larger thermal expansion coefficient of silver compared to silicon would be expected to put the back silver layer in tension compared to the silicon when in liquid nitrogen.

The 5-cycle thermal shock tests produced no discernable changes in 80% of the first lot tested, but decreased the fill factors to lower the peak output power by 1mW to 2mW in the remaining 20% of the lot. Examples are shown in Figure 17 and Figure 18. This result points out not an inherent problem with cell construction, but rather a measurement problem. These early ultra-thin solar cells did <u>not</u> have the common procedures of evaporation lot tape test, nor solder pull test. The reason is that the tape glue is so strong relative to the thin silicon that tape testing for contact adhesion is 100% destructive. Also, soldered-tab pull testing shatters the thin silicon far below the minimum forces in any published specifications for thick cells. Consequently, the experimental thin cells fabricated during the first half of the program had not even been subjected to the usual contact metallization testing procedures, except for visual inspection at contact sintering, anti-reflective coating and electrical measurement steps in the fabrication process.

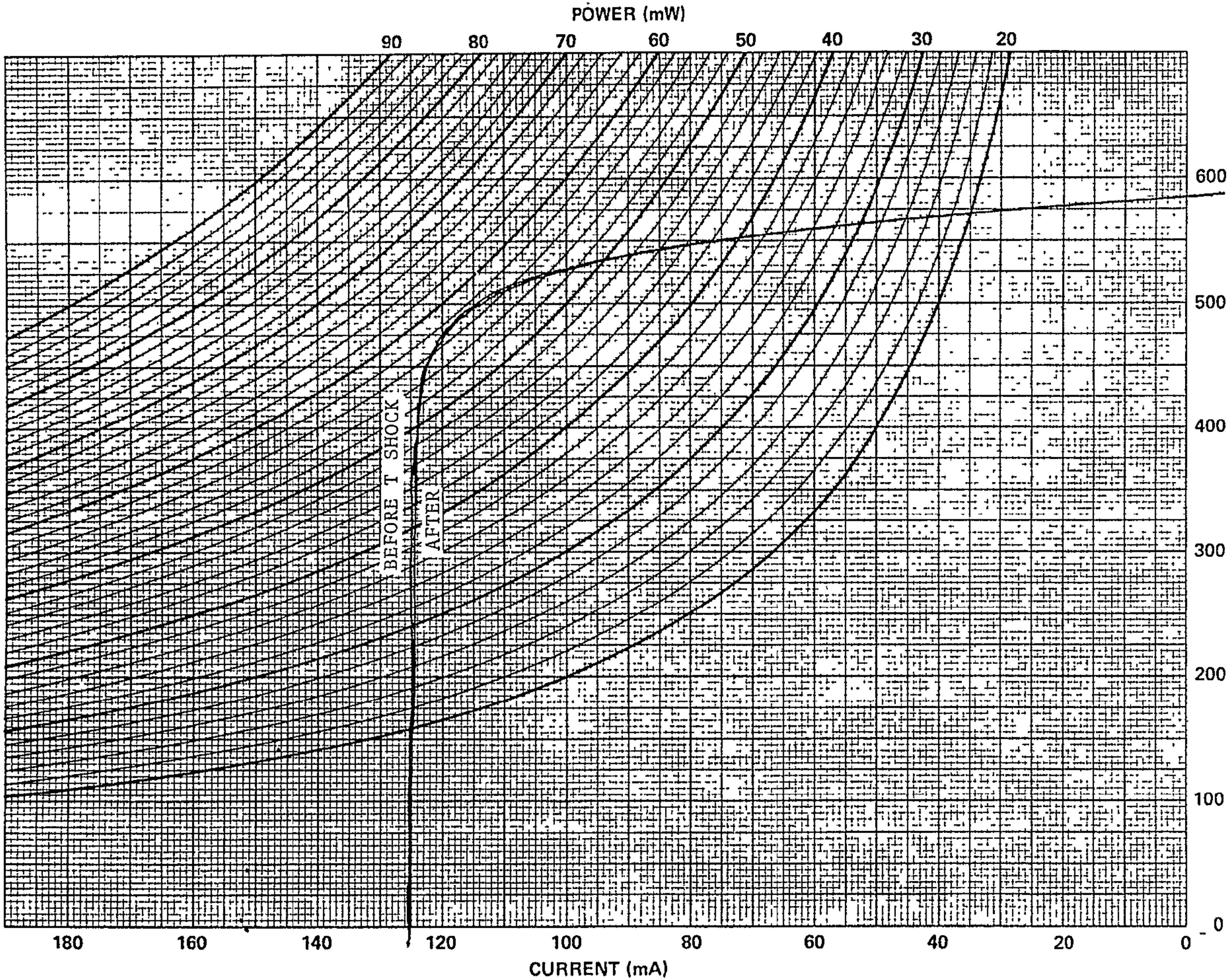


Figure 17. Cell Type .002" No. 76-4 By AC Date 8-19-76

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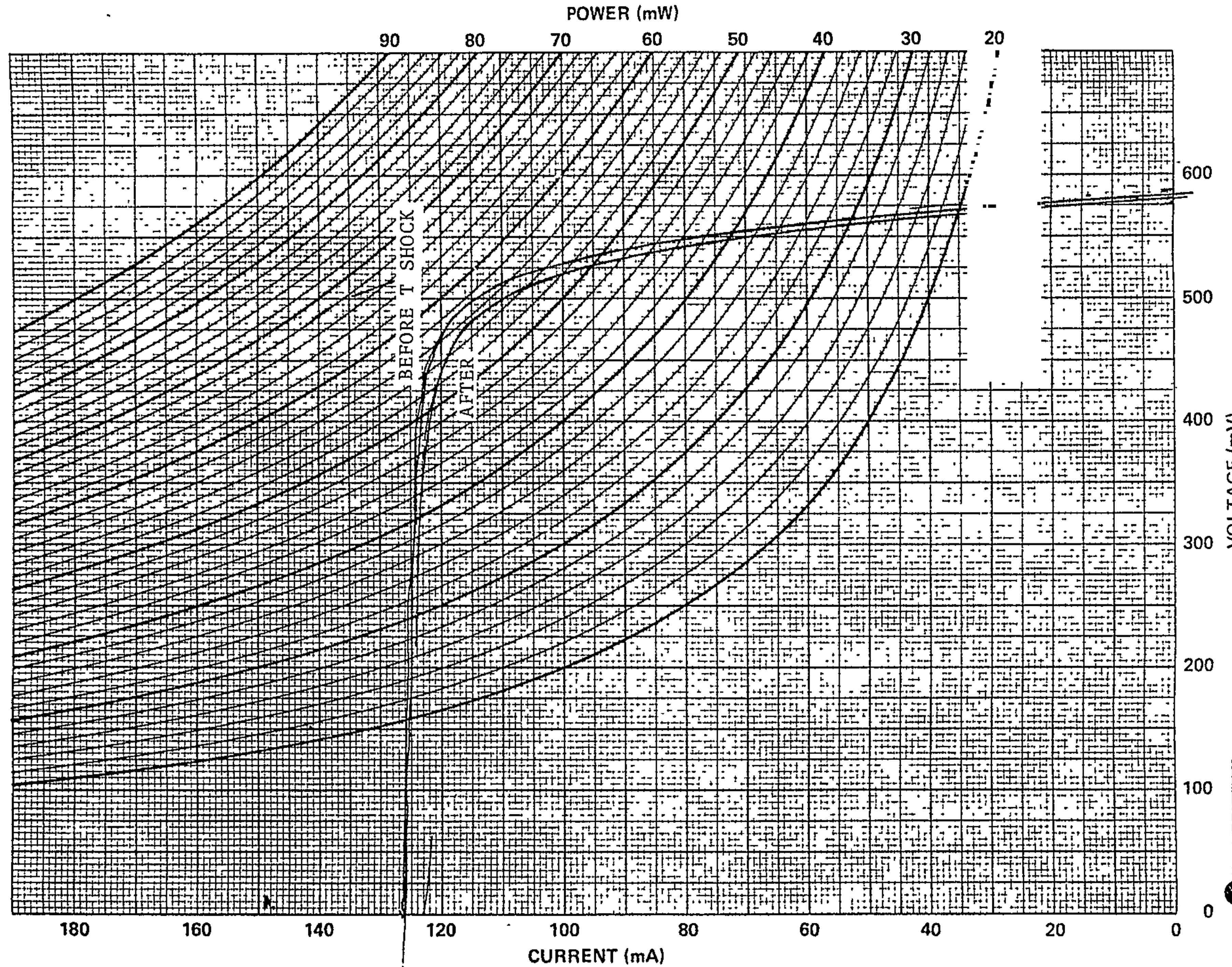

Figure 18.

Cell Type .002" No. 76-6 By Date 8-19-76

SOLAREX ROCKVILLE MARYLAND USA

A new measurement technique for assuring the contact adhesion reliability of very thin cells has to be found. Direct tape testing provided no information because the silicon itself shattered. It was suggested that perhaps the thermal shock test itself would be the most useful.

Subsequent study of this problem led to significant progress in techniques to assure contact adhesion. Improved attention to details of cleanliness before contact evaporation and contact sintering techniques were the most fruitful areas. The main attention in sintering technique was directed to reducing flexing of the solar cells before the contact sintering was completed. The usual structure has 6-8 microns of silver (plus thin Ti-Pd) over its entire back surface. Rapid heating to sintering temperature causes extreme flexing of the cell and apparently caused local delamination of the deposited metal on the front grid before intimate fusion with the silicon occurred in some cases. Changing the heat-up technique to avoid flexing of the cell until grid sintering occurs apparently eliminated the partial delamination. Series resistance increase as in Figure 18 was not observed after the flexure at thermal shock tests on sample quantities of the ultra-thin cells subsequently fabricated. In addition, in order to provide confidence in-process, co-cleaned thick silicon slices co-evaporated with ultra-thin cells are tape-tested for metal adhesion.

