SOLAREX

PILOT LINE REPORT

DEVELOPMENT OF A HIGH EFFICIENCY THIN SILICON SOLAR CELL

JPL CONTRACT NO. 954883

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BY

(NASA-CR-158028) PILOT LINE REPORT: DEVELOPMENT OF A HIGH EFFICIENCY THIN SILICON SOLAR CELL (Solarex Corp., Rockville, Md.) 65 p HC A04/MF A01 CSCL 10A
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TECHNICAL CONTENT STATEMENT

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ABSTRACT

In the latter part of 1976 Solarex achieved a break-through in fabricating ultra-thin (50 microns or less) silicon solar cells during JPL Contract 954290, under the auspices of NASA. Recognizing the importance of this breakthrough, NASA OAST provided funding through JPL to exploit this advance in an accelerated Pilot Line phase to test the manufacturability of such thin cells.

Solarex constructed a Pilot Line facility within two and a half months in early 1977 and during the succeeding month manufactured and delivered ultra-thin (50 micron) 4cm^2 silicon solar cells. In this present contract effort, the Pilot Line was utilized to implement experimental technology advances to increase cell efficiency and to demonstrate a capability for fabricating ultra-thin cells at a rate of 10,000 4 cm^2 cells per month. In addition, a small quantity (200) of large-area 25 cm^2 ultra-thin cells were fabricated by the Pilot Line to determine their feasibility of manufacture.

The first three quarters in the one-year term had scheduled deliveries of 1,000 4cm^2 cells each quarter and one group of 200 large-area cells, while the last quarter had 2,000 deliverable cells scheduled. Some difficulties were encountered in controlling manufacturing yield, largely due to the fact that the Pilot Line operation was not really continuous. The scheduled manufacturing quantities were far below

line capacity (about 1/30th) and consequently operator experience and familiarity were far from that to be expected in continuous full-rate operation. As a result, overall manufacturing yields were only half as good as expected. However, operation at full rate near the end of the last quarter did show the benefits of full operation and all required cells were delivered.

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SUMMARY

The principal goals of this Pilot Line effort were to implement experimental technology advances to increase the conversion efficiency of ultrathin 2cm x 2cm cells, to demonstrate a capability for fabricating such cells at a rate of 10,000 per month, and to fabricate 200 large-area ultrathin cells to determine their feasibility of manufacture. The major results are:

1) A production rate of 10,000 50μm cells per month with lot average AM0 efficiencies of 11.5% was demonstrated, with peak efficiencies of 13.5% obtained.

2) Losses in most stages of the processing have been minimized, the remaining exceptions being in the photolithography and metallization steps for front contact generation and breakage handling. These losses were largely associated with the start-stop nature of the Pilot Line operation and the attendant effect of intermittent operator experience.

3) It was determined that modifications of equipment would provide higher capacity by a better throughput match at three steps, i.e. the thinning etch, metal evaporation and AR coating deposition stations.

4) 5cm x 5cm cells were fabricated with a peak yield in excess of 40% for over 10% AM0 efficiency. Greater fabrication volume is needed to fully evaluate the expected yield and efficiency levels for large cells.

5) Average power per Pilot Line cell at AM0 increased from 59mW to 63mW over the contract period without surface texturing. (Textured experimental cells reached over 14.5% efficiency in the year.)

I. PILOT LINE DESCRIPTION

A. Introduction

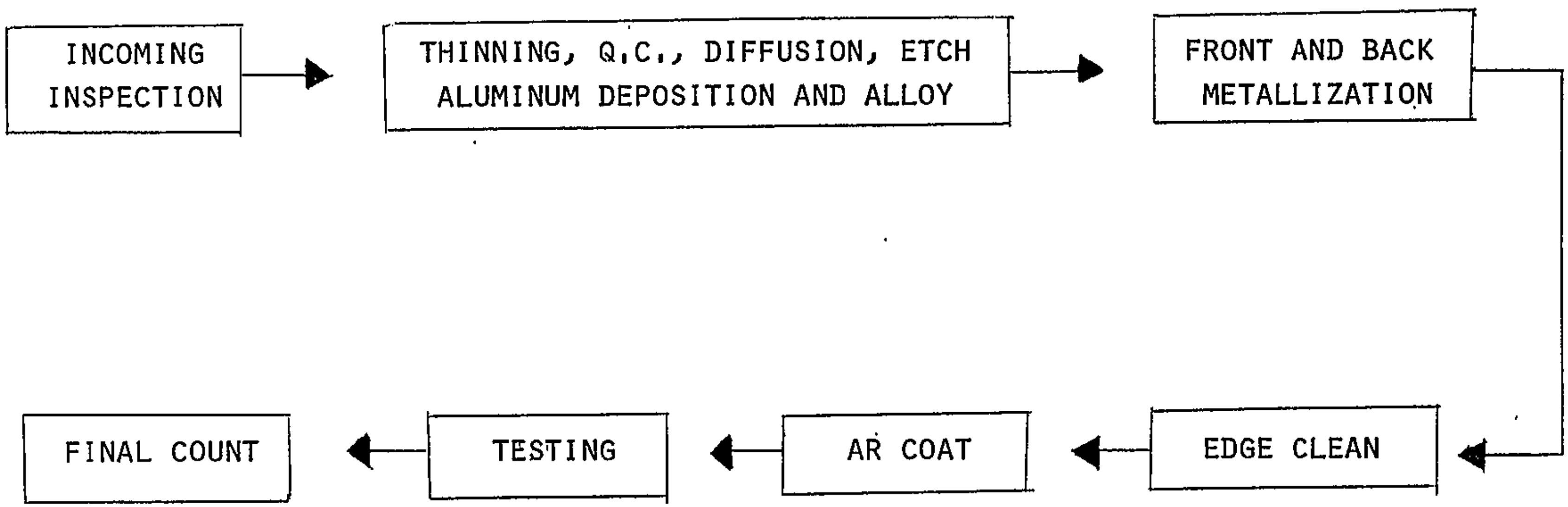
The R & D efforts by Solarex in 1976 under JPL Contract No. 954290 "Development of a High Efficiency Thin Silicon Solar Cell" produced a breakthrough showing that ultrathin solar cells, 50 microns or less in thickness, could be made in the laboratory and Solarex delivered hundreds of such experimental cells to JPL. The supporting agency, NASA OAST, through JPL recognized the importance of this advance and directed funding to quickly exploit this breakthrough in pilot production.

As described in the Pilot Line Report of June, 1977, Report No. SX/105/PL, Solarex created and began operating a Pilot Line Facility in less than three months. This Pilot Line was and is dedicated to manufacturing high performance ultrathin solar cells.

A process flow was established in 1977 to apply the experimental ultrathin cell fabrication technology in a production line sequence. Figure 1 is the process sequence diagram of the flow employed for the Pilot Line program. Differences from the 1977 flow were all within the second block in this year, and consequently did not alter the overall process flow or line organization. Improvements implemented to increase cell performance involved diffusion and alloy conditions developed in the parallel experimental effort. There was also to have been implementation of texturing in the last quarter, but it was

FIGURE 1

PROCESS SEQUENCE DIAGRAM



EACH STEP HAS ACCURATE ACCOUNTING AND LOSS MODE RECORD FOR ALL PROCESS LOTS.

requested by JPL that the line production capacity be demonstrated, which precluded application of a slightly slower process at that time.

B. Objectives

1. The primary objective of this Pilot Line effort under JPL Contract No. 954883 was to demonstrate that it is realistic to produce 2 mil thick cells with a reasonable yield and cost at a rate of 10,000/month. Successful demonstration allows a credible projection of feasibility for production of such cells at a rate of 100,000 cells per month.

2. To adopt those experimental process modifications proven to increase cell performance into the Pilot Line (with concurrence of the contract monitor).

3. To verify in a production setting, the optimum process controls. This included such items as aluminum metal deposition thickness and cell back cleanliness standards.

4. To determine over a significant time period, which process areas are most in need of yield and capacity improvement.

C. Work Plan and Schedule

The Pilot Line was organized under the Advanced Cell Development Department with efforts scheduled on a quarterly basis. The schedule matched required deliveries of 1,000 cells for each of the first, second and third quarters, 2,000 cells for the fourth quarter and 200 large-area cells for the second quarter. The program required Solarex to maintain a trained work force for the entire year, but did not allow for full utilization of this work force or the Pilot Line equipment. During the intervening times, personnel were temporarily assigned to other activities. During the early half of 1978, a major hourly personnel turnover occurred, attributable to this start-stop-shuttle atmosphere. The program schedule is shown in Figure 2, with successful completion within the contract term despite the above difficulties.

