Final Report

# RESEARCH AND DEVELOPMENT OF ELECTROFORMED ALUMINUM SOLAR CELL CONTACTS AND INTERCONNECTS

Prepared for
California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103
Attention: Mr. Mark Beckstrom

JPL Contract No. 952485

EOS Document 4039-Final 18 June 1970

ELECTRO-OPTICAL SYSTEMS
A XEROX COMPANY
PASADENA, CALIFORNIA 91107 · 213/351-2351

EOS

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ELECTRO-OPTICAL SYSTEMS
A XEROX COMPANY

# ABSTRACT

This report delineates the R&D effort to establish feasibility and demonstrate the fabrication of aluminum contacted electroplated silicon solar cells, and aluminum electroformed silicon solar cell interconnections.

The process parameters for fabricating the electroplated aluminum contacted silicon solar cells from N/P silicon diffused blanks were individually investigated. The parameters of masking, aluminum electroplating, and silicon monoxide antireflection (AR) coatings were integrated to produce aluminum contacted silicon solar cells.

The study, analysis, and development to establish feasibility of electroformed aluminum solderless interconnection of silicon solar cells are presented.

This report also presents tooling designs for aluminum electroplating individual silicon solar cells, four cell, and 25 cell matrices.

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ILLUSTRATIONS (contd)

## SECTION 1

## OVERALL PROGRAM SUMMARY

This report covers the technical progress accomplished under JPL Contract No. 952485 "Research and Development of Electroformed Aluminum Solar Cell Contacts and Interconnects," for the period from June 1969 to June 1970. The program was divided into three main tasks. These are:

I. Development of Electroformed Aluminum Solar Cell Contacts

II. Development of Electroformed Aluminum Solar Cell Interconnected Contacts

III. Design of a 25-Cell, 5 Parallel x 5 Series Electroformed Aluminum Interconnected Matrix and the Tooling Design for its Fabrication.

The tasks were accomplished consecutively. The primary objective was to develop and demonstrate feasibility of a one-step process of electroforming the aluminum contacts and interconnections of four silicon solar cells into a multicell matrix.

The process parameters for fabricating the electroplated aluminum contacted silicon solar cells from N/P silicon diffused blanks were individually investigated. The parameters of the cell blank were defined, and the process parameters of masking, aluminum electroplating, and silicon monoxide antireflection (AR) coating were integrated to produce aluminum contacted silicon solar cells as follows:

a. Silicon Solar Cell Diffused Blanks:

| | |
|---|---|
| Dimensions: | 0.788 x 0.788 x 0.015 inch (2 x 2 x 0.038 cm) |
| Finish: | Sandblasted finished on the 'P' side, and lapped 5 micron finish on the 'N' side |
| Base Resistivity: | 1 to 3 ohm-cm |

Diffused Junction Depth: $\approx$ 0.3 micron
Sheet Resistance: 34 ±12 ohms/square, (Ref. Fig. 1-1).

b. Masking:
The photoresist (KMER) masking technique produced the most durable and definitive plating mask.

c. Plating Parameters:
The most desirable aluminum contact material is obtained when it is electrodeposited under the following conditions:

Aluminum Bath Composition,

| | |
|---|---|
| $AlCl_3$: | 3.4 molar |
| $LiAlH_4$: | 0.3 molar |
| Solvent: | Anhydrous ether |
| Current Density: | 15A/ft$^2$ |
| Temperature of Bath: | 22 to 25$^\circ$C |
| Plating Time: | 30 minutes |
| Plating Thickness: | 0.5 mil |

d. Sintering:
Plated silicon solar cells were sintered at 320$^\circ$C for 10 minutes in a nitrogen atmosphere.

e. Edge Etching:
The sintered silicon solar cells were edge etched in a 50 percent HCL solution for 1 hour.

f. Antireflection Coating (AR):
The cell peak power increased 15 to 17 percent when a 1400 angstrom layer of silicon monoxide (AR) coating was applied to the bare electroformed aluminum contact solar cells.

g. Electrical Output Data:
The following current measurements were obtained on a total of 99 cells electroplated during this study when measured at 100 mW/cm$^2$ tungsten at 28$^\circ$C.

Short Circuit Current ($I_{sc}$)

| Current | No. of Cells |
|---|---|
| $\geq$ 120 mA | 52 |
| $\geq$ 115 mA | 29 |
| $\geq$ 110 mA | 12 |
| $\leq$ 109 mA | 6 |

Current at 400 mV ($I_{400}$)

| Current | No. of Cells |
|---|---|
| $\geq$ 110 mA | 26 |
| $\geq$ 105 mA | 25 |
| $\geq$ 100 mA | 13 |
| $\geq$ 95 mA | 8 |
| $\geq$ 90 mA | 9 |
| $\leq$ 89 mA | 18 |

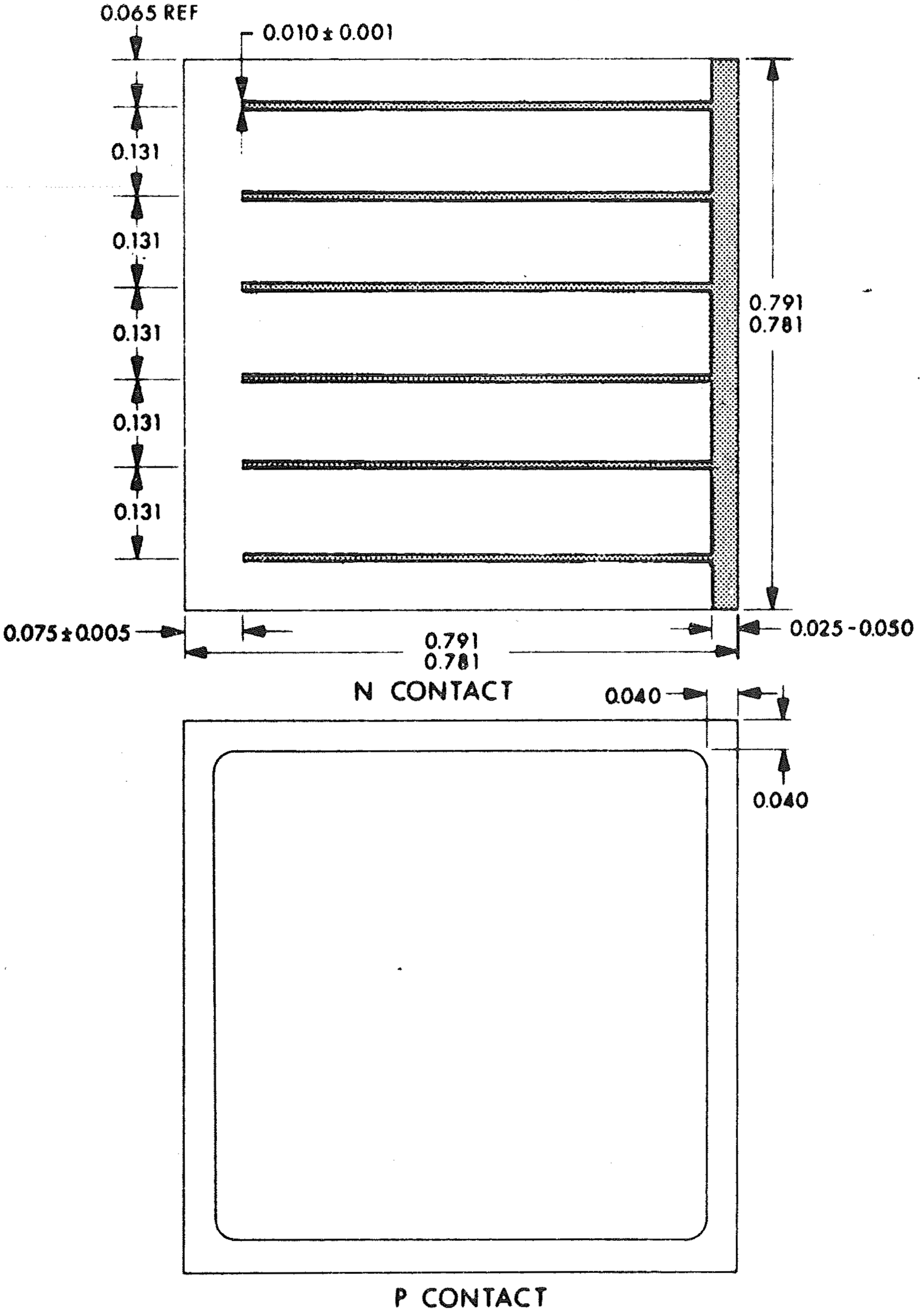


Figure 1-1. Solar Cell with Aluminum Plated Contacts
(All dimensions shown are in inches)

h. A selection of the higher electrical output cells in the above group were subjected to a test program consisting of two groups of 25 cells each.

Group 1

1. Mechanical inspection
2. Electrical test
3. Temperature humidity
4. Mechanical inspection
5. Electrical test
6. Contact pull test

Group 2

1. Mechanical inspection
2. Electrical test
3. Thermal shock
4. Mechanical inspection
5. Electrical test
6. Low temperature soak
7. Mechanical inspection
8. Electrical test
9. High temperature soak
10. Mechanical inspection
11. Electrical test
12. Thermal vacuum
13. Mechanical inspection
14. Electrical test
15. Contact pull test

The results of the tests follow; the pre and post test mean and standard deviation current of the cells ($I_{400}$) as measured at 400 mV, 100 mW/$cm^2$ tungsten at 28°C.

Group I, Humidity Test

| | Pre Test | Post Test |
|---|---|---|
| Mean (mA) | 108.6 | 99.3 |
| Standard (mA) Deviation | 5.72 | 9.19 |

Group II, Environmental Tests

| | Pre Test | Thermal Shock | Low Time Soak | High Time Soak | Thermal Vacuum |
|---|---|---|---|---|---|
| Mean (mA) | 108.1 | 99.4 | 97.0 | 89.9 | 88.1 |
| Standard (mA) Deviation | 4.72 | 15.84 | 17.58 | 20.65 | 20.78 |

Degradation of currents are larger than would be anticipated for silver-titanium silicon solar cells; the loss in current can be attributed primarily to increased series resistance in the contacts, which in the case of aluminum contacts is caused by oxidation of the contact surface.

The study, analysis, and development to establish feasibility of electroformed aluminum solderless interconnections of silicon solar cells was accomplished under Task II of this program. Pairs of cells were simultaneously contacted and interconnected with aluminum in both the series and parallel direction. The final configuration of four interconnected silicon solar cells, shown in Fig. 1-2 was achieved.

The following parameters were determined as a result of this study.

a. Electroformed aluminum interconnections of both parallel and series configuration are feasible.

b. Interconnected solar cells require the use of a top contact silicon solar cell configuration, Ref. Fig. 1-3.

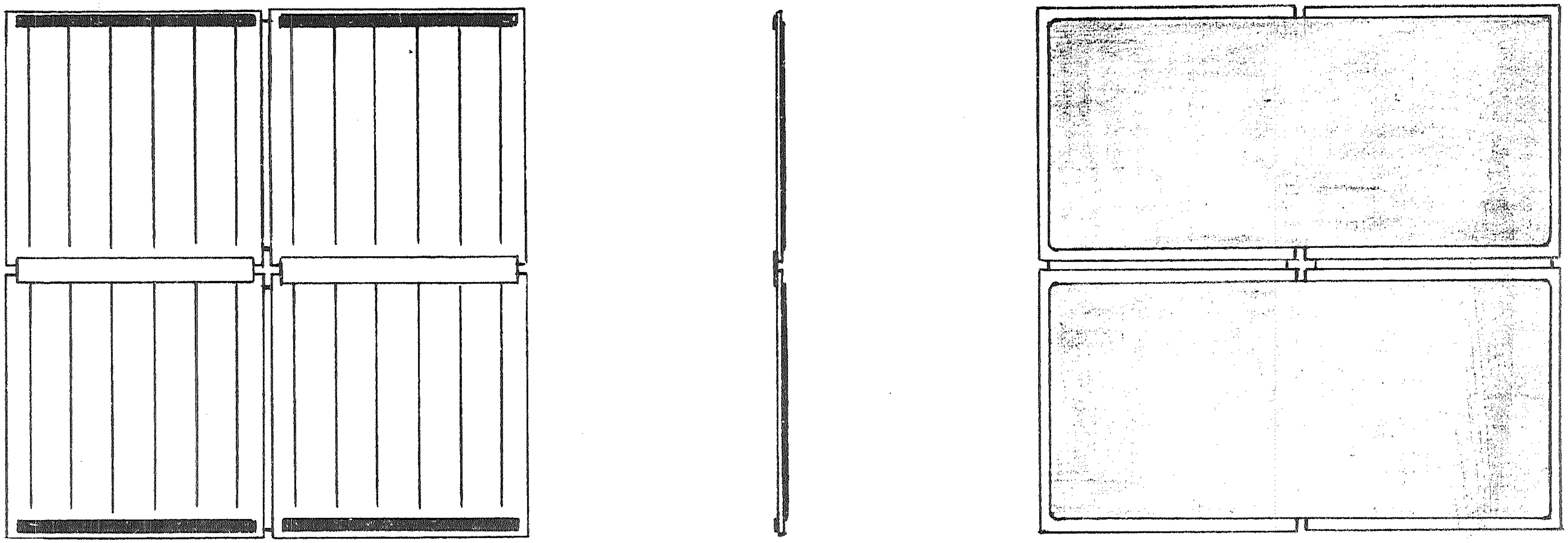
c. The plating solution, current density, and temperature used for the individual solar cell plating are directly applicable to multicell interconnection plating.

d. A fixture design was developed for the multicell matrix, Ref. Fig. 1-4, and the use of 1 mil aluminum foil was proven for the fixture mandrel gasket.

e. Contact sintering is not used on electroformed aluminum interconnected solar cell matrices because of the interconnection plating thickness.

f. Silicon monoxide (AR) coating is applicable but was not used on the aluminum interconnected matrices of solar cells. The integral diffusion glass coating was utilized for the (AR) coating as a cost saving innovation.

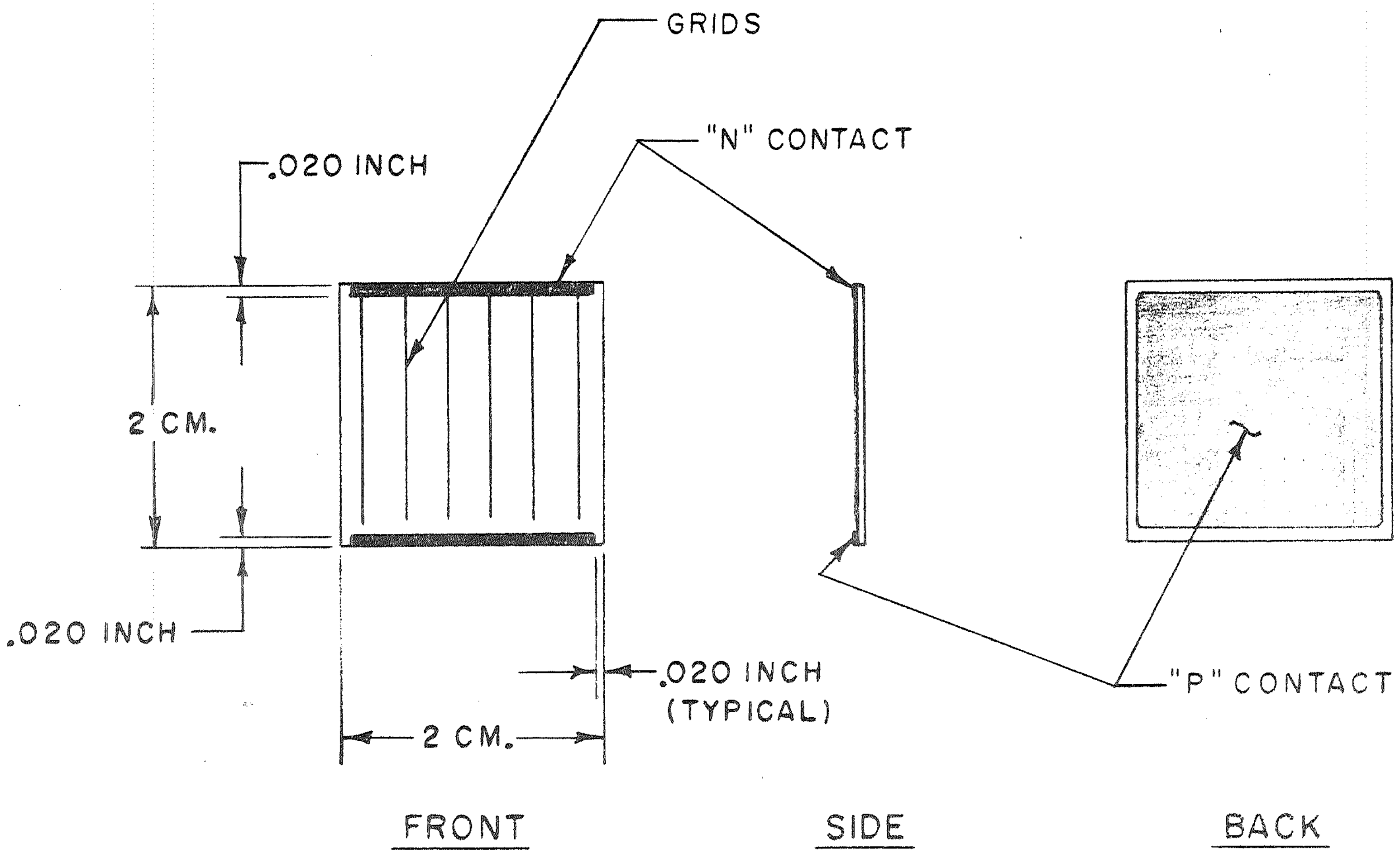
In general, this study has proven the feasibility of this interconnection approach. However, considerably more work is necessary to develop this into a pilot production operation.



FRONT SIDE BACK

FOUR CELL INTERCONNECTED MATRIX

Figure 1-2.



TOP CONTACT SOLAR CELL

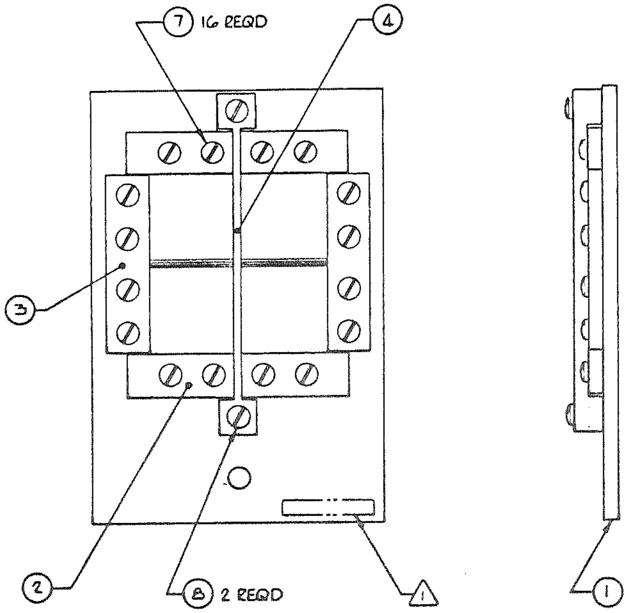
Figure 1-3.

SECURITY CLASSIFICATION

UNCLASSIFIED

NOTES: UNLESS OTHERWISE SPECIFIED

⚠ IDENTIFY WITH ASSEMBLY NO. 12705-4039-114 APPROX WHERE SHOWN WITH 1/8 HIGH GOTHIC CHARACTERS PER EOS STD ST4000-3.



| QTY REQD | | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | 9 |
| | 2 | | | | SCREW, PAN HD 4-40 UNC×3/8 LG | MOLDED NYLON | MIL-M-20693 COMPA TYPE I | | | 8 |
| | 16 | | | | SCREW, PAN HD, 4-40 UNC×1/4 LG | MOLDED NYLON | MIL-M-20693 COMPA TYPE I | | | 7 |
| | | | | | | | | | | 6 |
| | | | | | | | | | | 5 |
| | 1 | | | 4039-117 | DIVIDER | | | | | 4 |
| | 2 | | | 4039-116-3 | SUPPORT | | | | | 3 |
| | 2 | | | 4039-116-1 | SUPPORT | | | | | 2 |
| | 1 | | | 4039-115 | BASE PLATE | | | | | 1 |

LIST OF MATERIALS

| | | | | | | |
|---|---|---|---|---|---|---|
| ON | THRU | PART DASH NO. | NEXT | FINAL | NEXT ASSY | USED ON |
| EFFECTIVE SERIAL NO. | | | QTY REQD PER ASSY | | APPLICATION | |
| USAGE DATA | | DRAWING LEVEL | | | | |

UNLESS OTHERWISE NOTED LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ±
.XXX ± ±
√ RMS
DO NOT SCALE
MATERIAL
TREATMENT/FINISH
SIMILAR TO
ACT. WT. CALC. WT.

CONTRACT NO.
DRAWN Darmack DATE 4-?-70
CHECK K.W.
DESIGN Darmack 4-10-70
MFG.
DESIGN ACTIVITY APPD
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
FIXTURE ASSEMBLY,
SOLAR CELL SUBMODULE

DWG SIZE D
CODE IDENT NO. 12705
DWG NO. 4039-114
SCALE 2/1
RELEASE DATE
SHEET 1 OF 1

4039-114

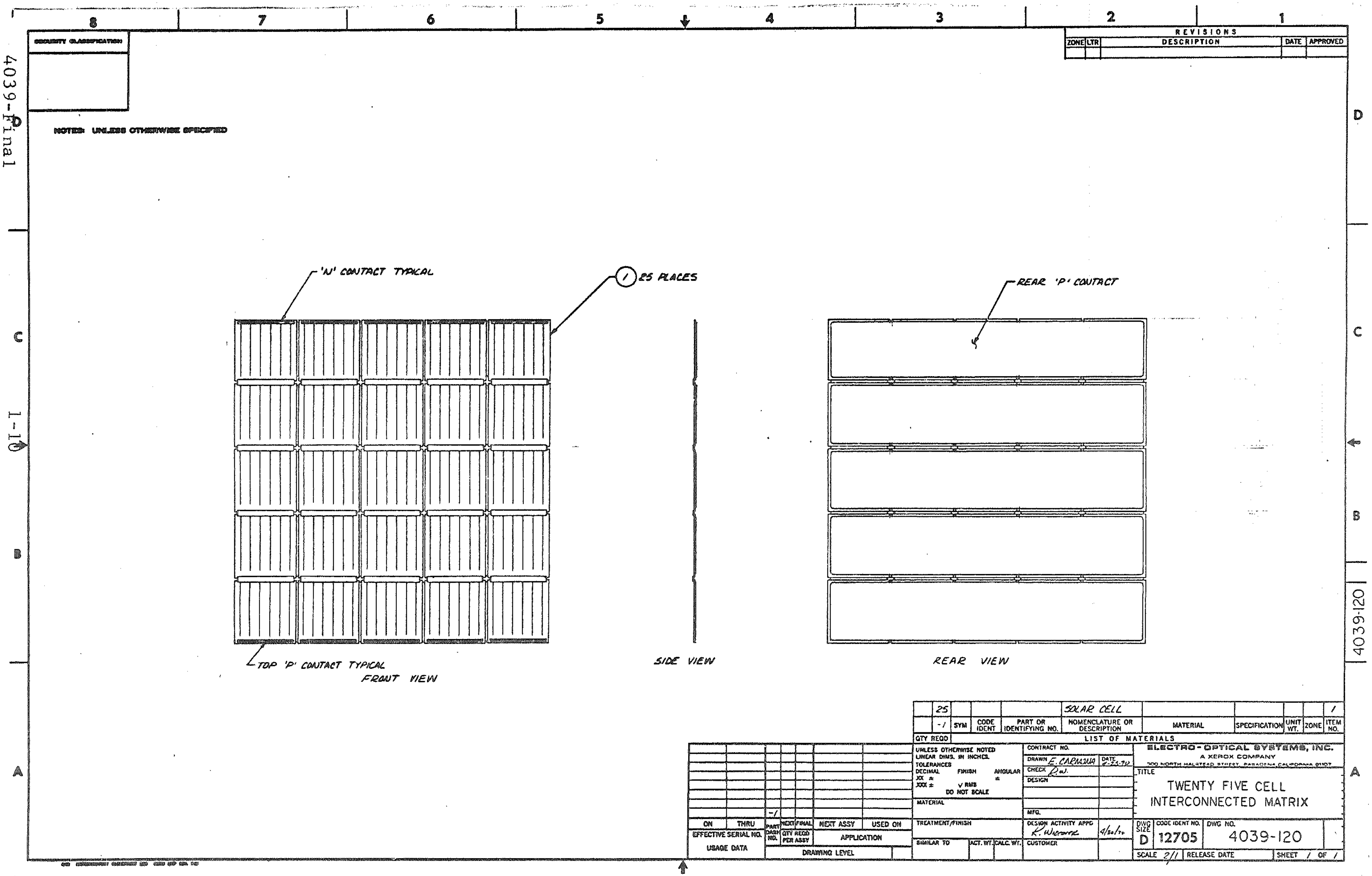
Figure 1-4.