K. Minimization of Bowing

Thin silicon slices of only some 50 microns thickness have some residual bowing after etching to thickness, as do the solar cells after processing. This curvature is a result of the cells' flexibility, residual stress in the silicon and having full coverage of 8 microns of silver on the backs of the solar cells v.s. silver only in the gridwork on the fronts. Upon cooling after the contact sintering treatment the silver (which has the larger coefficient of thermal expansion) shrinks more than the silicon, adding slightly to the curvature as mentioned above. This does not occur to any significant degree for thick cells where the silver is a small fraction of the silicon thickness and the slices are too stiff to bow significantly.

Although the residual bowing of finished 50 micron 2cm x 2cm cells is only in the neighborhood of a millimeter at room temperature it does increase significantly upon dropping some 200^oC to liquid-nitrogen temperature. Since we have not observed fracturing of cells even with the latter degree of bowing, it is not necessarily deleterious to cell life in space environments. However, in this program we have experimented with interrupting the continuity of the silver layer on the cell back to observe its effect on the bowing from differential expansion. It was found that interrupting the silver on the back by shadowing with a screen grid which eliminated some 10% to 20% of the silver area reduced the bowing by approximately a factor of five. After cooling in liquid nitrogen the usual five-millimeter bowing of uncovered 2cm x 2cm cells was reduced to approximately one millimeter. Very similar results were obtained with a dot pattern which eliminated approximately 50% of the silver coverage on the backs. Sample cells from this experiment were forwarded to JPL for evaluation.

Although gaps were introduced in the back silver layer's current path, no significant increase in series resistance was observed. This was not surprising, considering the full coverage of the cell back by the p+ aluminum alloyed layer under the interrupted Ti-Pd-Ag.

L. Absorptance and Emittance Measurements

The absorptance and emittance of representative ultrathin solar cells were measured with ceria doped microsheet covers attached. The absorptance was obtained by measuring reflectance from 240nm to 2500nm on our Beckman DK-2A spectrophotometer with its Gier-Dunkle integrating sphere, weighing with AM0 spectral irradiance in 100nm intervals and subtracting the result from unity. The emittance was obtained by measuring wide-band long wave infra-red reflectance with our Gier-Dunkle infra-red reflectometer and subtracting the reflectance from unity. The values obtained for absorptance for 50 micron cells were found to lie in the range of 0.85 to 0.87 with the differences due mainly to the reflectance at the silicon-aluminum interface. The emittance with the ceria doped covers was 0.85, which results in alpha to epsilon ratios of 1.00 to 1.03.

Earlier efforts under this contract were concerned with the reflectance at the back silicon interface, which was not a consideration in selecting these samples. They were not optimized for internal reflectance, but just picked from later representative samples. Changing the internal reflectance does alter the absorptance.

M. Handling Techniques

The resiliency of ultra-thin silicon is very dependent upon the thinning technique, but with the technology developed in this program, as described above, the handling becomes considerably less critical. These rather springy cells have been routinely subjected to almost the same handling during processing as cells of conventional thickness. All chemical etching, rinsing, etc. is done in the conventional plastic carriers employed in high-volume production of thick silicon solar cells. Diffusion and alloying is routinely done with the cells standing in high-density quartz boats; requiring only slightly greater care in loading and unloading than thick cells. Loading of each piece is done with conventional tweezers in a surprisingly cavalier fashion without breakage.

A step which does require caution is evacuating or back-filling evaporators, as these very light cells are prone to blow about in the air stream. Throttling the back-filling air flow into the evaporators and restraining the slices to the tooling has solved the problem and only added a few minutes to the operation.

Another processing step requiring some care is rinsing and centrifugal spin-drying. High flow rates normally employed to rapidly flush deionized water rinsers can fracture cells restrained in baskets and must be throttled to gentler flows. Similarly, although centrifugal drying in commercially available spin-dryers does not contribute to slice breakage by itself (thanks to low slice mass and flexibility), spray rinsing or fast acceleration while the slices are constrained by the baskets can produce breakage. Consequently, slices were rinsed after chemical processing steps in a recirculating deionized rinser and spun dry in a Fluoroware Systems spin dryer at moderate speeds.

It now appears that there are rather few significant problems in handling very thin cells during processing and that they can be treated much like thick cells, except for avoiding very rapid jerks or other high torque situations during individual steps or transfers. None of these reasonable precautions are inherently production rate limiting.

Other aspects of handling which require some caution were discovered early in the program. Although the ultra-thin cells are extremely flexible and quite resistant to breakage in normal handling, they can be crushed with relatively moderate forces. As just discussed, this can occur with slices constrained to wet-processing plastic baskets. Crushing can also occur in thickness measurement or shipping. Thickness measurement with micrometers, calipers or dial gauges can apply extreme localized stresses unless great care is taken in handling. Consequently, an out-of-contact differential capacitance thickness gauge (ADE Corp. "microsense") was obtained for measuring large quantities of slices in the Pilot Line phase of this program. Such an instrument only requires passing the slices between sensors spaced a millimeter or so apart and eliminated breakage at thickness measurement.

Shipping breakage was found to be due to using polystyrene foam containers with cell slots under 2cm in depth. These containers allowed the box lid to crush the cells against the slot bottom without bowing, for forces less than affected cells of conventional thickness in shipping. Boxes with slots deeper than 2cm eliminated the problem, as the cells do not suffer any significant breakage rattling in the deeper slots.

N. Production Rate-Limiting Steps

After a considerable review of the process technology for fabricating ultra-thin silicon solar cells in this program we had to conclude that there really are not any steps limiting production rates other than the thinning etch for the starting slices and subsequent rinsing steps. Beginning with conventional slice thicknesses as-sawn of some 13 to 16 mils (330 to 400 microns), the NaOH etching alone takes approximately 45 minutes to reduce the slice thickness to some 50 microns. In addition, starting slices were sorted into narrow ranges of thickness in order to produce batches of etched slices of the same thickness, which took additional time. Thinner starting slices would, of course, reduce the etching time. This process is, however, a batch-etching process and etching more slices simultaneously would alleviate the time factor. So far, there was not production-quantity pressure to etch more than approximately 50 slices at once, but a larger etch bath could as easily be monitored by the same operator doing well over a hundred slices at a time.

Handling speeds are necessarily slightly slower than with conventional slices and cells, but the extra second or so per transfer is not felt to be rate-limiting in the overall process time. Rinsing is also a bit slower due to gentler flow rates for rinse water, but only amounts to minutes per batch processed.

It should be mentioned that the process employed in this program at Solarex avoided any difficulties in loading shadow-mask tooling with ultra-thin slices by employing photolithography for front-pattern gridline generation. This latter technology creates intimate mask contact with vacuum chucks and air pressure which eliminates any difficulties with slice bowing and mechanical flattening apparatus.

O. Radiation Resistance

Ultra-thin silicon solar cells would be expected to be more tolerant of bulk crystal damage than silicon solar cells of conventional thicknesses. This improved tolerance to radiation damage in the crystal bulk is simply due to the fact that these cells do not have minority carriers generated by longer wavelengths of incident light 200 microns or so from the collecting junction. Consequently, power loss due to high-energy electron bombardment would be expected to be lower for ultra-thin cells.

Figure 19 is a plot of the relative peak power output as a function of accumulated 1MeV electron dose for 50 micron and 250 micron thick similarly processed uncovered 2cm x 2cm cells which all had equivalent short-wavelength response. Also shown for comparison in Figure 19 are data from Meulenberg, Curtin and Cool* on relative peak power degradation of 225 micron and 250 micron thick uncovered planar surface high-efficiency cells from other manufacturers. The ultra-thin cells still produce over 90% of their beginning-of-life power at an accumulated 1MeV electron dose of $7x10^{14}cm^{-2}$. The 85% of beginning-of-life power level is not reached by these ultra-thin cells until the accumulated 1MeV electron dose exceeds $1x10^{15}cm^{-2}$. Consequently, designs for space power systems which would utilize these ultra-thin cells could work with considerably improved end-of-life conditions.

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* A. Meulenberg, D.J. Curtin and R.W. Cool, "Comparative Testing of High Efficiency Silicon Solar Cells", 12th IEEE Photovoltaic Specialists Conference Proceedings, Baton Rouge, La., 1976, pp. 238-246.