For the first three quarters ending respectively on December 31, 1977, March 31, 1978, and June 30, 1978, processing lots of up to 450 cells (typically 300 cells) were started. For the fourth and final quarter ending September 30, 1978, the starting size of lots was increased to 1,050 cells for all but the final lot.

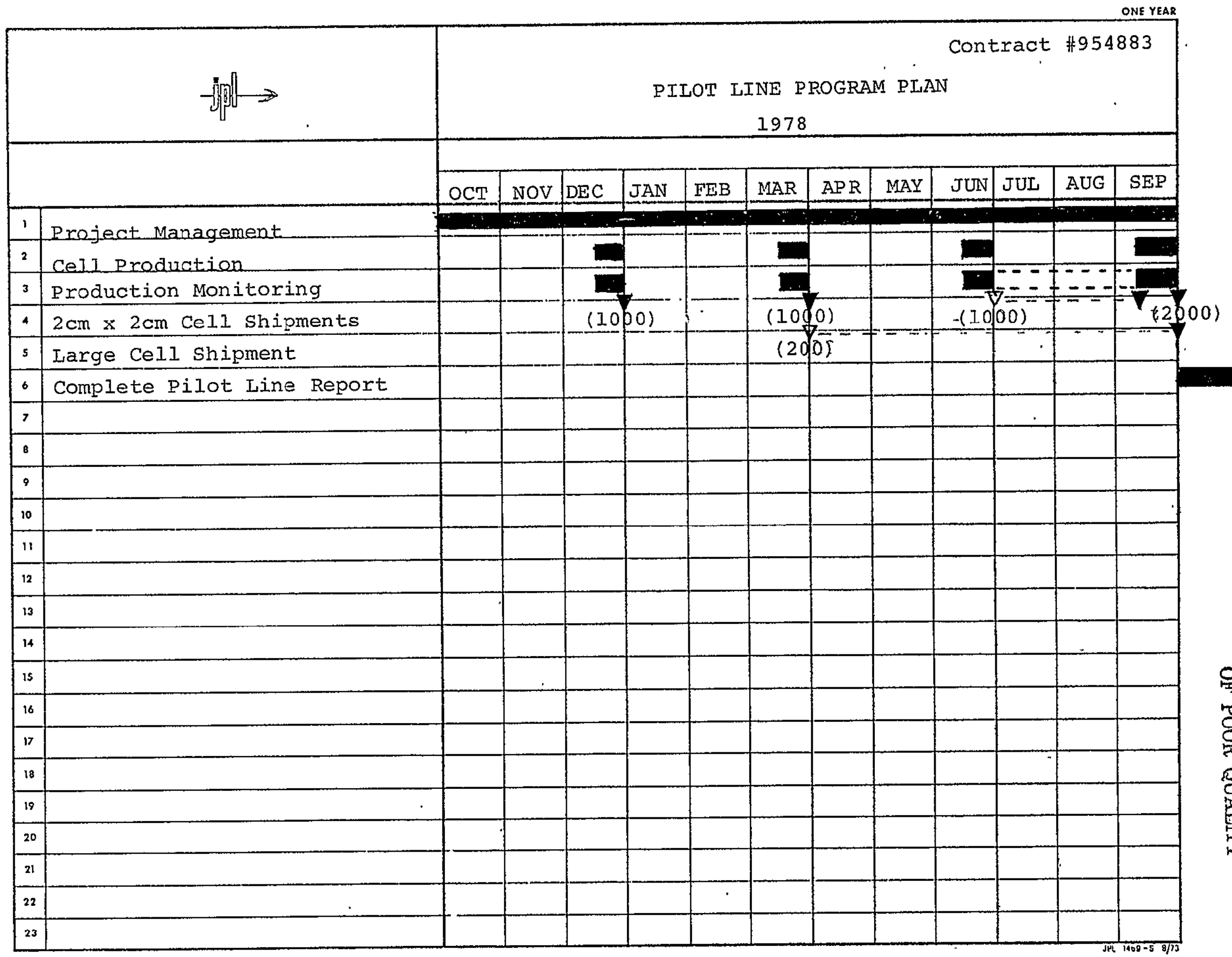


Figure 2.

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II. RESULTS AND DATA

A. General Discussion - Yield and Power

A summary of the yield results by quarter is given in Table I, with the code for the reject modes on the following page. The reject modes are given as percent of starts to facilitate comparisons between quarters. A total of 27,516 cells were started in order to ship the 5000 2cm x 2cm deliverable. The typical power output per cell is given by quarters in Figure 3.

The yield was lower than the initial results in 1977 especially for the operation in the third quarter. The third quarter was impacted by very high hourly personnel turnover and retraining. However the first, second and fourth quarters (28.0%, 33.7%, 27.6%) were also below expectations.

The starting and stopping of the pilot line proved to be fully as damaging to yield as anticipated. Because the capacity of the line is much greater than was required for the contract delivery schedule, each quarter involved restarting operation at a rate to fabricate the required cells, and then reduction of line operation. Operators should be continuously exercising a pilot line, otherwise costly oversights occur upon resumption of production rate. Continuous operation provides opportunity for synchronizing operations and results in fewer losses.

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*The yield was better than reflected by these numbers, as is discussed in Section C following.

LOT NO.	STARTED COUNT	REJECTION CATEGORIES AS % OF STARTS											PASSED COUNT	YIELD %
		A	B	C	D	E	F	G	H	I	J	K		
FIRST QUARTER	4890	20.3	4.0		0.6	3.4	1.2	30.6	2.9	1.8	7.2		1367	28.0
SECOND QUARTER	4050	16.9	5.3		1.5	4.2	0.3	30.8	1.1	1.6	4.6		1363	33.7
THIRD QUARTER	8526	26.4	3.8		0.4	6.8	2.2	25.8	4.4	0.9	10.1		1640	19.2
FOURTH QUARTER	10050	21.6	3.3		1.1	0.8	1.5	35.9	1.4	0.8	5.9		2774	27.6
YEARLY TOTAL	27516	22.2	3.9		0.9	3.6	1.5	31.1	2.6	1.1	7.3		7144	26.0

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TABLE I

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 any gridline is severed or missing, 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 60mW output without coverslide at AM0.

