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TOPICAL REPORT

DEMONSTRATION OF THE FEASIBILITY OF AUTOMATED SILICON SOLAR CELL FABRICATION

by

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prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
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16. Abstract

A study effort was undertaken to determine the process steps and design requirements of an automated silicon solar cell production facility. Identification of the key process steps was made and a laboratory model was conceptually designed to demonstrate the feasibility of automating the silicon solar cell fabrication process. A detailed laboratory model was designed to demonstrate those functions most critical to the question of solar cell fabrication process automating feasibility. The study and conceptual design have established the technical feasibility of automating the solar cell manufacturing process to produce low cost solar cells with improved performance. Estimates predict an automated process throughput of 21,973 kilograms of silicon a year on a three shift 49-week basis, producing 4,747,000 hexagonal cells (38mm/side), a total of 3,373 kilowatts at an estimated manufacturing cost of $0.866 per cell or $1.22 per watt.

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Contract NAS3-18566

DEMONSTRATION OF THE FEASIBILITY OF AUTOMATED SILICON SOLAR CELL FABRICATION

Report - TR3

TOPICAL REPORT
TASK I AND TASK II

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October 1975

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I. SUMMARY

This topical report summarizes the preliminary results of a study and design to demonstrate automated silicon solar cell production feasibility.

A study phase of the effort was undertaken to determine the process steps and design requirements of an automated silicon solar cell production facility. Identification was made of the key process steps and a laboratory model was conceptually designed to demonstrate the feasibility of automating silicon solar cell fabrication processes. A detail design of the laboratory model was made to demonstrate those functions most critical to the question of solar cell fabrication process automating feasibility.

The principal steps in the selected baseline process sequence are a sodium hydroxide etch; phosphine diffusion junction formation; front and rear contact screen printing; spin-on A/R coating; and score and break to final size.

A two step etch was employed using 30 percent sodium hydroxide to remove 15 to 25 micrometers of silicon with an additional 15 to 25 micrometers removed in hot 1 percent sodium hydroxide to produce crystalographically textured surface which exhibits lower reflectance (rendering A/R coating less critical) and improves metallization adherence. Evaluation of spin-on versus phosphine sources was unable to identify a satisfactory alternative to the phosphine process. Simultaneous diffusion of the N^+ and P^+ regions using spin-on diffusion sources was unsuccessful, although screen printing of the P^+ source proved promising. Screen printing of the front and rear contacts was successful and spin-on A/R coatings were found to give excellent performance even though the ideal index of refraction is not available.

The conceptual design and cost projections for an automated solar cell production facility using the selected process sequence yields an estimated manufacturing cost of $0.866 per cell or $1.22 per watt based on a facility processing 21,973 kilograms of silicon into 4,747,000 hexagonal cells with 38mm sides equivalent to a total of 3,373 kilowatts per year on a 3 shift, 49-week basis.

II. INTRODUCTION

A. BACKGROUND

This topical report describes the results of the preliminary phases of the scope of work of NASA/Lewis Contract NAS3-18566, a cost-plus fixed fee (R and D Type) contract.

B. OBJECTIVE

The objective of this contract scope of work is demonstration of automated silicon solar cell production feasibility.

C. METHODOLOGY

The technical aspects of the work are separated into the following tasks:

Task IA - Study effort to determine process steps and design requirements of an automated silicon solar cell production facility.

Task IB - Identification of key process steps and conceptual design of a laboratory model to demonstrate feasibility of automating silicon solar cell fabrication processes.

Task II - Detailed design of laboratory model to demonstrate those functions most critical to the question of solar cell fabrication process automating feasibility.

Task III - Construction, assembly, and operation of laboratory model; analysis of operation; ascertainment of process cost reduction areas attainable by automation and recommendation of needed technological developments.

C. STATUS

Tasks I and II have been completed. This Topical Report summarizes the activities carried out in these first two tasks.

III. PROCESS EVALUATION AND SELECTION

A. INTRODUCTION

The Automation Feasibility Demonstration program was initiated with the Spectrolab low cost solar power facility and processes as a point of departure. This facility had been established using processes selected as being compatible with eventual mechanization.

One of the major innovations in this facility was the use of screen printed thick film techniques to replace the relatively costly vacuum deposition process for forming metal contacts. The facility also obtained cost advantages by the use of larger silicon slices (51mm diameter discs) wafered directly from the grown crystal. For the purposes of this program it was proposed that the standard cell process be modified as follows:

a) Use high resistivity material (7-13 ohm-cm or higher).

b) Reduce diffusion temperature to provide a shallow junction, as in our high-efficiency "Helios" space cells.

c) Add a back-surface field by means of a simultaneous P^+ diffusion.

d) Re-optimize our contact pattern for a higher diffused layer sheet resistance.

e) Add a slicing operation to shape the cell into a square, rectangular, or hexagonal form to maximize packing factor.

In addition it was proposed to evaluate and identify alternative processes for junction formation and AR coating which would be amenable to mechanization.

For reference purposes the Baseline Process sequence shown in Figure 1 was proposed based on the above considerations. To facilitate discussion of

Figure 1

Baseline Process Operations

Starting material: Etched silicon blanks, 78mm diameter, 0.15mm thickness, resistivity and conductivity type optional.

1) Spin on P-type diffusant and bake.
2) Spin on N-type diffusant on other surface and bake.
3) Diffuse in belt furnace.
4) Remove diffusion oxides in HF, rinse and dry.
5) Screen print back contact and bake.
6) Screen print front contact and bake.
7) Fire contacts.
8) Spin on AR coating and bake.
9) Cut to final size and shape.
10) Test and sort.

the process evaluation and selection, a more generalized statement of process organization is shown in Figure 2.