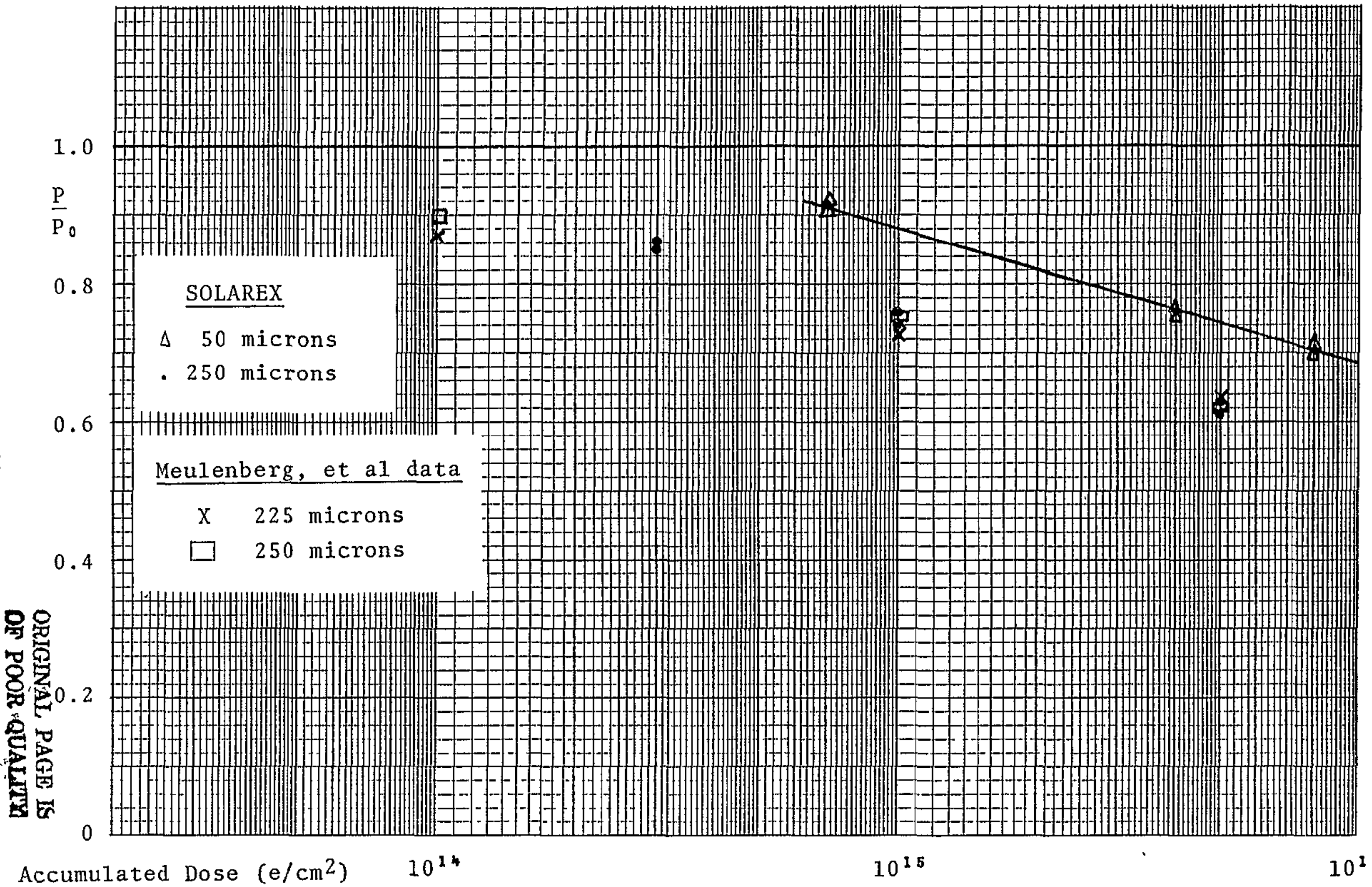


FIGURE 19. CHANGE OF P_{max} WITH ACCUMULATED 1 MeV ELECTRON DOSE FOR CONVENTIONAL-THICKNESS AND ULTRA-THIN CELLS.

P. Pilot Line Program

A few months into the second year of this program NASA-OAST and JPL requested that pilot production of ultra-thin high-efficiency silicon solar cells be implemented to produce thousands of such cells for assembly trials. A Pilot Line was designed, dedicated equipment was obtained and installed, personnel were trained for its operation and the line was successfully operated to produce the required solar cells, all in a time span of slightly over a quarter. A copy of the previously released report covering the entire pilot production portion of this program is attached to this report as an Appendix.

The highly successful pilot production program demonstrated that ultra-thin silicon solar cells have the potential to be manufactured with acceptable yield and reasonable cost.

Q. Fabrication Processes Developed Specifically for Ultra-Thin Cells

Successful fabrication of ultra-thin silicon solar cells required not only the breakthrough in etching technology, but also tailoring several process steps to result in good processing yields. Those felt to differ from standard solar cell processing practices common throughout the industry are specified as follows.

1. Slice Thinning

   Starting as-sawn (100)-oriented slices (pre-cleaned in solvents) are placed vertically in Teflon plastic slice carrier baskets. These baskets are immersed in approximately six inches of NaOH + H_2O solution maintained at 100^oC to 110^oC in a stainless steel vessel. The etching solution is from 18% to 40% by weight NaOH, with 22% being near optimum for reproducibility, but not critical. Slice thickness reduces at a rate of approximately 7 microns per minute.

   At the completion of alkaline etching the basket is rinsed in tap water and then immersed in a 50:50 solution of concentrated HCl and water for ten minutes to remove alkali-silicate residues before final rinsing.

2. Diffusion

   Slices are dipped for 10 seconds in 10:1 to 20:1 diluted HF, rinsed in deionized water, spun dry at low speed (approximately 500 rpm) and 50-100 are stood vertically in a slotted quartz diffusion boat.

They are then loaded into a 90mm quartz diffusion tube flushed with argon in a tubular furnace set at 860°C. Insertion of the loaded boat into the hot zone of the furnace tube should be done with gradual motion over a three minute period. Diffusion source gasses are then turned on for 20 minutes with the following flow composition:

Argon	:	2.3 liters per minute
1% Phosphine in Argon	:	2.3 liters per minute
Pure oxygen	:	0.3 liters per minute

Withdrawal is also a slow pull in argon atmosphere. Sheet resistance of the resulting diffused n layer should be in the immediate neighborhood of 80 ohms per square.

3. Back Aluminum Alloy
The diffusion glass alone is removed from the slices in 10:1 diluted HF and the slices are rinsed in deionized water. Pure aluminum (99.999%) is evaporated on one side of the slices to a thickness of 2000Å-5000Å.

The slices are then placed vertically into another quartz diffusion boat and loaded into a furnace set at 800°C with argon atmosphere (5 liters per minute flow) and kept in the hot zone for 10 minutes. Loading and unloading are also performed over 3 minutes each. The rear n layer is not removed, but alloyed through.

4. Front Gridline Pattern
In order to eliminate breakage of ultra-thin cells in shadow-mask tooling (they bow slightly and are difficult

to maintain in close contact without a high incidence of breakage) photolithography with Shipley Co. photoresist type AZ1350J is employed for gridline generation. Standard processes as recommended by the manufacturer are employed, with application spinning at approximately 2500 rpm, and care in developing and rinsing not to agitate the slices too violently while immersed in the solutions. Gridline pattern employs 5 micron lines spaced no more than 0.18 cm apart.

5. Metallization
   Ti-Pd-Ag, unchanged from practice for thick cells.

6. Edge Finishing
   Same as for thick cells.

7. AR Coating
   Tantalum oxide powder is pre-melted with an electron beam before the actual deposition. Coating is deposited on the cells by electron-beam evaporation from the previously melted source.

8. Contact Sintering
   Ultra-thin cells warp on heating and can loosen gridlines before sintering occurs. Cells should be heated from the front so that gridline sintering temperature is reached before the rest of the cell is at temperature.

9. Handling
   Slice transport with tweezers should not exceed 50-70% of the speeds usually employed with thick slices.

Wet-processing baskets should not be jerked while in solutions or rinses. Slices should be positioned in basket slots so as to already bear on outboard slice edges before accelerating in spin dryers. Inattention to this detail will increase breakage markedly as the rinse-water-droplet mass is very significant compared to slice masses.

Gentle restraint of slices over complete area and throttled backfilling of vacuum systems eliminates breakage from flutter and flying out of tooling.

Storage and shipping containers must be such that the cells cannot be subjected to high edge forces, especially without room to curl under the force.

Slices and cells should not be picked up by corners with tweezers.

Use flat-blade tweezers in handling, preferably the type with at least half-centimeter-wide ends.

10. Contact Adhesion Tests
Common tape-testing and bond pull-strength tests are both destructive. Tape testing by evaporation lot is inferred by association from tape-testing of co-evaporated thick slices.

11. Other Steps
Other than specifically mentioned in the above ten topics the standard techniques employed in solar cell manufacturing technologies are fully applicable. Caution should be exercised in applying sharp 4-point probes, performance test probes, etc.

IV. CONCLUSIONS & RECOMMENDATIONS

A. Conclusions

The breakthrough in slice thinning technology made the fabrication of flexible ultra-thin silicon solar cells feasible.

A fabrication process for ultra-thin cells tailored to relatively high cell efficiencies with concurrent good fabrication yields has been demonstrated, including pilot production quantities.

These cells have extremely high power to weight ratios, already producing over 60 mW from 2cm x 2cm cells 50 microns in thickness under 1AU AM0 illumination with covers attached.

B. Recommendations

Further investigations to further improve the efficiencies of ultra-thin silicon solar cells are warranted. Cells of 2cm x 2cm x 50 microns have been routinely produced with conversion efficiencies of 11%, while a few cells reaching 12.5% have been fabricated. This would entail careful experimentation with technologies to improve the longer-wavelength photocurrent collection and to produce voltage improvement, while not jeopardizing processing yields.

Further pilot production of ultra-thin cells is warranted to familiarize the photovoltaic community with quantities of such cells and the performance of arrays.

Larger cell sizes should be fabricated. Some few larger cells were experimentally fabricated during this program with little difficulty compared to 2cm x 2cm cells, but not in any quantity.

SOLAREX

PILOT LINE REPORT

DEVELOPMENT OF A HIGH EFFICIENCY THIN SILICON SOLAR CELL

JPL CONTRACT NO. 954290

June, 1977

Report No. SX/105/PL

By

Joseph Lindmayer, et al

SOLAREX CORPORATION

1335 Piccard Drive

Rockville, Maryland 20850

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology Sponsored by the National Aeronautics and Space Administration under Contract NAS-7100.

TECHNICAL CONTENT STATEMENT

I. ABSTRACT

In the latter part of 1976 Solarex achieved a breakthrough in fabricating ultra-thin (50 micron or less) silicon solar cells during JPL Contract 954290, under the auspices of NASA. The results were presented in a briefing at JPL in October and also presented at the 12th IEEE Photovoltaic Specialists Conference at Baton Rouge, La. in November, 1976. Recognizing the importance of this breakthrough, NASA OAST through JPL provided funding to exploit this advance in an accelerated pilot line phase. The program was to test the manufacturability of such thin cells to show that the new cell is not only a laboratory curiousity.