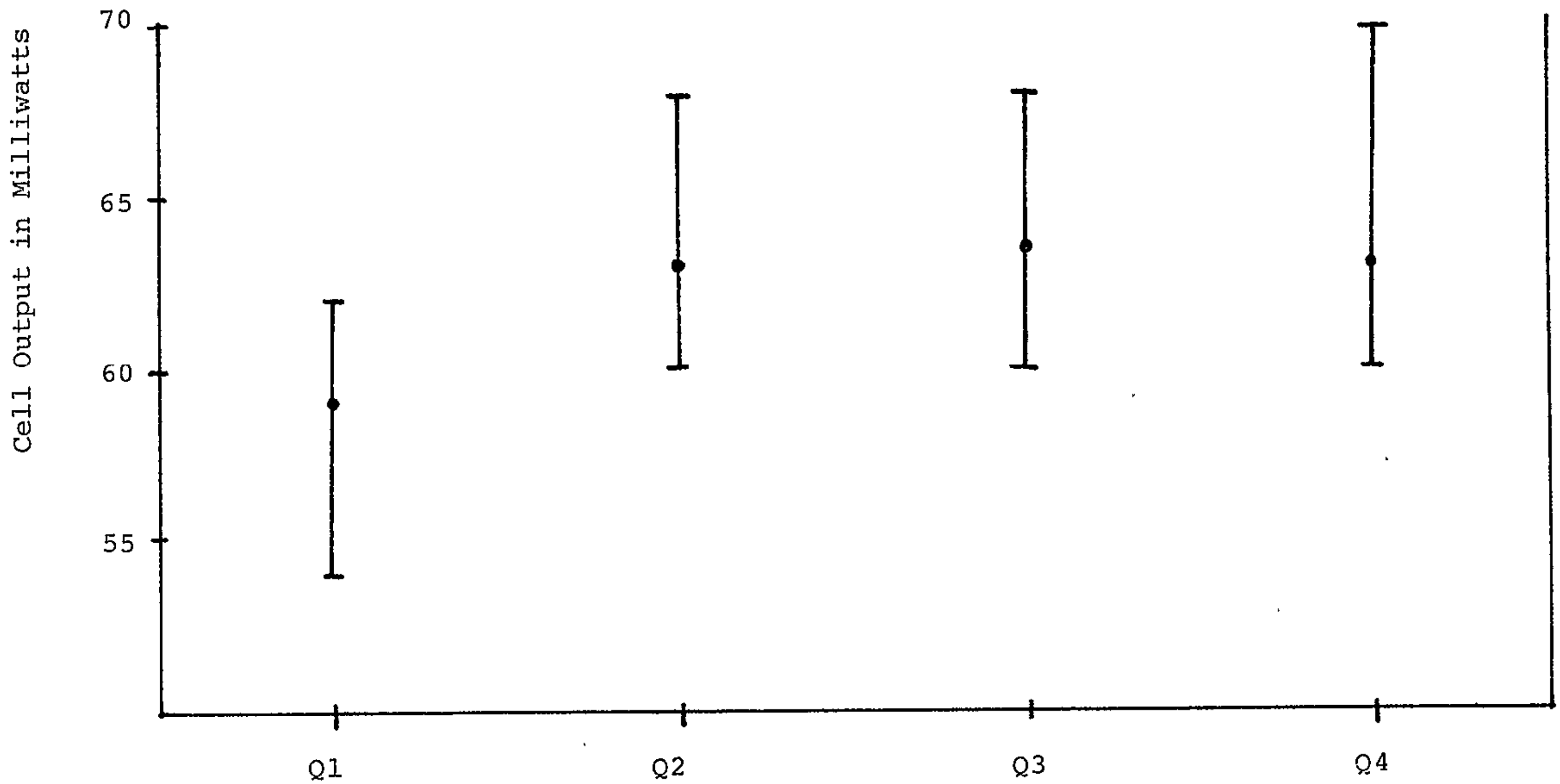
K. Dimensional reject

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

Figure 3.

TYPICAL CELL POWER AT AM0

(The minimum, average and maximum values are all averages of the values of each lot).



There are two approaches for more productive operation in the future. Continuous operation of the Pilot Line could be maintained to relieve the start-stop training stress. Additionally, a program could be undertaken to upgrade the process equipment sophistication such that some of the existing process steps become more immune to the start-stop human factor.

There was an additional factor imposed on delivered cells, namely cosmetic acceptance standards. Many cells that clearly passed the letter of NASA cell specifications were categorized as rejects for failing even more stringent appearance standards imposed by Solarex. This is discussed further under Reject Modes in part C following.

B. Achievement of Objectives

1. It has been demonstrated that a production rate of 10,000 cells per month can be achieved with present equipment (when a yield of about 50% is maintained in steady production) for 50 micron cells with over 11.5% average efficiency of AM0.

2. The average power per cell at AM0 increased from 59 milliwatts in the first quarter to 63 milliwatts in the third quarter. This improved the power to weight ratio of the cells by 6.8%. The process changes involved convex flexure of cell fronts during diffusion and additional techniques in aluminum alloy product removal to allow increasing the thickness of evaporated backside aluminum. The optimum thickness was between 6000Å and 8000Å for the Pilot Line application.

3. The increased level of cleanliness of the cell backside achieved also resulted in fewer losses for back metal contact rejects (down from 7% in 1977 to 2.6% in 1978).

4. It was determined that a need for alterations to provide higher capacity exists in etch thinning, metal evaporation and AR coating deposition operations to readily operate at a rate of 10,000 cells per month.

5. It was determined that two areas (front metal contacts and operator handling breakage) are most in need of improvement. It was further determined that significant improvement in both of these areas is realistic by means of the recommended operational mode changes.

C. Reject Modes

The relative distribution of reject modes is seen in Figure 4. Gridlines, contacts, breakage and low electrical performance (in that order) account for the major portion of all losses.

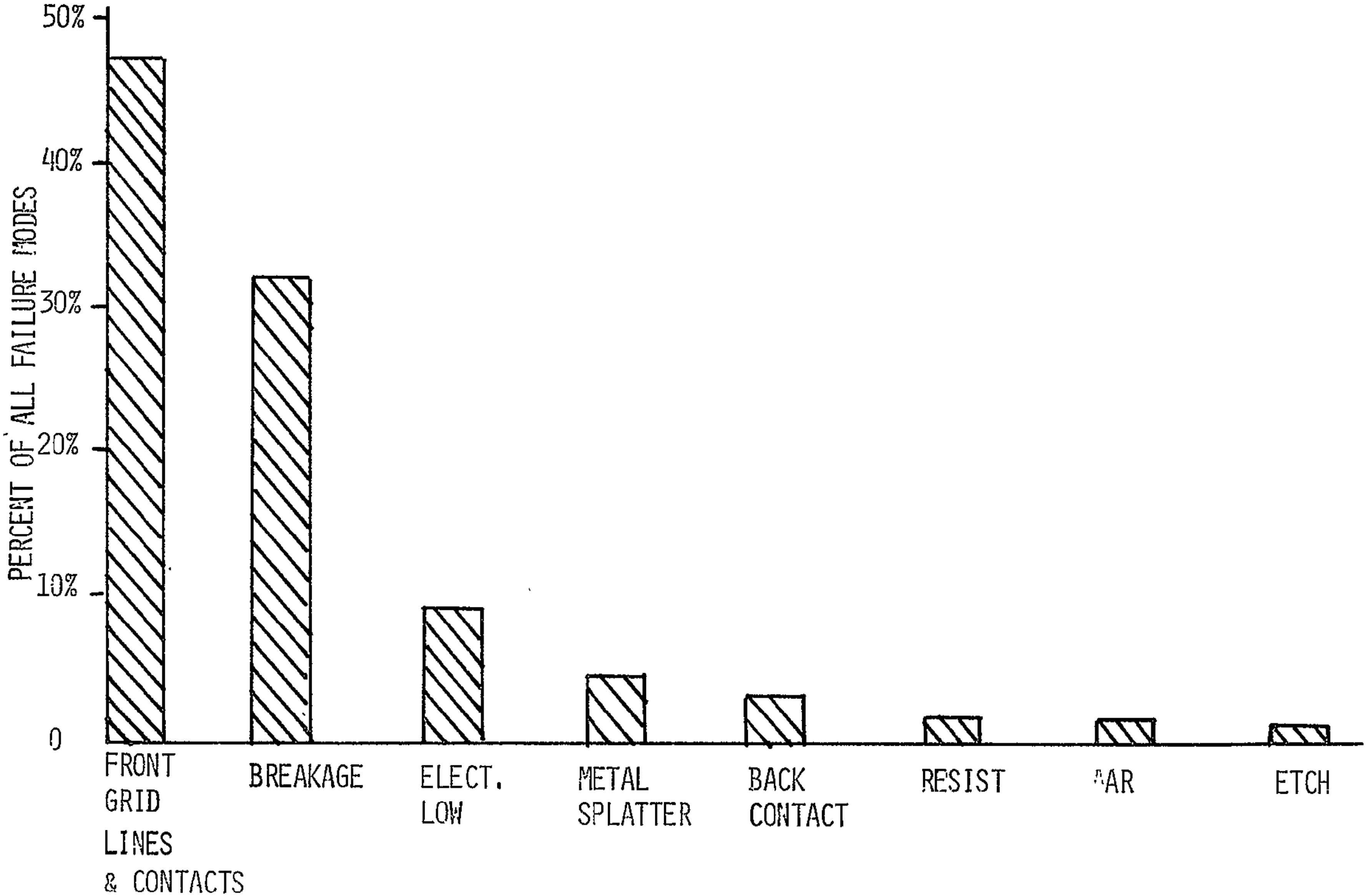
FRONT GRIDLINES & CONTACTS

The attrition was primarily operator related in cleaning operations, etc. There is good reason to believe that a maximum failure rate below 15% for front contacts throughout all processing is to be expected in full-rate operation. Even the full-rate capacity-demonstration operating mode at the end of the fourth quarter was not quite sufficient to demonstrate yield improvement within the time of the contract effort. However, in the week following, the Pilot Line personnel were assigned to manufacturing ultrathin cells for orders placed by NASA-Lewis and General Electric outside of the contract effort. The immediate full-rate experience background finally resulted in yields over 48% with the same personnel. This demonstrated the need for continuous specialized familiarity and run-up time for the personnel, on the order of at least a few weeks of intensive production operations, in order to achieve high yields for production quantities. This was the case for the first Pilot Line operations in 1977.

Characteristically, the front contacts are either sound and well bonded to the cell, or catastrophically weak in bond strength. To verify this, ten cells randomly selected from electrical

FIGURE 4.

DISTRIBUTION OF FABRICATION ATTRITION



reject cells (acceptable in all other respects) were tested for contact bond strength. Leads were soldered to the pads and pull tests were made. To avoid breaking the 2 mil cell, the cells were epoxy bonded to 12 mil thick silicon substrates. These assemblies were then placed in a Unitek Pull Tester , Model 6-029-01 and the leads stressed to failure in the plane of the cell. In no case did the metal contact or the solder joint fail. All failures were of the epoxy bond and resulted in tearing out sections of the 2 mil cell. The average test strength was 874 grams and the minimum well above 500 grams. The average bond strength of the metal contact to the cell was greater than 874 grams by an indeterminate amount.