The original scope of Task III was modified to delete the fabrication of 20 cell matrices and changed to the design of a 25 cell matrix and the tooling for this unit.

The 25 cell matrix is shown in Fig. 1-5. This modular unit could be used directly for a solar panel laydown application. The N and P bus bars or module terminations would depend upon the type of circuit application. However, conventional end terminations, similar to those used on the JPL Mariner panels could be used.

The plating fixture is shown in Fig. 1-6. This fixture is functionally similar to the fixture used to make the four cell Task II matrix.

Based on the experience gained in this program, EOS is confident that the 25 cell matrix fixture designed in the Task III effort of this program would produce aluminum electroformed solar cell matrices.



LIST OF MATERIALS

| QTY REQD | | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
|---|---|---|---|---|---|---|---|---|---|---|
| | 25 | | | | SOLAR CELL | | | | | 1 |
| | -1 | | | | | | | | | |

| ON | THRU | PART DASH NO. | NEXT | FINAL | NEXT ASSY | USED ON |
|---|---|---|---|---|---|---|
| | | -1 | | | | |

EFFECTIVE SERIAL NO.
USAGE DATA
QTY REQD PER ASSY
APPLICATION
DRAWING LEVEL

UNLESS OTHERWISE NOTED
LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ± ±
.XXX ± √ RMS
DO NOT SCALE
MATERIAL
TREATMENT/FINISH
SIMILAR TO
ACT. WT.
CALC. WT.

CONTRACT NO.
DRAWN E. CARMINA DATE 4-25-70
CHECK R.W.
DESIGN
MFG.
DESIGN ACTIVITY APPD K. Wi[illegible] 4/30/70
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
TWENTY FIVE CELL
INTERCONNECTED MATRIX

DWG SIZE D
CODE IDENT NO. 12705
DWG NO. 4039-120
SCALE 2/1
RELEASE DATE
SHEET 1 OF 1

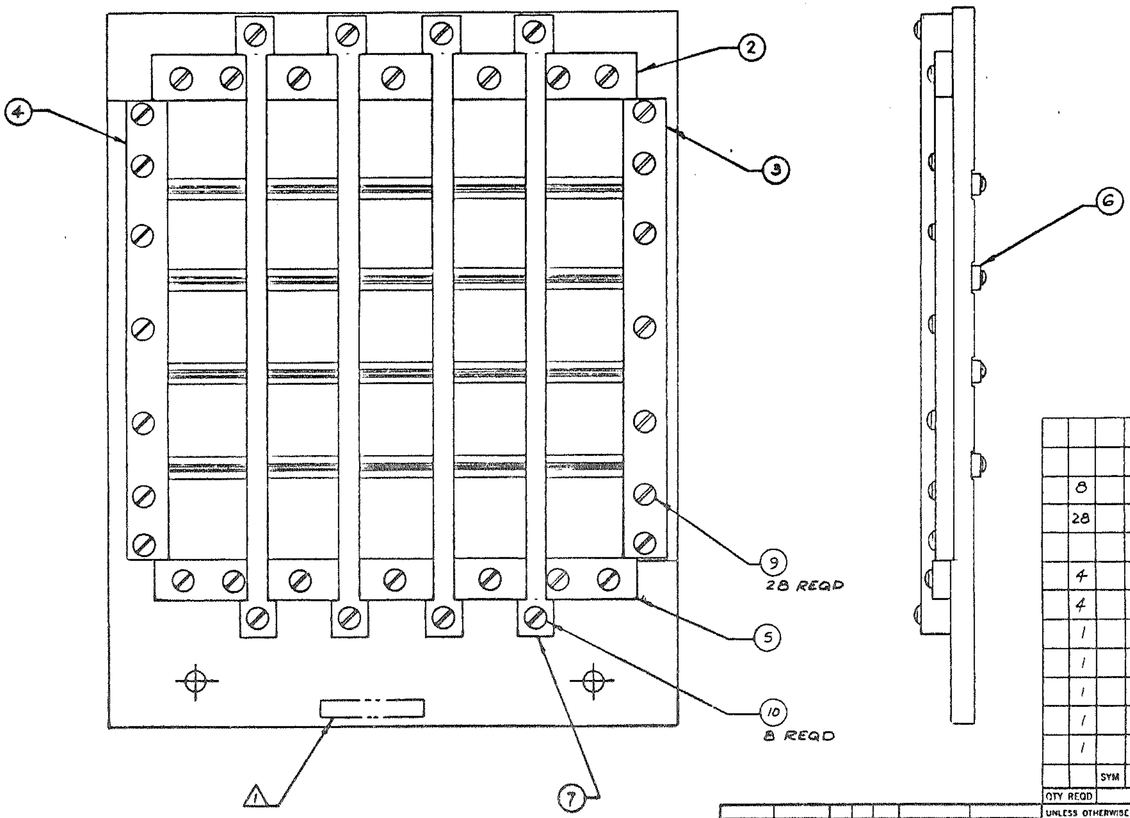
Figure 1-5.

SECURITY CLASSIFICATION

UNCLASSIFIED

NOTES: UNLESS OTHERWISE SPECIFIED

1. IDENTIFY WITH ASSEMBLY NO. 12705-4039-121 APPROX WHERE SHOWN WITH 1/8 HIGH GOTHIC CHARACTERS PER EOS STD ST4000-3



| ZONE | LTR | REVISIONS DESCRIPTION | DATE | APPROVED |
|---|---|---|---|---|

| QTY REQD | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
|---|---|---|---|---|---|---|---|---|---|
| 8 | | | | SCREW PAN HD 4-40UNC x 3/8 LG | MOLDED NYLON | MIL-M-20693 COMPA TYPE I | | | 10 |
| 28 | | | | SCREW PAN HD 4-40 UNC x 1/4 LG | MOLDED NYLON | MIL-M-20693 COMPA TYPE I | | | 9 |
| | | | | | | | | | 8 |
| 4 | | | 4039-124-1 | DIVIDER UPPER | | | | | 7 |
| 4 | | | 4039-123-1 | DIVIDER LOWER | | | | | 6 |
| 1 | | | -7 | SUPPORT | | | | | 5 |
| 1 | | | -5 | | | | | | 4 |
| 1 | | | -3 | | | | | | 3 |
| 1 | | | 4039-127-1 | SUPPORT | | | | | 2 |
| 1 | | | 4039-122-1 | BASE | | | | | 1 |

LIST OF MATERIALS

| | | | | | |
|---|---|---|---|---|---|
| ON | THRU | PART DASH NO. | NEXT / FINAL | NEXT ASSY | USED ON |
| EFFECTIVE SERIAL NO. | | | QTY REQD PER ASSY | APPLICATION | |
| USAGE DATA | | DRAWING LEVEL | | | |

UNLESS OTHERWISE NOTED LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ± ±
.XXX ± √ RMS
DO NOT SCALE

MATERIAL

TREATMENT/FINISH

SIMILAR TO | ACT. WT. | CALC. WT.

CONTRACT NO.
DRAWN | DATE 2/3/70
CHECK R.W.
DESIGN
MFG.
DESIGN ACTIVITY APPD R. Wittrick 2/10/70
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
FIXTURE ASSEMBLY
SOLAR CELL SUBMODULE

DWG SIZE D | CODE IDENT NO. 12705 | DWG NO. 4039-121

SCALE | RELEASE DATE 2/1 | SHEET 1 OF 1

4039-121

Figure 1-6.

# SECTION 2

# TASK I

## 2.1 SUMMARY

The process parameters for fabricating the electroplated aluminum contacted silicon solar cells from N/P silicon diffused blanks were individually investigated. The parameters of the cell blanks were defined, and the processing parameters of masking, aluminum electroplating, and silicon monoxide antireflecting (AR) coating were integrated to produce aluminum contacted solar cells as follows:

a. Masking: The photoresist (KMER) masking technique produced the most durable and definitive mask.

b. Plating Parameters: The most desirable aluminum contact material is obtained when it is electrodeposited under the following conditions:

Aluminum Bath Composition:

| | |
|---|---|
| $AlCl_3$: | 3.4 molar |
| $LiAlH_4$: | 0.3 molar |
| Solvent: | Anhydrous ether |
| Current Density: | 15 $A/ft^2$ |
| Temperature of Bath: | 22 to 25°C |
| Plating Time: | 30 minutes |

c. Sintering: The final sintering profile for plated silicon solar cells was 330°C for 10 minutes in a nitrogen atmosphere at ambient pressure.

d. Edge Etching: The final edge etching profile for plated silicon solar cells was a HCL 10 second dip.

e. Antireflection Coating (AR): The peak power increased 15 to 17 percent when a 1400 angstrom layer of silicon monoxide (AR) coating was applied to the bare electroplated aluminum contact solar cells.

f. Electrical Output Data: The following current measurements were obtained on a total of 99 cells electroplated during this study when measured at 100 $mW/cm^2$, tungsten at $28^\circ C$.

Short Circuit Current ($I_{sc}$)

| Current | No. of Cells |
|---|---|
| ≥ 120 mA | 52 |
| ≥ 115 mA | 29 |
| ≥ 110 mA | 12 |
| ≤ 109 mA | 6 |

Current at 400 mV ($I_{400}$)

| Current | No. of Cells |
|---|---|
| ≥ 110 mA | 26 |
| ≥ 105 mA | 25 |
| ≥ 100 mA | 13 |
| > 95 mA | 8 |
| ≥ 90 mA | 9 |
| ≤ 89 mA | 18 |

## 2.2 CHOICE OF CELL BLANKS

Two considerations must be made in selecting a solar cell blank to be used in the electroformed aluminum contact process: (1) the surface finish on both the diffused 'N' type and bulk 'P' type sides, and (2) the sheet resistance of the diffused layer.

The currently used evaporated Ag-Ti contacted cell process employs relatively smooth chem-polished surfaces on both 'N' and 'P' sides. This is due to the fact that since the evaporated layers of metal are thin, more thickness uniformity can be obtained on a smooth surface. In a plated contact process, a rougher surface is more desirable because the roughness tends to increase the mechanical bond of the metal silicon interface, thus impeding contact peeling.

As to the comparitive quality of diffused layers characteristics on rough versus chem-polished surfaces, recent results of Tsai* indicate

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*J. C. Tsai, "Shallow Phosphorous Diffused Profiles in Silicon:, Proc. IEEE, Vol. 57, No. 9, Sept. 1969.

no significant difference between the two. For this program, 1 ohm-cm 'P' type blanks having an 'N' type diffused junction depth of approximately 0.3 μm and a sheet resistance of 34 ±2 ohms/square were used. With this type of cell blank, a direct comparison to MM'69 type cells could be made, providing a measure of effectiveness of the plated aluminum contacts. The diffused cell blanks were procured under the following specifications:

| | |
|---|---|
| Dimensions: | 0.788 x 0.788 x 0.015 inch (2 x 2 cm cell) |
| Finish: | 5 micron finish on diffused side, sandblasted finish on 'P' side |
| Base Resistivity: | 1 to 3 ohm-cm |
| Junction Depth: | $\approx$ 0.3 μm |
| Sheet Resistance: | 34 ±12 ohms/square |

## 2.3 THICKNESS OF CONTACTS AND CONTACT GEOMETRY

The thickness of the aluminum contacts must be evaluated on the basis of electrical resistance (potential drop), stress, and weight. It has been calculated that the electrical resistance is at an acceptable level if the thickness is approximately 0.5 mil. This calculation is presented in Appendix A.

A thickness of 0.5 mil would provide a pore-free, continuous layer of aluminum. The voltage drop across the grid line (MM'69 solar cell configuration) is 9.0 mV. Further considerations are: (1) the stress experienced for this thickness of aluminum on a 15-mil silicon wafer during thermal shock cycling; and (2) the required mechanical properties of the aluminum for a reliable contact. A calculation shows that the stress experienced in the thermal shock cycling is about three times the yield strength of the aluminum. However, the elongation of the electrodeposited aluminum with this yield strength and modulus is approximately 26 percent. Thus, failure of the aluminum-silicon bond due to yield is prevented by the compensating flexing due to the high elongation of the aluminum. These calculations of thermal stress in the aluminum-silicon bond are presented in Appendix B.

The final evolved contact geometry configuration is shown in Fig. 2-1, and a photo of a typical cell is shown in Fig. 2-2.

## 2.4 MASKING STUDIES

Several different techniques for masking the silicon wafers were evaluated. The three types of masking materials tried were photoresist, polyethylene emulsion, and rubberized ink. Masking is required to define the areas to be plated and thus achieve the desired contact configuration. The photoresist, Kodak KMER, was selected as it was found that the polyethylene coating offered insufficient definition for the grid lines and the ink decomposed in the plating solution.

The photoresist proved to be stable in the plating solution, maintained sharp shape configuration, and was easy to apply and remove.

## 2.5 OPTIMIZATION OF THE PLATING SOLUTION

In the electrodeposition study, three plating baths were evaluated by comparing the quality of the thin layers of aluminum electrodeposited and the relative mechanical properties of the aluminum. The pyridine additive bath produces the highest tensile yield strength. However, the pyridine itself was found to be incompatible with the masking material. The mixed ether also has better mechanical properties than the National Bureau of Standards (NBS) bath, but at a thickness of about 0.5 mil the electrodeposit has some pores. The aluminum electrodeposited from the NBS bath has a yield strength of only 11,000 psi but provides a pore-free deposit at 0.5 mil. Also, the photoresist mask is stable in this bath.

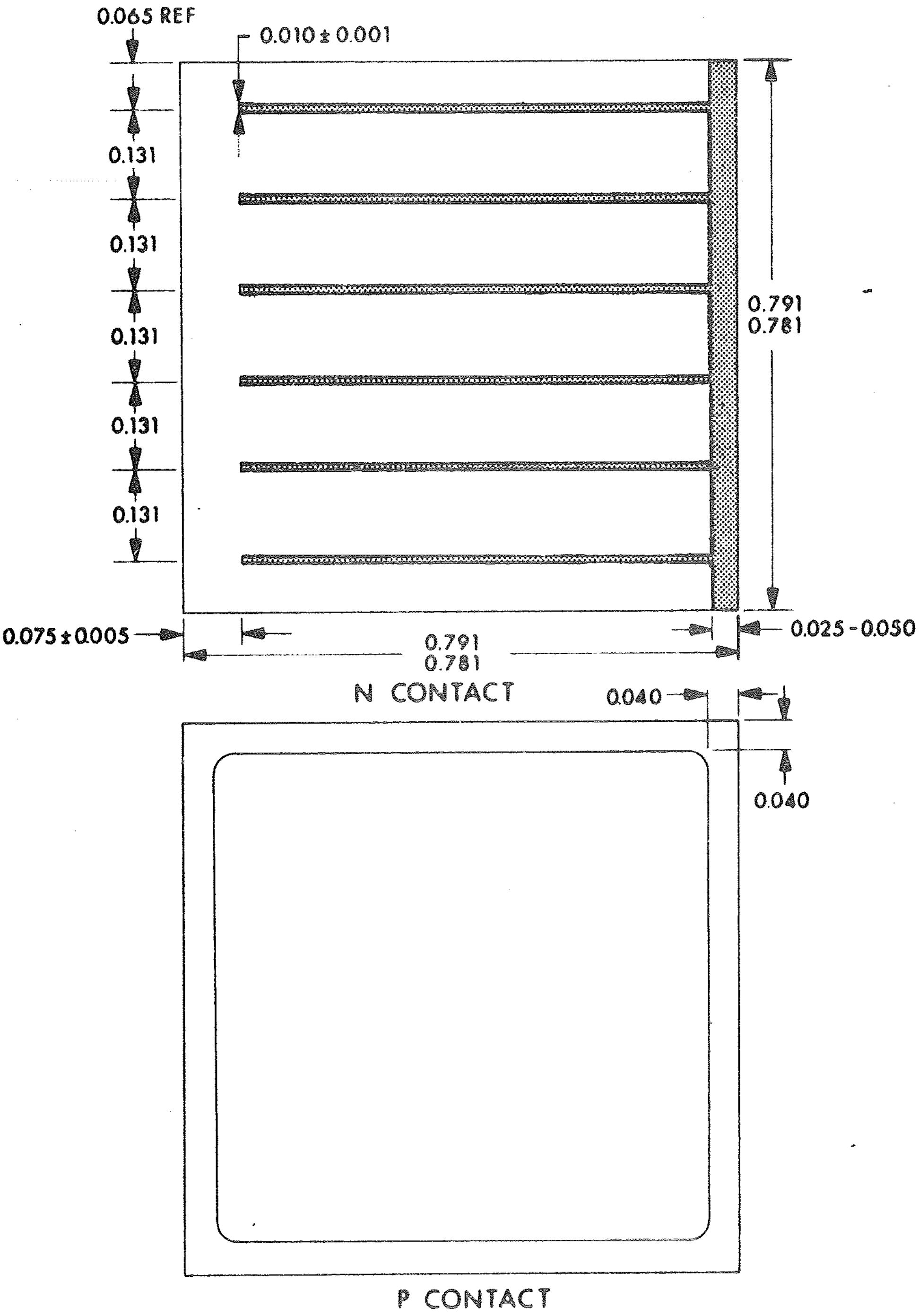


Figure 2-1. Solar Cell with Aluminum Plated Contacts (all dimensions shown are in inches)

36057 A

37075

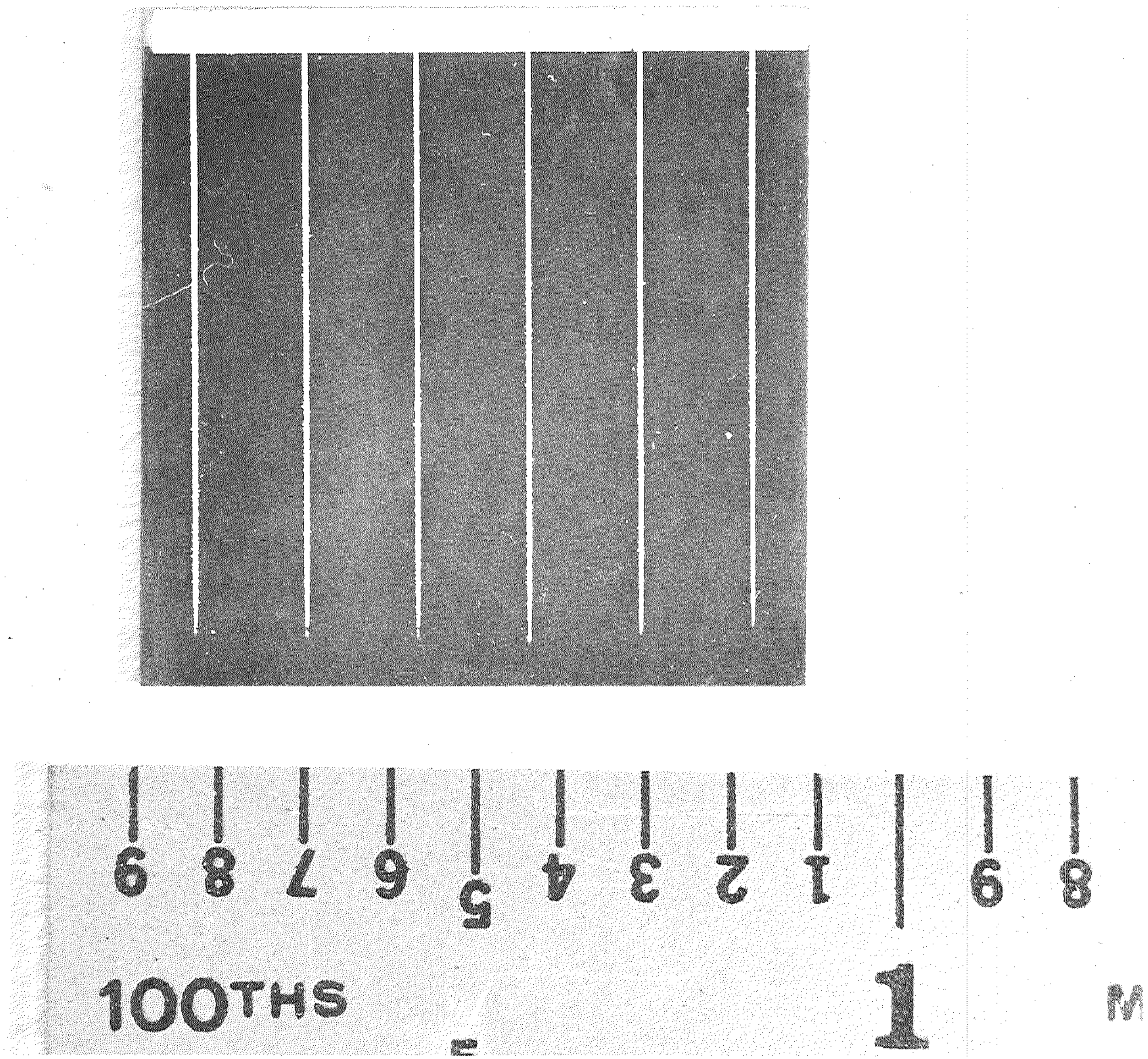


Figure 2-2. A Typical Aluminum Electroplated Solar Cell Fabricated at EOS

A goal of our effort during this period was to optimize the NBS bath to increase the yield strength with minimum alteration in other mechanical properties and chemical characteristics. It was found that by changing the lithium aluminum hydride concentration from 0.5 molar to 0.3 molar, the yield strength is increased to 15,000 psi. The modulus of elasticity remained unchanged at $9 \times 10^6$ psi, the elongation decreased from 26 percent to 24 percent, and the photoresist mask remained stable. The aluminum plating bath to be used in this program will be referred to as the modified NBS bath. Its chemical composition is as follows:

| | |
|---|---|
| Aluminum chloride | 3.4 molar |
| Lithium aluminum hydride | 0.3 molar |
| Solvent (anhydrous diethyl ether) | |

The plating parameters required to be investigated using the modified NBS bath are current density and temperature. The most desirable plating conditions would consist of plating in the shortest possible time at ambient temperature. These conditions correspond to electrodepositing at the highest permissible current density but with an acceptable temperature rise contributed by the accompanying $I^2R$ heating. Current density not only is directly related to the process time but also determines the grain size of the electrodeposit. The current density effects of the modified NBS bath were observed to be as follows for a deposit of 0.5-mil thickness:

| Current Density ($A/ft^2$) | Appearance of Deposit |
|---|---|
| 1 - 5 | Contained pores; larger grain |
| 10 | Fewer pores and smaller grain than at 5 $A/ft^2$ |
| 15 | No pores; fine grain |
| 20 | No pores; fine grain |
| 30 | No pores; fine grain; excessive gassing at the anode |

The platings at 10 to 25 A/ft$^2$ were all acceptable. A current density of 15 A/ft$^2$ was selected because at around 20 A/ft$^2$ external cooling is required to extract the $I^2R$ heat and prevent too rapid and too large a temperature rise from ambient temperature.

## 2.6 ELECTROPLATING PROCESS

The individual solar cells were electroplated in a plating fixture (see Fig. 2-3) in accordance with the EOS Process Specification No. 4039-MP-I, Reference Appendix C.

This process specification contains the complete process including the sintering, silicon monoxide antireflection coating, and acceptance testing criteria.

## 2.7 PERFORMANCE OF ELECTROFORMED ALUMINUM CONTACT SOLAR CELLS

Over 100 cells were electroplated during Task I. A group of 99 cells were analyzed as follows:

The electrical performance of a group of 99 electroformed aluminum plated silicon solar cells is shown in Fig. 2-4. This histogram shows the short circuit current ($I_{sc}$), the current at 400 mV ($I_{400}$), and the open circuit voltage ($V_{oc}$) of the cells as measured under test conditions of 100 mW/cm$^2$ of tungsten at a temperature of 28°C. All cells were silicon monoxide (AR) coated.

A review of the data shown in Fig. 2-4 indicates that the short circuit current ($I_{sc}$) was a near normal bell shaped distribution, with an average current of 119.2 mA, whereas the current at 400 mV ($I_{400}$) and the open circuit voltage ($V_{oc}$) were spread over a wider distribution. Power output curves of two of the cells are shown in Figs. 2-5 and 2-6. These curves are typical for the cells shown in Fig. 2-4.