Solarex constructed a Pilot Line facility within two and a half months and during the succeeding month manufactured and delivered on schedule, 2000 of the newly developed ultra-thin (50 micron) 4 cm^2 silicon solar cells. In addition, it delivered 1000 cells that were made during the construction period.

During the intial stages of the pilot line installation, personnel were hired and trained on existing Solarex equipment in the new technology developed at Solarex for fabricating and handling ultra-thin silicon solar cells. Successful completion of the construction and training phase within this short time frame is felt to be a major achievement.

As the operational phase of the Pilot Line Program proceeded, steadily increasing yields and consistent electrical performance were attained.

This Pilot Line Program has demonstrated that Ultra-thin silicon solar cells with excellent power-to-weight ratios could be readily manufactured in a production setting with an acceptable yield and reasonable cost.

II. TABLE OF CONTENTS

III. SUMMARY

Under the auspices of the Jet Propulsion Laboratory for NASA OAST, a Pilot Line facility for producing ultra-thin (50 microns), 4 cm^2 silicon solar cells was constructed and put into operation at Solarex with the following objectives:

1) To demonstrate the feasibility of fabricating larger quantities of high efficiency, ultra-thin silicon solar cells in a semi-production setting.

2) To develop manufacturing techniques conducive to an acceptable mechanical and electrical yield.

3) To determine production rate limiting operations and provide recommendations for improvement.

4) To manufacture and deliver (within a 30 day production period) 2000 ultra-thin, 2cm x 2cm solar cells.

This set of objectives was successfully accomplished and the cells delivered precisely on schedule.

IV. PILOT LINE DESCRIPTION

A. Introduction

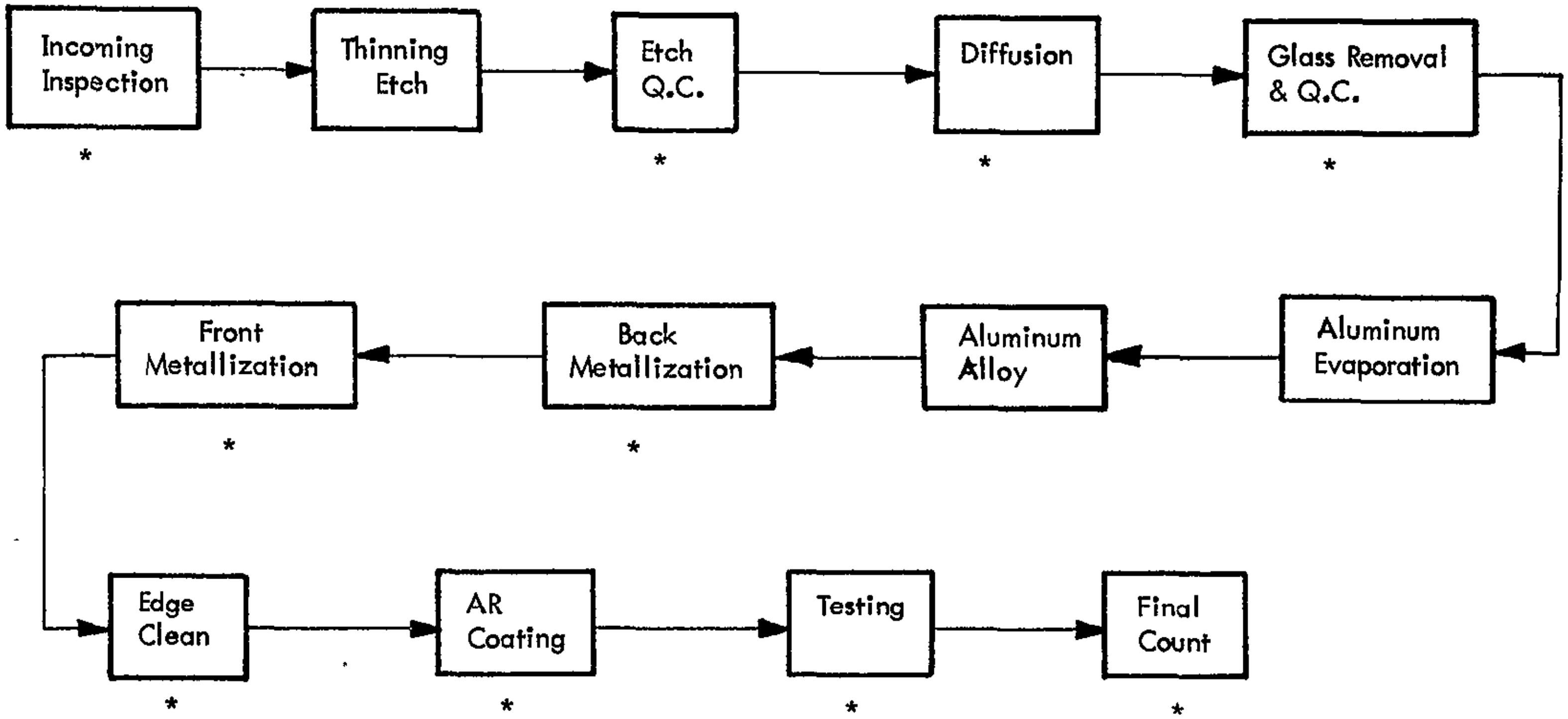
The R & D efforts by Solarex in 1976 under JPL Contract 954290 "Development of a High Efficiency Thin Silicon Solar Cell" produced a breakthrough showing that ultra-thin cells, 50 micron or less in thickness, can be made in the laboratory and Solarex delivered hundreds of such experimental samples to JPL. This laboratory work was so successful that it became feasible to try pilot production. The supporting agency, NASA/OAST, through JPL recognized the importance of this advance and made funding available to quickly exploit this breakthrough.

In January, 1977, Solarex began the creation of a Pilot Line facility for the manufacture of ultra-thin silicon solar cells. A considerable amount of internal construction and rearrangement of existing facilities was required to incorporate the additional equipment and space necessary to institute the program. Within two and a half months, Solarex purchased, received in-house, installed and put into operation the equipment required to meet the manufacturing goals of this effort while also training new personnel to operate the Pilot Line.

A process flow was established corresponding to the frozen technology to be used during the production phase. Exhibit I is the process sequence diagram for the flow employed in the program. Steps are noted in the diagram where accurate accounting and recording of loss modes were made for yield analysis.

Program and production managers generated a working plan that would allow for delivery of completed cells on schedule at a reasonable yield. Working within this framework the Pilot Line completed the production phase one day ahead of the projected schedule.

PROCESS SEQUENCE DIAGRAM



* – Steps with accurate accounting and loss mode record.

EXHIBIT I

B. Objectives

The primary objective of this effort under JPL Contract No. 954290 was to demonstrate in a short time that 2 mil thick silicon solar cells are reproducible and can be processed in quantity with a reasonable yield, at reasonable cost.

In addition, this Pilot Line effort was to demonstrate with a relatively large quantity of such thin solar cells that they are not particularly fragile, as was widely supposed.

C. Work Plan & Schedule

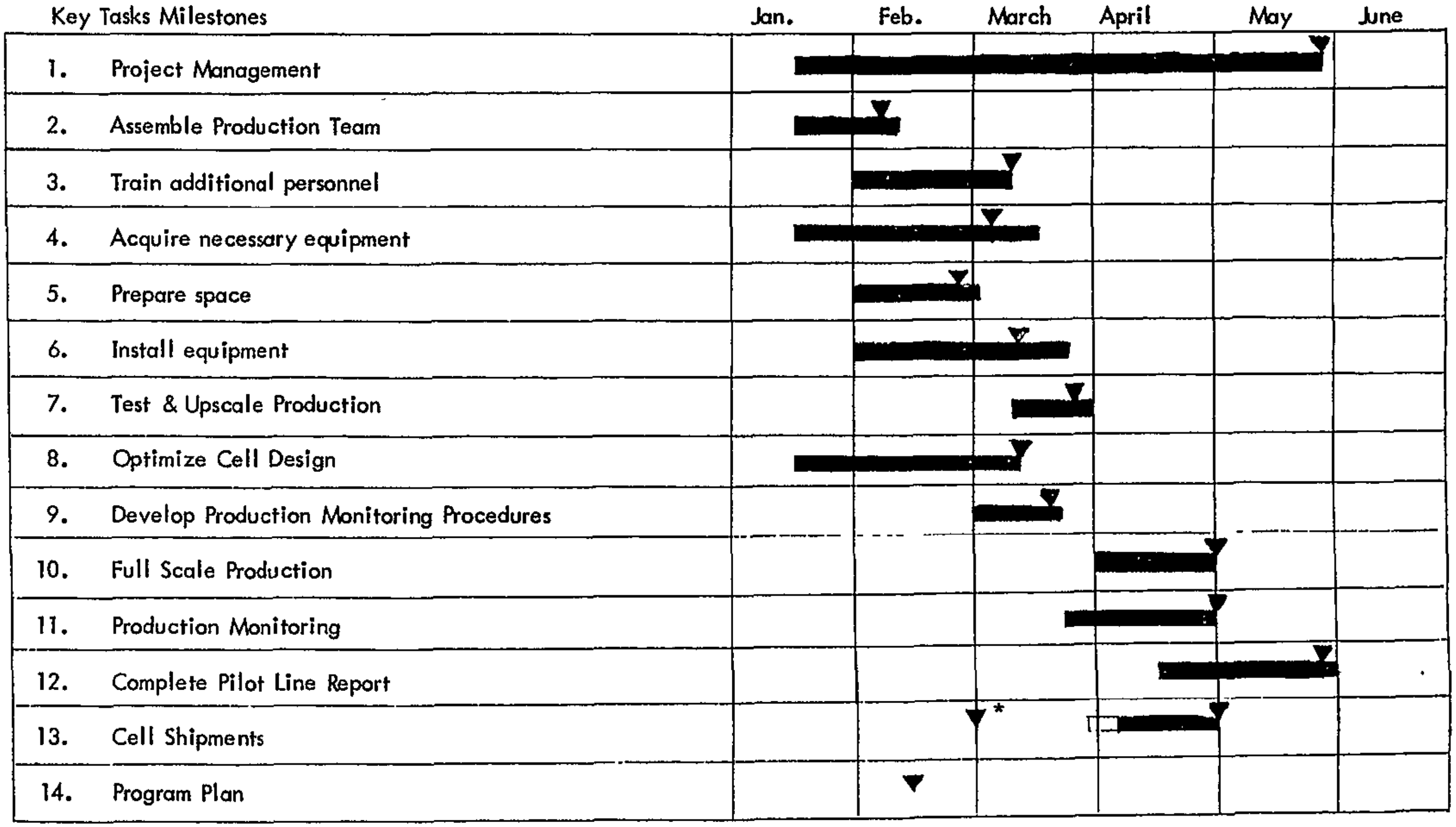
This Pilot Line Program was of very short duration from the time of commencement to the end of the manufacturing stage. As can be seen from the Program Plan attached as Exhibit II, only two and a half months were allowed to complete all preparations for pilot production, which then had only one month to complete the delivery schedule prescribed by JPL.