For the deliverable cells Solarex imposed restrictive cosmetic standards not in the NASA Cell Specifications, withholding from shipment cells which had minor severances of fine lines in the grid pattern. This cosmetic criterion required the fabrication of additional cells to complete deliveries. However, it was felt that the high visibility of these cells in associated NASA/JPL programs precluded shipment of cells with gridline defects as contractually deliverable items.

BREAKAGE

The use of automatic spin dryers has kept the breakage loss in drying down to an acceptable level at less than 4%. The handling breakage is high at 22% and would be reduced with steady full-rate operation. The inverse proof of this is seen by the figures by quarters in Table I. The operators had reduced their handling breakage from 20.3% down to 16.9% from the first to the second quarter. Then there was a replacement of many operators and the breakage went up to 26.4% in the third quarter. As the new operators obtained more experience, the handling breakage decreased to 21.6% for the fourth and final quarter (and even more in a separate effort thereafter).

Proper tweezer maintenance is an important factor in reducing breakage. Trained operators constantly check their tweezers and either discard or repair the tips as soon as a burr or distortion occurs. A wide tip tweezer is essential in avoiding point loading of the cell by the tweezer at pick-up. Plastic coated tweezers are being considered.

The various liquid immersion steps in wet-chemistry processes are high breakage areas unless care is exerted in insertion and withdrawal. The air-liquid interface is the highest hazard for the ultrathin cells. This is apparently because of the tendency for the surface tension of the liquid to exert localized force loading on the cells and their contact points with carriers.

ELECTRICAL REJECTS

The loss rate of over 7% to "electrical rejects" is somewhat arbitrary, as there was a step function increase in the minimum acceptable power criterion imposed during the contract when the process was altered to improve cell efficiency. A few milliwatts reduced threshold of acceptance (i.e. from 60mW down to 57mW) would have almost eliminated the electrical yield loss.

METAL SPLATTER

These failures are extremely operator dependent and are usually a minor factor as is seen for the fourth quarter. The third quarter again illustrates the results of a start-stop operation, personnel turnover and retraining.

OTHER FAILURE MODES

The remaining 7.3% of the failures are distributed among the other stations and are not considered noteworthy.

D. Large-Area Cells

One means to improve the productivity in assembly of large ultralightweight arrays and to improve areal packing density would be to employ large ultrathin solar cells. With such large cells the alternative packing density and assembly productivity advantages of wrap-around-contact cell configurations for conventional sizes could be achieved without resort to more complicated and costly cell fabrication. Therefore, it was of interest to investigate Pilot Line fabrication of large-area ultrathin cells.

In this program a study was performed to determine the optimum dimensions of a large-area cell for Pilot Line fabrication. One constraint of economic significance is that the highest volume production of Czochralski silicon ingots in the U.S. is concentrated on three inch (76mm) diameter. Therefore, for the moderate future it would be wise to utilize a cell size which uses the majority of the area available in a three-inch diameter ingot. Cells of other than rectangular shape do not result in high packing densities for any conceivable geometric arrangements in arrays, so it was decided that the large-area cells must still be rectangular in shape. Cell sizes in multiples of one centimeter which utilize the majority of the cross-sectional area of a three-inch ingot are 4cm x 6cm or 5cm x 5cm. Since the square geometry utilizes another square centimeter of ingot cross section, it was obvious that a 5cm x 5cm cell would be the most economical from the standpoint of materials cost.

In addition, less total stress in handling and thermal expansion will occur with the square cell than with a 6cm dimension on one axis. As a consequence of these considerations it was decided to proceed with the 5cm x 5cm geometry and a gridline design was generated.

Pilot Line processing of the large ultrathin cells in this program was a relatively small-scale effort to generate 200 completed cells. This quantity was sufficient to demonstrate the areas to be improved and the unique needs for different handling techniques as compared to smaller ultrathin cells. Three areas were identified which resulted in obvious impact on large cell performance or fabrication yield. First of all, it became very apparent that considerably more breakage in processing occurred with the larger cells, and that it mainly happened in wet-process steps (etching, rinsing, etc.). Some of these steps are directed only to one side of the cell and need not require total immersion. For example, some wet operations could be carried out on rotating vacuum chucks while process fluids are sprayed onto the exposed surface. This type of technique is employed for numerous operations in integrated circuit processes with excellent results. Available high throughput automated apparatus used in that industry is not directly translatable to ultrathin cells, but modified versions could be developed. Also, for necessary full-immersion wet process steps it would be advisable to evaluate plastic cassette holders sized specifically to 5cm x 5cm and having optimized cell-support rails to minimize point forces on cell edges.

Second, employing evaporated aluminum film thicknesses for back surface field formation which improved 2cm x 2cm cell performance resulted in a much higher probability for formation of lumps or balls on a large cell. This reduced the mechanical yield of the large area cells despite careful attention to complete removal of the aluminum after alloying. In addition, the average open-circuit voltage experienced with the 5cm x 5cm cells was lower than for the 2cm x 2cm cells. Both of these effects point out the need for an improved back surface field formation technique in order to implement high-yield large-area cell production.

Third, the total stress from the differential thermal expansion of silicon and silver upon heating for tantalum oxide densification and contact sintering is greater for the large-area cells. This results in more net bowing of these cells and more stress on gridlines. Either an interrupted (or gridded) back metallization or application of less silver to the back of the large cells would be of great benefit in eliminating deleterious effects of differential thermal expansion and help to raise the processing yield.

The impact of these three areas on large-cell fabrication in the Pilot Line program was to produce very low overall yields of 0-5% in most of the lots tried. A final lot fabricated in the fourth quarter after the capacity-demonstration run-up, with extreme attention to handling and thermal shock did result in a small lot with 44% yield. However, the productivity of this approach was not high, and the three areas discussed above would be fruitful topics for improvement prior to large-scale fabrication of large-area ultrathin cells.

A total of 200 cells having an AMO efficiency at 25°C greater than 10% were fabricated during the contract period. The maximum efficiency obtained was 11.8% (400 mW peak power). The short circuit current densities, the open-circuit voltages, and fill factors of the $25cm^2$ cells were on average less than those measured on $4cm^2$ cells. This appears to be due to 1) less uniform back surface fields over the large area and 2) less than optimum grid design, which resulted in values of series resistance, which could be further reduced.

It is expected that further efforts with $25cm^2$ cells would lead to improvements in all three areas.

E. Costs and Projections

1. Cost Experience

Production costs for the ultrathin cell experienced in this effort are seen in Tables II, III and IV. A 2cm x 2cm delivered cell cost $14.19 to produce on the Pilot Line, for which labor and overhead comprise 68.4% of the total. The single most important factor that modifies all of the elements in the cost is yield, and yield is something that can be increased by full-rate line operation.

2. Cost and Yield Relation

Obviously, when one considers the effect of processing yields on cell cost an inverse relationship dominates. For full operation the Pilot Line should reach overall processing yields around 50%, which would reduce the costs shown in the tables by a factor of 2.5 for the finished cells.

3. Effect of Acceptance Criteria on Apparent Cell Cost

It would have been possible to reduce costs to about 70% of the experienced level by minor adjustments of the acceptance criteria for finished cells.

If the minimum acceptable efficiency were reduced from 11% to 10.5% for the 2 x 2cm cells at AM0, the yield to delivery would have increased by several percent. The present requirements for strongly bonded contacts should be kept; however, minor severances of the fine grid network would normally be accepted. Including acceptance of the minor discontinuities

TABLE II

MATERIALS AND HANDLING COSTS PER CELL

(For a 20% Yield of Deliverable Cells)

ITEM	COST PER CELL ¢	PERCENT OF TOTAL
General	3.30¢	1.9%
Etch, Diffn. & Alloy	26.80	15.4
Metal Contacts	130.20	74.7
AR Coating	6.60	3.8
Edge Cleaning	7.33	4.2
Total	174.23	100
$1.74 Materials Cost per Ultra-Thin Cell		

TABLE III

LABOR COSTS FOR PROCESSING ULTRA-THIN CELLS

(For a 20% Yield of Deliverable Cells)

CATEGORY	COST PER CELL ¢	PERCENT OF TOTAL
General	8.7¢	2.2%
Etch, Diffn. & Alloy	42.5	10.7
Metal Contacts	90.2	22.8
AR Coating	74.6	18.8
Edge Cleaning	60.0	15.2
Testing	120.00	30.3
Total	396.¢	100.0%
$3.96 Labor Cost per Ultra-Thin Cell		

TABLE IV

COMBINED COSTS FOR ULTRA-THIN CELLS

(For a 20% Yield of Deliverable Cells)

CATEGORY	COST PER CELL, $	PERCENT OF TOTAL
Silicon	2.75	19.4
Materials	1.74	12.3
Labor	3.96	27.9
Overhead	5.74	40.5
TOTAL	14.19	100.1
$14.19 was the cost of producing a good cell.		

corresponds to the output in Table I, reducing the costs per cell experienced to $10.91.