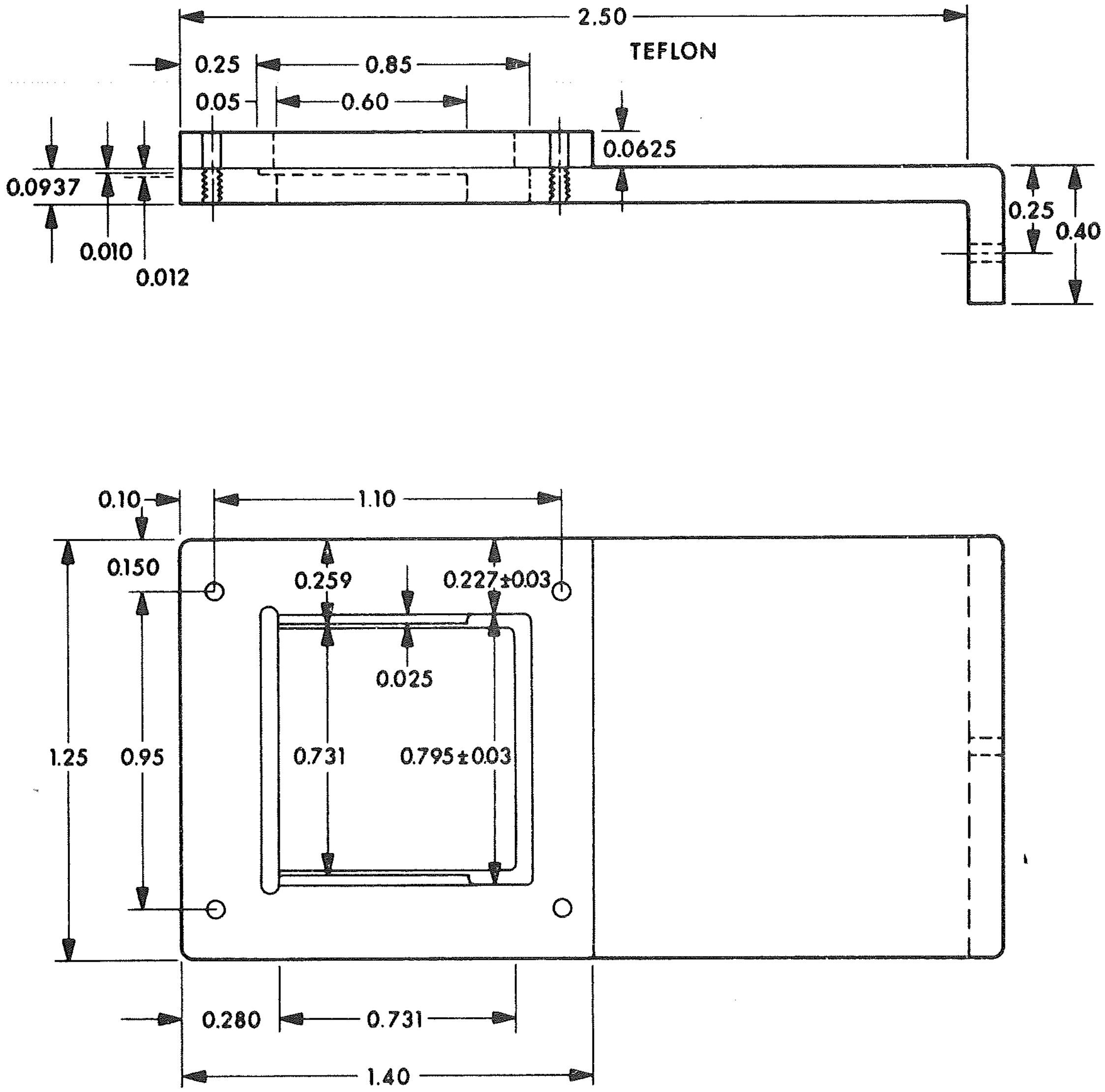


Figure 2-3. Plating Fixture (all dimensions are in inches)

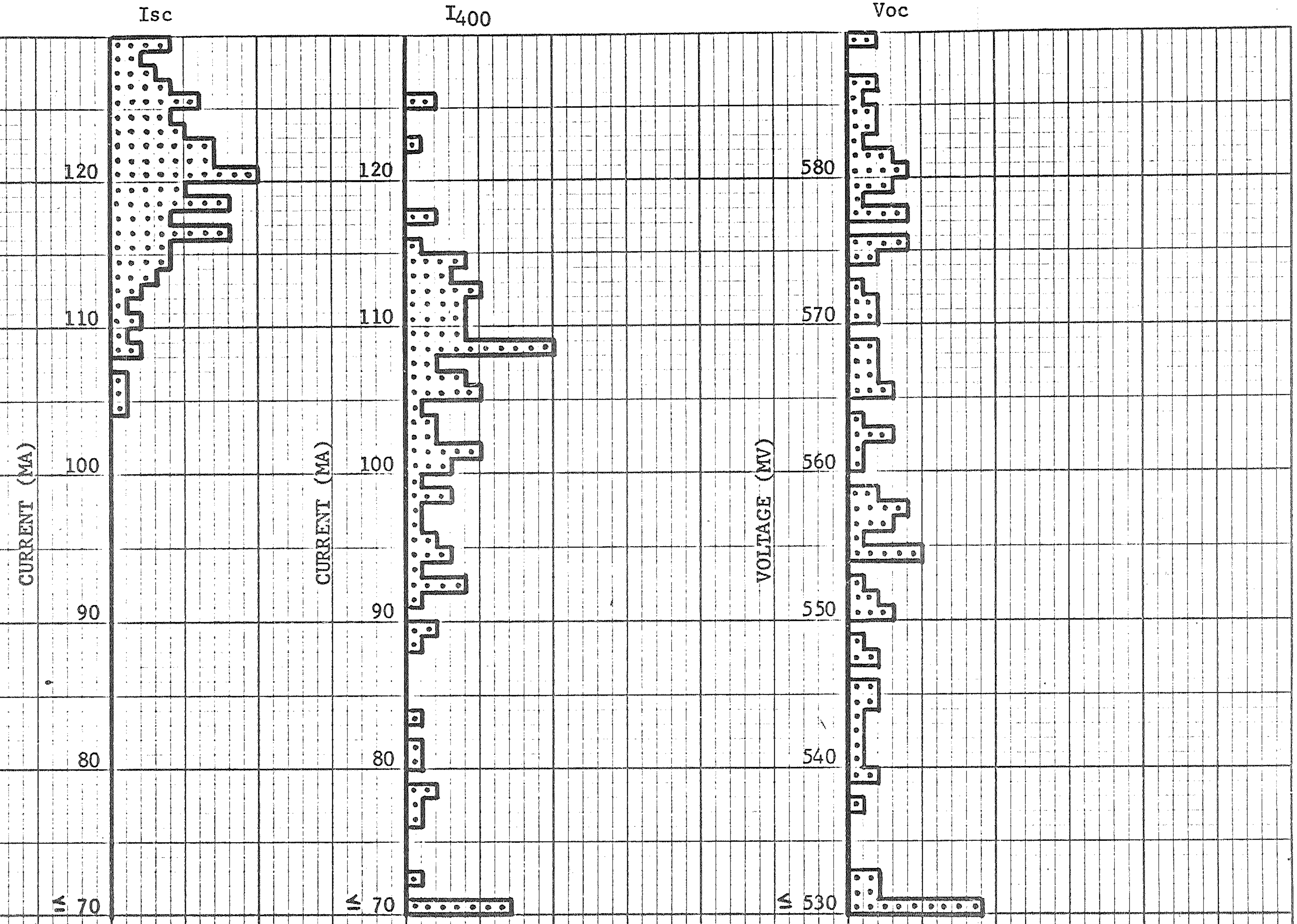
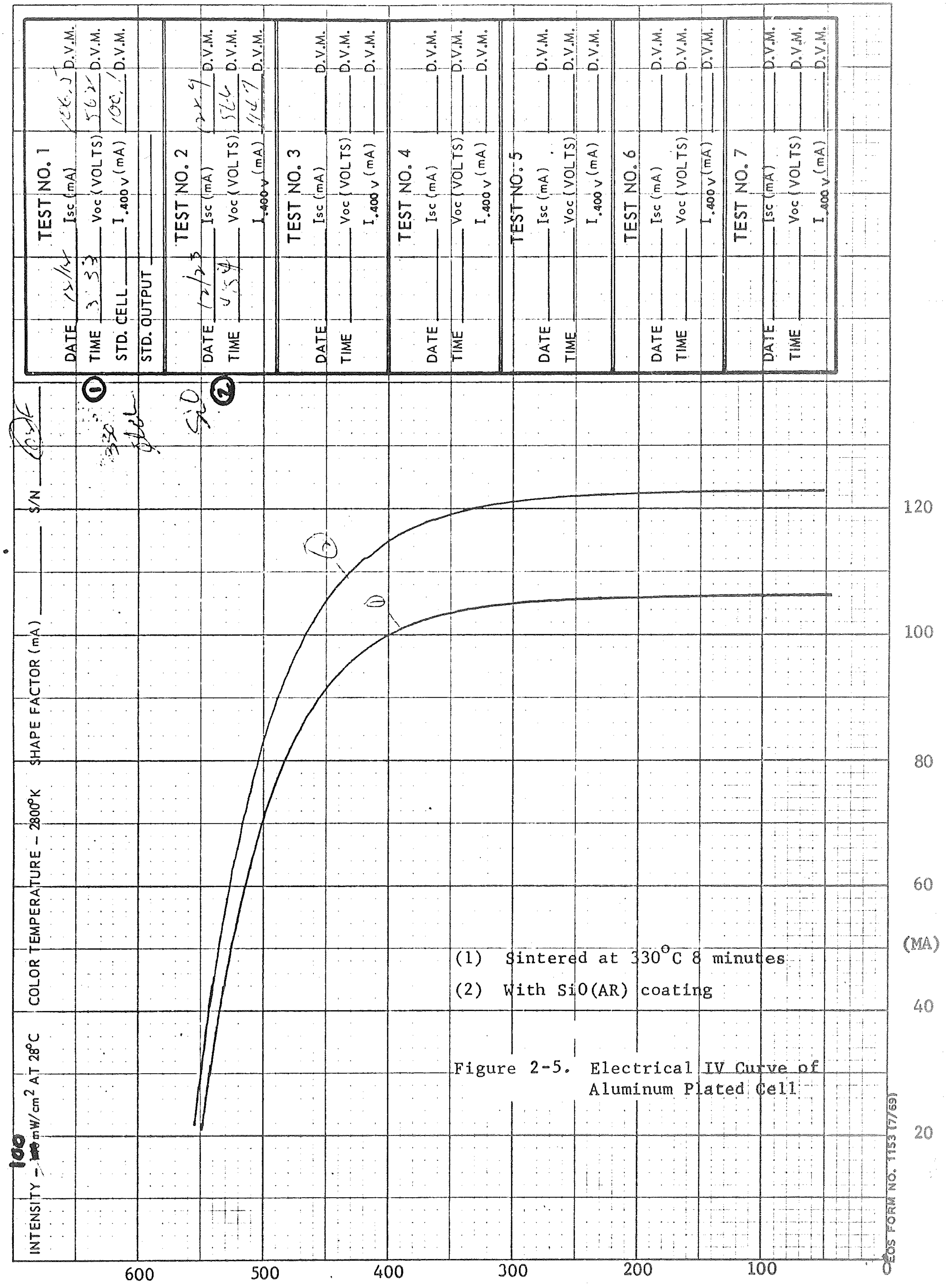


Figure 2-4. Electrical Distribution of 99 Cells



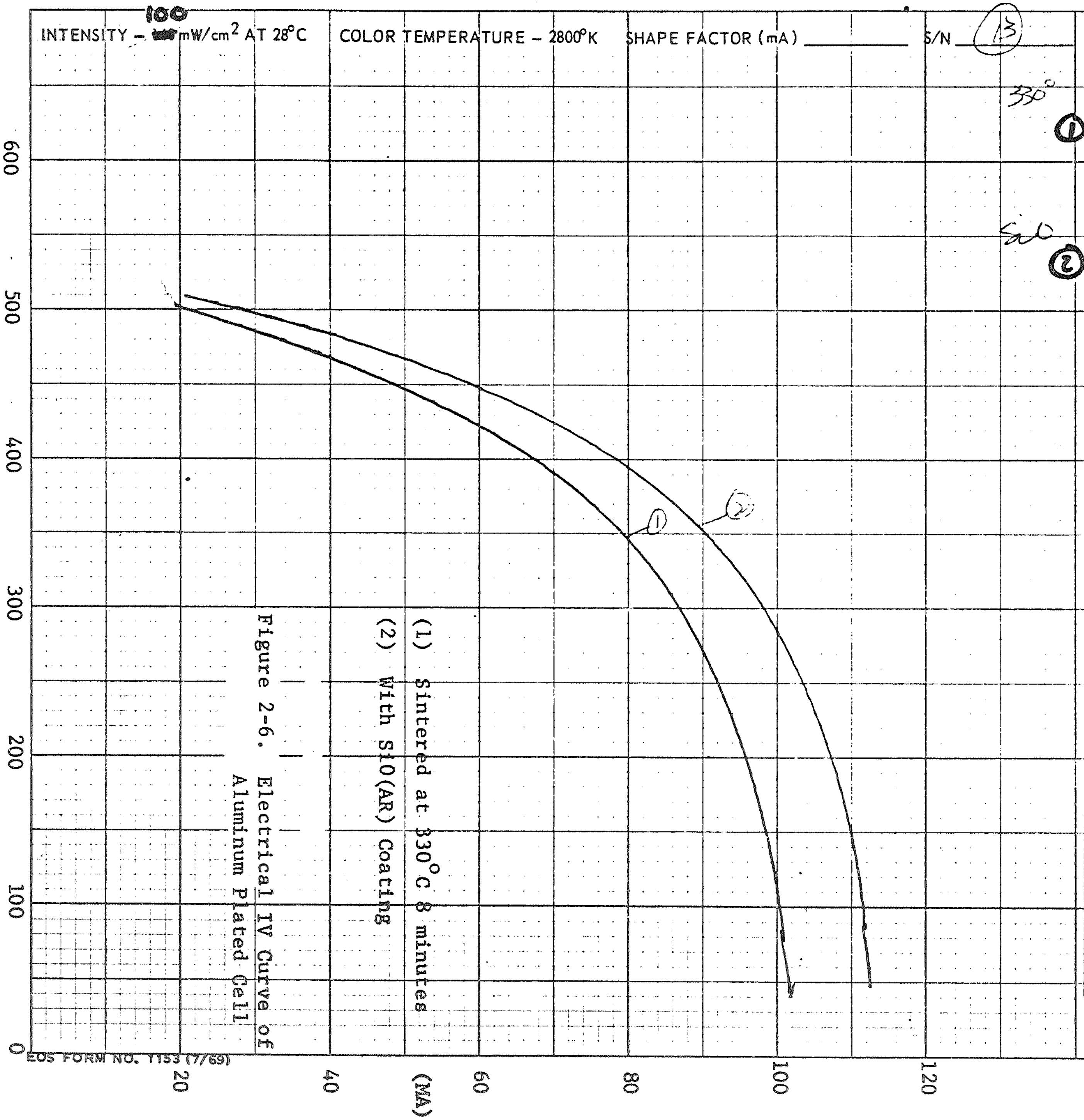
(1) Sintered at 330°C 8 minutes

(2) With SiO(AR) coating

Figure 2-5. Electrical IV Curve of Aluminum Plated Cell

HEWLETT-PACKARD/MOSELEY DIVISION
9270-1006
FOR USE ON AUTOGRAF RECORDERS
10 UNITS/DIVISION

INTENSITY – 100 mW/cm$^2$ AT 28°C COLOR TEMPERATURE – 2800°K SHAPE FACTOR (mA) ________ S/N ⑬



(1) Sintered at 330°C 8 minutes

(2) With SIO(AR) Coating

Figure 2-6. Electrical IV Curve of Aluminum Plated Cell

| | | |
|---|---|---|
| **TEST NO. 1** | | |
| DATE 12/12 | Isc (mA) 102.4 | D.V.M. |
| TIME 3:16 | Voc (VOLTS) .532 | D.V.M. |
| STD. CELL ______ | $I_{.400\,V}$ (mA) 68.7 | D.V.M. |
| STD. OUTPUT ______ | | |
| **TEST NO. 2** | | |
| DATE 12/24 | Isc (mA) 113.9 | D.V.M. |
| TIME 10:30 | Voc (VOLTS) .531 | D.V.M. |
| | $I_{.400\,V}$ (mA) 78.8 | D.V.M. |
| **TEST NO. 3** | | |
| DATE ______ | Isc (mA) ______ | D.V.M. |
| TIME ______ | Voc (VOLTS) ______ | D.V.M. |
| | $I_{.400\,V}$ (mA) ______ | D.V.M. |
| **TEST NO. 4** | | |
| DATE ______ | Isc (mA) ______ | D.V.M. |
| TIME ______ | Voc (VOLTS) ______ | D.V.M. |
| | $I_{.400\,V}$ (mA) ______ | D.V.M. |
| **TEST NO. 5** | | |
| DATE ______ | Isc (mA) ______ | D.V.M. |
| TIME ______ | Voc (VOLTS) ______ | D.V.M. |
| | $I_{.400\,V}$ (mA) ______ | D.V.M. |
| **TEST NO. 6** | | |
| DATE ______ | Isc (mA) ______ | D.V.M. |
| TIME ______ | Voc (VOLTS) ______ | D.V.M. |
| | $I_{.400\,V}$ (mA) ______ | D.V.M. |
| **TEST NO. 7** | | |
| DATE ______ | Isc (mA) ______ | D.V.M. |
| TIME ______ | Voc (VOLTS) ______ | D.V.M. |
| | $I_{.400\,V}$ (mA) ______ | D.V.M. |

The wide spread of values from $I_{400}$, and $V_{oc}$ are caused by differences in the IV curve shape illustrated by Figs. 2-5 and 2-6. This change in the curve shape is caused by the effects of series and shunt resistance in the cell. These values were not measured on the cells in question. However, the most likely cause for the wide variance in the $V_{oc}$ is shunt resistance which has a minimal effect on the $I_{sc}$, but lowers the $I_{400}$ and $V_{oc}$.

Cells normally have a shunt resistance in excess of 1000 ohms* and this factor may generally be neglected on conventional silver titanium solar cells made with polished 'N' surfaces. The aluminum plated solar cell requires a relative rough 'N' surface, Ref. Subsection 2.2 of this report. While this rough surface does not materially affect the diffused layer characteristics, it does affect the metallic aluminum layer to silicon interface. The diffusion depth of approximately 0.3 microns is small when compared to the surface finish of 5.0 microns, and the relatively rough surface of the cell can contain surface microcracks. JPL has kindly given EOS a series of scanning electron microphotographs of the aluminum/silicon interface. The best picture (Fig. 2-7) shows the rough surface of the silicon and the corresponding silicon side of the aluminum plating, illustrating the migration of the aluminum plating into the silicon surface crevices. This picture was taken at 4400X magnification and the aluminum plating is peeled up away from the silicon surface providing an excellent view of the interface.

Some cells had severe shorts, and it was theorized that these cells had surface microcracks in which the aluminum plating had migrated, shorting through the N/P junction of the cell. One cell that had a shorted condition was cracked into four fragments, and the dark reverse current of each of the four fragments was measured. The measurements indicated that only one of the fragments was shorted, which showed that the

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*Centralab, Solar Space Manual, para. 1.1.4.

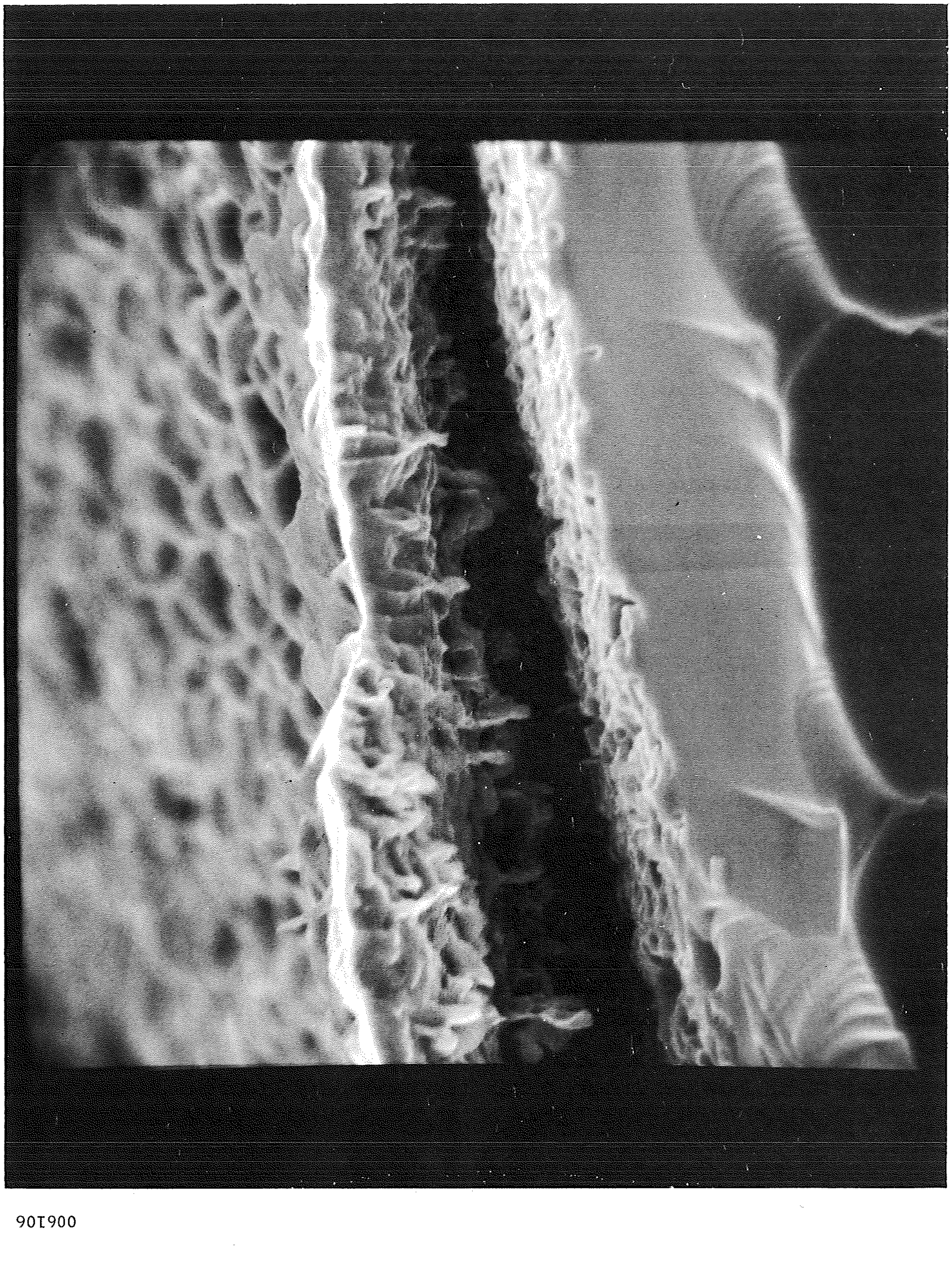

Figure 2-7. 4400X Magnification of Silicon/Aluminum Interface

006106

aluminum plating surface penetrations are not uniformly distributed, but highly localized.

A second source of cell shunting is caused by stray overplating of the edges of the cells, causing a shorting or shunting of the N/P junction. This condition was again illustrated by microphotographs taken by JPL. This condition can be readily corrected by removing the stray plating from the edge of the cell by a HCL etch which dissolves the aluminum without affecting the silicon. The quantity of the shorting that can be removed by edge etching of a typical shorted production cell is illustrated in Fig. 2-8. The shape factor* in this example was improved by 6.0 mA as a result of HCL edge etching. Figure 2-9 shows the corresponding dark reverse current of the same cell before and after edge etching. It can be seen that the shorting has been substantially reduced. The residual shunting at 0.47 volts amounted to 25 μA, or represented only approximately 0.03 percent of the working current.

The use of edge etching with HCL has been adopted as a standard part of the aluminum electroplating fabrication process.

## 2.8 DETERMINATION OF CONTACT RESISTANCE

Contact resistance is the electrical resistance associated with the junction between two conducting layers. It is the difference between the measured resistance across a contact junction and the resistance of a fully-conducting continuous member. This resistance is caused by the constriction of current flow lines as they pass through the asperities of the touching surfaces.