B. SURFACE PREPARATION

Etching in sodium hydroxide solutions had been used for some time in the production of low cost solar cells, and appeared to offer several advantages as compared to acid etching. Firstly, hydroxide etching is a milder process, much less expensive and more readily controlled than acid etching. Secondly, hydroxide etching produces a rougher surface which exhibits lower reflectance (rendering AR costing less critical) and improving the adherance of metallization.

To explore this process, saw-cut wafers were etched in sodium hydroxide/water solutions containing 3%, 10% and 30% NaOH by weight. Results were:

a) The variation of etch rate with temperature corresponds to the activation energy value of 0.56 eV given in the literature.

b) The etch rate at any temperature varies approximately as the square root of the hydroxyl ion concentration.

c) The addition of detergent to the etch reduces the etch rate, to a greater extent at lower NaOH concentrations.

d) Ultrasonic agitation increases etch rate only slightly.

e) Substantially more uniform etching is obtained in 30% NaOH than at lower concentrations, when samples with equal amounts of material removed are compared.

f) The lower the NaOH concentration, the smaller, deeper, and better defined are the crystallographic pits, and this effect is independent of etch temperature.

g) The depth of mechanical damage in the sawing process, as determined by microscopic examination of samples etched to various depths and

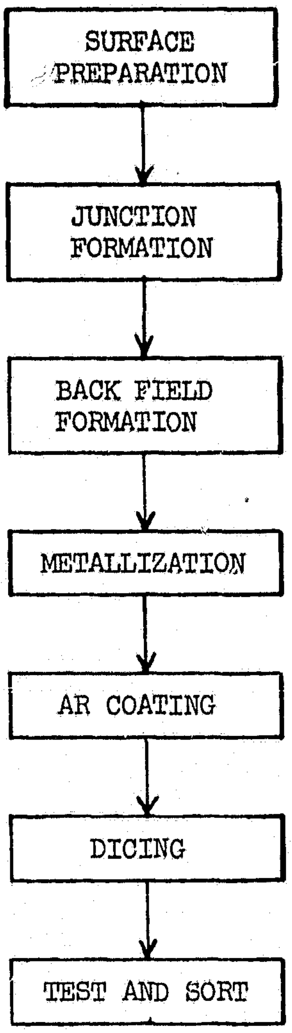


Figure 2
Process Organization

also by noting the change in etch rate with depth, is about 15 micrometers.

Based on these results, a two-step etching process was decided on. The first step is etching in hot 30% NaOH to a depth of 15 to 25 micrometers. In the second step an additional 15 to 25 micrometers is removed in hot 1% sodium hydroxide to produce a crystallographically textured surface.

C. JUNCTION FORMATION

Junction formation by diffusion from spin-on type dopant sources was evaluated as an alternative to tube furnace diffusion from a phosphine source. In particular an intensive effort was made to codiffuse boron for the P^+ back field with phosphorous or arsenic for forming the junction. These studies were unable to identify a satisfactory alternative to the phosphine process, which was selected as the process to be used for the demonstration.

Inherent to the diffusion process is the formation of a low resistivity N type envelope surrounding the wafer. Poor device performance is obtained if this envelope is permitted to contact the P^+ back field region or the back metallization contact. In order to eliminate this problem a back etch facility was devised and constructed. This processing step following diffusion removes the N^+ layer on the back of the wafer where the P^+ back field and/or metal contact will be subsequently formed. The dicing operation which will be used in the final stages of processing may enable the elimination of back etch process step, a possibility which will be investigated during Task III.

D. BACK FIELD FORMATION

The "baseline process" proposed simultaneous diffusion of the N^+ and P^+ regions, using spin-on diffusion sources. Attempts to reduce this concept to a practical process were not successful.

Somewhat more promising results were obtained by forming the P^+ region from a silk screened aluminum paste fired to form an alloyed contact. However, there remain a number of potential problems. The presence of the aluminum metallization interferes with the N^+ diffusion, requiring that the back field process follow the N type diffusion. It has been found that a firing temperature of 850°C is required to form an effective back field. This firing temperature has the effect of increasing the depth of the junction. It also leads to the formation of aluminum balls which are frequently firmly attached to the metallization pad and create problems in subsequent processing and mounting on module and array substrates. The formation of these balls is prevented by prefiring the aluminum paste at 650°C. There is some evidence that this prefiring may degrade the effectiveness of the back field formed by the subsequent high temperature firing. The aluminum firing also results in thermal stresses which cause warpage of the wafers which may be troublesome.

These questions will be closely evaluated during the early stages of the demonstration phase in order to ascertain the magnitude of their impact and to undertake corrective measures if necessary.

E. METALLIZATION

The silk screen metal paste process has been found satisfactory. Improved results have been obtained by protecting the front face to prevent microfractures. Not only is the curve shape improved, but adhesion is increased to the point that failure occurs by fracture of the silicon wafer rather than separation of the metallization.

The use of a silk screened silver pad fired on the aluminum back has been found to make a suitable solderable contact. It has not been possible to cofire the silver solder pad and the aluminum.

F. AR COATING

In contrast with disappointing results obtained with spin-on diffusion sources, spin-on AR coatings were found to give excellent performance even though an ideal index of refraction is not available. The use of textured surfaces and coverslides make the performance less sensitive to perfection of the AR coating. The interaction with interconnect soldering remains a potential problem.

G. DICING

No problems were encountered in dicing using a technique wherein the cell is saw scribed part way through from the back side and then broken. A suitable rotating table system to mount on existing equipment is being designed and constructed.