Combining these two changes would have increased the yield of deliverable cells by about 10%, which would have corresponded to reducing cell cost to $9.46. Maintaining 50% yield from full operation line would result in a cost of under $5.00 for 2cm x 2cm ultrathin cells.

III. TECHNOLOGY AND PROCEDURES

A major result of this year's work is a substantial increase in power conversion efficiency over last year for ultrathin Pilot Line cells. This was accomplished by transferring technology developed in the parallel experimentation efforts to Pilot Line cell processing.

A. Process Technology and Procedures

The starting material was 2 ohm-cm, p-type, boron doped, CZ grown silicon. In the Pilot Line production a 25% 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 smooth to within a micron. The etching operation is consistently able to provide 50 micron slices with an excellent yield using a two-step approach (over 90%).

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

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 25% 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.

A number of alloy-diffusion programs were used during the year which resulted in similar cell performances. The p+ back surface was formed by vacuum desposition of $\sim$ 7000+ Å of aluminum followed by alloying at a temperature of 850°C or 900°C for 15 or 10 minutes, respectively.

Wafers were tilted in angled-slot diffusion boats so that the front side was convex during the diffusion process, a utilization of results from experimental fabrication efforts. Phosphorus diffusions into the p-type silicon were done at 850°C for 15 minutes in PH_3, Ar, and O_2 gases. The diffusion results were evaluated by sheet resistance measurements employing a Signatone 4-point probe and constant-pressure mount. The sheet resistance was in the range of 100-120 ohms per square.

In the latter part of the contract period, back alloy products were removed by etching in HCl, followed by rinsing the cells in an ultrasonic de-ionized water bath. This gave more consistent results with respect to the output power of the cells and internal reflection.

Both the front grid and the rear surface contacts were comprised of titanium - palladium - silver. Sequential evaporation of a thin metal sandwich and pattern generation accomplished with photolithography masking techniques was followed by silver electroplating to a total thickness of seven microns.

The antireflective coating was produced by vacuum deposition of oxygen-depleted tantalum oxide with an electron beam source. The cells were then sintered at 450°C for 45 seconds.

IV. EVALUATION CRITERIA AND PROCEDURE

A. Thickness Control

All cells were measured after etching using an ADE Microsense thickness gauge (Model 6033), to assure that the cell thickness was within specification (.0002" ± .0005").

B. Resistivity and Sheet Resistance

Starting slice resistivity was evaluated before etch and phosphorous-diffused n-type layers were evaluated after diffusion by sheet resistance measurement, both employing a Signatone 4 point probe with constant-pressure mount, constant-current power supply and DVM readout.

C. In-line Contacts Criteria

In-line Q.C. of the titanium-palladium-silver deposition for front and back contacts was done by tape testing co-evaporated scrap pieces of silicon. The Veeco/Kronos Automatic Deposition System performed reliably. Excellent yields were realized from all vacuum deposition operations.

The cells fabricated in the last quarter had an additional in-line screening test prior to AR coating, wherein vigorous scrubbing with cotton swabs was employed on the gridlines and contact areas. Any cells showing evidence of delamination were rejected at that point.

D. Electrical Performance

Cell electrical performance was measured using Solarex's Xenon simulator, Kepco electronic load and an x-y plotter. All measurements were made under AM0 ($135.3 mW/cm^2$) conditions at 25°C. Minimum acceptable peak power for the program was established without cover slide at 60mW (11%). Relative blue and red response were also measured using Corning filters #9788 and #2408, respectively. (These cells show gain upon covering.)

From time to time, more detailed opto-electronic measurements were made in order to determine optical and electronic loss mechanisms. This included reflectance vs λ, dark I-V, quantum yield vs λ, series resistance determinations and optical gain upon covering.

E. Final Q.C. Inspection Criteria (Mechanical)

Tighter Q.C. Inspection was initiated in the last quarter. The revised procedure is as follows:

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

1. There shall be no voids greater than 0.5mm penetrating the contact which expose either the sub-metal or silicon. Two voids less than 0.5mm 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 microscopically inspected for the following at a magnification of at least 10X.

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 subbuss gridlines.

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 ± 0.002 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 at a magnification of at least 10X.

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.

V. HANDLING AND SAFETY PRECAUTIONS

Operator experience and the tweezer design and maintenance are two requirements for reduced breakage. The proper tweezer is a wide tip stainless steel model (35ASA, manufactured by EREM, a Swiss firm). Operators learned with increasing experience to sense the presence of burrs or distortions of tweezer tips which could cause cell breakage. Often a minor grinding or sanding of the tips restored damaged tweezers to acceptable quality.

The nature of the breakage failure of these ultrathin cells is of interest. Under a compressive bending force, a "crazing" rupture can sometimes occur. Other stress failure modes such as point impact and tensile forces, resulted in a "tearing" of the cell, somewhat like tearing paper. As described in the Pilot Line Report for 1977, proper shipping boxes (styrofoam) with properly sized slots to avoid crushing are essential for shipping cells safely. Similarly, the use of an ADE Microsense non-contacting thickness gage is essential for thickness measurements.

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

VI. RATE LIMITING PROCESS STEPS

During the contract, it became apparent that three process steps would need additional apparatus to match the true production capacity of the rest of the process. These steps are etch thinning, metal contact processing and AR coating deposition. This is of course in addition to dealing with the start-stop problem that is rate limiting on output because of its effect on yield.

The etch thinning station had been rate limiting until the two-stage etching started using two NaOH baths for separate rough sizing and final trimming to thickness in the fourth quarter. This small addition increased the etch-thinning processing rate by 500%.

Front metal contact deposition and processing does require more tooling. The two metal evaporators were utilized for three process steps (aluminum, front contact and back contact) which all followed wet processing steps. Either use of heaters to dry the cells after loading into the evaporators or predrying ovens would speed up the pumping time to expected rates without hindrance by residual moisture. On the other hand, if future aluminum application shifts to screening or other methods the evaporator load would be reduced by a third.

The AR coating station has the greatest rate limitation at the present time. Improved larger cell-holder tooling for the two vacuum deposition systems (not NASA-furnished so far) could increase the throughput rate to reach 1,000 cells per day capacity.

VII. TECHNIQUES TO IMPROVE YIELDS

A. General

The electrical and mechanical yields of ultrathin solar cells could be improved to result in high manufacturing yields in a Pilot Line or full-scale production environment. Electrical yields have generally been very good, and the main question is the acceptable minimum cell efficiency required. There has been a scatter in open-circuit voltage for these cells because the injecting junction is much closer to the back contact region than for cell of conventional thickness. The higher the requirement on efficiency, the more important the back field will become. Mechanical yields are a much more pressing question, since they account for the great majority of processing attrition in fabricating ultrathin cells. The mechanical yields were dominated by breakage losses and gridline/contact losses. The breakage can be improved by certain changes in handling and processing apparatus, while improvement of gridline/contact losses depends both on operator procedures/training and equipment automation. The following discussions address these in turn, including estimates of cost and time to develop and initiate improvements.

B. Electrical Yield

The cells fabricated in the Pilot Line effort during the year showed an attrition due to low performance of only about 7%, of which one-half exceeded 10% efficiency, but not our arbitrary minimum of 11%. These lower output cells all suffered from low open-circuit voltages, which could be eliminated by implementing the results of the next six-month experimentation effort on back surface field formation techniques. Greater reproducibility of high open-circuit voltages would help a good deal to eliminate the low end of the present distribution, which is shown for the beginning and ending quarters in Figure 5.

There were a few cells (approximately 2% of starts for 2cm x 2cm, but 15% for 5cm x 5cm) which suffered from junction shunting due to ball-alloying of aluminum through to the front junction. Improved back surface processes would also alleviate this problem, and leave only very small electrical performance losses due to a small incidence of gridline silver thickness variation.