The contact resistance of electroformed aluminum contacts on silicon wafers is of special interest to this program. Different techniques

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*Shape factor is defined herein as the change in current from short circuit current to the current at 400 mV.

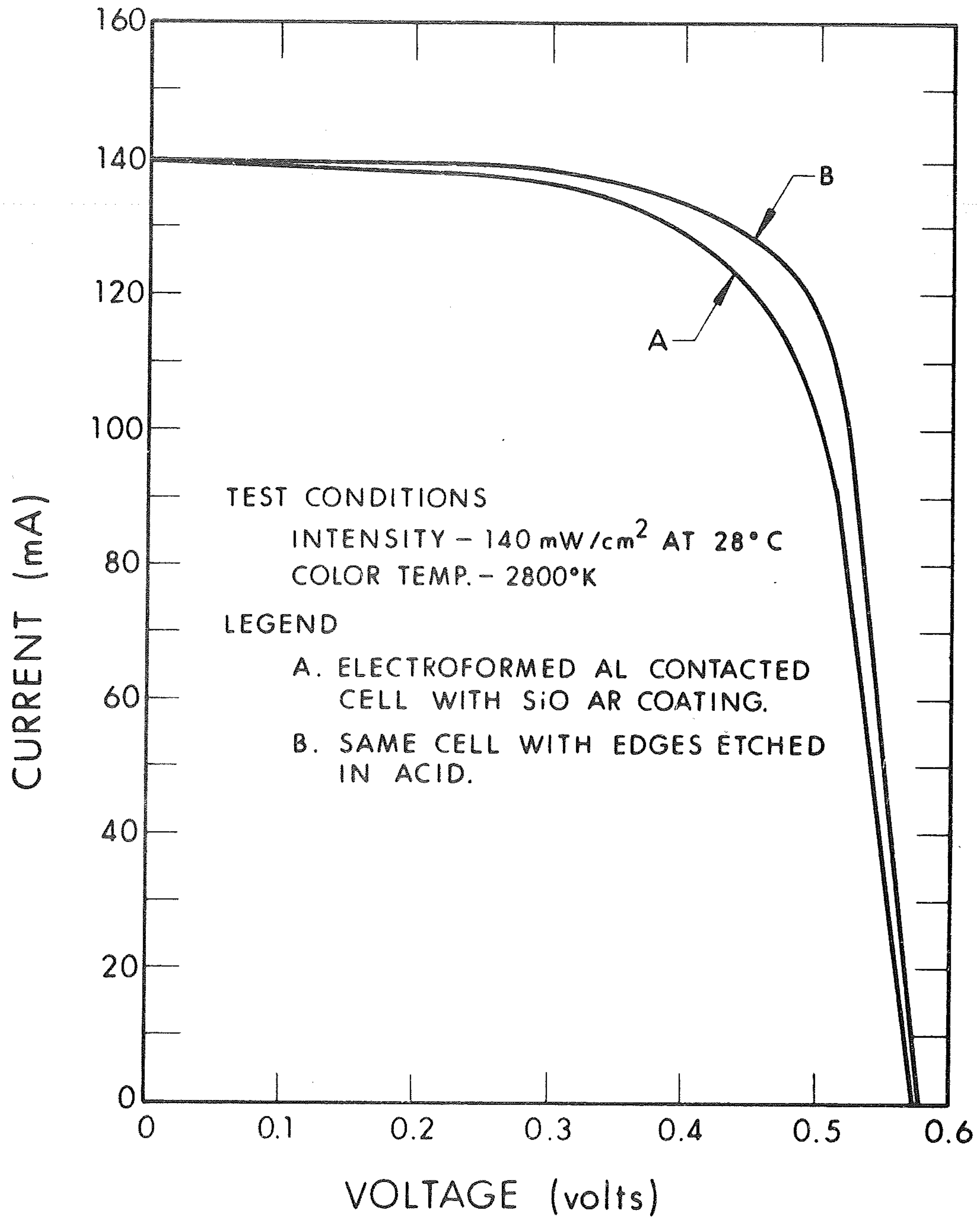


Figure 2-8. Improvement of Cell Output After Edge Etching

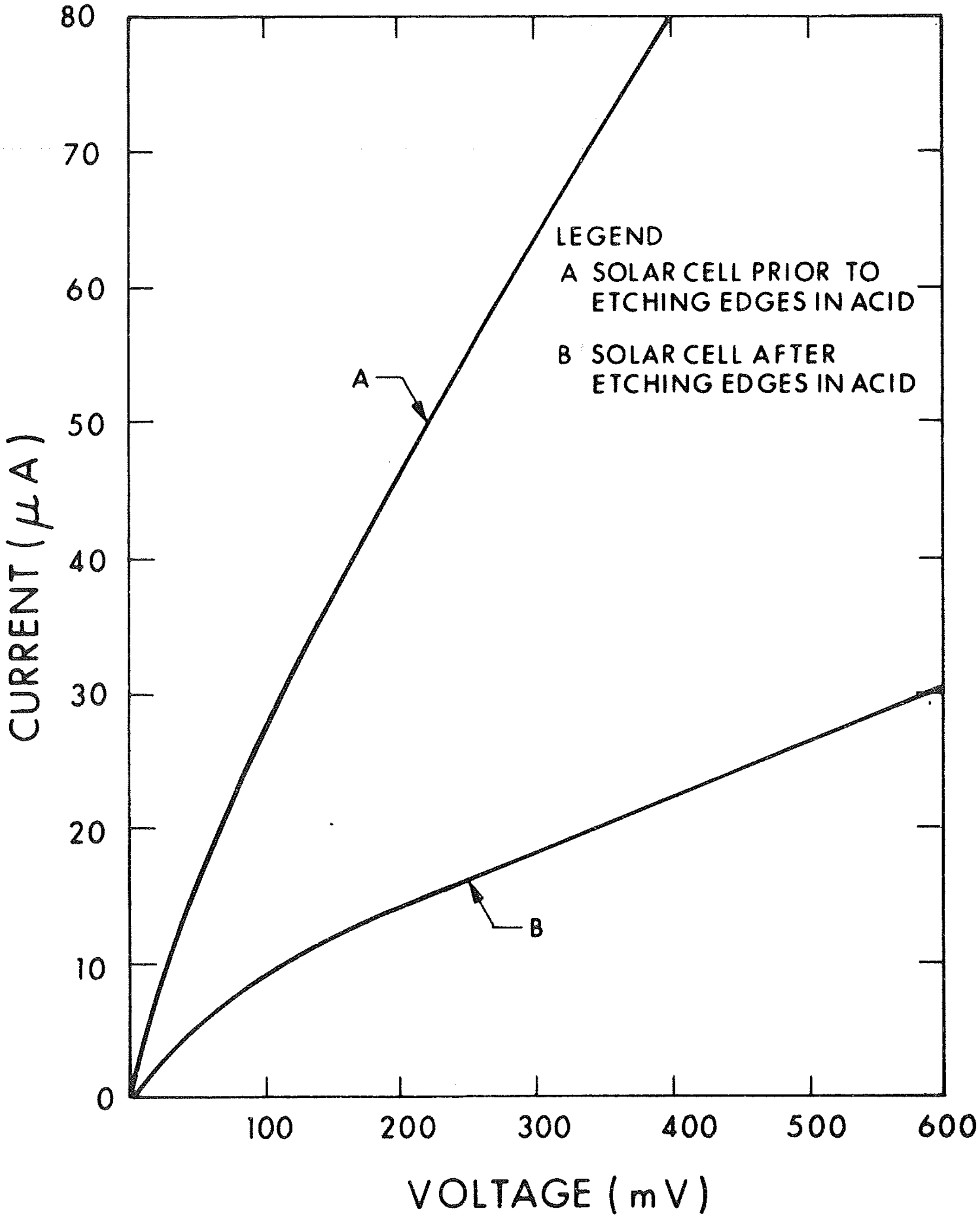


Figure 2-9. Effects on Dark Reverse Current After Edge Etching

developed by various labs have been employed to obtain very reliable values of contact resistance. In determining the contact resistance for electroformed contact solar cells, we have designed a very simple experiment consisting of the measurement of the resistance between electroformed grid lines. (Ref. Fig. 2-10.) The relation between the measured resistance and the contact resistance is given by the following equations:

$$R = 2R_{contact} + \frac{\rho si l}{wt}$$

where

$l$ = distance between contacts which varies,

$w$ = length of contact strip

$t$ = depth of junction

$\rho si$ = resistivity of top diffused layer

$$R_{contact} = \begin{pmatrix}\text{constant resistance} \\ \text{in ohms cm}^2\end{pmatrix} \div \begin{matrix}\text{area of} \\ \text{contact} \\ wxT\end{matrix}$$

$T$ = width of the aluminum grid line

The procedure is to measure R between contacts that are adjacent, 1 apart, 2 apart, ... is illustrated by Fig. 2-10. These values are plotted in Fig. 2-11 and the contact resistance is obtained as it is extrapolated to zero separation. The slope of the curve is $\rho si/wt$.

An experiment was conducted where the measured contact resistance was 2 ohms for the electrodeposited grid and 0.88 ohm after a heat treatment of 240°C for 10 minutes. The converted value of contact resistance in units of ohm-cm$^2$ is:

$$1.75 \text{ ohm} = \frac{\text{Contact Resistance (ohm-cm}^2)}{\text{Area}} = \frac{C}{A} = \frac{C}{wT}$$

$$C = \frac{1.75\ (0.0152\ \text{cm})(1.0\ \text{cm})}{2} = 1.3 \times 10^{-2}\ \text{ohm-cm}^2$$

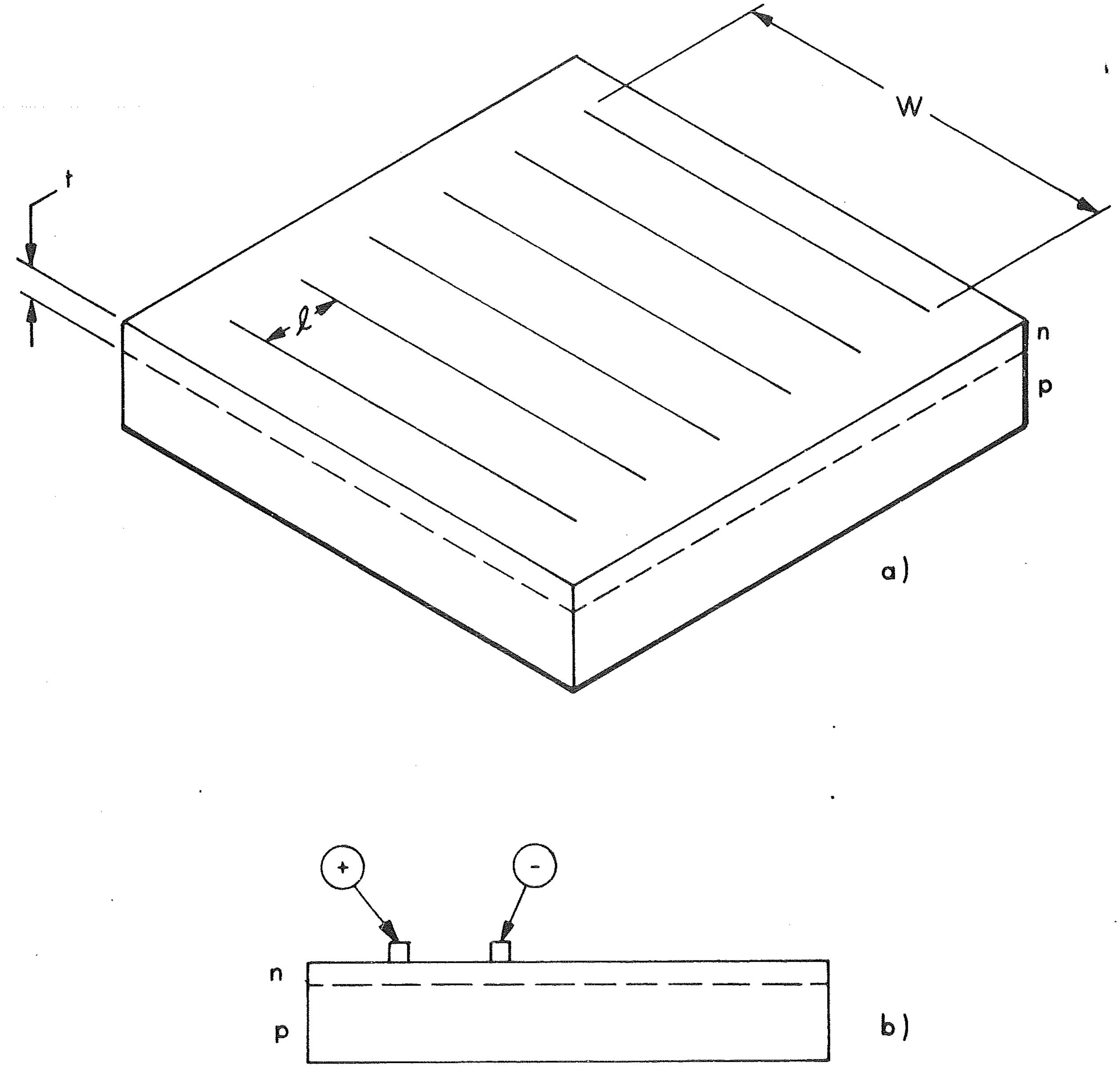


Figure 2-10. Test Cell for Measuring Contact Resistance

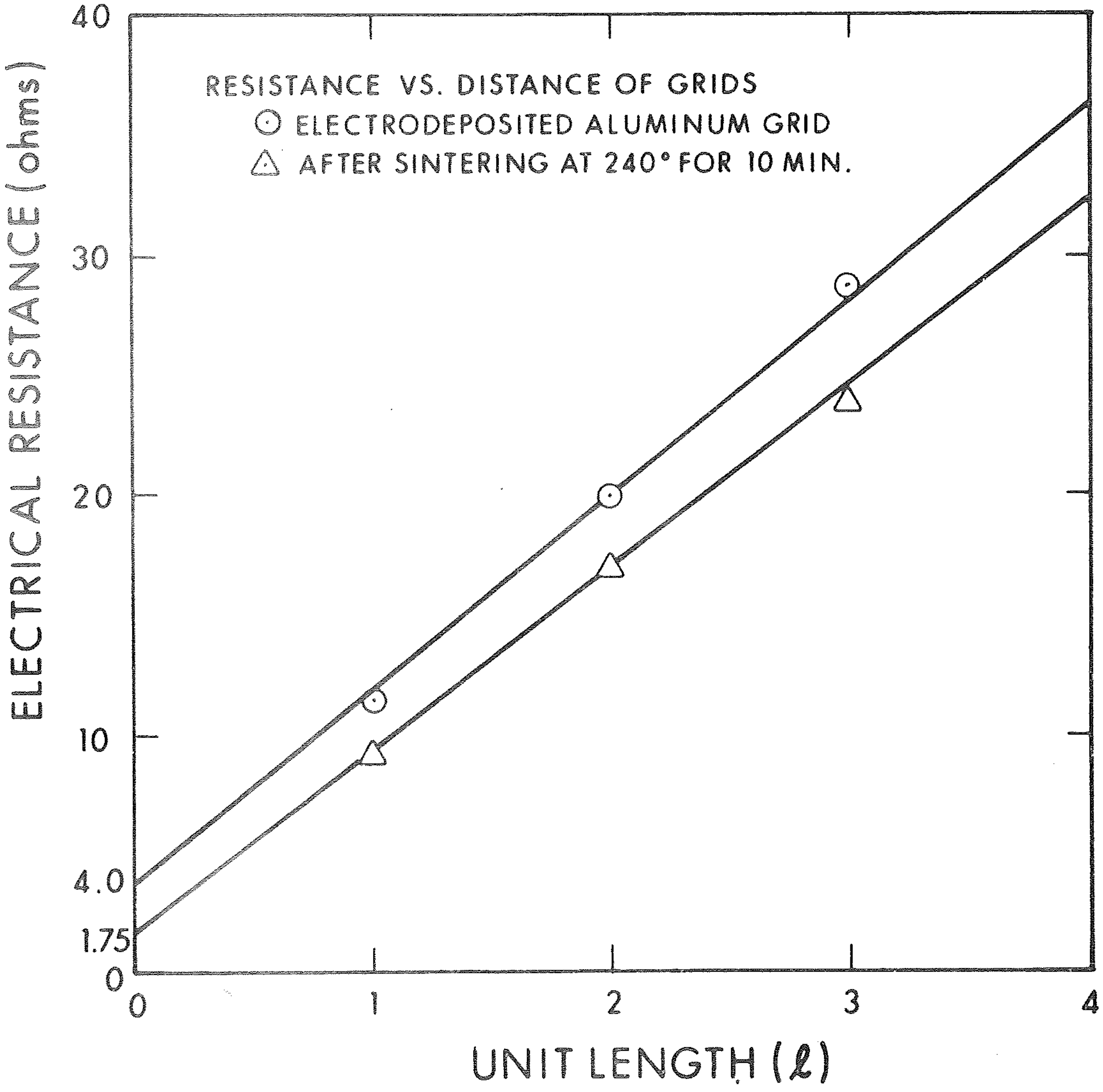


Figure 2-11. Grid Line Resistance

The contact resistance reported for evaporated aluminum contacts to silicon (0.010 ohm-cm, N type) was 8.3 x $10^{-2}$ ohm-$cm^2$. The value calculated above corrected for a comparable type of silicon is approximately one-fifth that of the evaporated aluminum contact.

## 2.9 ADHESION OF THE ALUMINUM ELECTRODEPOSIT TO SILICON SURFACE

Adhesion of electroformed aluminum to the silicon wafer was evaluated using commercially available silicon wafers for the solar cell. These cells are normally lap finished on the back side and mirror polished on the active side. Aluminum platings were electrodeposited on both surfaces to observe any differences in adhesion. The adhesion was poor on the polished side and fair on the lapped side. The pull test value for the lapped side was approximately 800 grams. The aluminum could be easily rubbed off from the polished side.

The low adhesive strength of the samples tested above indicates that a sintering step is necessary. Plated samples were sintered in an autoclave at 320°C for 2 minutes. Pull tests performed on the aluminum on both the polished side and the lapped side were all valued at about 1800 grams. The failure modes were either cracking of the silicon wafer or pulling off a chunk of the silicon. There were no failures due to peeling off the aluminum from the silicon surface on the sintered samples. For this program a surface finish of 5 microns is used instead of a polished surface. With the 5-micron finish surface, premature peeling of contacts (i.e., presintering) is completely eliminated. The effects of sintering temperature-time profile and liquid nitrogen thermal shock on adhesive strength are presented in Table 2-I.

The results of this study indicate that on individual cells with 0.5 mil contact thickness a postplating sintering operation should be used. Further studies modified the sintering profile, and a final sintering operation of 320°C for 10 minutes in a nitrogen ambient pressure atmosphere was selected.

## TABLE 2-I

## EFFECT OF SINTERING TEMPERATURE AND TIME ON ADHESIVE STRENGTH OF ELECTROFORMED ALUMINUM ON SILICON WAFERS

| Type of Wafer | Surface Finish | | *PULL TEST VALUE (GRAMS) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | No sintering | No sintering; $LN_2$ shock | 300°C, 2 min | 300°C, 2 min; $LN_2$ shock | 350°C, 2 min | 350°C, 2 min; $LN_2$ shock | 400°C, 2 min | 400°C, 2 min; $LN_2$ shock |
| Nondiffused | 5μ | | 550 | 500 | 1875 | 1825 | 2025 | 2100 | 2050 | 2075 |
| Diffused | 5μ | n | 500 | 500 | 1750 | 1750 | 2150 | 2150 | 1975 | 2050 |
| | | p | 1300 | 1200 | 1850 | 1800 | 2300 | 2225 | 2150 | 1950 |

* Pull test procedure for electroformed aluminum on silicon wafer:

(1) Solder No. 22 AWG tinned copper lead to center of aluminum-plated wafer.

(2) Perform pull test using Hunter tensile tester.

## 2.10 TESTING OF ELECTROPLATED CELLS

As a part of Task I, EOS selected a group of 50 cells, from the 99 cells reported in Subsection 2.7 of this report. The higher electrical output cells were selected for the test. The lot was split into two test groups of 25 cells each, and Table 2-II illustrates the test sequence to which each group of 25 solar cells were subjected.

TABLE 2-II

SOLAR CELL TESTS

| Group 1 (25 cells) | Group 2 (25 cells) |
|---|---|
| 1. Mechanical Inspection | 1. Mechanical Inspection |
| 2. Electrical Test | 2. Electrical Test |
| 3. Temperature Humidity | 3. Thermal Shock |
| 4. Mechanical Inspection | 4. Mechanical Inspection |
| 5. Electrical Test | 5. Electrical Test |
| 6. Contact Pull Test | 6. Low Temperature Soak |
|  | 7. Mechanical Inspection |
|  | 8. Electrical Test |
|  | 9. High Temperature Soak |
|  | 10. Mechanical Inspection |
|  | 11. Electrical Test |
|  | 12. Thermal Vacuum |
|  | 13. Mechanical Inspection |
|  | 14. Electrical Test |
|  | 15. Contact Pull Test |

### 2.10.1 ENVIRONMENTAL TESTS

This subsection presents the type, deviation if any, and results of each of the environmental tests performed. The electrical performance data is represented in Subsection 2.10.2; therefore, the results shall pertain to the mechanical degradation only after each of the environmental tests. Two groups of solar cells were processed through testing; 25 cells were subjected to the temperature humidity tests, and 25 solar cells were subjected to the remaining environmental tests.

After each test, as shown in Table 2-II the cells were subjected to a visual damage inspection with the unaided eye. If any damage was noted, the cells were inspected with 20X microscope and the damage recorded.

### 2.10.1.1 Temperature Humidity

A total of 25 solar cells in Group 1 were subjected to a 30 day temperature humidity test.

The temperature and humidity was recorded continuously, and the test operations were as follows:

a. Place the cells in the Teflon holding fixture.

b. Open the chamber and place the holding fixture in the humidity chamber.

c. Seal the chamber and insure that all monitoring equipment to be used in the test is calibrated and functioning properly.

d. Adjust the chamber temperature to $5^{o}$C and the relative humidity to 95 percent or greater.

e. When the chamber temperature and humidity have stabilized, maintain this condition for 15 to 20 minutes.

f. After the 15 to 20 minute equilibrium period, lower the chamber temperature to $0^{o}$. Maintain this temperature for 4 hours, ±5 minutes.

g. Following the four hour soak, the chamber temperature and humidity shall be raised to $125^{o}$ $\pm 5^{o}$C and greater than 95 percent respectively. The cells shall soak at this temperature for 30 days.

h. After completion of the 30 day soak, normal atmospheric (ambient) conditions shall be restored in the chamber at a rate not to exceed +10°C per minute.

i. Open the chamber and remove cell holding fixture from chamber.

Results

All test parameters were satisfactorily met and no mechanical degradation occurred or was noted to the 25 solar cells.

### 2.10.1.2 Thermal Shock

A total of 25 solar cells in Group 2 were subjected to 20 thermal shock cycles.

The temperature was recorded every minute during the temperature changes, and the test operations were as follows:

a. Place the sample solar cells in the cell holding fixture.

b. Connect the thermocouples from the two cells located in the center of the holding fixture to monitoring equipment.

c. Insure that all monitoring equipment to be used in the test is calibrated and functioning properly.

d. Place the test fixture with the cells into the temperature chamber and locate on the heated plate.

e. Seal the chamber and increase the cell temperature to 200°C ±5°C at an initial temperature rate of change of 100°C +10°C per minute.

f. Maintain the cell temperature at 200°C ±5°C for one hour ±5 minutes.

g. Upon completion of the one hour soak, reduce the cell temperature to -196°C ±5°C at a rate of change of 100°C +10°C.

h. Open temperature chamber and remove holding fixture. Place on the plate setting on dry ice.

i. Controlling the cell temperature of 100°C +10°C change per minute, remove holding fixture from dry ice and immerse bottom of fixture into $LN_2$.

j. Maintain the 100°C +10°C change per minute by lowering the fixture into the $LN_2$.

k. When the 100°C ±10°C can no longer be controlled, immediately immerse the cells and fixture into the $LN_2$.

l. Maintain the cell temperature at -196°C ±5°C for one hour ±5 minutes.

m. After one hour soak, remove fixture from $LN_2$ and place on plate setting or dry ice.

n. Controlling the 100°C change per minute, remove from dry ice.

o. As cell temperature reaches ambient, open temperature chamber and place cells on heated plate.

p. With (e) through (o) defined as one cycle, repeat (e) through (o) for a total of 20 cycles.

q. After the last low temperature soak (-196°C ±5°C), return the cell temperature to ambient at a rate of temperature change of 100°C +10°C.

r. Open the chamber and disconnect the thermocouples.

s. Remove test fixture from chamber.