H. PROCESS SUMMARY

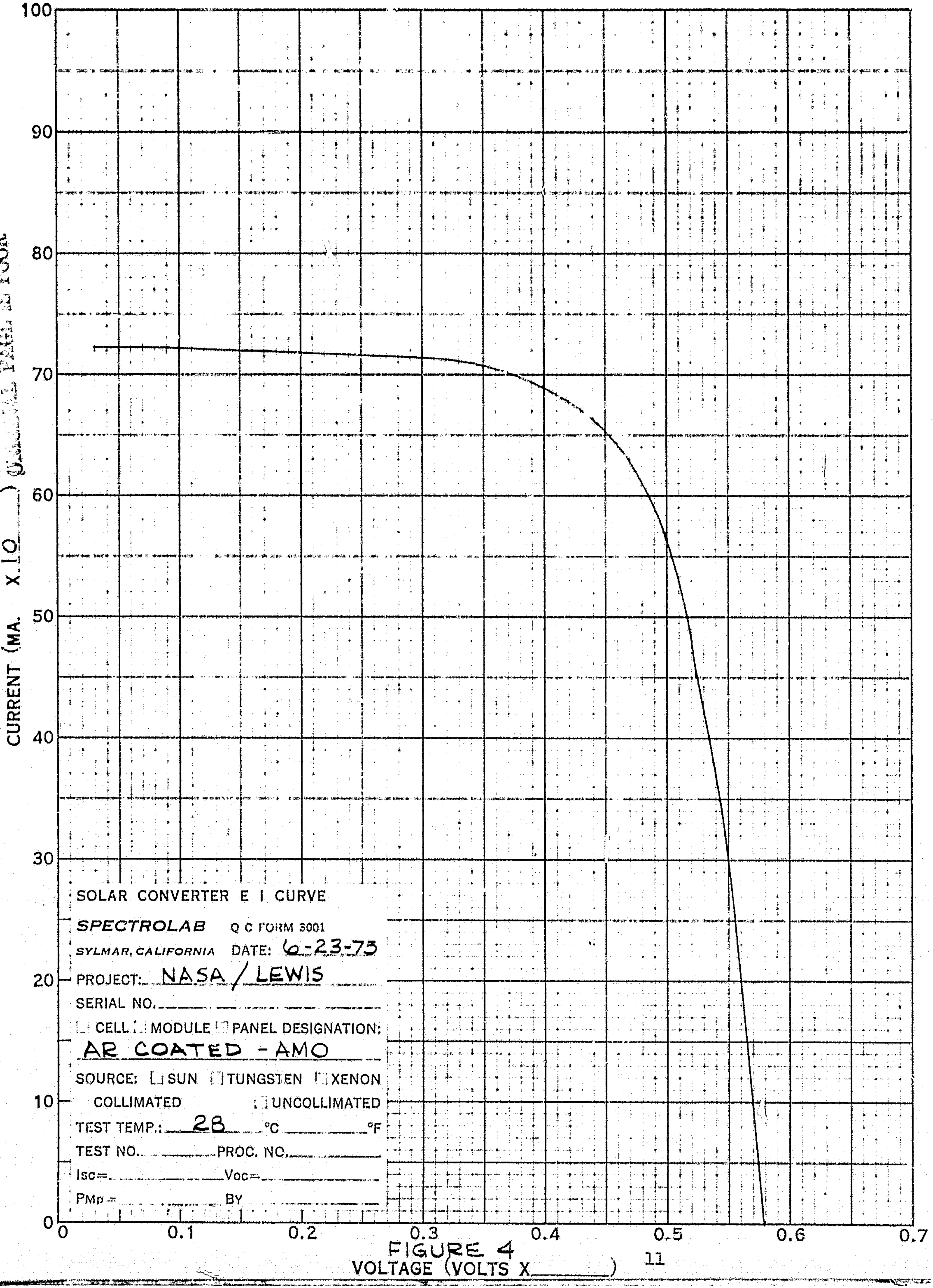
The process sequence derived from the study phase (Task IA) is compared with the baseline sequence in Figure 3.

The cells produced by the modified process are expected to have characteristics at 28°C and Air Mass 0 comparable to the best cells produced during the study phase. The curve for such a cell in the form of a 51mm round cell is shown in Figure 4 and has a peak power density of 144 watts per square meter.

Figure 3

IMPACT OF STUDY PHASE ON BASELINE PROCESS SEQUENCE

	Baseline Process	Modified Process
1a.	--	NaOH Etch
2.	Spin and bake P type diffusant	--
3.	Belt furnace diffusion	Phosphine diffusion
4.	Strip oxides	Strip oxides and back etch
5.	--	Print and bake Al back
6.	--	Fire aluminum back
7.	Screen print and bake back contact	Screen print and bake front contact
8.	Screen print and bake front contact	Screen print and bake back contact
9.	Fire contacts	Fire contacts
10.	Spin and bake AR coating	Spin and bake AR coating
11.	Cut to final size and shape	Cut to final size and shape
12.	Test and sort	Test and sort



SOLAR CONVERTER E I CURVE

SPECTROLAB Q C FORM 3001

SYLMAR, CALIFORNIA DATE: 6-23-75

PROJECT: NASA / LEWIS

SERIAL NO.

☐ CELL ☐ MODULE ☐ PANEL DESIGNATION:

AR COATED - AMO

SOURCE: ☐ SUN ☐ TUNGSTEN ☐ XENON

COLLIMATED ☐ UNCOLLIMATED

TEST TEMP.: 28 °C °F

TEST NO. PROC. NO.

Isc= Voc=

PMp = BY

FIGURE 4

IV. CONCEPTUAL DESIGN

A. CONCEPTUAL DESIGN OF AUTOMATED SOLAR CELL PRODUCTION FACILITY

A block diagram showing the major functional components of the suggested facility is presented in Table 1, with individual process steps detailed in Table II. The process relationships are further developed in Table III which presents a suggested factory organization, details of yields and thruputs. Estimated Capital costs are presented in Table IV. Elements of the manufacturing costs are presented in Tables V, VI and VII and are combined in Table VIII. This analysis estimates a manufacturing cost of $0.866 per cell or $1.22 per watt based on a facility processing 21,973 kilograms of silicon into 4,747,000 hexagonal cells with 38mm sides (3,373 KW) per year on a 3 shift, 49 week basis.