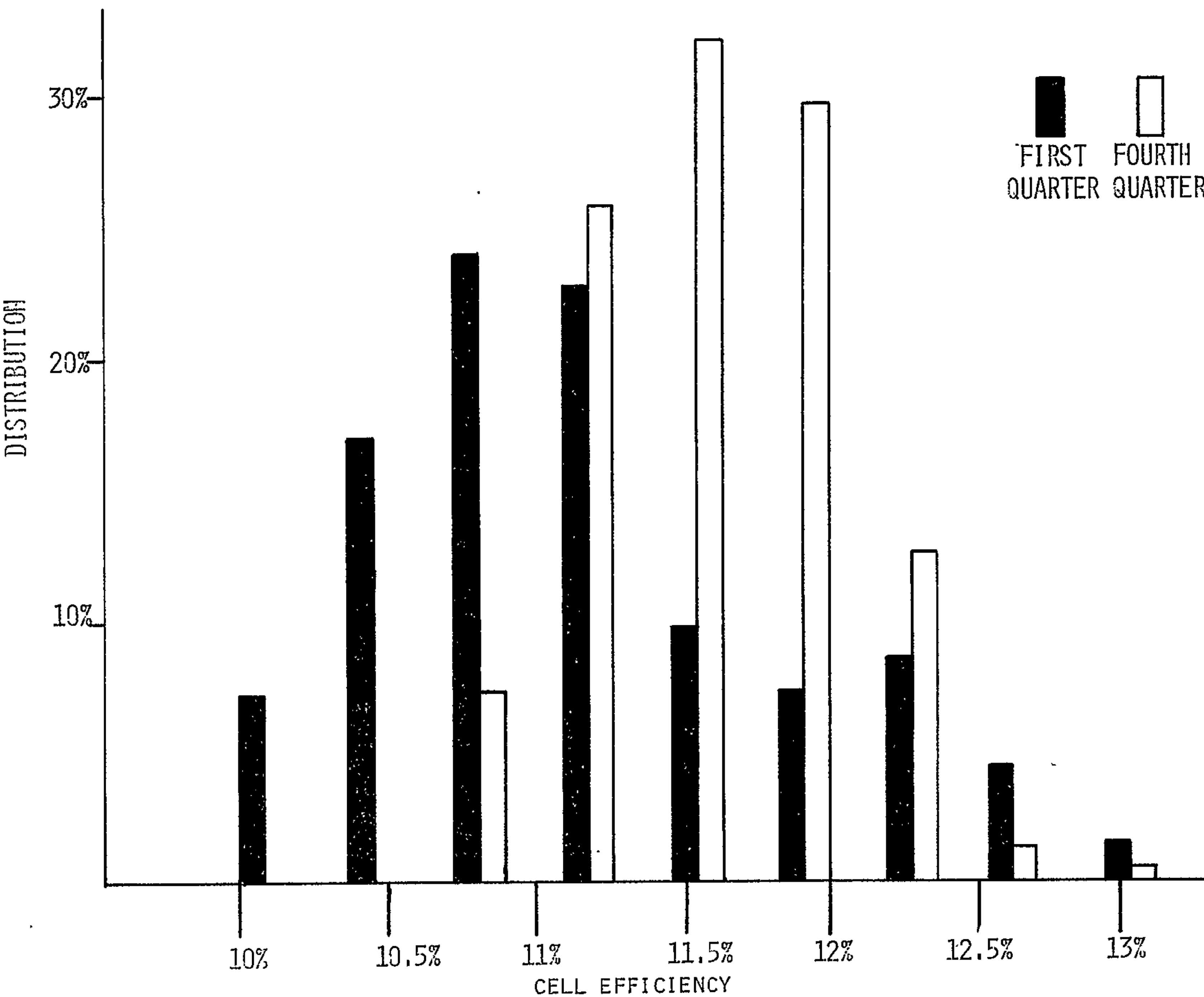
The present experimentation schedule for back surface formation technique implementation in experimental cells calls for six (6) months at a funding level of $50,000. Subsequently, evaluation on a Pilot Line manufacturing basis could be done with full operation over a minimum of a month period.

C. Mechanical Yield

Following full-rate run-up at the end of the last quarter, ultrathin 2cm x 2cm cells were subsequently fabricated with total breakage losses of only 26% of the cells started. This improvement was largely due to personnel training and process familiarity, with the great majority of the remaining breakage still occurring in wet-chemistry steps. As suggested

FIGURE 5.

DISTRIBUTION OF CELL EFFICIENCIES



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in Section II earlier in this report, some of the wet-process steps could be changed to operations with supporting rotating vacuum chucks. Such apparatus would be usable for single-side operations (e.g., such as photoresist developing) and the cells would be fully supported over their total area. This would eliminate some of the present liquid-immersion breakage. Also, it is possible to custom-design plastic cassettes specifically for ultrathin cell immersion-processing steps which are not available as standard items. These could include different designs for edge restraints which would relieve the stress of liquid surface tension or point forces on the cells.

Both these approaches could be implemented for the Pilot Line within six (6) months, with an equipment development cost of approximately $25,000 for the chuck system and $20,000 for the custom cassettes.

The gridline/contact mechanical yield experienced in the Pilot Line operation was partly influenced by very restrictive gridline criteria intentionally tighter than usually required. Relaxing to the usual criteria on gridlines, but fully imposing in-line and final microscopic critical-area contact criteria finally resulted in only a 16% overall reject rate for gridlines and contacts.

Some improvements over even this level could undoubtedly be made by various means. One is to implement equipment modifications for better cell surface outgassing prior to contact metal evaporation, and another is to functionally provide for stripping and re-applying contacts to suspect cells while still in process. The former is mainly a moderate equipment modification, while the latter is related to line organization, equipment utilization, and Q.A. procedures. These could be developed and initiated within three (3) months at a total equipment and labor cost of under $15,000.

Another improvement involving equipment would be to employ automatic light integrators on the photoresist exposure equipment. The Pilot Line as presently configured does not have such automation, and consequently a good deal of operator judgement is involved in determining correct exposures. This has led to significant processing attrition attributable to unexposed photoresist residues, etc., which resulted in contact and gridline mechanical difficulties. Such automatic control equipment is available commercially for a few thousand dollars, as is automatic temperature-controlled developing equipment. This sort of automation was not installed in the original Pilot Line, since that was an extrapolation of laboratory procedures. However, such equipment is very helpful in large-throughput production lines.

VIII. PROJECTION OF FUTURE EFFICIENCIES

The average efficiency of the most recent Pilot Line production run was 11.6% (AM0, 25°C) and a maximum efficiency of 13.5% was obtained. Figure 6 shows typical I-V curves obtained from cells produced during this run.

The next most logical step to make in efficiency improvement is to fabricate textured cells in Pilot Line quantities. In the experimental program, textured cells having an average efficiency of 13.7% (59-cell lot) and a maximum efficiency of ~14.7% were recently fabricated. Figure 7 shows the power output of the highest efficiency cell obtained to date along with the blue and red response. Texturing both sides of a cell results in higher short circuit current densities (up to ~43 mA/cm^2) and consistently higher open circuit voltages (averaging above 580mV) when evaporated aluminum is the source for the production of a back surface field.

In a Pilot Line effort, it is expected that within six months average efficiencies close to 13% can be attained, and maximum values of 14.5% are likely. It is possible that within six months higher open-circuit voltages can be consistently obtained as a consequence of research efforts on pastes, evaporated aluminum, etc. If this is the case, we expect that the average efficiency would increase to over 13.5% in Pilot Line implementation.