This short-fuse program was subdivided into four monthly divisions of effort. The first month consisted of program planning by management concurrent with organizing an in-house team, defining equipment requirements and commencing acquisition, and working on device and process definition experimentation. The second month entailed finishing equipment acquisition, training new production personnel in ultra-thin cell processing techniques, facilitizing the Pilot Line area, equipment installation, further experimentation with device processing and delivery of 1000 experimental-process solar cells. During the third month, training, installations and process definition were completed, production trials and upscaling were effected and both the Thin Cell Lot Follower form and production monitoring procedures were developed.

PILOT LINE PROGRAM PLAN

1977

Contract No. 954290



* Shipment of 1,000 Cells per Uni. Mod. #3

EXHIBIT II

The fourth month was the production phase of the Pilot Line, which was planned for a capacity of 3000 solar cells per month and produced 2000 within its first month. The following month was scheduled for compilation and analysis of results for this report. Although this was a very short schedule before the production phase, the milestones were accomplished in a timely manner and the production phase reached its goal a day ahead of schedule.

A highly aggressive and flexible approach to equipment acquisition and new employee training was required to adhere to the schedule. Equipment available only on long lead time was side-stepped and the whole country scoured for equivalent used and refurbished equipment available for immediate delivery. All required items were obtained and put into service almost immediately upon arrival. The new personnel training was adapted on a person-to-person basis to best utilize training from other fields and accelerate proficiency in the various processing steps for ultra-thin silicon solar cells.

D. Results & Data

Fabrication of the 2000 deliverable ultra-thin solar cells during April 1977 was subdivided into daily lots starting out with 150 cells, ranging up to 450 cells, with a usual starting lot of 300. The total number started was 5173 to result in the 2000 delivered solar cells, with a rising yield in successive lots. Individual lots are tabulated in Exhibit III in terms of number started, reject categories and quantities, the number passing final Q.C. and the percent yield for each lot. In addition, overall totals and percentages are presented.

LOT HISTORIES & YIELD

LOT NO.	STARTED	Rejection Categories A	B	C	D	E	F	G	H	I	J	K	PASSED	YIELD %
1601	150	9	6	6				117	12				0	0
1602	300	34	6	49		18	2	52	10	6			123	41
1603	300	26		14		16	41	61	77				65	22
1604	300	18	13	47	1	37	6	75	19	1	1	4	78	26
1605	300	9	4		2	1	107	60	11		2		104	35
1606	300	88	1	5		4	2	58	22		4		116	39
1607	450	72	12	36		6	3	92	25	1	5	9	189	42
1608	300	83	6	4		13		54	19	20		13	88	29
1609	300	54	22	25			10	41	25		8	6	109	36
1610	300	7	7	15		7		96	18		3	2	145	48
1611	300	5	8	66		4	12	165	3				37	12
1612	300	42	20	36	6			39	14		4	8	131	44
1613	450	33	6	48	2			57	28		11	6	259	56
1614	412	10	17	27		1	8	71	28		16	5	229	56
1615	411	28	1	70		6		35	42	24		12	193	47
1616	300	26	14	23		3		28	6	4	3	10	183	61
TOTALS	5173	544	143	471	11	116	191	1101	359	56	57	75	2049	
Percentages		11	3	9	0	2	4	21	7	1	1	1		

EXHIBIT III

EXPLANATION OF REJECTION CODE

A. Broken by operator

Cells broken during insertion or removal from any machine during operation of any machine (except spin-dryer or rinser) or during any handling operation.

B. Broken in spin dryer

Cells broken during spin drying cycle.

C. Broken in rinse cycle

Cells broken during rinsing cycle.

D. Etch imperfection

Cells having severe etch pits, severely tapered edges, non-uniform thickness or stained and/or foggy surfaces.

E. Metal splatter

Cells having particles or lumps of metal deposited during metal evaporation.

F. Resist failure

Cells on which the resist peels during developing, cells that do not develop a clean pattern, cells which show badly tapered pattern edges, or cells with many pinholes in the resist field.

G. Front contact failure

Cells on which the front contacts are peeling or delaminating, or in which the buss or any sub-buss is severed, or from an evaporation lot which fails tape test on thick silicon sample substrates.

H. Back contact failure

Cells on which the back contact is peeling or delaminating, or has bubbling under the back contact or has voids greater than 0.5mm, or from an evaporation lot which fails tape test on thick silicon sample substrates.

I. Improper AR coating

Cells having any area not covered by a uniform layer of anti-reflective coating, cells with other than a deep metallic blue color or cells with visible scratches in the AR coating.

J. Electrical reject

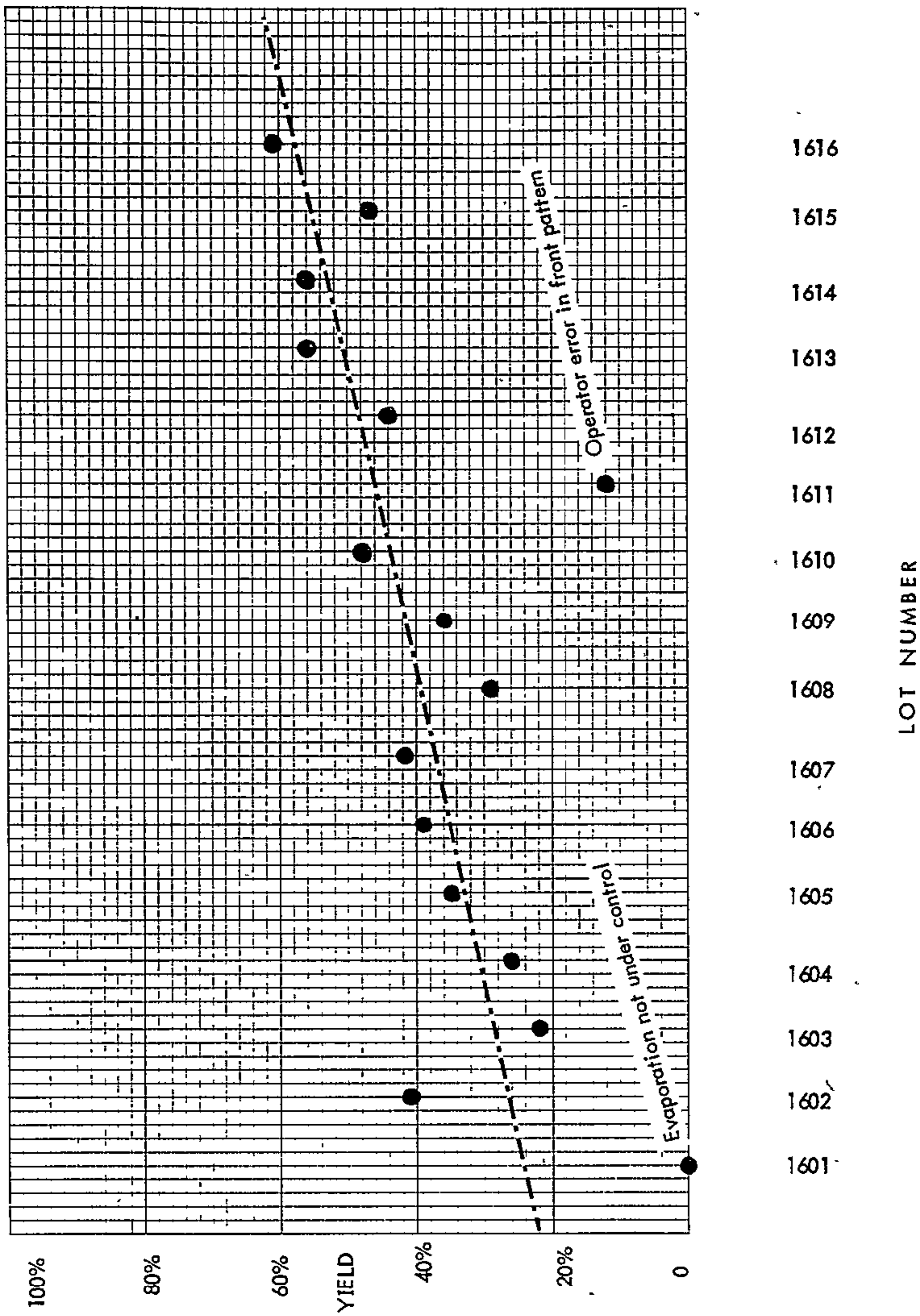
Less than 55 mW output without coverslide at AM0.