## Results

Two of the original 25 cells subjected to the shock test failed to produce an electrical output due to mechanical degradation. Cell No. 85 cracked. The crack extended across the face of the cell from the approximate center at the N contact to the lower right side, approximately 1/4 in. from the bottom of the cell. Three grid lines were broken due to the crack. The other cell, No. 97, had the P contact completely delaminated.

Prior to the shock test this cell was visually inspected and approximately 50 percent of the P contact area appeared bubbled and blistered; this condition would indicate poor adhesion. The remaining 23 solar cells showed no signs of mechanical degradation.

All test parameters were satisfactorily completed.

### 2.10.1.3 Low Temperature Soak

The 23 remaining cells from Group 2 were subjected to a low temperature soak test for 168 hours.

The temperature was recorded every minute during temperature changes, and at -196°C the temperature was recorded every two hours. The test operations were as follows:

a. Mount the cells on the cell-holding fixture.
b. Place fixture in the temperature chamber.
c. Connect the thermocouples on the test cells (two located at the center of the test fixture) to monitoring equipment.
d. Seal the test chamber and verify that all monitoring equipment to be used in the test is calibrated and functioning properly.
e. Lower the temperature of the cells to -196°C +5°C at a rate not to exceed 25°C per minute.
f. After the cell temperature has stabilized at -196°C ±5°C, maintain this temperature for 168 hours.
g. After the 168-hour soak, increase the cell temperature to ambient at a rate not to exceed 25°C per minute.

#### Results

No mechanical degradation was noted to the solar cells due to the low temperature soak test. All test requirements were satisfactorily accomplished.

### 2.10.1.4 High Temperature Soak

The 23 remaining cells from Group 2 were subjected to a high temperature soak test for 168 hours.

The temperature was recorded every minute during temperature changes, and at 200°C the temperature was recorded every 2 hours. The test operations were as follows:

a. Mount the cells on the cell holding fixture.

b. Place fixture in the temperature chamber.

c. Connect thermocouples on the test cells (two located at the center of test fixture) to monitoring equipment.

d. Seal the test chamber and verify that all monitoring equipment to be used in the test is calibrated and functioning properly.

e. Raise the temperature of the cells to 200° ±5°C at a rate not exceeding 25°C per minute.

f. After the cell temperature has stabilized at 200° ±5°C, maintain this temperature for 168 hours.

g. After the 168-hour soak, reduce the chamber temperature to ambient at a rate not to exceed 25°C per minute.

### Results

All test requirements were satisfactorily completed. No mechanical degradation occurred to the solar cells due to the high temperature soak.

### 2.10.1.5 Thermal Vacuum

The 23 remaining cells from Group 2 were subjected to a thermal vacuum cycle test for a total of 12 days.

The temperature was recorded every minute during temperature changes. At -125°C, the temperature was recorded every 15 minutes, and at +125°C the temperature was recorded every 4 hours. The test operations were as follows:

a. Mount the cells on the environmental test fixture so that the cells do not contact each other.

b. Place the test fixture in the thermal vacuum test chamber.

c. Connect thermocouples on the two cells located in the center of the holding fixture, to monitor equipment.

d. Seal the test chamber and insure that all monitoring equipment to be used in the test is calibrated and functioning properly.

e. Reduce chamber pressure to $1 \times 10^{-5}$ mm Hg or less and maintain until step (j).

f. Reduce the cell temperature to -125 ±5°C at a rate not to exceed 10°C per minute.

g. Maintain this temperature of -125 ±5°C for four hours ±15 minutes.

h. Increase the cell temperature to +125 ±5°C at a rate not exceeding 10°C per minute.

i. Maintain cells at +125 ±5°C in the chamber for 12 ±0.5 days.

j. Upon completion of the 12 day soak, allow the temperature and pressure to return to normal (ambient) conditions. The rate of temperature change shall not exceed 10°C per minute.

k. Open chamber and remove test fixture with cells.

## Results

No mechanical degradation occurred to the solar cells due to the thermal vacuum test. All the test parameters were not satisfactorily accomplished. In an attempt to reach the low temperature of -125 ±5°C it was determined that this temperature could not be reached utilizing the present test setup. It was then determined to continue testing with the lowest possible temperature obtainable. This temperature was approximately -95°C. Other than this deviation all test requirements were satisfactorily accomplished.

### 2.10.1.6 Cell Contact Pull Test

A total of 8 cells, 4 from each test group of 25 cells were subjected to a contact pull test. The test was conducted by soldering a 26 gauge solid wire to the 'N' and 'P' contacts of each cell, and individually pulling each wire until failure occurred.

Results

The following list illustrates test group, cell serial number, P or N contact, and pull strength in grams:

| Cell S/N | Test Contact | Test Group | Pull Strength | Remarks |
|---|---|---|---|---|
| 120 | P | Humidity Test Only | 700 grams | Cell broke, not contact |
| 124 | P | Humidity Test Only | 550 grams | Cell broke, not contact |
| 2 | N | Humidity Test Only | 400 grams | Cell broke, not contact |
| 116 | N | Humidity Test Only | 300 grams | Pulled plating on contact |
| 94 | P | All Environmental Tests | 1200 grams | Cell broke, not contact |
| 74 | P | All Environmental Tests | 1200 grams | Cell broke, not contact |
| 42 | N | All Environmental Tests | 50 grams | Pulled plating on contact |
| 89 | N | All Environmental Tests | 400 grams | Cell broke, not contact |

### 2.10.2 ELECTRICAL TESTS

Prior to and after the completion of each environmental test an electrical performance test was performed. The test conditions were to be at 140 $mW/cm^2$. However, the light source was calibrated utilizing JPL Specification 502802 entitled "Calibration of Tungsten Light Test Console." This specification instructs the one calibrating to set the intensity level at 100 $mW/cm^2$; consequently, the cells were tested at 100 $mW/cm^2$, and it was not recognized as the incorrect intensity until the solar cells had undergone various environmental tests. It was then decided to continue testing at 100 $mW/cm^2$ so that correlations could be made, utilizing the electrical data, before and after the environmental tests.

A test temperature of 28 $\pm 1^{\circ}C$ was used for all tests. Current-voltage (I-V) curves were made for all cells, the short circuit ($I_{sc}$) current, the current at 400 mV ($I_{400}$), and the open circuit voltage were separately recorded on each (I-V) curve as read off the digital meters.

### 2.10.2.1 Results

In general the output of the cells decreased as a result of the humidity and environmental tests. With the exception of the 2 cells which had mechanical failures after the thermal shock test, Ref. Subsection 2.10.1.2. No mechanical degradation was noted.

The complete electrical history of the two groups of test cells are shown in Tables 2-III and 2-IV. These tables list the $I_{sc}$, $I_{400}$, and $V_{oc}$ of each cell at each significant step in the fabrication and testing sequence. The Table 2-III shows the experimental sintering profiles used on some of the cells. In some cases cells were sintered twice, once at $250^{\circ}C$ for 2 minutes and again at $330^{\circ}C$ for 8 minutes. A definite increase in $I_{400}$ can be seen between the two sintering temperatures.

## TABLE 2-III

## ELECTRICAL DATA - TEMPERATURE/HUMIDITY TEST

| Cell No. | Post 2 Min, 250°C Sinter | | | Post 8 Min, 330°C Sinter | | | Post 20 Sec HCL Etch | | | Post 2 MinHCLRe-Etch | | | Post SiO Coating | | | Post 30 Day Humidity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Isc | Voc | I.400V | Isc | Voc | I.400V | Isc | Voc | I.400V | Isc | Voc | I.400V | Isc | Voc | I.400V | Isc | Voc | I.400V |
| 2 | | | | 104.8 | .513 | 97.8 | | | | | | | 120.8 | .575 | 110.9 | 118.5 | .571 | 103.2 |
| 5 | 103.9 | .559 | 84.3 | 104.5 | .563 | 87.6 | 103.4 | 562.4 | 88.0 | | | | 120.4 | .566 | 101.7 | 117.6 | .562 | 89.0 |
| 11 | | | | 99.4 | .550 | 86.8 | | | | | | | 116.8 | .554 | 101.6 | 114.6 | .540 | 86.8 |
| 12 | 104.5 | .514 | 84.6 | 105.8 | .514 | 87.2 | 104.9 | .573 | 87.7 | | | | 118.9 | .575 | 94.0 | 114.0 | .575 | 82.9 |
| 14 | 98.0 | .541 | 87.8 | 98.8 | .543 | 90.2 | 97.8 | .542 | 91.3 | 95.6 | .544 | 89.5 | 110.9 | .550 | 104.5 | 106.5 | .547 | 98.3 |
| 19 | 110.5 | .571 | 99.5 | 111.0 | .572 | 100.3 | 110.7 | .570 | 100.3 | | | | 125.3 | .514 | 114.3 | 124.0 | .570 | 106.1 |
| 21 | 106.3 | .571 | 93.6 | 106.7 | .572 | 94.8 | 104.2 | .566 | 92.3 | | | | 120.1 | .574 | 108.5 | 120.5 | .570 | 104.2 |
| 23 | 102.5 | .551 | 93.2 | 103.0 | .554 | 97.1 | | | | | | | 120.4 | .551 | 112.2 | 119.3 | .554 | 105.0 |
| 29 | 100.1 | .551 | 91.3 | 99.9 | .553 | 92.3 | | | | | | | 115.9 | .556 | 105.7 | 114.4 | .549 | 98.0 |
| 30 | 103.3 | .573 | 95.8 | 103.1 | .576 | 96.8 | | | | | | | 116.1 | .577 | 110.5 | 113.8 | .575 | 101.3 |
| 113 | | | | 107.3 | .576 | 97.0 | | | | | | | 124.0 | .579 | 111.4 | 119.0 | .566 | 98.1 |
| 114 | | | | 113.1 | .583 | 102.8 | | | | | | | 130.2 | .584 | 117.4 | 128.2 | .580 | 109.5 |
| 116 | | | | 103.6 | .577 | 97.2 | | | | | | | 119.4 | .581 | 111.5 | 115.1 | .578 | 104.9 |
| 118 | | | | 107.8 | .561 | 91.9 | | | | | | | 127.5 | .557 | 105.6 | 126.0 | .535 | 80.2 |
| 119 | | | | 111.2 | .572 | 94.0 | | | | | | | 128.5 | .580 | 108.9 | 125.9 | .514 | 102.0 |
| 120 | | | | 111.1 | .570 | 89.2 | | | | | | | 127.5 | .571 | 97.5 | 125.1 | .558 | 82.2 |
| 121 | | | | 109.8 | .576 | 95.4 | | | | | | | 125.7 | .577 | 110.2 | 122.8 | .570 | 103.4 |
| 124 | | | | 110.3 | .574 | 97.1 | | | | | | | 125.7 | .578 | 108.9 | 124.3 | .566 | 92.7 |
| 125 | | | | 114.8 | .581 | 98.8 | | | | | | | 131.0 | .583 | 112.6 | 129.4 | .578 | 107.0 |
| 128 | | | | 104.0 | .578 | 95.3 | | | | | | | 116.7 | .581 | 106.7 | 115.7 | .576 | 101.4 |
| 132 | | | | 111.4 | .583 | 101.7 | | | | | | | 126.0 | .585 | 114.9 | 124.9 | .582 | 107.5 |
| 133 | | | | 111.9 | .582 | 102.3 | | | | | | | 128.2 | .586 | 117.9 | 127.0 | .582 | 112.9 |
| 134 | | | | 111.3 | .578 | 97.3 | | | | | | | 122.5 | .581 | 112.0 | 121.7 | .579 | 109.1 |
| 135 | | | | 107.1 | .578 | 94.8 | | | | | | | 121.4 | .582 | 110.2 | 120.6 | .578 | 105.3 |
| 140 | | | | 106.1 | .561 | 90.9 | | | | | | | 123.5 | .561 | 105.8 | 116.6 | .552 | 91.5 |

## TABLE 2-IV

## ELECTRICAL DATA - ENVIRONMENTAL TEST

| Cell No. | Post 8 Min, 330°C Sinter | | | Post 20 Sec,HCL Edge Etch | | | Post SiO Coating | | | Post Thermal Shock | | | Post Low Temp. Soak | | | Post Hi Temp Soak | | | Post Thermal Vac. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Isc | Voc | I.400V | Isc | Voc | I.400V | Isc | Voc | I.400V | Isc | Voc | **I.400V** | Isc | Voc | I.400V | Isc | Voc | I.400V | Isc | Voc | I.400V |
| 35 | 100.7 | .572 | 92.3 | | | | 115.2 | .574 | 105.8 | 114.0 | .564 | 67.4 | 111.8 | .565 | 66.2 | 95.7 | .555 | 46.5 | 101.5 | .560 | 51.8 |
| 36 | 103.1 | .543 | 95.6 | 102.6 | .541 | 92.9 | 117.7 | .545 | 105.4 | 117.7 | .545 | 106.4 | 116.9 | .544 | 105.2 | 116.8 | .538.3 | 102.6 | 116.2 | .536 | 96.8 |
| 38 | 109.3 | .578 | 90.0 | 110.7 | .577 | 92.8 | 125.0 | .580 | 108.9 | 125.0 | .571 | 91.4 | 122.9 | .571 | 88.5 | 122.1 | .560 | 75.2 | 121.4 | .558 | 75.1 |
| 39 | 105.3 | .578 | 95.8 | | | | 120.7 | .579 | 108.4 | 121.1 | .580 | 107.5 | 120.0 | .579 | 106.9 | 119.2 | .577 | 103.6 | 119.4 | .577 | 103.2 |
| 41 | 103.4 | .559 | 96.7 | | | | 121.4 | .562 | 113.2 | 118.5 | .561 | 109.7 | 120.6 | .560 | 111.4 | 119.6 | 556 | 108.8 | 119.5 | .556 | 108.5 |
| 42 | 107.8 | .557 | 97.9 | | | | 122.4 | .557 | 109.1 | 123.5 | .560 | 111.2 | 121.8 | .559 | 109.2 | 122.2 | .557 | 106.7 | 121.9 | .558 | 108.1 |
| 43 | 99.6 | .566 | 94.6 | | | | 116.0 | .568 | 109.8 | 118.0 | .568 | 110.6 | 117.2 | .566 | 110.6 | 115.7 | .566 | 108.4 | 116.0 | .564 | 108.6 |
| 45 | 105.6 | .568 | 96.8 | 106.3 | .566 | 96.4 | 124.4 | .572 | 115.0 | 124.7 | .570 | 110.8 | 123.4 | .570 | 110.1 | 122.3 | .568 | 107.5 | 121.0 | .567 | 105.7 |
| 46 | 105.8 | .575 | 98.6 | | | | 120.4 | .577 | 111.7 | 121.5 | .576 | 112.0 | 120.4 | .576 | 111.0 | 118.4 | .574 | 107.3 | 117.9 | .572 | 106.7 |
| 50 | 101.7 | .569 | 94.2 | | | | 117.4 | .571 | 108.7 | 117.9 | .565 | 88.0 | 116.9 | .564 | 79.1 | 114.8 | .561 | 68.0 | 112.8 | .560 | 65.1 |
| 54 | 103.4 | .564 | 94.5 | 103.8 | .564 | 95.1 | 122.1 | .568 | 111.0 | 122.2 | .566 | 109.7 | 120.9 | .565 | 108.9 | 119.5 | .563 | 106.5 | 120.2 | .557 | 100.1 |
| 55 | 110.1 | .572 | 97.8 | | | | 126.5 | .575 | 112.9 | 120.3 | .566 | 61.4 | 115.8 | .566 | 56.5 | 106.5 | .562 | 49.0 | 108.4 | .560 | 48.9 |
| 70 | 106.1 | .559 | 91.1 | 106.5 | .560 | 93.5 | 124.6 | .565 | 109.4 | 124.8 | .566 | 108.6 | 123.3 | .565 | 108.0 | 122.3 | .552 | 95.0 | 123.2 | .551 | 93.3 |
| 74 | 101.5 | .554 | 89.5 | 100.0 | .558 | 90.3 | 116.9 | .562 | 102.9 | 116.5 | .558 | 95.1 | 115.8 | .555 | 92.4 | 114.6 | .555 | 88.0 | 114.0 | .552 | 86.5 |
| 85 | 101.2 | .554 | 88.4 | | | | 118.9 | .555 | 101.1 | | | | | | | | | | | | |
| 89 | 105.2 | .547 | 98.9 | 103.9 | .548 | 96.5 | 118.3 | .551 | 108.5 | 118.3 | .551 | 108.5 | 117.3 | .549 | 106.0 | 116.5 | .551 | 106.3 | 113.8 | .549 | 104.9 |
| 90 | 97.4 | .559 | 90.9 | 94.2 | .558 | 84.3 | 113.3 | .563 | 99.1 | 113.5 | .560 | 90.5 | 112.5 | .558 | 79.5 | 111.5 | .553 | 75.4 | 110.8 | .550 | 64.4 |
| 94 | 101.4 | .572 | 92.6 | | | | 116.5 | .575 | 106.1 | 114.9 | .569 | 67.0 | 112.7 | .568 | 61.1 | 100.6 | .564 | 47.5 | 111.5 | .567 | 47.3 |
| 97 | 107.8 | .579 | 90.7 | | | | 121.4 | .577 | 98.8 | | | | | | | | | | | | |
| 100 | 103.8 | .577 | 86.7 | | | | 119.8 | .880 | 107.3 | 120.9 | .578 | 91.5 | 119.6 | .579 | 90.8 | 120.2 | .576 | 84.7 | 119.6 | .576 | 72.0 |
| 101 | 106.5 | .565 | 87.4 | | | | 125.0 | .560 | 100.8 | 125.9 | .551 | 95.2 | 125.0 | .552 | 90.2 | 124.0 | .552 | 88.3 | 124.3 | .555 | 92.0 |
| 108 | 104.8 | .576 | 99.2 | | | | 121.4 | .579 | 113.9 | 121.5 | .577 | 112.5 | 120.7 | .516 | 111.0 | 117.6 | .570.0 | 105.8 | 119.0 | .572 | 107.0 |
| 109 | 102.5 | .575 | 94.2 | | | | 119.7 | .580 | 109.1 | 119.8 | .579 | 107.2 | 118.7 | .579 | 107.2 | 115.0 | .576 | 99.5 | 115.7 | .574 | 102.0 |
| 110 | 110.1 | .566 | 99.6 | | | | 126.9 | .567 | 114.8 | 126.1 | .568 | 115.6 | 125.5 | .568 | 114.4 | 124.8 | .559 | 103.6 | 124.4 | .555 | 100.4 |
| 111 | 110.3 | .581 | 98.6 | | | | 126.2 | .583 | 112.2 | 126.8 | .581 | 109.1 | 124.9 | .519 | 106.8 | 124.6 | .548 | 83.2 | 124.4 | .540 | 78.4 |

| Cell No. | $I_{400}$ (250°C) | $I_{400}$ (330°C) | $I_{400}$ $\Delta$ | $I_{400}$ $\Delta$% |
|---|---|---|---|---|
| 5 | 84.3 | 87.6 | 3.3 | + 3.91 |
| 12 | 84.6 | 87.2 | 2.6 | + 3.07 |
| 14 | 87.8 | 90.2 | 2.4 | + 2.73 |
| 19 | 99.5 | 100.3 | 0.8 | + 0.80 |
| 21 | 93.6 | 94.8 | 1.2 | + 1.28 |
| 23 | 93.2 | 97.1 | 3.9 | + 4.18 |
| 29 | 91.3 | 92.3 | 1.0 | + 1.09 |
| 30 | 95.8 | 96.8 | 1.0 | + 1.04 |
| Average | 91.26 mA | 93.28 mA | 2.02 mA | + 2.2% |

Further examination of the sintering showed that in practice the actual sintering at 330°C ran from 8 to 10 minutes depending on the individual sintering run. A safety factor of 10°C was established and the sintering firmly established at 320°C for 10 minutes.

Edge etching was not performed on all cells fabricated, only cells which indicated a poor I-V curve shape were etched as indicated by the Tables 2-III and 2-IV. Analysis of the $I_{400}$ current values of pre and post etch show:

| Cell No. | $I_{400}$ (Pre Etch) | $I_{400}$ (Post Etch) | $I_{400}$ Δ | $I_{400}$ Δ% |
|---|---|---|---|---|
| 5 | 87.6 | 88.0 | 0.4 | +0.46 |
| 12 | 87.2 | 87.7 | 0.5 | +0.57 |
| 14 | 90.2 | 91.3 | 0.1 | +1.21 |
| 19 | 100.3 | 100.3 | 0 | 0 |
| 21 | 94.8 | 92.3 | -2.5 | -2.63 |
| 36 | 95.6 | 92.0 | -2.7 | -2.82 |
| 38 | 90.0 | 92.8 | 2.8 | +3.11 |
| 45 | 96.8 | 96.4 | -0.4 | -0.41 |
| 54 | 94.5 | 95.1 | 0.6 | +0.63 |
| 70 | 91.1 | 93.5 | 2.4 | +2.63 |
| 74 | 89.5 | 90.3 | 0.8 | +0.83 |
| 89 | 98.9 | 96.5 | -2.4 | -2.41 |
| 90 | 90.9 | 84.3 | -6.6 | -7.25 |
| Average | 92.87 mA | 92.41 mA | -0.46 mA | -0.49% |

The edge etching data obtained with the test cells was a random positive and negative distribution. Subsequent studies showed that the 20 second etch did not remove the aluminum stray edge overplating except where it was extremely light. The edge etching parameters were changed to a total etching immersion time of 1 hour in a 50 percent solution of HCL, and incorporated into the procedure as standard practice for all cells.

The total electrical performance of the Group 1 and Group 2 test cells is shown in Tables 2-III and 2-IV. A histogram of the $I_{400}$ current values of the two groups of cells has been prepared to visually display the test point readings and is shown in Fig. 2-12.

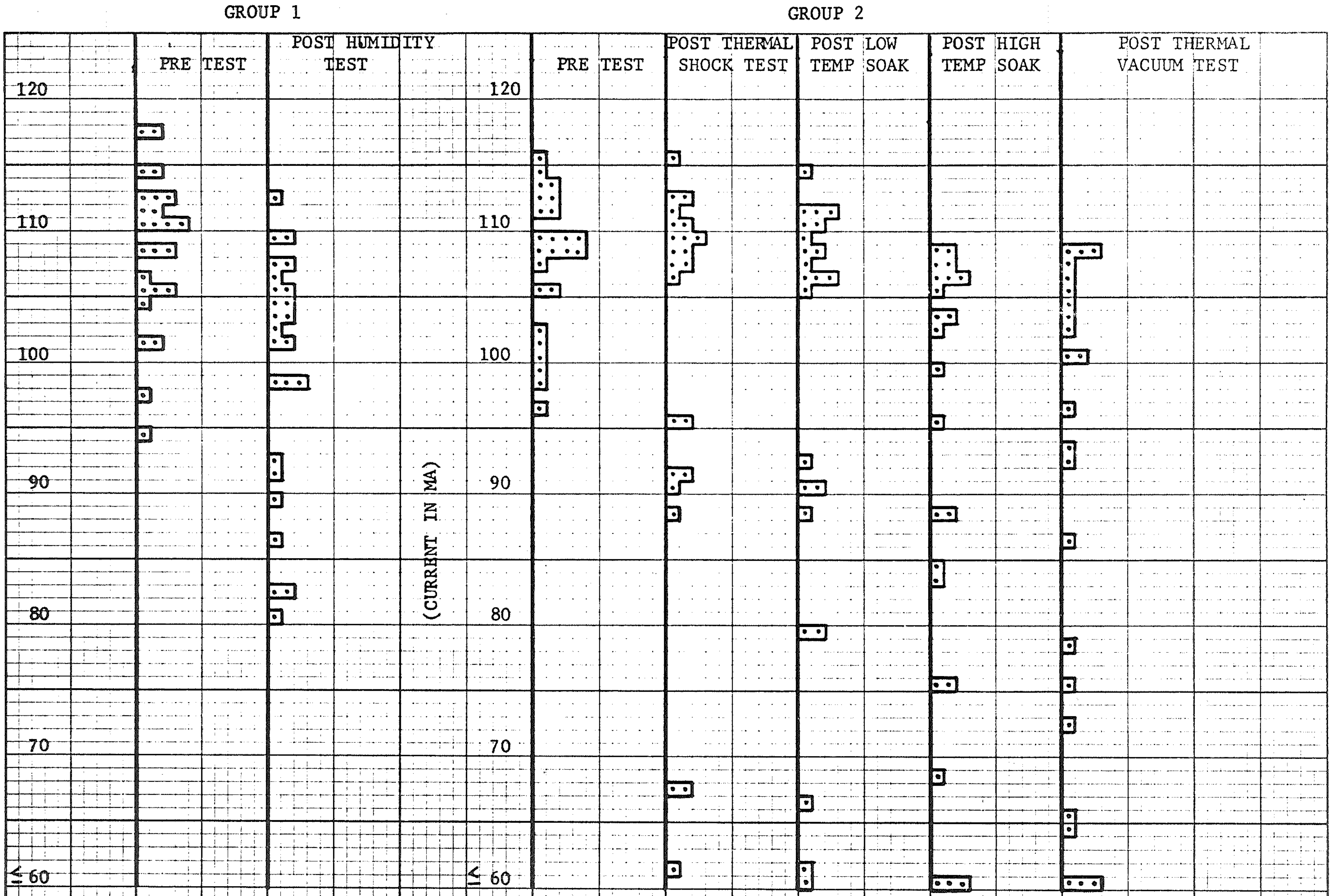


Figure 2-12. Electrical Distribution ($I_{400}$) of Test Cells

The effects of the various tests on the distribution of the current $I_{400}$ in the solar cells is clearly indicated by the histograms in Fig. 2-12. Note that the distribution for the pretest condition in both Groups 1 and 2 is essentially Gaussian, i.e., normal. Subjecting the cells to one or more tests has the effect of spreading-out the distribution and moving its "center of mass" toward lower values of $I_{400}$. This effect is well illustrated for the cells in Group 2. Thus, the tests tend to increase the standard deviation of the distribution, and lower its mean.