The proposed process starts with 76mm round wafers cut from P-type Czochralski crystals. The advent of some form of ribbon crystal would result in the substitution of ribbon strips of some arbitrary but finite length as starting material. After cleaning and etching to remove saw damage and develop a tetrahedral surface structure, the silicon substrate would be diffused in a batch type gaseous phosphorous diffusion facility. The diffusion step would accommodate ribbon strips up to three inches width and two feet length without modification. Some alteration in design of the cleaning and etching facility would be required to accommodate ribbon strips, and use of the tetrahedral surface structure would be precluded if the surface of the strip were not [100] crystal planes.

After back etching, the wafers will be processed through a thick film facility to produce an aluminum back field, solderable front and rear

TABLE I

PROCESS ORGANIZATION

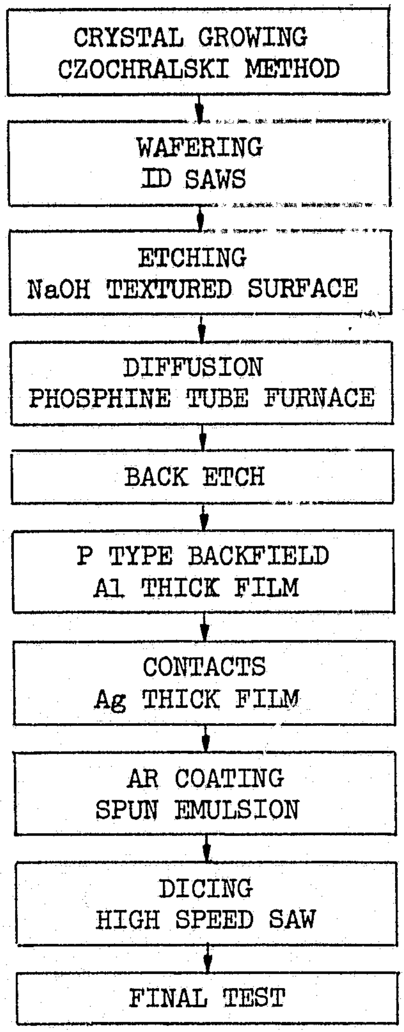


TABLE II

PROCESS FLOW DETAIL - AUTOMATED SOLAR CELL DEMONSTRATION

Process Step	Automation Method	Demonstration Method
Crystal growing	Czochralski	
Mounting	Hot Plate	
Sawing	I.D. Saw	
Basket Load	Mechanical	Hand
Clean	Basket Dip	Basket Dip
Basket Transfer	Mechanical	Hand
Polish Etch	Basket Dip 30% NaOH Hot	Basket Dip 30% NaOH Hot
Basket Transfer	Mechanical	Hand
Texture Etch	Basket Dip Hot 1% NaOH	Basket Dip Hot 1% NaOH
Basket Transfer	Mechanical	Hand
Rinse	Basket Dip	Basket Dip
Dry	Centrifuge	Centrifuge
Unload	Hand Dump	Hand Dump
Quartz Boat Load	Mechanical	Hand
N Diffusion	Tube Furnace (Phosphine)	Tube Furnace (Phosphine)
Unload	Hand Dump	Hand Dump
Back Etch	Water-cooled Mechanically Loaded Fixture	Water-cooled Hand Loaded Fixture
Dry	Centrifuge	Centrifuge
Print Aluminum Back Field Source	Automatic Silk Screen Printer	Manual Silk Screen Printer
Bake	Belt Furnace	Electric Oven
Quartz Boat Load	Mechanical	Hand
Alloy and Diffuse	Tube Furnace	Tube Furnace
Unload	Hand Dump	Hand Dump
Print Back Contact	Automatic Silk Screen Printer	Manual Silk Screen Printer
Bake	Belt Furnace	Electric Oven
Print Front Contact	Automatic Silk Screen Printer	Manual Silk Screen Printer
Bake and Fire	Belt Furnace	Belt Furnace
HF Rinse	Water Cooled Mechanized Fixture	Water Cooled Hand Load Fixture