K. Dimensional reject

Cells having planform dimensions other than 0.787 ± 0.001 inches and a thickness other than 0.002 ± 0.0005 inches.

EXHIBIT IV

PILOT LINE YIELD



The yield from starting silicon to solar cells passed by final Q.C. improved during the month of production, as shown in Exhibit IV. The overall yield is completely meaningless, as the operators made mistakes particularly at the beginning. In addition, the modus operandi had to be found. Had the production phase been longer, the yield would have probably continued to improve on a steady basis as the production personnel gained further proficiency and experience.

Since this effort was a first-trial production, a great deal of engineering support time was expended which would not occur with full scale production and previously experienced personnel. During the pilot production phase in April, the operating Pilot Line which processed the 2000 ultra-thin solar cells was comprised of four (4) just-trained operators, an experienced foreman and a Q.C. inspector. Of course, additional support was available in the form of incoming material inspection, packaging and shipping, etc. Engineering support was available continuously, including additional training.

The average peak power output uncovered* at 25°C under AM0 illumination conditions is shown in Exhibit V for each lot processed. Both the limits and the mean values are given for the cells produced with the frozen technology employed. As can be seen, the mean power in the latter half of the production was about 58 mW. This could be improved, but the technology was frozen for the April pilot production.

The peak power output for ultra-thin silicon solar cells varies with thickness, decreasing as the available generation volume decreases for any particular fabrication technology employed. Plots have been submitted in previous reports under JPL Contract No. 954290 for experimentally fabricated thin silicon solar

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* The high index of tantalum oxide produces gain on coversliding.

TWO MIL CELL POWER OUTPUT

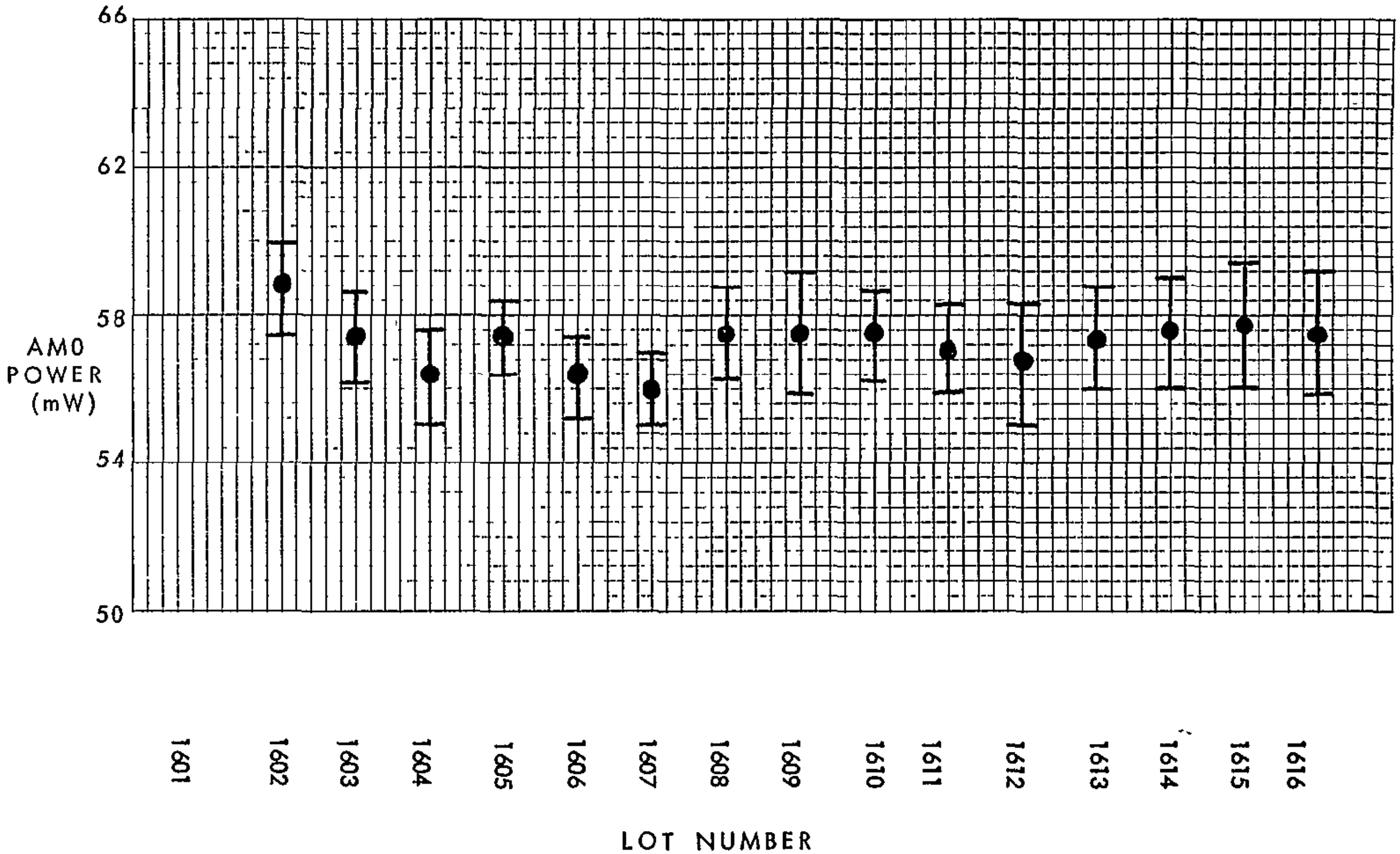

EXHIBIT V

cells, but those were not all processed identically. From this Pilot Line effort we now have data for output power as a function of thickness for cells processed nearly identically in quantity. Exhibit VI shows the AM0 output power as a function of thickness (limited by the tolerance range in this program) for a quantity of cells picked at random from the cells which passed Final Q.C. It should be noted that there is a fairly strong dependence of output power on cell thickness in this range. Consequently, comparison to other thin cells must be scrupulously viewed in terms or actual thicknesses, lest one concludes that an unexpectedly high of low cell efficiency is process related. A 65 mW cell, 75 microns thick would fit the same trend as shown here, but have a worse power-to-weight ratio than 58 mW at 55 microns thickness.

POWER VS. THICKNESS
(without coverslide)

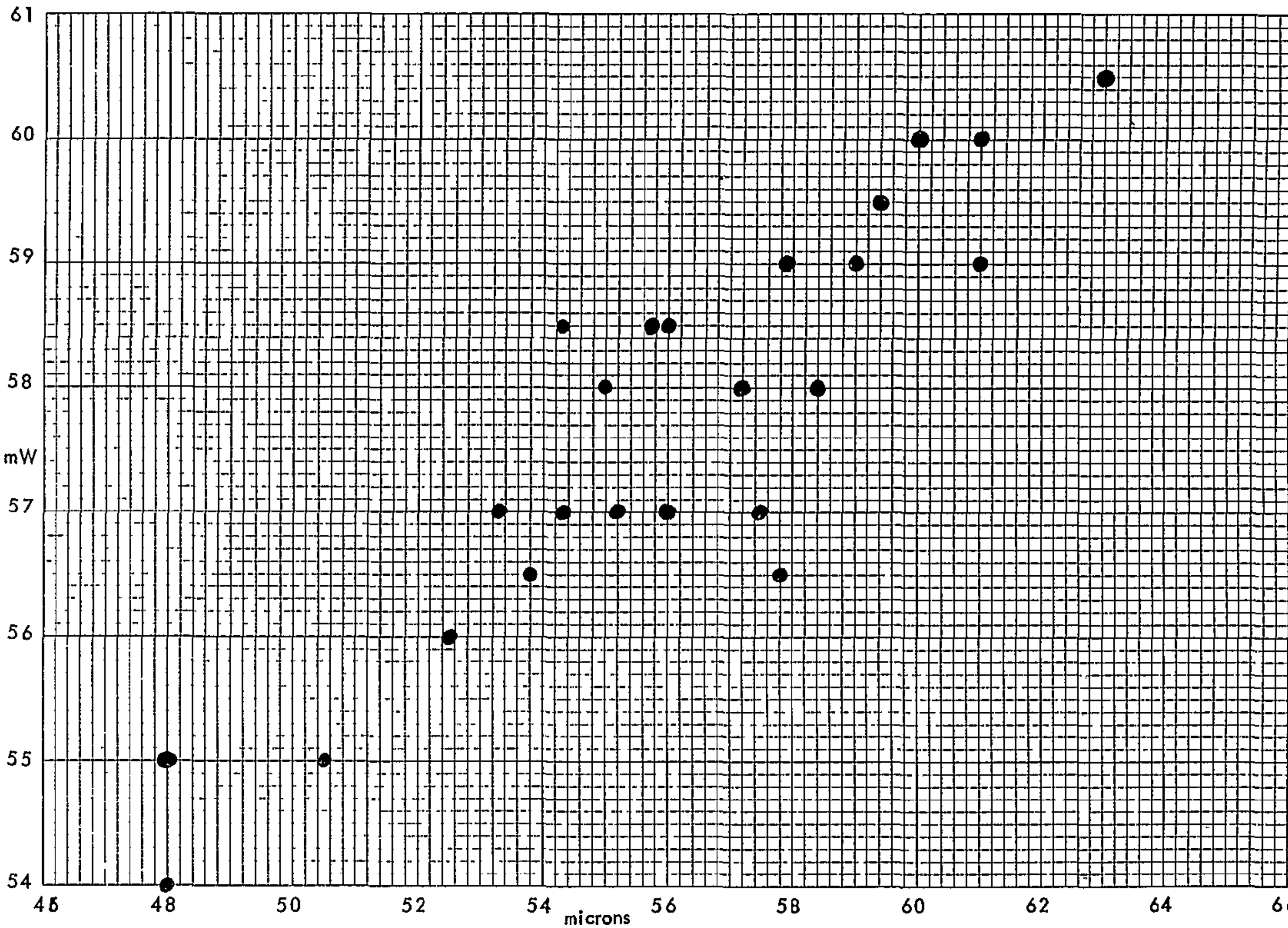

EXHIBIT VI

V. TECHNOLOGY & PROCEDURES

In early April, 1977, Solarex notified JPL that it had frozen the technology to be used during the Pilot Line production phase, which, at that time, would provide both good electrical and mechanical yield. Although not an optimized technology, it provided a reliable framework within which the Pilot Line could attain its production goals.