From Fig. 2-12, the post-test distributions do not appear to be Gaussian. However, it is possible to compute the mean and standard deviation of any set of data, regardless of its form. The mean and standard deviation of the current $I_{400}$ for the pretest and post-test conditions of Groups 1 and 2 are shown in Table 2-V. Note that the effect of the various tests is to increase the standard deviations and lower the mean, as indicated by the histograms in Fig. 2-12.

Although the means and standard deviations of the pretest and post-test data are conspicuously different (Table 2-V), it is important to determine if these differences are statistically significant. In other words, what can be said regarding the equality of the population means and population standard deviations of pretest and post-test data? In order to test the hypotheses of equal means and equal standard deviations, the seven populations from which the seven sets of sample data (shown in Fig. 2-12) are taken are assumed to be normally distributed. Although the post-test data in Fig. 2-12 does not appear to be normally distributed, we shall assume that the parent populations are indeed normally distributed. (The pretest sample data in Fig. 2-12 appears to have a normal distribution.) By applying the "t" test to the pretest and post-test data of Group 1, we find that the means of the two parent populations are not equal at a 5 percent level of significance. (The conclusion that the population means are unequal would become more

## TABLE 2-V

### MEAN AND STANDARD DEVIATION OF THE CURRENT ($I_{400}$) OF THE TEST CELLS AS MEASURED AT 400 MV, 100 MW/CM$^2$ TUNGSTEN, AT 28°C.

| | Humidity Test | | Environmental Test | | | | |
|---|---|---|---|---|---|---|---|
| | Pre Test | Post Test | Pre Test | Thermal Shock | Low Temp Soak | High Temp Soak | Therm Vac. |
| Mean | 108.6 | 99.3 | 108.1 | 99.4 | 97.0 | 89.9 | 88.1 |
| Standard Deviation | 5.72 | 9.19 | 4.72 | 15.84 | 17.58 | 20.65 | 20.78 |

(All values shown in mA)

## TABLE 2-VI

### AVERAGE ELECTRICAL DEGRADATION DURING TESTING SEQUENCE

| Test Sequence | $I_{sc}$ | % Ave | 1 at 0.4V | % Ave | $V_{oc}$ | % Ave | Remarks |
|---|---|---|---|---|---|---|---|
| Initial Electrical | 123.7 | | 108.6 | | 0.572 | | 25 cells processed through temp/ humidity test only. |
| Post Humidity Test | 120.2 | -2.8 | 98.9 | -8.9 | 0.567 | -0.87 | |
| Initial Electrical | 120.7 | | 108.1 | | 0.569 | | Initial electrical test based on 25 solar cells; remaining test data based on 23 cells due to 2 failures after thermal shock. |
| Post Thermal Shock | 120.5 | -0.16 | 99.4 | -8.0 | 0.567 | -0.35 | |
| Post Low Temp Soak | 119.3 | -0.99 | 97.0 | -2.4 | 0.566 | -0.18 | |
| Post High Temp Soak | 116.7 | -2.1 | 89.9 | -7.3 | 0.561 | -0.88 | |
| Post Thermal Vacuum | 117.3 | +0.51 | 88.1 | -2.0 | 0.560 | -0.18 | |

significant - i.e., meaningful - if this conclusion were reached at a smaller level of significance, e.g., a 4 percent level of significance.) Applying the "F" test to the pretest and post-test data of Group 1, we find that the standard deviations of the two parent populations are not equal at a 5 percent level of significance. (Again, this conclusion becomes more significant the smaller the level of significance.)

By applying the "t" test to the pretest data and thermal shock data of Group 2, we find that the means of the two parent populations are not equal at a 5 percent level of significance. The same result is obtained when the "t" test is applied to the pretest data and each of the three remaining sets of post-test data, in Group 2. When the "F" test is applied to the pretest data and thermal shock data, we find that the standard deviations of the two parent populations are not equal at a 5 percent level of significance. The same result is obtained when the "F" test is applied to the pretest data and each of the three remaining sets of post-test data.

The average degradation of all test points of Group 1 and Group 2 cells are shown in Table 2-VI.

Degradation of test values are larger than would be anticipated for conventional silver-titanium silicon solar cells, the sharp drop off of the I-V curve as illustrated by Fig. 2-13 which shows the actual I-V curves of test cell No. 50, are attributable to an increased series resistance in the cell. This increase in series resistance is believed due to an increase in contact resistance caused by oxidation of the aluminum contacts, and is typical of the test cells. Therefore the large loss shown by the test data, while real may be only caused by contact oxidation which can be corrected.

## 2.11 COST ANALYSIS FOR THE PRODUCTION OF ELECTROFORMED AL CONTACT SOLAR CELLS

A preliminary analysis has been performed to determine the cost for electroforming aluminum contacts to 2 x 2 cm diffused n/p silicon wafers on a pilot production basis. A pilot operation consists of one electroforming unit manned by an engineering specialist. On a manufacturing operation, a production operator would man several electroforming units after the unit is loaded and electrodeposition is initiated on each unit. The calculation assumes that 100 wafers are plated in each unit at a time. The time analysis as observed in our laboratory is summarized in Table 2-VII.

However it must be understood that these costs are strictly estimates based on a projected pilot production operation, and do not contain any mechanical or electrical yield factors, which would vary depending upon use criteria.

HEWLETT-PACKARD/MOSELEY DIVISION
9270-1006
FOR USE ON AUTOGRAF RECORDERS
10 UNITS/DIVISION

INTENSITY – ~~140~~ 100 mW/cm² AT 28°C    COLOR TEMPERATURE – 2800°K    SHAPE FACTOR (mA) ________    S/N 50 F

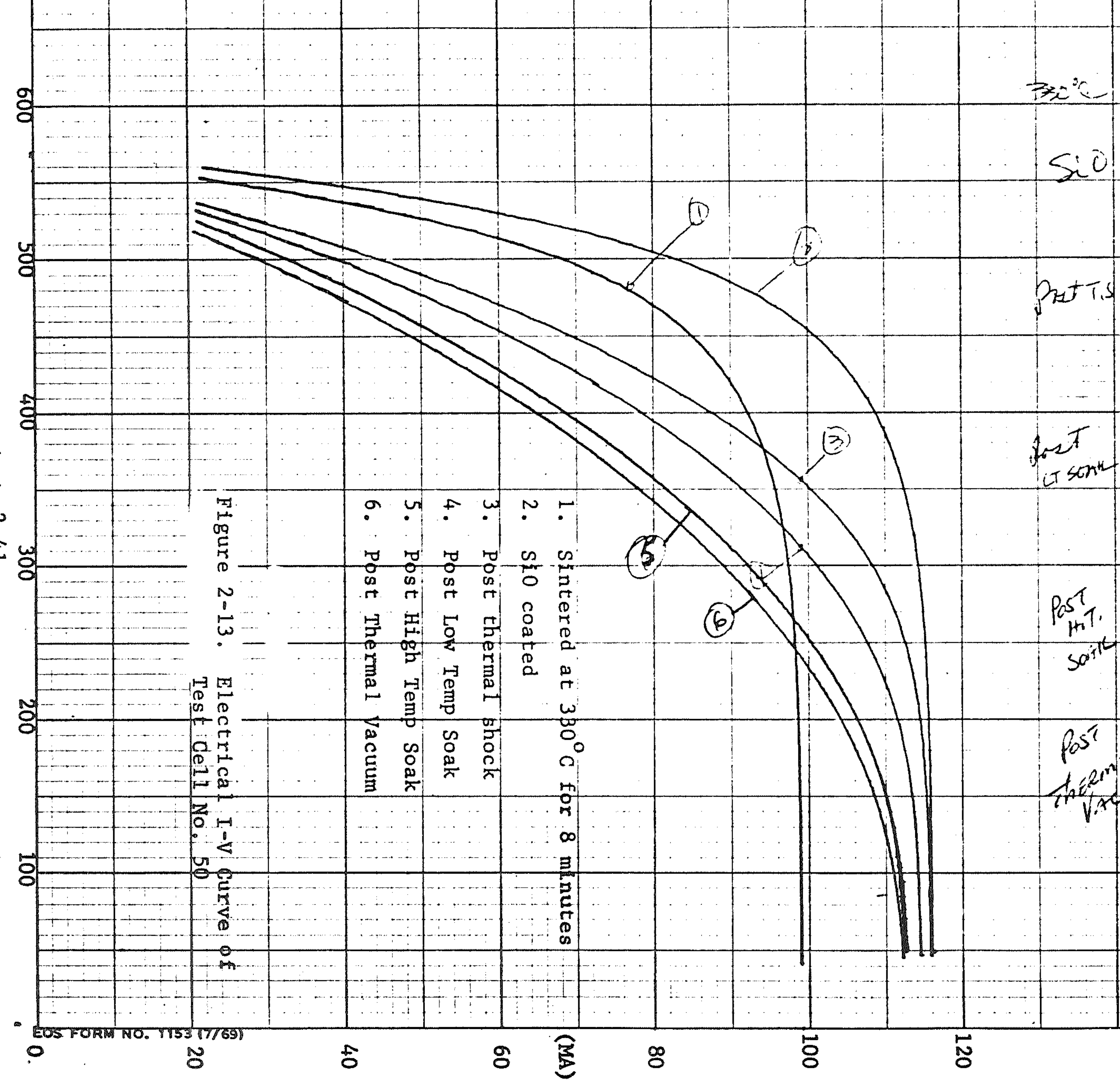


Figure 2-13. Electrical I-V Curve of Test Cell No. 50

1. Sintered at 330°C for 8 minutes
2. SiO coated
3. Post thermal shock
4. Post Low Temp Soak
5. Post High Temp Soak
6. Post Thermal Vacuum

330°C

TEST NO. 1 ①
DATE 12/19    Isc (mA) 101.7 D.V.M.
TIME 9:37    Voc (VOLTS) .564 D.V.M.
STD. CELL ________    I.400 V (mA) 94.8 D.V.M.
STD. OUTPUT ________

SiO

TEST NO. 2 ②
DATE 12/23    Isc (mA) 117.4 D.V.M.
TIME 1:31    Voc (VOLTS) .571 D.V.M.
I.400 V (mA) 103.7 D.V.M.

Post T.S

TEST NO. 3 ③
DATE 1/8/70    Isc (mA) 117.9 D.V.M.
TIME 1:32    Voc (VOLTS) .565 D.V.M.
I.400 V (mA) 88.0 D.V.M.

Post LT Soak

TEST NO. 4 ④
DATE 1/1/70    Isc (mA) 114.9 D.V.M.
TIME [illegible]    Voc (VOLTS) .562 D.V.M.
I.400 V (mA) 74.1 D.V.M.

Post H.T. Soak

TEST NO. 5 ⑤
DATE 1/26/70    Isc (mA) 114.8 D.V.M.
TIME 4:27    Voc (VOLTS) 561 D.V.M.
I.400 V (mA) 68.0 D.V.M.

Post Therm Vac

TEST NO. 6 ⑥
DATE 2/11/70    Isc (mA) 112.8 D.V.M.
TIME ________    Voc (VOLTS) 560 D.V.M.
I.400 V (mA) 65.1 D.V.M.

TEST NO. 7
DATE ________    Isc (mA) ________ D.V.M.
TIME ________    Voc (VOLTS) ________ D.V.M.
I.400 V (mA) ________ D.V.M.

EOS FORM NO. 1153 (7/69)

## TABLE 2-VII

## TIME ANALYSIS FOR ELECTROFORMING ALUMINUM OPERATIONS

| Operation No. | Operation | Time/Lot (min) |
|---|---|---|
| 1. | Degrease wafer | 15 |
| 2. | Etch wafer | 10 |
| 3. | Rinse in alcohol | 5 |
| 4. | Load electroforming fixture | 15 |
| 5. | Load in plating tank | 15 |
| 6. | Unload electroforming fixture | 15 |
| 7. | Wash finished cell | 5 |
|  | Total | 80 = 1.333 hr. |

The costs computed for the entire electroformed aluminum contact solar cell with SiO coating with either diffused or nondiffused wafer as starting material are as follows:

I. Basis: Starting material - silicon wafer, diffused, 100-cell lot

|  | DL (manhours) |
|---|---|
| Masking | 3.250 |
| Electroforming operation | 1.333 |
| SiO coating | 1.000 |
| Mechanical classify | 0.500 |
| QA inspection and test | 0.500 |
|  | 6.583 |

6.583 ÷ 100 = 0.06583 hr/cell

| | | |
|---|---|---|
| 0.06583 x 3.00/hr | = | $0.198 |
| OH (150%) | = | 0.297 |
| | | 0.495 |
| Cost of diffused wafer | = | 2.000 |
| Miscellaneous cost per cell | = | 0.080 |
| | | 2.575 |
| G&A (15%) | = | 0.386 |
| | | 2.961 |
| Profit (15%) | = | 0.444 |
| Total cost per cell | = | $3.405 |

II. Basis: Starting material - silicon wafer, nondiffused 100-cell lot

| | DL (manhours) |
|---|---|
| Diffused, etch | 0.550 |
| Masking | 3.250 |
| Electroforming operations | 1.333 |
| SiO coating | 1.000 |
| Mechanical classify | 0.500 |
| QA inspection and test | 0.500 |
| | 7.133 |

7.133 ÷ 100 = 0.07133 hr/cell

| | | |
|---|---|---|
| 0.07133 x 3.00/hr | = | $0.214 |
| OH (150%) | = | 0.321 |
| | | 0.535 |
| Cost of wafer | = | 1.000 |
| Miscellaneous cost per cell | = | 0.100 |
| | | 1.635 |
| G&A (15%) | = | 0.245 |
| | | 1.880 |
| Profit (15%) | = | 0.282 |
| Total cost per cell | = | $2.162 |

# SECTION 3

# TASK II

## 3.1 SUMMARY

This phase of the program involved the study, analysis and development to establish feasibility of electroforming aluminum solderless interconnections of silicon solar cells. These studies have resulted in the following conclusions:

a. Electroformed aluminum interconnection of both parallel and series configuration are feasible.

b. Use of a top contact solar cell configuration for the interconnected cells.

c. Development of a multicell fixture design and selection of aluminum as the most practical plating fixture material.

d. Develop the use of aluminum shim stock for an intercell fixture gasket.

e. The plating solution and current density used on Task I is directly applicable to the multicell plating.

In general this study has proven the feasibility of this interconnection approach; however, considerable more work is necessary to develop this into a pilot production operation.

## 3.2 SOLAR CELL AND MATRIX CONFIGURATION

### 3.2.1 SOLAR CELL CONFIGURATION

This study only considered N/P solar cells of a basic 2 cm x 2 cm size. Other cell sizes would be for the most part equally affected by the following considerations.

a. Top and bottom contact, or conventional N/P configuration solar cells. This cell, which is the most common configuration in use throughout the solar cell industry today, has its 'n' contact along one edge of the front face of the cell with the grid lines emanating from the 'n' contact, with the 'p' contact being essentially the entire back surface: Ref. Fig. 3-1. All solar cells fabricated under Task I of this contract were of the top and bottom contact configuration.

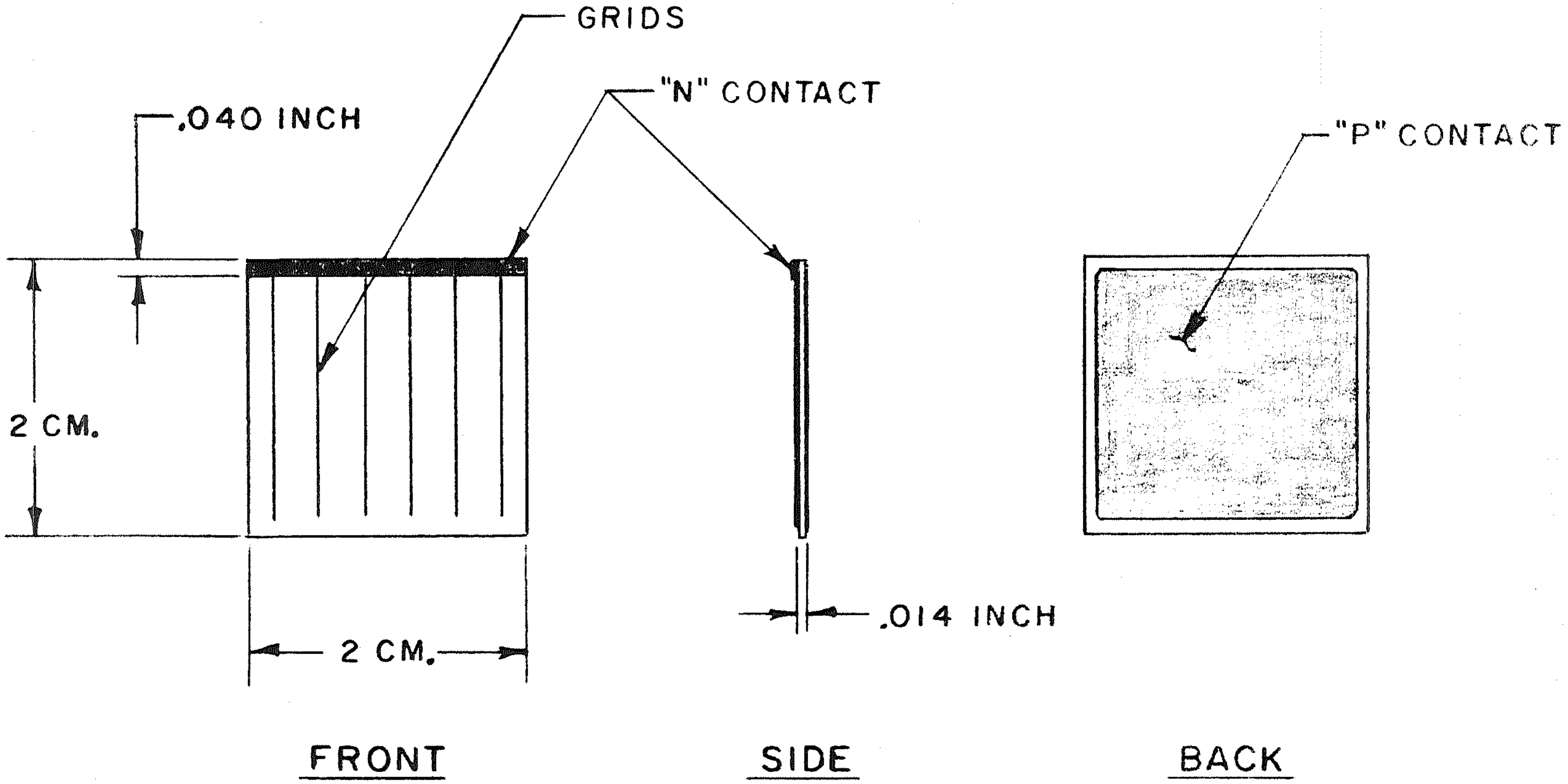
b. Wrap-around contact solar cell. This cell configuration has both the 'n' and 'p' contacts on the back side of the solar cell: Ref. Fig. 3-2. The primary advantage of this type of solar cell is its increased front surface active area by virtue of the elimination of the 'n' contact strip. This cell configuration is not new to the industry, having been made on various experimental bases for at least five years.

   This cell configuration has not been used in space power applications primarily because it has never been available at a competitive cost to the conventional solar cells. Neglecting the retooling costs associated with changing the cell configuration, the wrap-around solar cell has serious power loss problems associated with the wrap-around 'n' contact which, despite its increased active area make it non-competitive with conventional solar cells.

c. Top contact solar cells. These cells are a variation of both cells previously described, being basically an attempt to utilize some of the advantages of each. The top contact solar cell has a modified conventional 'n' contact and grid configuration with the addition of a 'p' contact bus area on the front face of the solar cell. This cell configuration is not new, having been developed and made on an experimental basis by Centralab Semiconductor, Inc. approximately two and a half years ago.

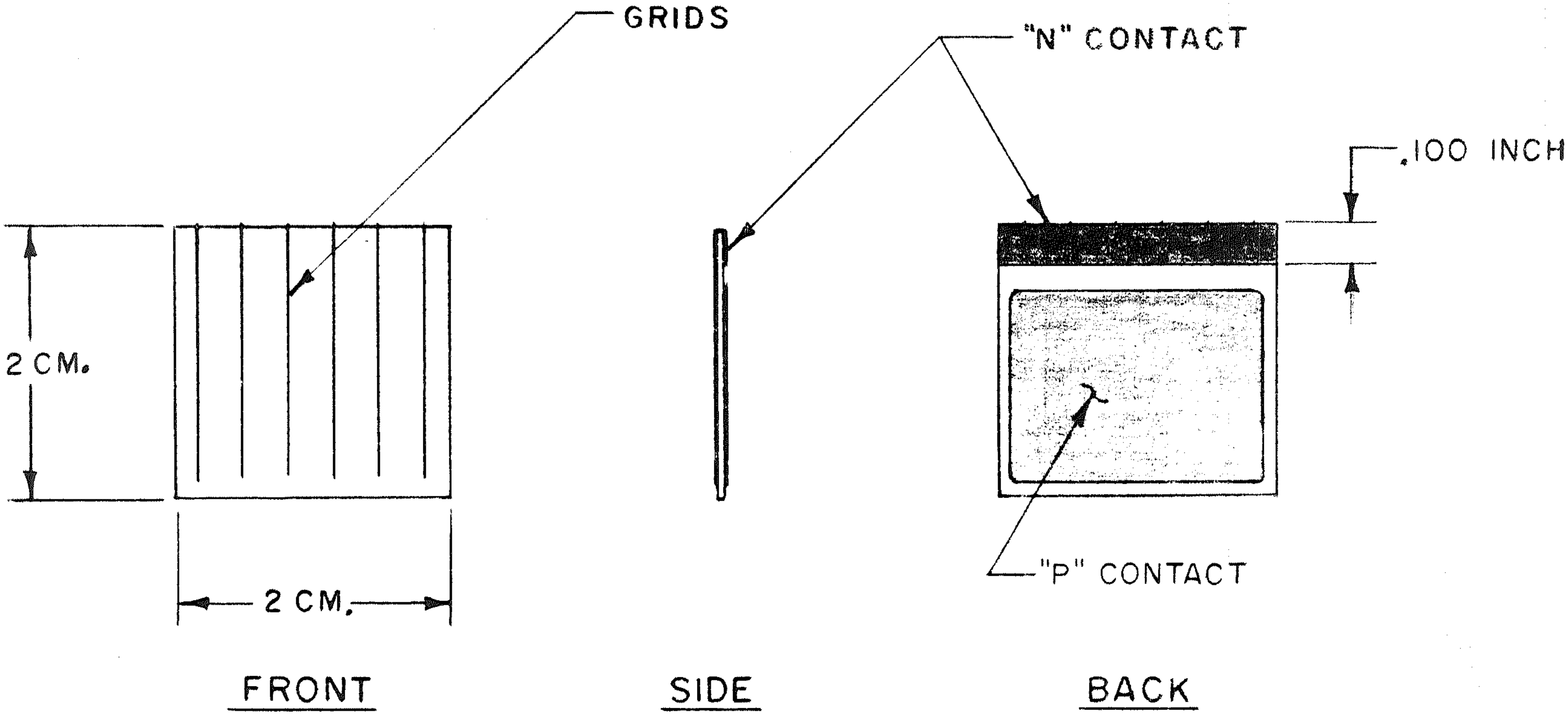
   The disadvantage of this cell configuration is that a certain portion of the active area of the cell must be given up to form the 'p' contact bus area requiring modification of the 'n' contact to retain the equivalent active area of a conventional solar cell. However, tests performed on this type of cell configuration showed that it did not suffer the power loss problems associated with a wrap-around solar cell, and is competitive powerwise with a conventional solar cell.