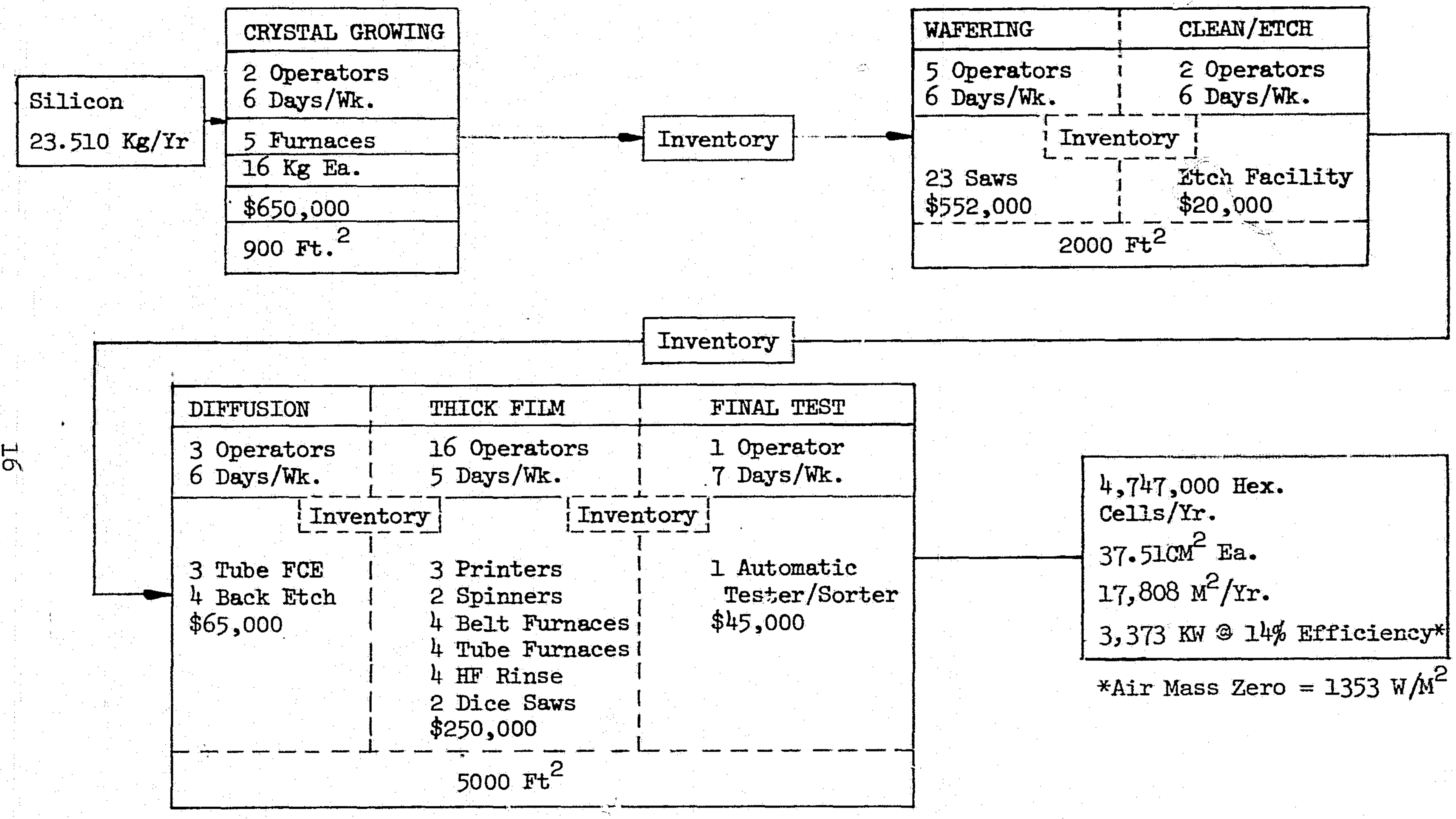
TABLE II-Cont'd.

PROCESS FLOW DETAIL - AUTOMATED SOLAR CELL DEMONSTRATION

Process Step	Automation Method	Demonstration Method
Dry	Centrifuge	Centrifuge
AR Coat	Automatic Spinner	Hand Loaded Spinner
Bake	Belt Furnace	Electric Oven
Dice	Diamond Blade Saw	Diamond Blade Saw
Test	Solar Simulator	Solar Simulator
Interprocess Transfer	Mech. Load	Hand Load

TABLE III

FACTORY ORGANIZATION



*Air Mass Zero = 1353 W/M^2

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TABLE IV

EQUIPMENT DETAIL

			UNIT ANNUAL CAPACITY 24 HR., 7 DAY, 49 WK.			BALANCED LINE CAPACITY						CAPITAL	
STEP	EQUIPMENT	NEED DESIGN	INPUT	OUTPUT	SHRINKAGE %	SHIFTS	DAYS	UNITS	INPUT	OUTPUT	EXCESS	UNIT	TOTAL
Crystal Gr.	16 Kg Czochralski	No	6050 Kg.	5585 Kg.	7.7	3	6	5	23,803 Kg.	21,973 Kg.	1962 Kg.	$ 130,000	$ 650,000
Wafering	ID Saw, Automatic	No	1155 Kg.	295,000 Waf.	5.45	3	6	23	21,973 Kg.	5,612,000	203,000	24,000	552,000
Cleaning	Ultrasonic	No	3,240,000	3,240,000	-	3	6	3	5,612,000	5,612,000	2,719,000	2,000	6,000
Polish/Etch	Automatic Basket Dip	?	8,100,000	8,000,000	1.23	3	6	1	5,612,000	5,543,000	1,314,000	12,000	12,000
Dry	Centrifuge	No	16,000,000	16,200,000	-	3	6	1	5,543,000	5,543,000	8,342,000	2,000	2,000
Diffusion	Tube Furnace	No	7,290,000	7,230,000	0.82	3	6	1	5,543,000	5,498,000	699,000	15,000	15,000
Back Etch	Automatic Water Cooled Fixture	Yes	1,940,000	1,920,000	1.03	3	6	4	5,498,000	5,441,000	1,142,000	12,000	48,000
Dry	Centrifuge	No	16,200,000	16,200,000	-	3	6	1	5,441,000	5,441,000	8,444,000	2,000	2,000
Print Al	Automatic Printer	No	12,000,000	11,900,000	0.83	3	5	1	5,441,000	5,396,000	3,104,000	12,000	12,000
Bake	8" Belt Furnace	No	12,200,000	12,200,000	-	3	5	1	5,396,000	5,396,000	3,318,000	25,000	25,000
Fire	Tube Furnace	No	2,430,000	2,410,000	0.82	3	5	4	5,396,000	5,352,000	1,534,000	2,500	10,000
Back Contact	Automatic Printer	No	12,000,000	11,900,000	0.83	3	5	1	5,352,000	5,308,000	3,192,000	12,000	12,000
Bake	8" Belt Furnace	No	12,200,000	12,200,000	-	3	5	1	5,308,000	5,308,000	3,406,000	25,000	25,000
Front Contact	Automatic Printer	No	12,000,000	11,900,000	0.83	3	5	1	5,308,000	5,264,000	3,236,000	12,000	12,000
Bake/Fire	8" Belt Furnace	No	12,200,000	12,200,000	-	3	5	1	5,264,000	5,264,000	3,450,000	25,000	25,000
HF Rinse	Automatic Water Cooled Fixture	Yes	1,940,000	1,920,000	1.03	3	5	4	5,264,000	5,210,000	276,000	12,000	48,000
Dry	Centrifuge	No	16,200,000	16,200,000	-	3	5	1	5,210,000	5,210,000	6,362,000	2,000	2,000
AR Spin	Automatic Spinner	No	4,750,000	4,720,000	0.635	3	5	2	5,210,000	5,177,000	1,566,000	15,000	30,000
Bake	8" Belt Furnace	No	12,200,000	12,240,000	-	3	5	1	5,177,000	5,177,000	3,537,000	25,000	25,000
Dice	High Speed Saw Automatic	No	4,720,000	4,650,000	1.48	3	5	2	5,177,000	5,100,000	1,543,000	12,000	24,000
Final Test	Tester - Sorter	Yes	5,100,000	4,747,000	7.00	3	7	1	5,100,000	4,747,000	-0-	45,000	45,000
											Miscellaneous		58,000
	Line Yield (Mech)		91%										1,640,000
	Final Test (Elec)		93%								Installation		240,000
	Combined Assembly Yield		85%										$ 1,880,000