Silicon chosen for the manufacturing phase was 2.0 ohm-cm, p-type, boron doped, CZ grown.

Etching techniques had already been dealt with extensively by Solarex R&D during the prior development of these thin cells. During the Pilot Line production phase, a 40% solution of NaOH in water was used for the silicon etch. It was maintained at a temperature slightly over 110°C and produced pillow-texture surfaces which were compatible with the rest of the operations. Newly trained operators, using a two-step approach were consistently able to provide 50 micron slices with an excellent yield (over 90%).

Solarex developed the following workable, reproducible procedure for thinning silicon slices to 2 mils (50 microns) by alkaline etching in the Pilot Line effort:

1) Prior to commencing etching the starting slices were measured with a calibrated ADE Corporation Microsense 6033 electronic thickness gauge and were sorted into 7 micron groups (e. g. 300± 3.5).

2) Slices taken from a thickness group were batch-etched with the 40% NaOH solution to approximately 100-125 microns using etch rates established previously for the temperature.

3) The slices were then re-measured and small corrections made for the observed etch rate were employed to time the remaining etching to produce thicknesses within the range of 40 microns to 65 microns for the whole group of slices.

Phosphorous diffusions of the p-type silicon were done at 865°C for 15 minutes in PH_3, Ar, O_2 gases. Previous experimental work, as reported earlier to JPL, had shown this temperature to be conducive to respectable electrical performance for the substrate resistivity used. The diffusion results were evaluated by sheet resistance measurement, employing a Signatone 4-point probe and constant-pressure mount. The sheet resistance was in the range of 50-70 ohms/square.

The p+ back surface was formed by vacuum deposition of 5000Å of aluminum followed by alloying at a temperature of 800°C for 10 minutes without removal of the rear n+ layer. Both the front grid and the rear surface contacts were comprised of titanium-palladium-silver. Front contact pattern generation was accomplished with photolithography masking techniques, rather than by shadow masking.

The anti-reflective coating was produced by vacuum deposition of tantalum oxide with an electron beam source, the system was then sintered at 450°C for about 1 minute.

VI. EVALUATION CRITERIA & PROCEDURE

All cells were measured after etching using an ADE Microsense thickness gauge (Model 6033), to assure that the cell thickness was within specification (.002" ± .0005").

Phosphorous-diffused n-type layers were evaluated after diffusion by sheet resistance measurement employing a Signatone 4 point probe with constant-pressure mount.

In-line Q.C. of the titanium-palladium-silver deposition for front and back contacts was done by tape testing scrap pieces of silicon from each evaporation. The Veeco/Kronos Automatic Deposition System performed very reliably once the proper program had been established. Except for the first production lot, excellent yields were realized from all vacuum deposition operations.

Final mechanical Q.C. criteria are documented in Exhibit VII.

Cell electrical performance was measured using Solarex's xenon simulator. All measurements were made under AM0 (135.6 mW/cm^2) conditions at $25^{o}C$. Minimum acceptable peak power for the program was established without cover slide.

EXHIBIT VII

FINAL Q.C. INSPECTION PROCEDURE
(Mechanical)
PILOT LINE PRODUCTION

I. The back contact of each cell will be visually inspected for the following:

1. There shall be no voids greater than 0.5 mm diameter penetrating the contact which expose either the sub-metal or silicon. Two voids less than 0.5 mm will be acceptable.

2. There shall be no evidence of any contact peeling.

3. There shall be no evidence of any bubbling under the back contact.

II. The front contacts of each cell will be visually inspected for the following:

1. Front contacts shall be located in accordance with Solarex drawing.

2. There shall be no evidence of any contact peeling or delamination.

3. There shall be no severing of any of the sub-buss contacts.

4. There shall be an allowable maximum of two (2) severed fine finger contacts. The severed gap shall not exceed 0.5 mm.

III. Sample quantities totaling 10% of each manufacturing lot will be mechanically measured for the following:

1. The areal dimensions shall be .787 inches x .787 inches ± 0.001 inch.

2. The cell thickness shall be .002 inches ± .0005 inches measured off the front contact.

IV. The front contacts will be mechanically tested using the following procedure:

1. The cell will be firmly held in position on a vacuum chuck.

2. A wooden swab shaft will be pulled across the contact areas (using a force of 50 grams).

3. The front contacts will then be visually inspected in accordance with Section II.

V. The anti-reflective coating will be visually inspected for the following:

1. Uniformity across the cell surface.

2. A deep metallic blue color corresponding to an established reference cell.

3. Absence of any scratches in the AR coating (from swab shaft testing) indicating improper evaporation technique or improper sintering.

VII. HANDLING & SAFETY PRECAUTIONS

Pilot line operators quickly demonstrated that ultra-thin solar cells can be handled quite easily without employing any production-restraining measures. The 50 micron devices are surprisingly flexible and are highly resistant to breakage when dropped. This aspect of the mechanical durability was demonstrated in a rather unconventional fashion for 2 mil cells at the end of the program. A randomly picked group of some thirty 2cm x 2cm ultra-thin cells was thrown from a dish into the air and allowed to fall four (4) feet to a table top. Exhibit VIII shows a photograph of the flying cells surviving this mistreatment.

Tweezers were used for cell handling during all fabrication steps that required operator handling and, as the program proceeded, Pilot Line operators developed a high degree of confidence in handling these cells. Exhibit IX shows the operator breakage for the program. Except for a couple of instances, percentage losses for this failure mode were within acceptable limits.*

Ultra-thin solar cells can be centrifugally spun dry in conventional plastic carriers. In some cases significant losses occured. The percentage losses experienced for the many spin drying operations on the Pilot Line was acceptable but could be improved further. The actual drying techniques can only be evaluated statistically with large enough quantities. Particularly interesting parameters are: supporting carrier shape, support in the carrier and spinning speed. The relatively good results were obtained because these solar cells can be stressed by bending to a surprising degree without cracking or shattering. The photograph in Exhibit X demonstrates the radius of curvature easily withstood by these highly flexible solar cells without damage.

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* Considering the number of handling steps and the short experience of the operators, this is a very respectable record.