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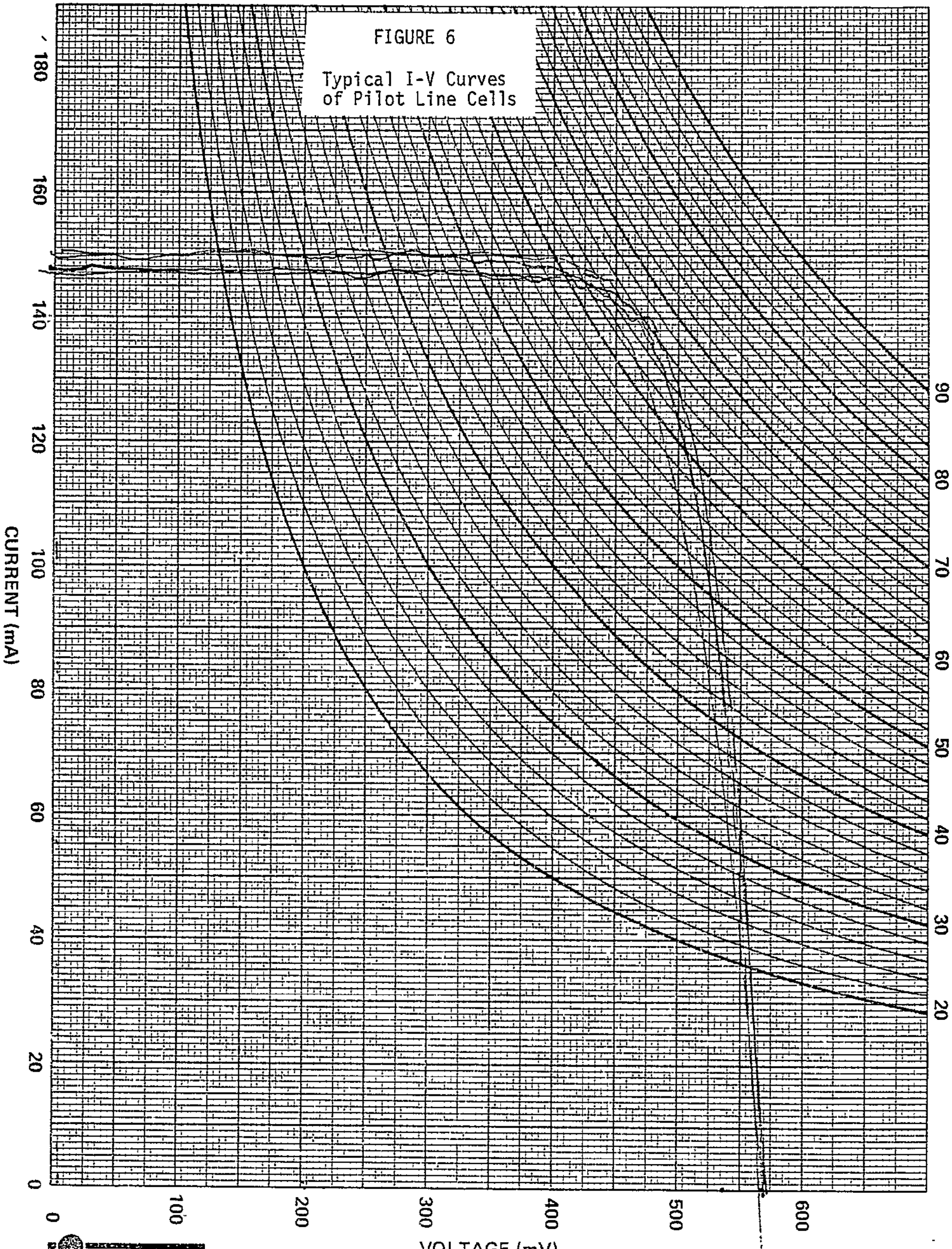

FIGURE 6

Typical I-V Curves of Pilot Line Cells

SOLAREX ROCKVILLE, MARYLAND USA

FORM 11134

AMO AR

Cell Type 2x2cm 2 mil No. 2203 By JC Date 10/8/78

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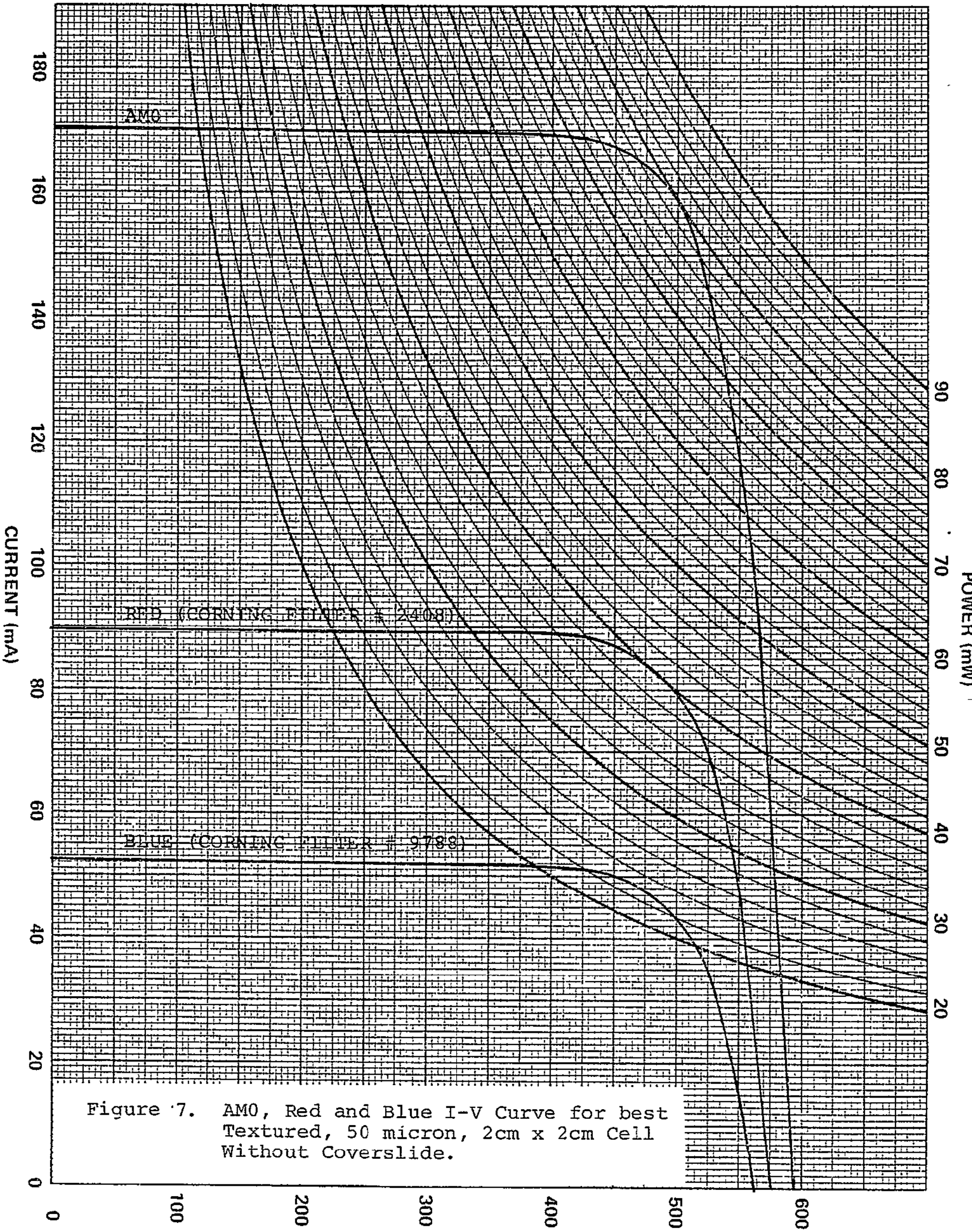

Figure 7. AM0, Red and Blue I-V Curve for best Textured, 50 micron, 2cm x 2cm Cell Without Coverslide.

SOLAREX ROCKVILLE, MARYLAND USA
FORM 11134

25°C

2 mil Textured
Cell Type 2x2cm. No. 2831-2-1 By TT Date 10/24/78

IX. REQUIREMENTS TO ACHIEVE 100,000/MONTH RATE

A. General Considerations

A Pilot Line program task required Solarex to determine the requirements to achieve a production capacity of one hundred thousand (100,000) ultrathin silicon solar cells per month, based upon the results of the Pilot Line. This section specifically addresses the requirements in terms of processes, equipment and personnel to reach such a capacity. Subsequent sections in this report address the cost and time required to implement such a production line capacity, and the per-cell cost projections for a total production of 1,500,000 cells. All of these are based upon cells of 2cm x 2cm geometry at a rate of 100,000 per month, or 40 square meters of delivered cell area per month.

In order to address a ten-times larger production capacity as compared to the present Pilot Line, one has to make some reasonable assumptions in extrapolation and separately address possible productivity improvements which could be realized. In this projection an average processing yield of 55% is assumed, so as to establish a baseline set of requirements. Also, equipment capacity in square centimeters of cell area per day and personnel requirements are on a single eight-hour shift. After discussing the requirements of this baseline projection we shall consider trade-offs between equipment and personnel for multi-shift operations and improvements in productivity for other cell sizes, etc. Also, the baseline projections are made for the immediate time frame.

B. Equipment Requirements

A yield of 55% requires input of approximately 180,000 cell starts per month, or 8,500 per day. With process technology as presently developed the required equipment for processing these cells is as follows for starting with three inch diameter slices of Czochralski silicon and ending with packed tested cells.

1. Incoming Silicon Inspection and Sorting

Incoming silicon wafers are checked for resistivity and sorted by thickness groups to facilitate precise thickness control during etching. For 8,500 cells per day this station will require a four-point probe and power supply for resistivity measurement, and electronic thickness gauge with one-micron resolution.

2. Area Sizing

The semi-automatic saws employed for slicing three-inch wafers into precise 2cm squares have capacities for producing 1500 squares per eight hours per machine. The requirement is therefore six saws.