   A variation of the top contact solar cell was first presented to JPL for review by EOS under this contract in the monthly report, 5 November 1969. The final design configuration of a top contact solar cell modified to make it more adaptable to electroformed aluminum inner connectors is shown in Fig. 3-3.



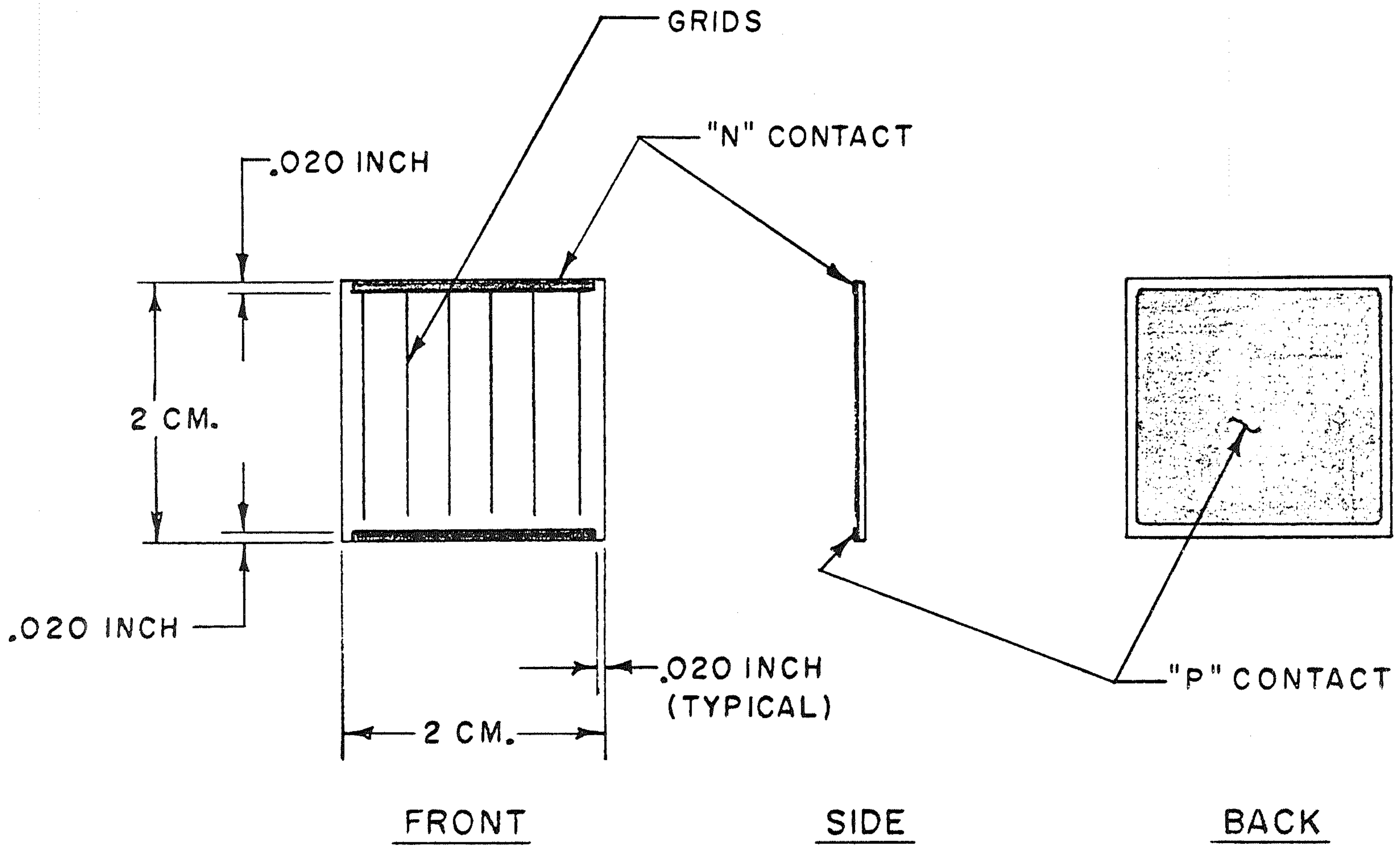
TOP AND BOTTOM CONTACT SOLAR CELL

Figure 3-1



WRAP AROUND SOLAR CELL

Figure 3-2



TOP CONTACT SOLAR CELL

Figure 3-3

The top and bottom contact cells, while being the most conventional in configuration, do not lend themselves to electroforming interconnections as it is necessary to bring the 'p' contact up and around from the bottom of one cell to the top of the adjacent cell's 'n' contact. This cell is the most suited for single cell contact electrodeposition; however, no practical means have been conceived to provide a mandrel bridge suitable for forming the interconnection, and therefore it was omitted for further consideration in the multicell arrangement.

The wrap-around cell has both 'n' and 'p' contact on the back surface of the solar cell, thereby making it apparently adaptable for electroforming interconnectors. The wrap-around cell configuration, with the 'n' contact requiring continuous plated continuity from front to back as well as an interconnection in the same area of the cell, does not lend itself to the mandrel bridge fixturing concept. In addition, the wrap-around cell has the previously described power loss problem attributable to internal shunting losses where the 'n' contact must traverse the edge and two corners of the cell. This, along with the real problem of bridging an interconnector to the same area of the cell also requiring a full edge plate, presents much of the same impracticalities as in the conventional cell configuration. EOS, therefore, did not consider this cell configuration for experimentation in the multicell matrix.

The top contact cell configuration has both 'n' and 'p' contacts on front or top surface of the solar cell, thereby making it adaptable to mandrel bridge fixturing. This cell configuration provided the best potential for the multicell arrangement and EOS adopted this JPL approved cell configuration for development into the electroformed interconnected matrix.

### 3.2.2 INTERCELL CONNECTOR CONSIDERATIONS

In order to interconnect solar cells by electroforming, the silicon wafers must be contacted electrically; this is most readily accomplished by means of a fixture mandrel. The function of the mandrel is twofold: first, to make electrical contact to the cell and, second, to provide a path or bridge to allow the electrodeposition to occur across the cells to create an interconnection.

The success of electrodeposited innerconnections is directly related to the fixture design and cell configuration, as well as the electrochemical plating techniques.

EOS has successfully demonstrated the plating techniques on single solar cells under Task I of this contract, and all experimental evidence has shown that these techniques are directly applicable to multicell arrangements. There is one basic difference when multicell arrangements are plated: the edge etch found necessary on single cells cannot be done in a practical manner on cell multiples. The elimination of stray aluminum overplate on the cell edges must therefore be solved by the fixture design. The problem becomes one of a fixture design problem, which relates directly to the cell configuration as follows:

### 3.2.3 MULTICELL ARRANGEMENT

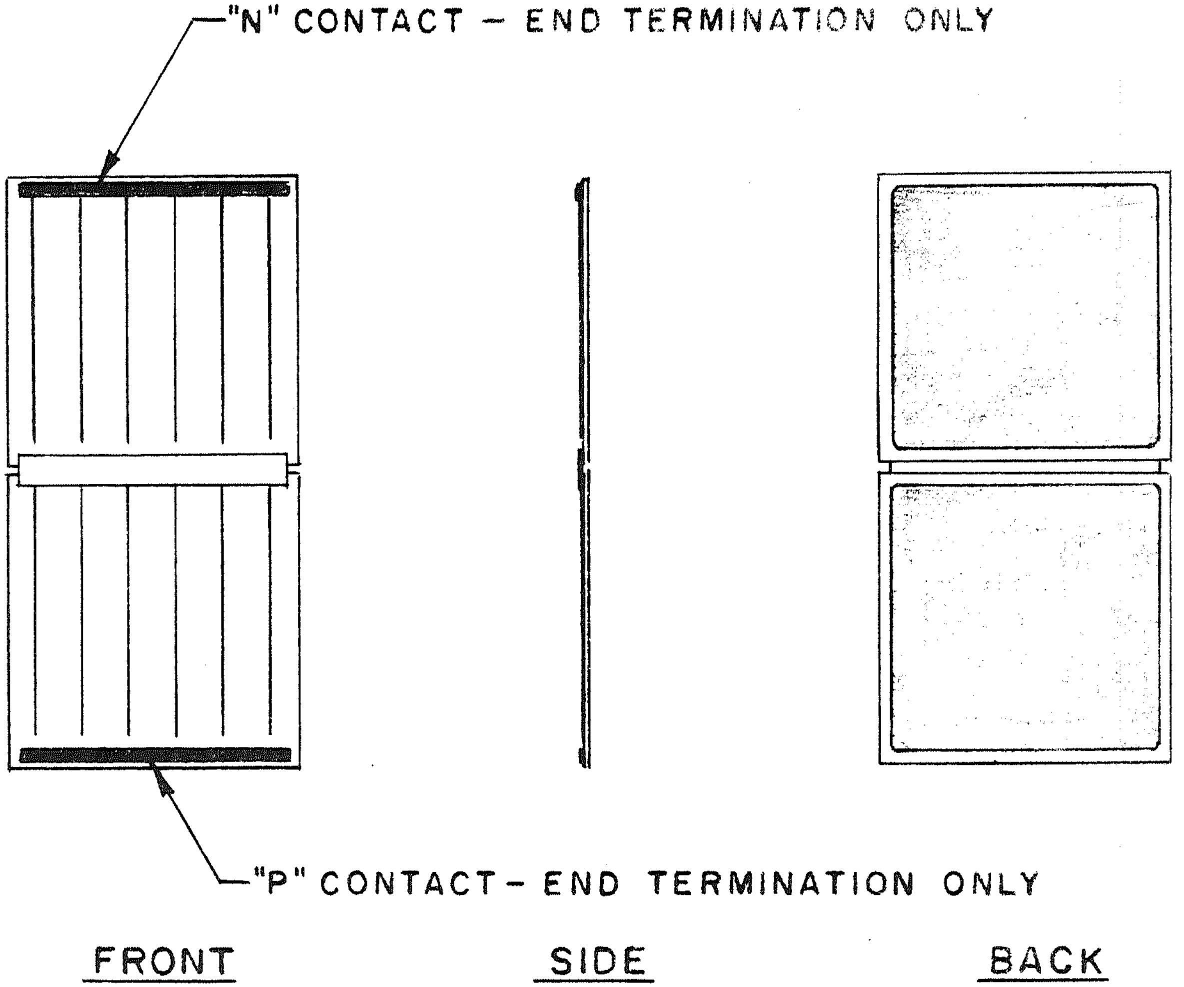
EOS, utilizing the top contact cell described in this report, electroformed integral aluminum solar cell interconnectors to form four cell matrices of two cells in parallel and two cells in series.

This electroforming development work was accomplished in two steps: First, two cells were interconnected in series utilizing an electroformed aluminum interconnector bridging across the top surfaces for essentially the full width of the cells, as illustrated in Fig. 3-4. This was accomplished using a full width mandrel bridge between the cells.

The second step was to electroform four cells, two cells in parallel and two cells in series, into a single matrix, as illustrated in Figs. 3-5 and 3-6. The parallel interconnector can be electroformed on the back side of the cells for essentially the full width of the cell, thus having both series and parallel interconnections the maximum width consistent with the cell size, and also in two different planes for maximum matrix stability.

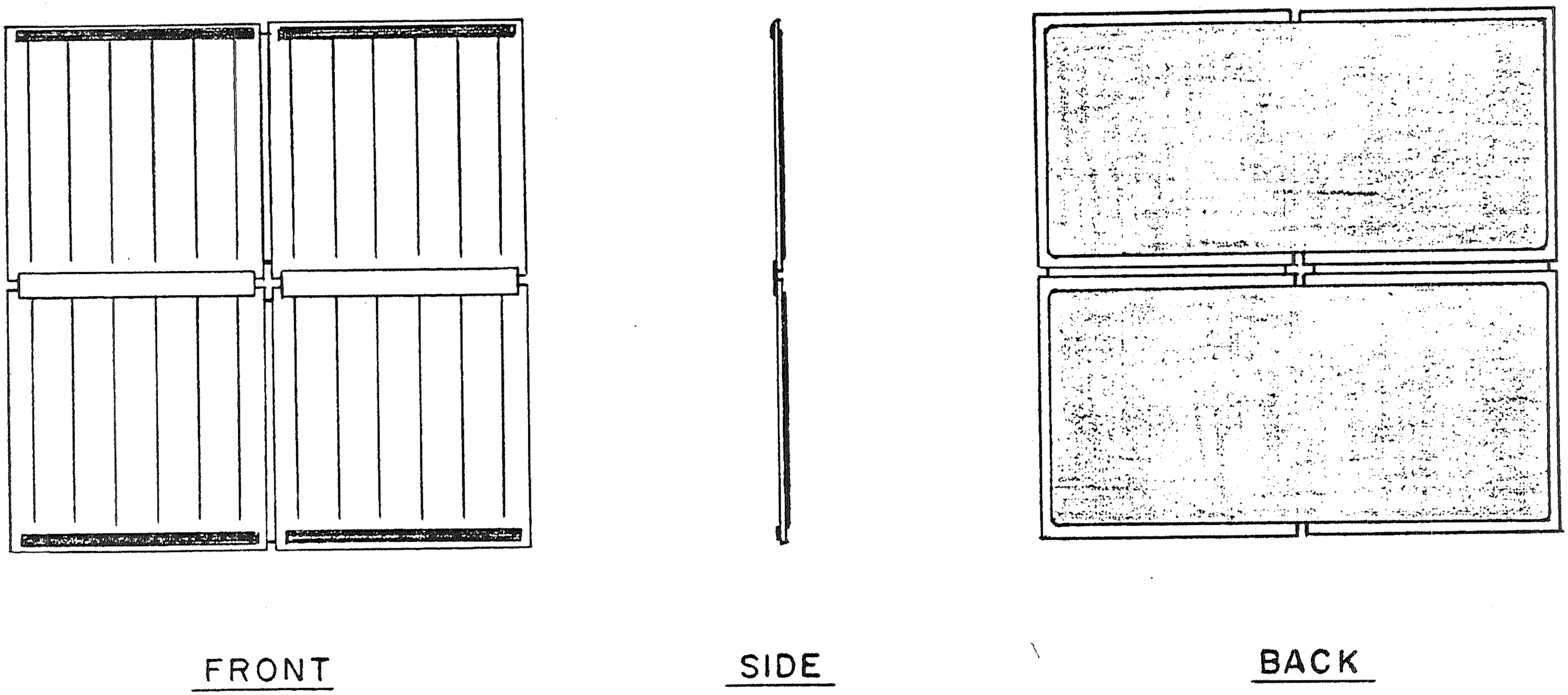
## 3.3 FIXTURE DESIGN

During the electroplating of individual cells in Task I, the cells were individually held in a plating fixture. The fixture provided the cathode connection to the cell necessary for the plating action. The fixture also provides a convenient means of containing the cell in the desired position with respect to the anodes.



TWO CELL INTERCONNECTED MATRIX

Figure 3-4



FOUR CELL INTERCONNECTED MATRIX

Figure 3-5

670 21

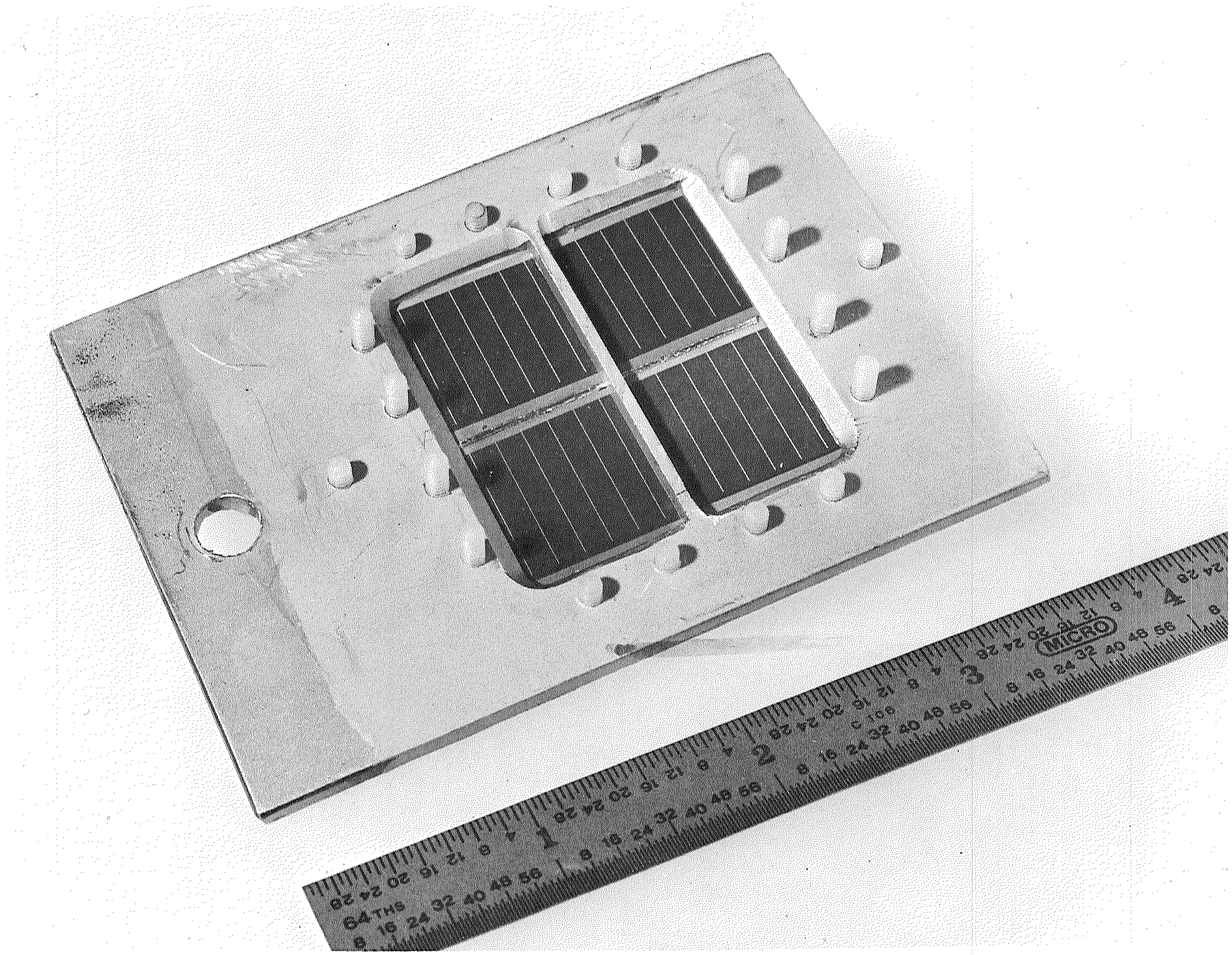


Figure 3-6. Typical Aluminum Electroformed 4-Cell Matrix, Fabricated at EOS

It became apparent at the outset of Task II that plating multiples of cells would require a fixture that would not only contain the cells and provide an electrical conductive path, but would also provide a bridging mandrel.

Early experiments were tried where the cells were positioned on a copper plate and tightly butted together to create a minimum gap between the cell edges. These cells were plated and the aluminum was allowed to build up to jump the gap between the butted cells in an attempt to get two cells interconnected. These attempts were a complete failure even though some success was obtained in plating cells together. The cells were tightly butted against each other and the electroplating had coated the edges shorting out the cells. The plating fixture had to provide a mandrel to form the spacing between the cells, Ref. Fig. 3-7. This type of fixture incorporating a gap mandrel would provide the spacing required; however, air gaps still remained between the cell edge and the fixture. These gaps were caused by the irregularities of the edge of the cell and the machining of the fixture itself.

All of the cell holding fixtures on Task I were machined from copper and Teflon-coated to prevent extraneous plating on the fixture and to prevent high conductivity of the copper from robbing the plating from the adjacent silicon surface. When a copper mandrel was tried for a two-cell interconnection, the top surface of the fixture mandrel was left uncoated to provide a plating path for the aluminum interconnection. When the cells were plated the high conductivity of the copper resulted in the aluminum plating on the mandrel surface and no plating on the silicon blanks with no interconnection.

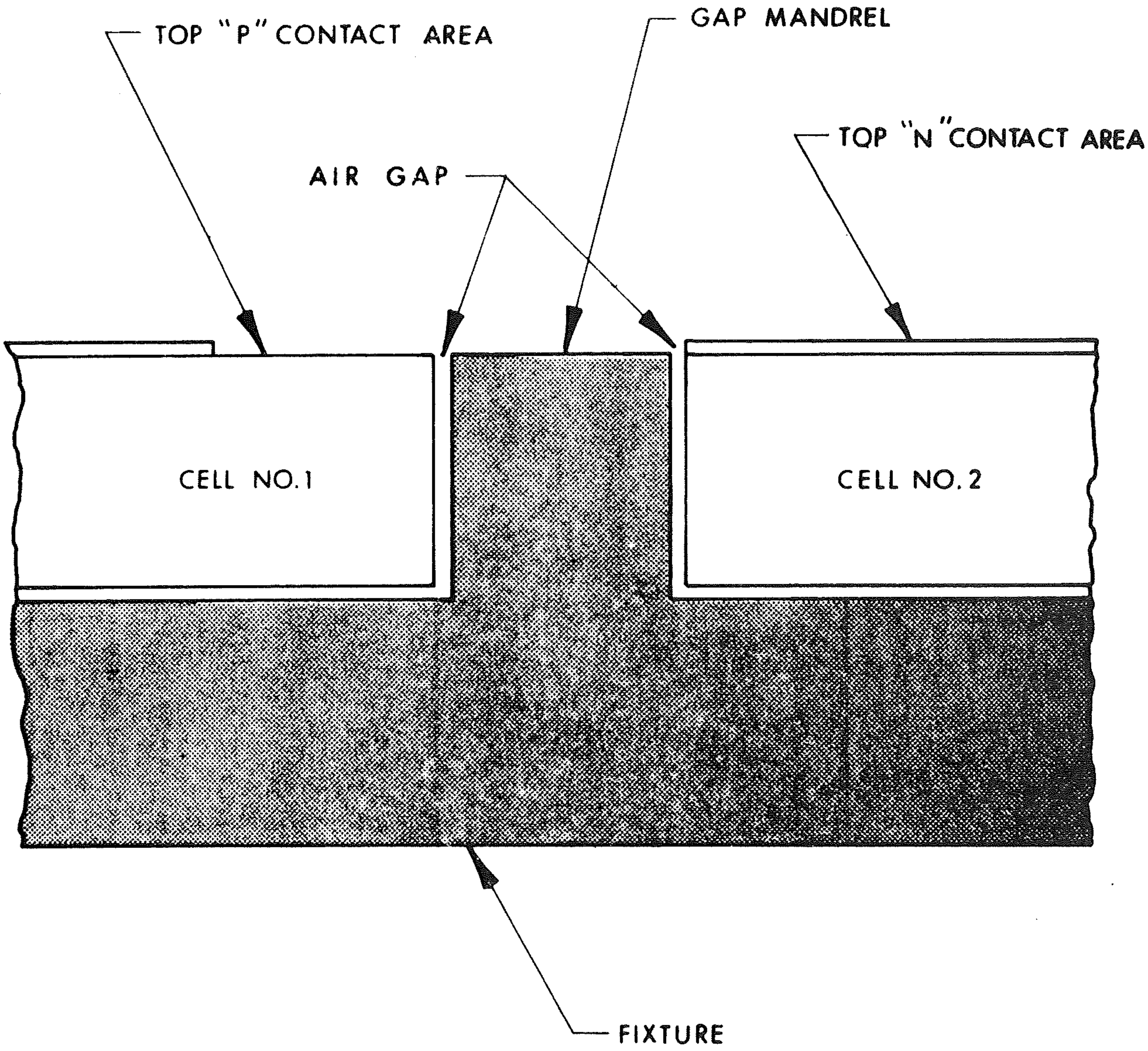


Figure 3-7. Section Through Plating Fixture Showing Cell and Mandrel Relationship

An attempt was made to correct both the fixture conductivity and air gap problem by making the fixture out of a blend of carbon filled polyethylene, and molded on the cell blanks to obtain intimate contact to the cell edges.