EXHIBIT VIII

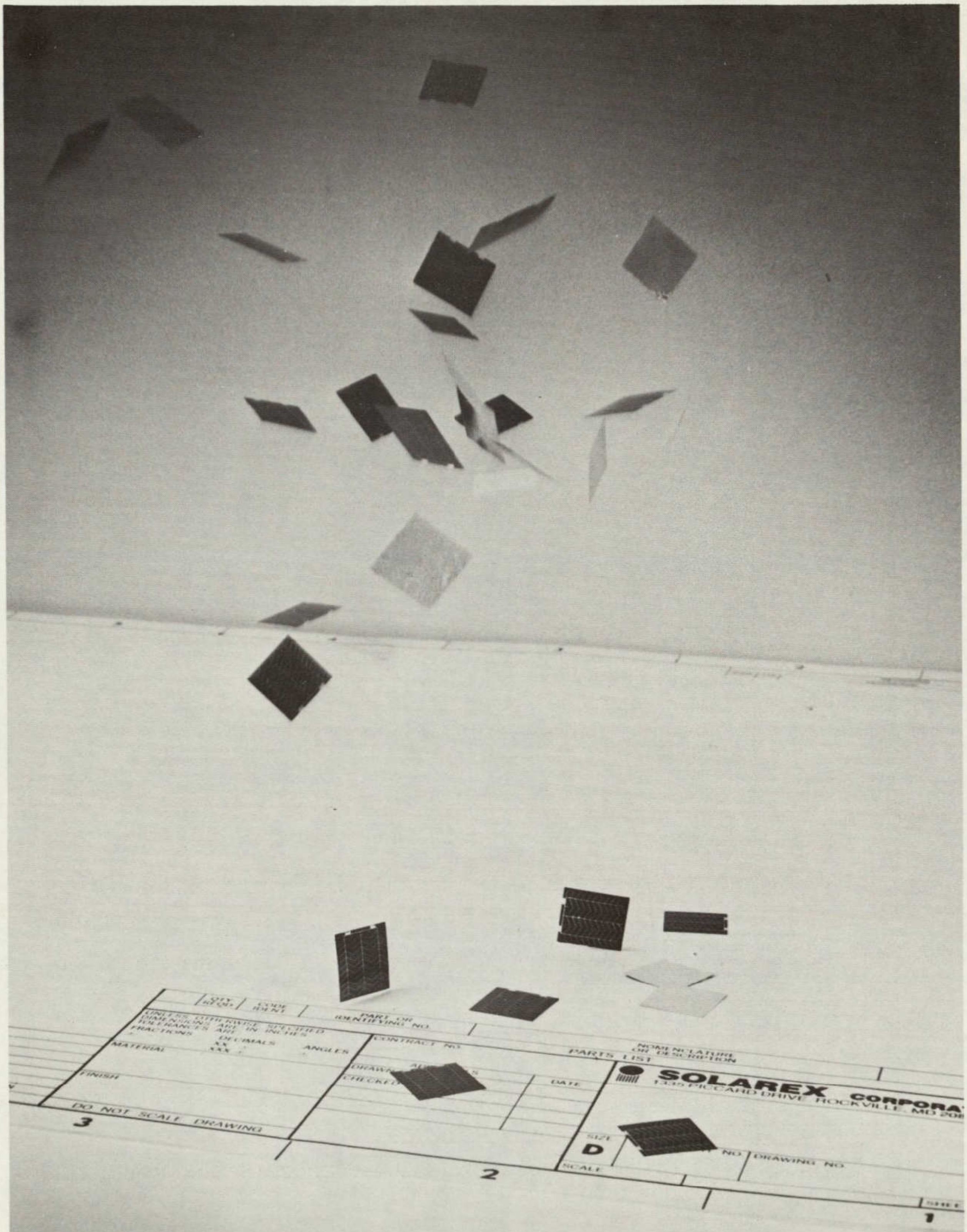
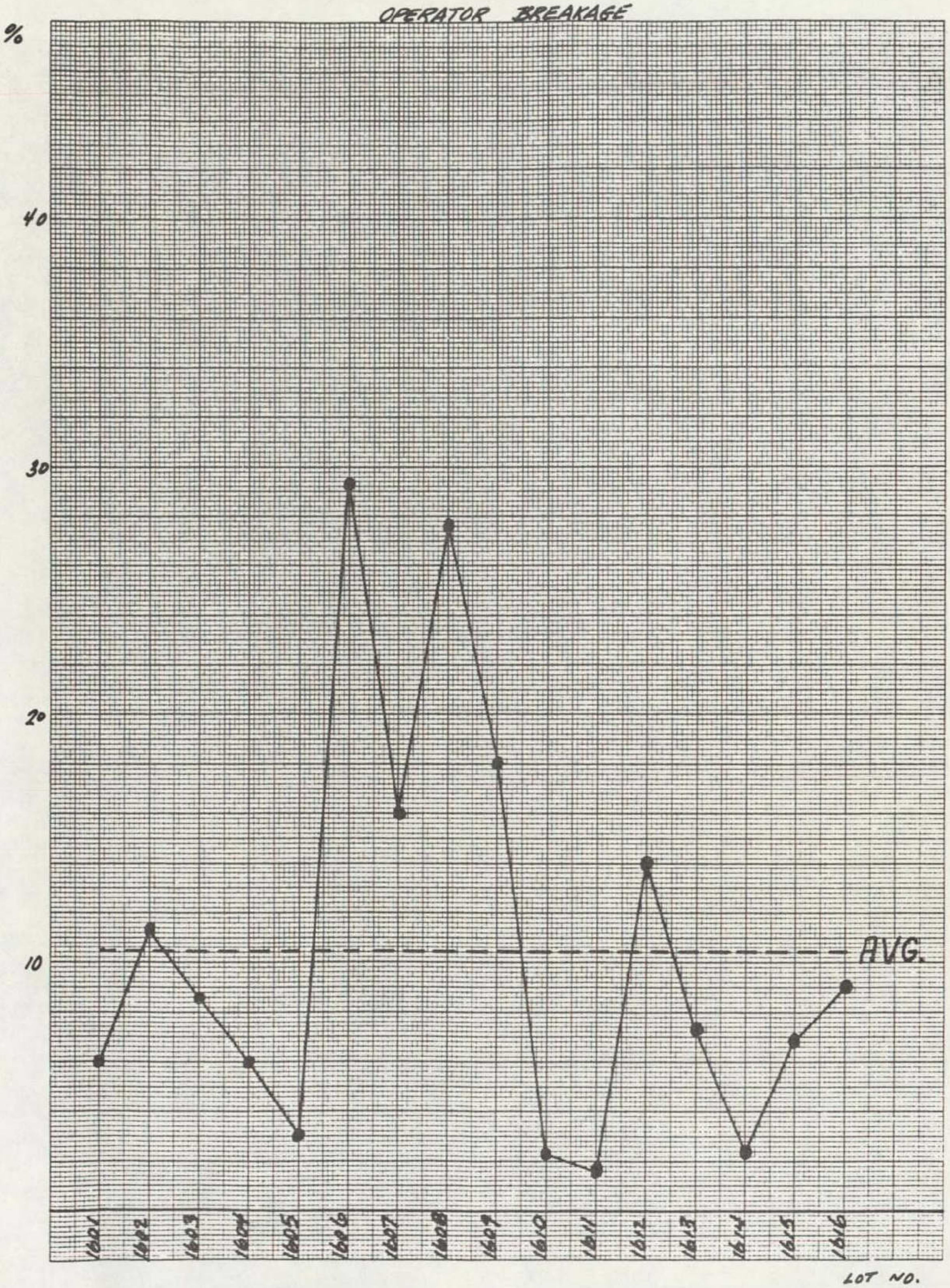


EXHIBIT IX



OPERATOR BREAKAGE
%
40
30
20
10
AVG.
1601
1602
1603
1604
1605
1606
1607
1608
1609
1610
1611
1612
1613
1614
1615
1616
LOT NO.

EXHIBIT X

The most damaging operations which have been experienced with ultra-thin silicon solar cells are thickness measurement and shipping. Thickness measurement with a mechanical instrument such as a micrometer, calipers of dial-guage probe can exert very high localized stresses which can fracture the cell or slice. This is eliminated by using an ADE Microsense non-contacting thickness gauge in this effort. In shipping, care must be taken to avoid the possibility of crushing the cells by force applied to an edge without allowing room for flexing.

No additional safety precautions were required for thin cell fabrication beyond those already in practice at Solarex in compliance with OSHA regulations.

VIII. FUTURE THIN CELL PRODUCTION

The pilot line facility was designed for a production capacity of 3000 2x2cm cells per month. Production during the month April showed that the main factors limiting the production rate were: AR Coating equipment capacity and pilot line manpower. The AR coating problem could easily be resolved by adding additional evaporators or retooling the present one. This present vacuum system was donated by Solarex. Retooling it for greater capacity was not considered since a capacity of only 3000 cells per month was required.

At the outset of the pilot line program it was determined that only four operators were needed to produce the required 2000 cells. While this proved sufficient to get the job done, it was a manpower level below the threshold at which job specialization can occur. This caused single operators to carry out multiple process steps and led to only cyclic use of available equipment. An increase in manpower and some additional equipment could easily raise the production capacity to 6,000 cells per month.

Our experience on the pilot line has demonstrated that production of ultra-thin solar cells is not inherently more difficult than the production of conventional 12-15 mil space cells. A production facility capable of producing 50,000 thin cells per month could be installed in as little time as six months. The initial cost of such a facility would be in the range of \$600,000 to \$800,000; of this amount, roughly \$500,000 would be for production and test equipment and the balance for equipment installation and modification, space preparation, man-power training and other system start up costs.

Once such a line is established and operating, the recurring costs should be in the \$5 per cell range (for 2x2cm cells).

An additional fact to consider in future thin cell research and production is the development and production of large area and differently shaped devices. During the program, perfect cells up to 3" in diameter could be made. Some of the cells were shaped into $39cm^2$ hexagons, 5x5cm squares and other rectangular shapes. Production of larger area devices can reduce cell processing costs and presumably array fabrication costs as well.

Finally, it must be noted that the cell thickness of 50 microns was set somewhat arbitrarily, as part of the pilot line technology. This demonstrated that a specified thickness can be tightly controlled. However, cells as thin as one mil have been fabricated and it appears that cell thickness is a parameter that can be varied to fit a particulor overall array design.

IX. FUTURE PRODUCTION - YIELD AND EFFICIENCY

The one-month pilot production phase demonstrated that ultra-thin cells could be processed with a reasonable yield; however, this short production phase did not determine the "typical" production yield for this technology. As the graph in Exhibit IV shows, yield improved steadily throughout the month. It is reasonable to assume that additional production will improve this yield even further. Both mechanical and electrical yield will increase with additional production experience. Increased familiarity in handling cells and using equipment should reduce breakage. Electrical yield will be improved and contact losses reduced as operators gain experience in the vacuum deposition of contacts and anti-reflection coatings. It is estimated that an additional six months of pilot production with underlying research support will result in typical production yields of 60-70% and electrical performance of 65 milli watts or higher. Ultimately electrical performance should reach 70 milli watts.

X. CONCLUSION

The pilot effort reported here conclusively demonstrates that paper-thin silicon cells can be manufactured with respectable yield and reasonable efficiency. These thin cells can be handled safely, can be welded to, and already exceed the typical efficiency of most cells presently in orbit. Moreover, independent JPL testing indicates a much improved end-of-life efficiency through increased radiation resistance.

The old fear of easily breaking thin cells is now shattered. In fact, for yet unexplained reasons, 2 mil cells exhibit a much greater mechanical integrity than thicker cells, four mil for example. Moreover, as a result of the consistent reproducibility shown during this effort, it can be said that solar cells can now be tailor-made with great accuracy to any thickness desired.

This tremendous reproducibility and relative straightforwardness of the process as now developed forcasts that ultimate quantity production costs will be competitive with prevailing high efficiency space cell prices. Moreover, if large area devices are accepted by the space cell community, unit cost will be even lower.

It has now been shown that the 2 mil silicon solar cell can be fabricated in quantity and is not by any means a laboratory curiosity. Further optimization of these cells and future production in large quantities will make lightweight, high-powered solar arrays a working reality at reasonable cost. Such applications for space missions are quite numerous and the implications for cost reduction in the expanding terrestrial field are significant.

Lastly we must take recognition of the fact that this entire program was accomplished in only three and one half months. This required the dedicated efforts of many individuals at Solarex and was only possible with the close cooperation and support of JPL and NASA/OAST personnel.