3. Thinning Etch

The use of two NaOH etch tanks in the Pilot Line operation to allow separate and simultaneous rough sizing in one tank while adjusting to final thickness in another resulted in an estimated capacity for 3,500 cells per day. For an 8,500 cell per day capacity three such dual-tank stations would be required. In addition, three HCl baths and de-ionized water rinsers and a spin dryer would be necessary.

4. Diffusion and Back Alloy

At full utilization, it would take five tubular furnaces of 120mm bore size to do the high-temperature processing for 8,500 cells per day; i.e., at a rate of 2,000 cells per tube per day allowing for present cleaning times. An equal number (5) of both etch tanks and ultrasonic baths, plus a spin dryer would be required for alloy-product removal.

5. Metal Evaporators

Assuming that the back aluminum would still be applied by evaporation, there would be three evaporation cycles for every cell. Use of multiple 26" evaporators instead of a single in-line load-lock large system is preferable in terms of down time and redundant reliability. Since such a 26 inch system can do the three separate coating steps for 2,000 cells per day, (if they are well dried), the 8,500 cell per day input would require five such 26 inch diameter evaporators. A controller for metal deposition rate and its attendant recorder can service two evaporators (since rarely are two ready simultaneously), so only three deposition control systems would be needed.

6. Gridline Patterning

Solarex employs photolithography for gridline patterning which utilizes centrifugal photoresist application, heating to dry the film, timed ultraviolet exposure of the pattern, tank developing and stripping, de-ionized water rinsing and cassette spin drying. A four-head photoresist spinner with dispensers, three develop/strip tanks, eight cassette-size ultrasonic cleaners and two de-ionized water rinsers would be required for this operation, plus two ultraviolet exposure systems. For volume production the exposure systems should be automatic with integral sensors and controls for integrating ultraviolet flux to assure uniformity.

7. Silver Electroplating

At present, the Pilot Line electroplating bath can deposit silver to build up the Ti-Pd-Ag metallization thickness on both sides of the cells to seven microns at a rate of 2,000 cells per day. The processing yield to this step will probably be under 85%, so only four tanks would be required. The station would also require two cascade rinsers, two de-ionized water rinsers and a spin dryer.

8. Antireflective Coating

Vacuum deposition of tantalum oxide produces considerable outgassing of the source and chamber walls; opposite to the gettering effect of titanium. Consequently, even with high packing density tooling in 26 inch diameter evaporators, five such systems would be required to daily coat the 6,000 expected surviving cells within each eight-hour shift. Also, a belt sintering furnace for contact sintering and tantalum oxide densification will be required at the station.

9. Final Inspection, Measurement and Sorting

This area will require a dedicated Xenon simulator, electronic load, meters, six-contact probe and inspection microscopes.

10. In-Line Tests, Inspections and Equipment Loading

It is estimated from scaling up the inspection, test and equipment loading work areas of the present Pilot Line that twenty work tables and ten five-shelf dessicator cabinets will be required for these interspersed areas.

B. Facility Size

Extrapolation of area requirements from the processing operations of the existing Pilot Line to the facility required for 100,000 cells per month predicates a minimum of 10,000 square feet of area for the line itself. Additional office and materials stockroom requirements raise this to a total of 15,000 square feet, assuming that overhead operations are not included in the facility itself.

C. Personnel Requirements

Such a manufacturing facility would require approximately six (6) months to set up the physical plant in empty space.

It is estimated from experience in setting up the Pilot Line and Solarex terrestrial-cell production lines that during the six month installation period the services of three (3) professionals and five (5) technicians would be needed, plus usual ratios for overhead operations.

After the installation phase a period of time would be required to train personnel and run-up the equipment operation to capacity. Scaling the Pilot Line to the full operation indicates a full staff of fourty (40) hourly operators (including foremen), a line supervisor, and two professionals. It is estimated from Solarex production line experience and Pilot Line experience extrapolation that it would take four months to train the staff and exercise operation. The professionals and the supervisor would be required at the start of this phase, while the hourly personnel would be added at the rate of ten (10) per month until fully staffed. This staffing build-up would produce a run-up to full production with an output as follows:

1st Month - - - -	20,000 cells
2nd Month - - - -	40,000 cells
3rd Month - - - -	60,000 cells
4th Month - - - -	80,000 cells
Thereafter - - -	100,000 cells

D. Productivity Considerations

As discussed repeatedly in earlier sections of this report, full-rate operation of a production line is required in order to maintain reasonable overall yields. Also, it is only in such an operating environment that low-productivity steps can be evaluated and modified. However, it is already obvious from the Pilot Line operation that a 2cm x 2cm cell geometry is too small for highest productivity. Although several operations (such as evaporation of metal or AR films) are area limited in throughput, the handling and testing are examples of piece-limited operations. In order to implement higher productivity with larger cells it will first be required to exercise high yield techniques for handling larger cells in processing.

The projections of equipment and personnel needs for the 100,000 cell per month capacity made above assumed only one work shift utilization of equipment. It has been found at Solarex that double-shift operation significantly increases output from the same equipment, with less than double the number of hourly operators. This is largely due to the fact that more than a single shift is required to complete all operations in fabricating a solar cell. Consequently, a double shift produces a faster net flow with less chance for surface contamination and pitfalls of even day to day start-stop operation. Therefore, the equipment estimates presented could likely be significantly reduced for two-shift operation. While the personnel requirement would increase, it would not double, since more efficient use of the equipment can be made.

X. ESTIMATE OF COST AND TIME TO IMPLEMENT EXPANDED PRODUCTION LINE

The experience gained fabricating the thin cells for this program indicates that no inherent difficulties will be encountered in developing a production facility capable of manufacturing 100,000 deliverable 2cm x 2cm thin cells per month. Table V outlines the expected equipment cost of $700,000. In addition to this cost there would be costs for construction, plumbing and electrical as well as the labor cost to order and set up the equipment. Table VI summarizes the total cost expected for setting up this production line. The total cost of $973,364 would result in a production line ready for start-up production. It is estimated that 6 months would be required for this effort.

Before 100,000 cells per month can be produced the production facility must go through a start-up and manpower training phase. This phase is expected to last four months at a total cost between $550,000 and $600,000. These costs are explained in Table VII. At the conclusion of this phase the production line would be delivering 2cm x 2cm cells at a rate of 100,000 per month.

TABLE V

Estimated Equipment Costs for Development of 100,000 Cells per Month Production Line

EQUIPMENT	ESTIMATED COST ($)
Materials Preparation	27,000
Diffusion & Alloy	43,000
Metal Deposition	200,000
General & Wafer Handling	41,000
Dicing	90,000
AR	245,000
Measurement	45,000
TOTAL	$691,000

TABLE VI

Costs for Set-up of Production Line

Capital Equipment	$ 691,000
Equipment Handling (10%)	69,100
Construction	25,000
Plumbing	5,000
Electrical	10,000
Labor	70,720
Overhead (145%)	102,544
TOTAL	$ 973,364

TABLE VII

Cost for 4 Mo. for Manpower Training and Start-up

Materials (500,000 cell starts)	325,000
Materials Handling (10%)	32,500
Misc. Equipment and Tooling	25,000
Labor	80,300
Overhead (145%)	116,440
TOTAL	$579,240

XI. COST PROJECTIONS

Based upon the operation of the thin cell Pilot Line and our general experience in cell production, cost projections have been formulated. The cost estimates are based upon a production rate of one hundred thousand (100,000) 2cm x 2cm thin cells per month at an expected yield of 55% as shown feasible by the Pilot Line. Table VIII is a tabulation of the expected materials cost per cell. Table IX lists the expected labor costs per cell based on a $5.00 per hour labor rate. Table X summarizes the estimated cost of this cell production with an expected cost of $5.16 per 2cm x 2cm cell. This total, however, does not include space QA requirements which as an estimate may add an additional 45% to the cell cost.

Finally, these cost estimates do not include capilatization of the equipment nor account for a training period for personnel. These costs were estimated in Section X and are costs that must be incurred before these cell prices are available.

PROJECTED CELL COST

Table VIII. Projected Materials Cost per Cell
(Based upon 55% Yield)

ITEM	COST PER CELL (¢)
General	1.16
Dicing	2.69
Metal Contacts	47.35
AR	2.4
Etch, Diff. & Alloy	9.75
TOTAL	63.35

PROJECTED CELL COST

TABLE: IX. Labor by Category (55% Yield)

CATEGORY	COST PER CELL (¢)
General	3.2
Etch, Diff. & Alloy	15.5
Metallization	32.8
AR	27.1
Dicing	21.8
Q.C.	43.6
TOTAL	144.0

TABLE: X. Projected Cell Cost (55% Yield)

CATEGORY	COST PER CELL ($)
Silicon	1.00
Materials	0.63
Labor	1.44
Overhead (145%)	2.09
TOTAL	5.16