TABLE V

CAPITAL REQUIREMENT SUMMARY

EQUIPMENT:	
Crystal Growing Area	\$ 650,000
Wafering	552,000
Cleaning & Etching	20,000
Diffusion	65,000
Thick Film and Dicing	250,000
Final Test	45,000
Miscellaneous	58,000
	1,640,000
Installation	240,000
	1,880,000
SPACE:	
Crystal Growing 900 ft^2@ \$40	36,000
Wafering & Etching 2000 ft^2 @ \$40	80,000
Cell Fabrication 5000 ft^2 @ \$40	200,000
Office & Laboratory 2000 ft^2 @ \$30	60,000
Storeage 4000 ft^2 @ \$20	80,000
	456,000
Total Facility Cost	2,336,000
Working Capital	750,000
TOTAL CAPITAL INVESTMENT	\$ 3,086,000

TABLE VI

LABOR REQUIREMENTS

CRYSTAL GROWING	
2 Opr x 24 Hr. x 6 Days x 49 Wks.	14,112 Hrs.
WAFERING, CLEANING, ETCHING	
7 Opr x 24 Hr. x 6 Days x 49 Wks.	49,392 Hrs.
CELL FABRICATION	
3 Opr x 24 Hr. x 6 Days x 49 Wks. = 21168	
16 Opr x 24 Hr. x 5 Days x 49 Wks. = 94080	
1 Opr x 24 Hr. x 7 Days x 49 Wks. = 8232	123,480 Hrs.
TOTAL FACTORY LABOR HOURS	186,984
@ \$3.00 / Hr. =	\$ 560,950
$\frac{\$560,952}{4,747,000 \text{ Cells}} =$	\$ 0.118 / Cell

TABLE VII

MATERIALS AND SUPPLIES

CRYSTAL GROWING	
Silicon 23,803 Kg @ $37.00	$ 880,710
Power	41,250
Argon	26,500
Crucibles @ $50	137,500
Spare Parts	100,000
	1,185,961
WAFERING, CLEANING, ETCHING	
Blades @ $80.00 Ea., 2000 Waf/Bl	237,420
Chemicals	93,000
	330,420
CELL FABRICATION	
Pastes and Chemicals	388,000
Misc. Materials	100,000
	488,000
TOTAL MATERIAL COSTS	$ 2,004,380

$$\frac{\$2,004,380}{4,747,000} \text{ Cells} = \$0.422 \text{ / Cell}$$

TABLE VIII

MANUFACTURING COST SUMMARY

	Annual Total	Per Cell
Labor	$ 560,950	$ 0.118
Overhead @ 150%	841,425	0.177
Material	2,004,380	0.422
Equipment Depr. (5 Yrs.)	376,000	0.083
Bldg. Depr. (25 Yrs.)	18,240	
Interest on Capital @ 10%	308,600	0.065
TOTAL FACTORY COST	$ 4,109,595	$ 0.866 / Cell

contacts and anti-reflective coating. Except for the latter process, these steps will use silk screen printers and firing furnaces which could be readily adapted to processing ribbon strips. The AR coating will be applied by spinning. It would be necessary to alter this step to a spray or flood coating process to accommodate ribbon strips.

As a final step, the wafers will be diced into square or hexagonal shape to provide an improved packing factor.

Various aspects of process requirements, performance estimates and cost factors are given in Tables III through VIII.

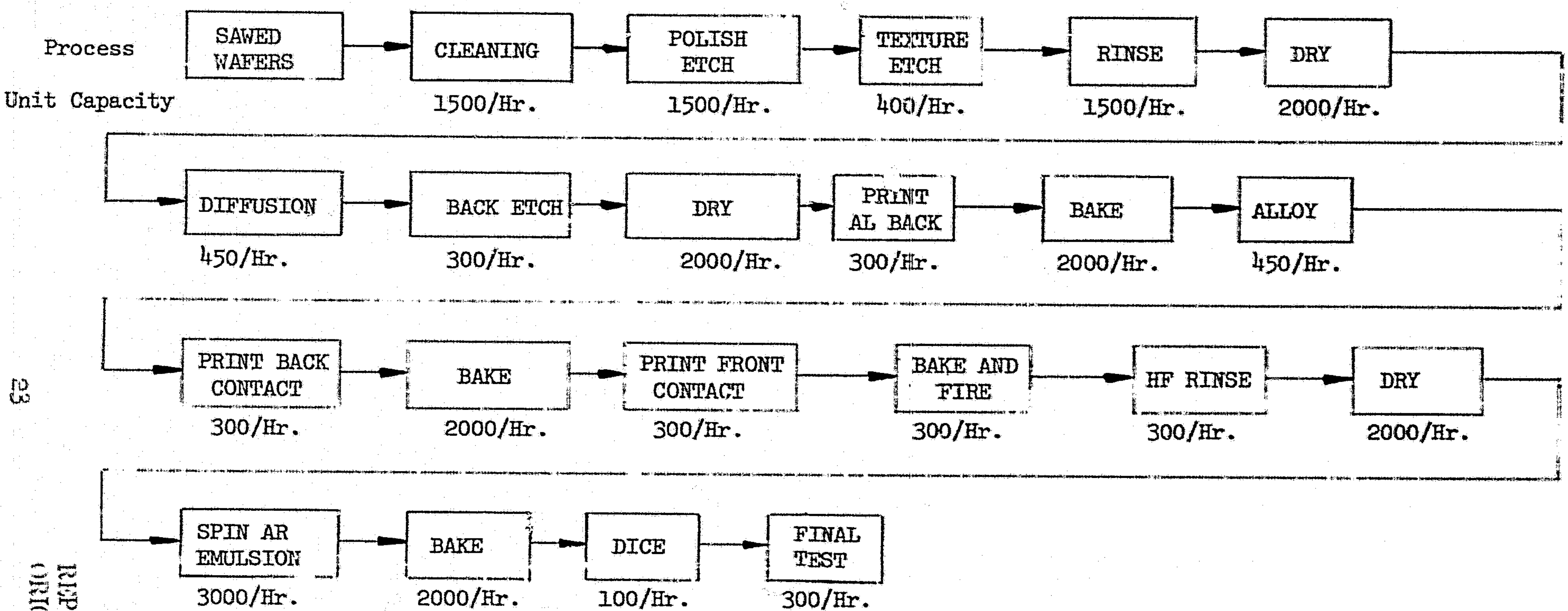
B. CONCEPTUAL DESIGN OF LABORATORY MODEL

Spectrolab's concept for implementing operation of the demonstration model consists of sharing the facilities, equipment and personnel of the existing low cost solar cell production facility at Spectrolab. This approach will benefit from the use of actual production equipment without the extra time, effort and attendant capital costs that would be required to establish an entirely new facility.

A block diagram of the process steps and components considered essential to the laboratory demonstration model are shown in Figure 5 with production capability of the presently available facilities. A more detailed tabulation of the specific process steps, comparing the proposed method for the demonstration facility with that of the conceptual automated production facility has been shown in Table II. A discussion of the demonstration model and its departures from the ultimate automated facility is given in the following paragraphs.

FIGURE 5

BLOCK DIAGRAM - DEMONSTRATION MODEL



The demonstration model will utilize the existing facilities of the Spectrolab Low Cost Solar Power Department, supplemented by facilities in other parts of the Spectrolab organization. This facility is presently tooled up to produce round cells 5.25 ± 0.16 cm. in diameter, as compared to a cell diameter of about 7.5 cm. for the ultimate automated facility. Jigs, fixtures and equipment for handling the larger size wafers is readily available from equipment suppliers, and the smaller size wafer proposed for the demonstration model is not deemed to be significant with respect to the feasibility demonstration. 5.25 cm. wafers will be obtained from the existing Spectrolab crystal growing and mechanical shaping facilities.

The subsequent steps of cleaning, etching and diffusion will use the same jigs, holders, fixtures and processes as the ultimate facility with the exception that an automatic transfer mechanism would be used in the cleaning and etching steps in the ultimate facility. The feasibility of such transfer mechanisms has been established by their use in various electroplating and chemical treatment applications. Commercially available equipment would perhaps require some minor modification.

The presently available back etch facility is hand loaded and adequate for establishing the technology feasibility. There is no known commercially available automated equipment which would be suitable.

The several steps of printing, baking and firing the thick film elements for the back field, and the front and back contacts will utilize non-automated equipment for silk screen printing and baking. In both cases the ultimate facility equipment (automatic printers and belt furnaces) has been well established in the thick film industry. Spectrolab purchased and will soon have installed a belt furnace for the combined baking/firing of the front and back contacts and this equipment can be used to verify the technical feasibility of the other bake steps. The aluminum back field alloy firing will be effected in standard tube furnace equipment.

The HF rinse of the thick film contacts requires the same equipment as the back etch. In the demonstration model the two processes will be carried out on the same equipment.

The AR coating and baking steps will use non-automated equipment in the demonstration model to establish technical feasibility readily transferable to commercially available automatic equipment.

In the demonstration model, dicing will be done on a modified K. O. Lee grinder in the Spectrolab Aerospace Department. The design of this modification is underway, and is expected to lead to prototype equipment which could be readily adapted to the ultimate facility.

The final test facility is a hand loaded solar simulator equipment. The ultimate facility will require the design of an automated test equipment having a high thruput rate. Existing manual equipment will be used for the laboratory model.

The demonstration facility will use hand loading of jigs and fixtures in lieu of mechanized loading and transfer mechanisms which are readily available for the ultimate facility.

The design requirements, production performance and estimated cost of those items of equipment for which commercial equipment is not available for the ultimate facility are given in Table IX.

TABLE IX

ULTIMATE PRODUCTION FACILITY

EQUIPMENT DESIGN REQUIREMENTS

Description	Steps for which required	Criteria	Estimated Cost
Etch facility	Back etch HF rinse	1. May consist of multiple stations 2. Shall be designed to accomodate the use of hydrofluric and hydrofluric-nitric acid solutions to the etching of two or three inch diameter silicon wafer structures on one side only. 3. Shall maintain the wafer temperature constant within ± 0.5°C during the prescribed etching cycle. 4. Shall have adjustable etch cycle times covering the range of 15 sec. to 1 minute followed by a deionized water rinse. 5. Shall have mechanized feed and discharge using standard semiconductor wafer cartridges. 6. Shall be capable of a minimum thruput rate of 240 wafers per hour.	$12,000
Dice saw	Dicing	1. Shall be capable of cutting hexagonal or square cells from two or three inch diameter wafers. 2. Shall have mechanized feed and discharge using standard wafer cartridges. 3. Shall have a maximum cycle time.	$12,000
Automatic Tester/Sorter	Final test	1. Shall test hexagonal, square or round cells for current at a preset voltage in the range of 0.4 to 0.5 volts under standard conditions of solar simulation illumination. 2. Shall sort tested cells into reject and 3 acceptable groups determined by adjustable current output settings. 3. Shall have mechanized feed from standard wafer cartridges. 4. Shall have a minimum thruput rate of 590 cells per hour.	$45,000

The proposed demonstration model will be compatible with the use of round blanks 5.25 cm. in diameter from which hexagonal, square, or rectangular cells may be cut. The model will be capable of producing N on P cells 0.015 cm. thick (minimum) with or wothout a P^+ back field.

V. DETAILED LABORATORY DESIGN

A. EXPERIMENTAL PLAN

The automation demonstration program will be executed in accordance with the starts schedule shown in Exhibit A. Material will be grouped into lots of 100 wafers with lot identity maintained through the cell fabrication process. In order to provide reasonable equipment loads, groups of 5 lots per day will be planned. The proposed schedule begins with short runs (1 and 2 days) and builds up to a sustained run lasting two weeks during the final month. The short runs during the early phases will provide opportunity to debug and refine processing techniques, record keeping and data collection and evaluation. The longer runs during the late stages of the schedule will provide opportunity for collection of information and data under typical production conditions.

Data for each lot will be collected on the proposed data log (Exhibit B). This record will provide information for the analysis of production rates, through-put, yields, operating costs, energy consumption, parameter distributions and process control. Data for process control will include thickness after etch, sheet resistivity after diffusion, and current at .450 volts after metallization under standard illumination, all on samples of 5 cells for each lot. Statistical evaluation of these data and the within lot parameter distributions will provide estimates of confidence limits for the control of these parameters in production processes, sensitivity to changes in process procedures, and the impact of these factors on the electrical output distribution of the final products. Additional process control measurements may be incorporated as indicated by experience during the demonstration runs.

Process control and lot distribution data will be utilized to evaluate the feasibility of eliminating additional process steps such as back etching after diffusion and the cleaning step after completion of thick film firing. This will be accomplished by elimination of individual process steps after sufficient runs have been accomplished to establish control limits, parameter means and distribution standard deviations. The results of the experimental runs will be compared with these standards for evaluation as to the statistical significance of possible changes induced by the process elimination.

The proposed demonstration is based on the processing of 51mm diameter wafers which will be diced into hexagons with 25mm sides. Two lots will be diced into rectangles 20x40mm. It is expected that one of these lots will be produced during the middle period of the demonstration phase after process control has been demonstrated, with the second lot being produced during the late stages of the program.

B. DESIGN DRAWINGS

The detail design drawings include a master process flow chart, drawing number D022471. This document serves as a top drawing to identify the processes in proper sequence and the specific and ancillary equipment associated with each process. Specific drawings are also identified in the Engineering Order EO-10045.

Exhibit A

AUTOMATION DEMONSTRATION

PROPOSED STARTS SCHEDULE

Week Ending	# of Days	# of Starts	Cum. Starts
October 24, 1975	1	500	500
November 7, 1975	1	500	1,000
November 21, 1975	2	1,000	2,000
December 5, 1975	2	1,000	3,000
December 19, 1975	3	1,500	4,500
January 9, 1976	3	1,500	6,000
January 30, 1976	4	2,000	8,000
February 20, 1976	5	2,500	10,500
March 12, 1976	5	2,500	13,000
March 19, 1976	5	2,500	15,500

Exhibit B

JOB 3804

SPECTROLAB, INC.

RUN #__________

DATA LOG - AUTOMATION DEMONSTRATION

LOT 02	OPERATION	DATE	TIME IN	OUT	START	GOOD	REJ	REMARKS
PHASE	▨ P.C. TEST	OPR	P.C. SAMPLE DATA					
01	ETCH							
	▨ THICKNESS		1	2	3	4	5	
02	DIFFUSION							
	▨ SHEET RES.		1	2	3	4	5	
03	BACK ETCH							
04	PRINT AL BACK							
05	ALLOY							
06	PRINT AG BACK							
07	PRINT FRONT							
08	FIRE							
09	CLEAN							
	▨ i @ .450 V.		1	2	3	4	5	
10	AR COAT							
11	DICE							
12	FINAL TEST							
	▨ CURRENT	650 MA	640 MA	630 MA	620 MA	610 MA	600 MA	
	DISTRIBUTION							
	AT	590 MA	580 MA	570 MA	560 MA	550 MA	540 MA	
	.450 VOLTS							
	1 SUN AT	530 MA	520 MA	510 MA	500 MA	490 MA	480 MA	
	AIR MASS 0							
	25°C	470 MA	460 MA	450 MA	440 MA	430 MA	420 MA	

VI. CONCLUSIONS

The study and conceptual design phase of this program have established the technical feasibility of automating the solar cell process to produce low cost silicon solar cells with improved performance.

Estimates predict an automated throughput of 21,973 kilograms of silicon per year, on a three shift, 49-week basis producing 4,747,000 hexagonal cells (38mm/side), equivalent to a total of 3,373 kilowatts, at a projected manufacturing cost of $0.866 per cell or $1.22 per watt.