The silicon blanks were placed on a thermally controllable platen, and a carbon polyethylene powder mixture was spread on top of the silicon blanks completely covering them. The temperature of the platen was increased to fuse the polyethylene, and simultaneously the carbon-filled polyethylene was flattened out by pressure exerted by means of a piston. The result was a sheet of carbon filled polyethylene studded with silicon blanks. In our experiments, we found polyethylene with 55 weight percent carbon loading has sufficient conductance to serve as plating mandrel. However, the aluminum electrodeposited on this conductive plastic was very porous and lacked mechanical strength. The molded polyethylene experiments were discontinued.

Molded metallic mandrels were investigated using various materials such as indium, soft solder, and Cerrobend. All of these were unsuccessful as the surface tension of the molten metals prevented them from wetting out the silicon and preventing the "air gap". No plating experiments were attempted with these mandrels.

The machined metallic fixture indicated the best feasibility toward obtaining an electroplated interconnection between two cell blanks. An attempt to overcome the copper conductivity problem was studied and alternate fixture materials were investigated. A mandrel was machined from a bismuth-tin alloy, "Cerrotru #281", which has a conductivity of 5% that of copper. This material would accept aluminum plating when flashed with gold. Sample cells, when plated on this mandrel, showed that an aluminum deposit could be made on the mandrel bridge without the robbing effect seen with copper. The gap between the mandrel bridge and the cell still presented a problem, however, as the plating in that area would be extremely thin and sometimes incomplete.

Further investigations showed that plating could be obtained using type 1100 aluminum for the plating mandrel. The aluminum has an electrical conductivity similar to copper; however, unlike copper it oxidizes quite readily and the surface oxide creates a condition suitable for plating, and one which the plated aluminum does not adhere to.

Aluminum has the advantage of being a stronger, more dimensionally stable material than the Cerrotru, and a plating fixture was machined from aluminum that would bridge two cells. This fixture would create two plated cells interconnected in either series or parallel configuration. This fixture is shown in Fig. 3-8, complete with the two anodes. The detail drawings of this fixture are shown in Figs. 3-9 3-10 and 3-11. This plating fixture masks all edges of the two cells being plated, preventing edge plating, except the two edges where the interconnections are formed. In this case only one edge needs to be protected, the n surface edge. This is necessary as it is impractical to edge etch the interconnected cells in the same manner as individual cells. Whereas this fixture design can solve the edge plating problem with one exception: it still has the "air gap" problem previously discussed. The gap problem warrants further discussion for it is actually a twofold problem. In order to plate an interconnection between two cells it is necessary to get the maximum plating activity at the edges of the cells to promote bridging, while at the same time the aluminum cannot be allowed to plate down the edge of the cell which contains the n contact; the edge plating will create a short in the cell.

47097

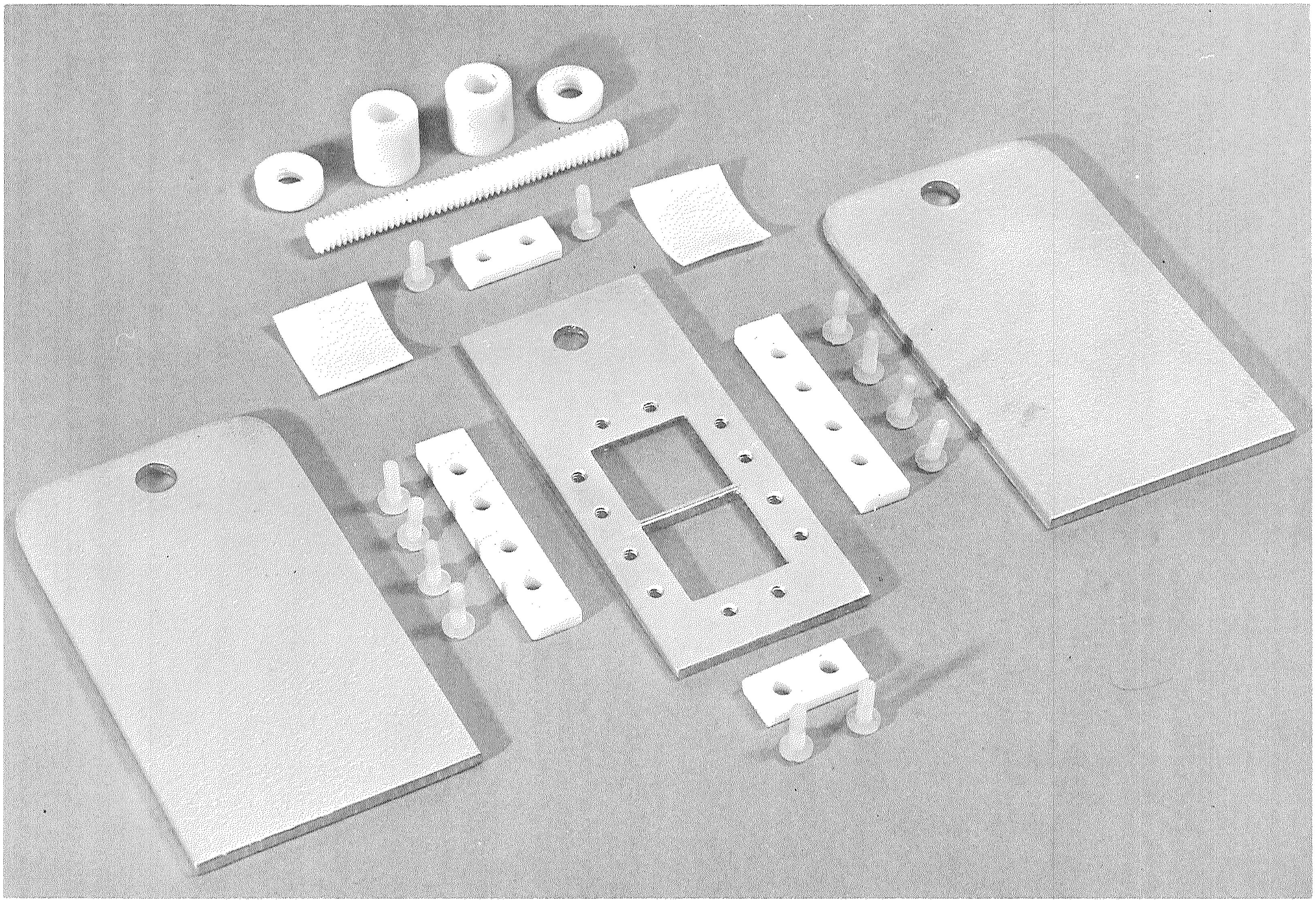


Figure 3-8. Two Cell Plating Fixture, with Anodes

SECURITY CLASSIFICATION

UNCLASSIFIED

| REVISIONS | | | | |
|---|---|---|---|---|
| ZONE | LTR | DESCRIPTION | DATE | APPROVED |
| | | | | |

NOTES: UNLESS OTHERWISE SPECIFIED

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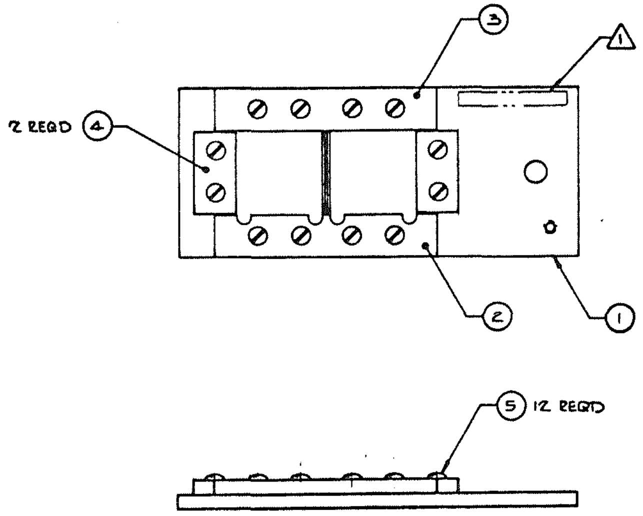


| QTY REQD | -1 | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | 6 |
| | 12 | | | | SCREW, PAN HD, 4-40UNC x 1/4 LG | MOLDED NYLON | MIL-M-20693 COMP A TYPE I | | | 5 |
| | 2 | | | 4039-113 | SUPPORT, SIDE | | | | | 4 |
| | 1 | | | 4039-112-1 | SUPPORT | | | | | 3 |
| | 1 | | | 4039-112-3 | SUPPORT | | | | | 2 |
| | 1 | | | 4039-111 | BASE PLATE | | | | | 1 |

LIST OF MATERIALS

| ON | THRU | PART DASH NO. | NEXT | FINAL | NEXT ASSY | USED ON |
|---|---|---|---|---|---|---|
| EFFECTIVE SERIAL NO. | | | QTY REQD PER ASSY | | APPLICATION | |
| USAGE DATA | | | DRAWING LEVEL | | | |

UNLESS OTHERWISE NOTED
LINEAR DIMS. IN INCHES
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ± ±
.XXX ± √ RMS
DO NOT SCALE

MATERIAL

TREATMENT/FINISH

SIMILAR TO | ACT. WT. | CALC. WT.

CONTRACT NO.
DRAWN Barnack DATE 3-7-70
CHECK R.W.
DESIGN
MFG.
DESIGN ACTIVITY APPD R. Wizemek 4/30/70
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
SOLAR CELL SUBMODULE,
ALUMINUM PLATING FIXTURE

DWG SIZE D | CODE IDENT NO. 12705 | DWG NO. 4039-110

SCALE 2/1 | RELEASE DATE | SHEET 1 OF 1

4039-110

Figure 3-9.

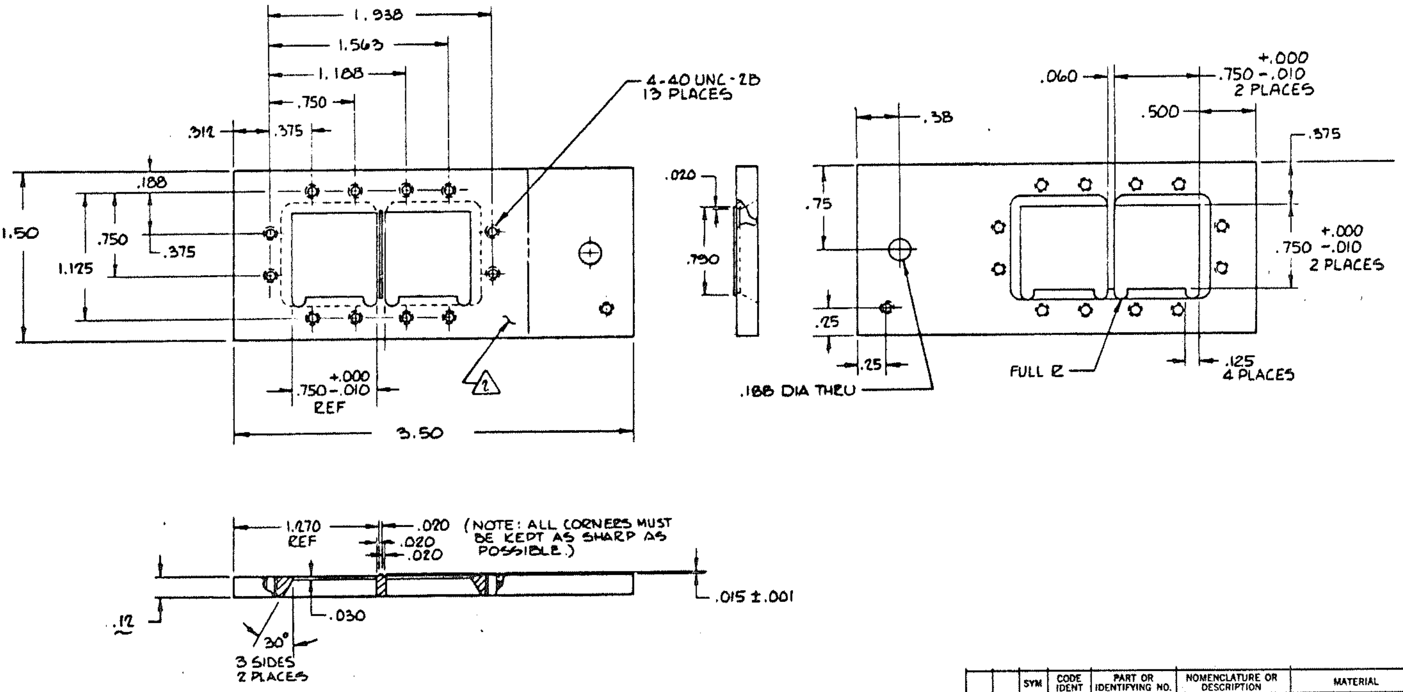
SECURITY CLASSIFICATION

UNCLASSIFIED

NOTES: UNLESS OTHERWISE SPECIFIED

1. REMOVE ALL BURRS & SHARP EDGES.

2. TEFLON COAT ALL SURFACES EXCEPT AREA & MACHINED RIDGE ON FRONT FACE OF PLATE DENOTED BY 2.



REVISIONS

| ZONE | LTR | DESCRIPTION | DATE | APPROVED |
|---|---|---|---|---|
| | | | | |

| | | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
|---|---|---|---|---|---|---|---|---|---|---|
| QTY REQD | | LIST OF MATERIALS | | | | | | | | |

UNLESS OTHERWISE NOTED LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL XX ± .01 XXX ± .005
FINISH 32 √ RMS
ANGULAR ± 0° 30'
DO NOT SCALE

MATERIAL 1100-H14 AL ALLOY PER QQ-A-561 C

TREATMENT/FINISH 2

SIMILAR TO | ACT. WT. | CALC. WT.

CONTRACT NO.
DRAWN Barnacle DATE 4-6-70
CHECK R.W.
DESIGN
MFG.
DESIGN ACTIVITY APPD R. Wizmmz 4/21/70
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
BASE PLATE,
SOLAR CELL SUBMODULE

DWG SIZE D | CODE IDENT NO. 12705 | DWG NO. 4039-111
SCALE 2/1 | RELEASE DATE | SHEET 1 OF 1

| | | | | | |
|---|---|---|---|---|---|
| | | | | 4039-110 | |
| ON | THRU | PART DASH NO. | NEXT / FINAL<br>QTY REQD PER ASSY | NEXT ASSY | USED ON |
| EFFECTIVE SERIAL NO. | | | | APPLICATION | |
| USAGE DATA | | DRAWING LEVEL | | | |

4039-111

Figure 3-10.

8 7 6 5 4 3 2 1

| REVISIONS | | | | |
|---|---|---|---|---|
| ZONE | LTR | DESCRIPTION | DATE | APPROVED |
| | | | | |

SECURITY CLASSIFICATION

UNCLASSIFIED

NOTES: UNLESS OTHERWISE SPECIFIED
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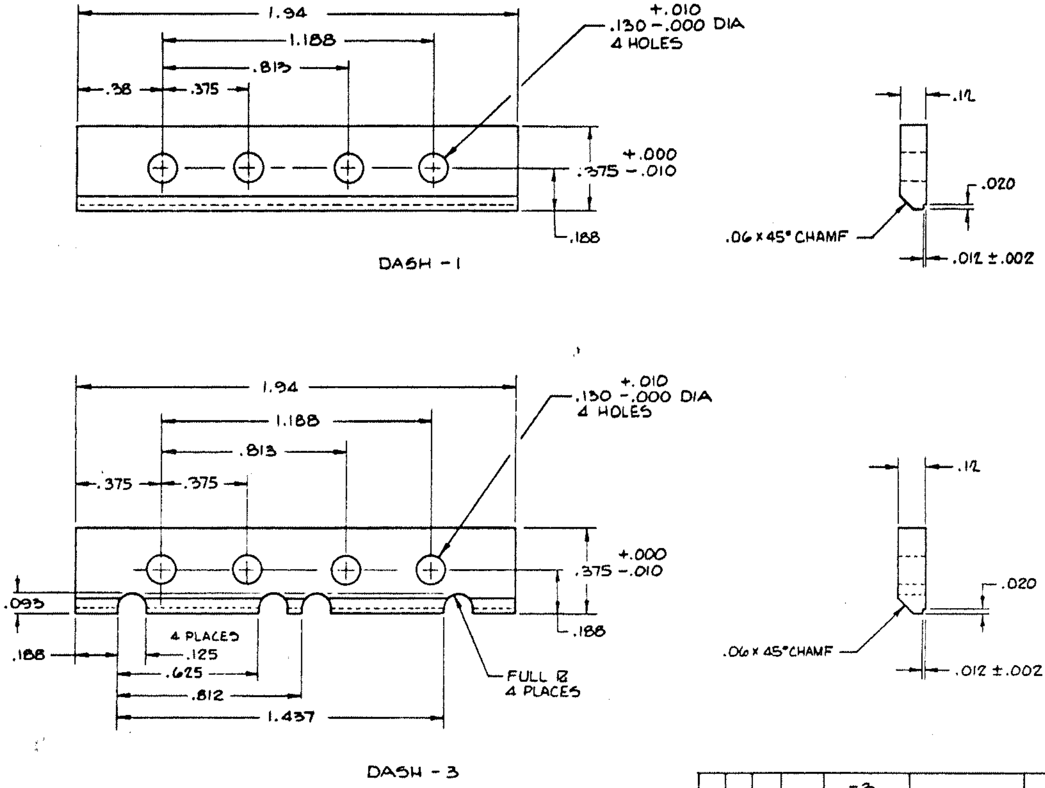

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| | | | | -3 | | TEFLON | MIL-P-22242 TYPE II | | | 2 |
| | | | | -1 | | TEFLON | MIL-P-22242 TYPE II | | | 1 |

QTY REQD — LIST OF MATERIALS

| | | | | | | |
|---|---|---|---|---|---|---|
| | | — | — | — | 4039-110 | — |
| ON | THRU | PART DASH NO. | NEXT | FINAL | NEXT ASSY | USED ON |
| EFFECTIVE SERIAL NO. | | | QTY REQD PER ASSY | | APPLICATION | |
| USAGE DATA | | DRAWING LEVEL | | | | |

UNLESS OTHERWISE NOTED
LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ± .01 — ± —
.XXX ± .005 √ RMS
DO NOT SCALE

MATERIAL

TREATMENT/FINISH

SIMILAR TO | ACT. WT. | CALC. WT.

CONTRACT NO.
DRAWN Gu Sarmack DATE 2-6-70
CHECK Rou.
DESIGN
MFG.
DESIGN ACTIVITY APPD R. Wizziner 4/30/70
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
SUPPORT,
SOLAR CELL SUBMODULE

DWG SIZE D | CODE IDENT NO. 12705 | DWG NO. 4039-112

SCALE 4/1 | RELEASE DATE | SHEET 1 OF 1

Figure 3-11.

At the suggestion of JPL, EOS investigated using a metallic foil to aid the electroformed bridge. Two basic types of foil configurations were tried: a flat, and 'U' bend. The materials used were copper, gold plated copper, and aluminum foils. None of the flat foils plated over successfully, as it was difficult to keep the foil flush with the face of the cell. The unplated copper foils had the robbing effect which could be expected, and the gold plated copper was the same result.

The 'U' bend configuration showed the best result with the aluminum foil and excellent interconnection bridges were electroplated between p and p contacts, parallel interconnections. The soft 1-mil-thick aluminum foil serves as a gasket between the cell edge and the fixture mandrel, Ref. Fig. 3-12. The use of the aluminum foil gasketing was further expanded to facilitate the more complicated series interconnection. In this case the foil served to not only act as a gasket as described above, but also as a mask to prevent electroplating of the n/p juction on the corner edge of the cell, Ref. Fig. 3-13. This 'S' bend foil configuration was used to electroform series interconnections between cells, and proved to be a satisfactory masking technique.

The development of the 2-cell fixture leads directly to the design adaptation of the 4-cell series/parallel matrix plating fixture. This fixture, complete with its plating anodes, is shown in Fig. 3-14. The assembled fixture ready for plating is shown in Fig. 3-15. The detail drawings of this fixture are shown in Figs. 3-16, 3-17, 3-18, and 3-19.

## 3.4 ELECTROPLATING PROCESS

### 3.4.1 PROCESS

The electroplating process specification 4039-MP-II, Ref. Appendix D, gives the complete process description for making the 4-cell series/parallel matrix as required in Task II of this program, and differs from Task I individual procedure in three basic areas as follows.

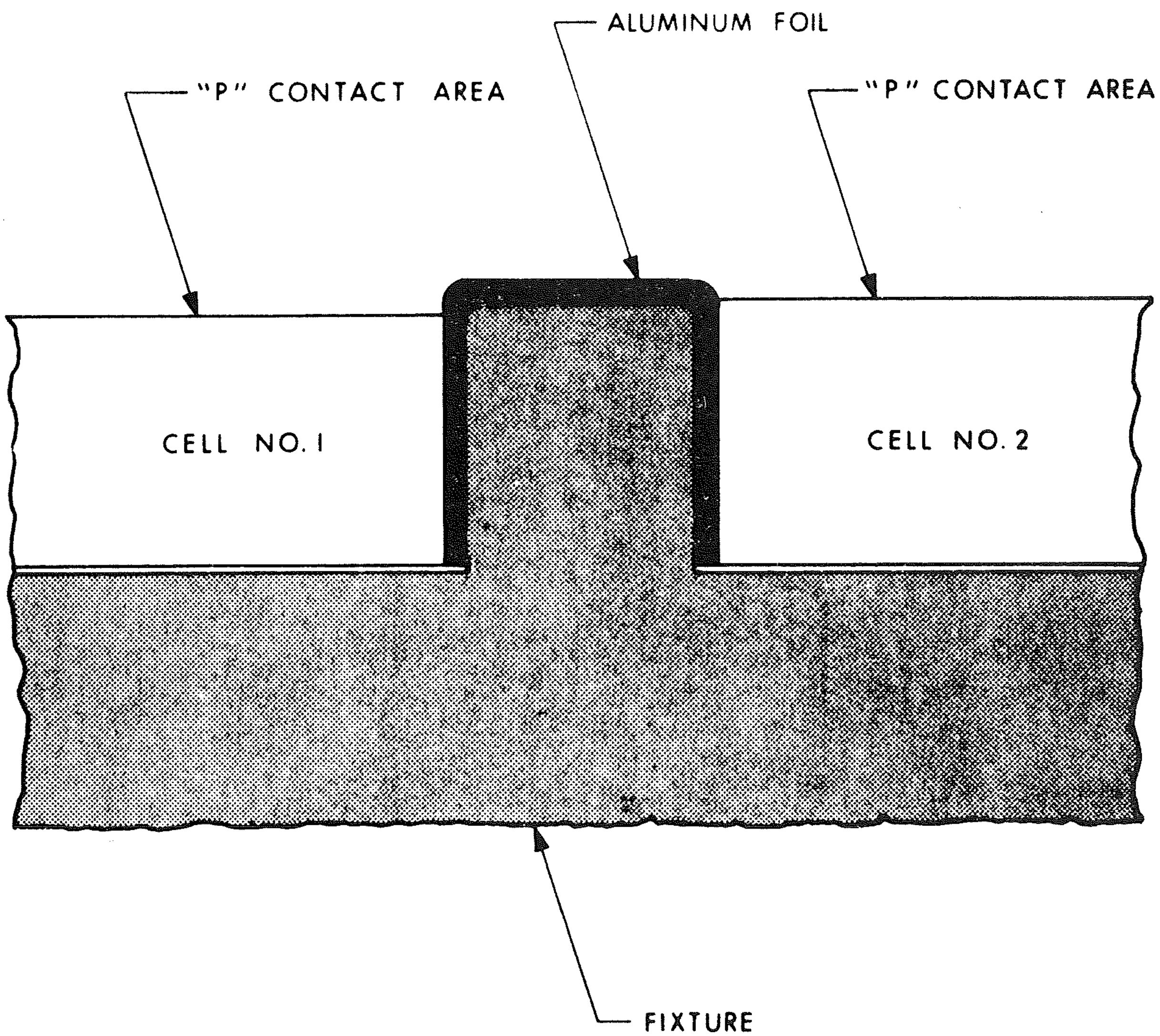

Figure 3-12. Section Through Plating Fixture Showing Foil Position for Parallel Interconnection Plating

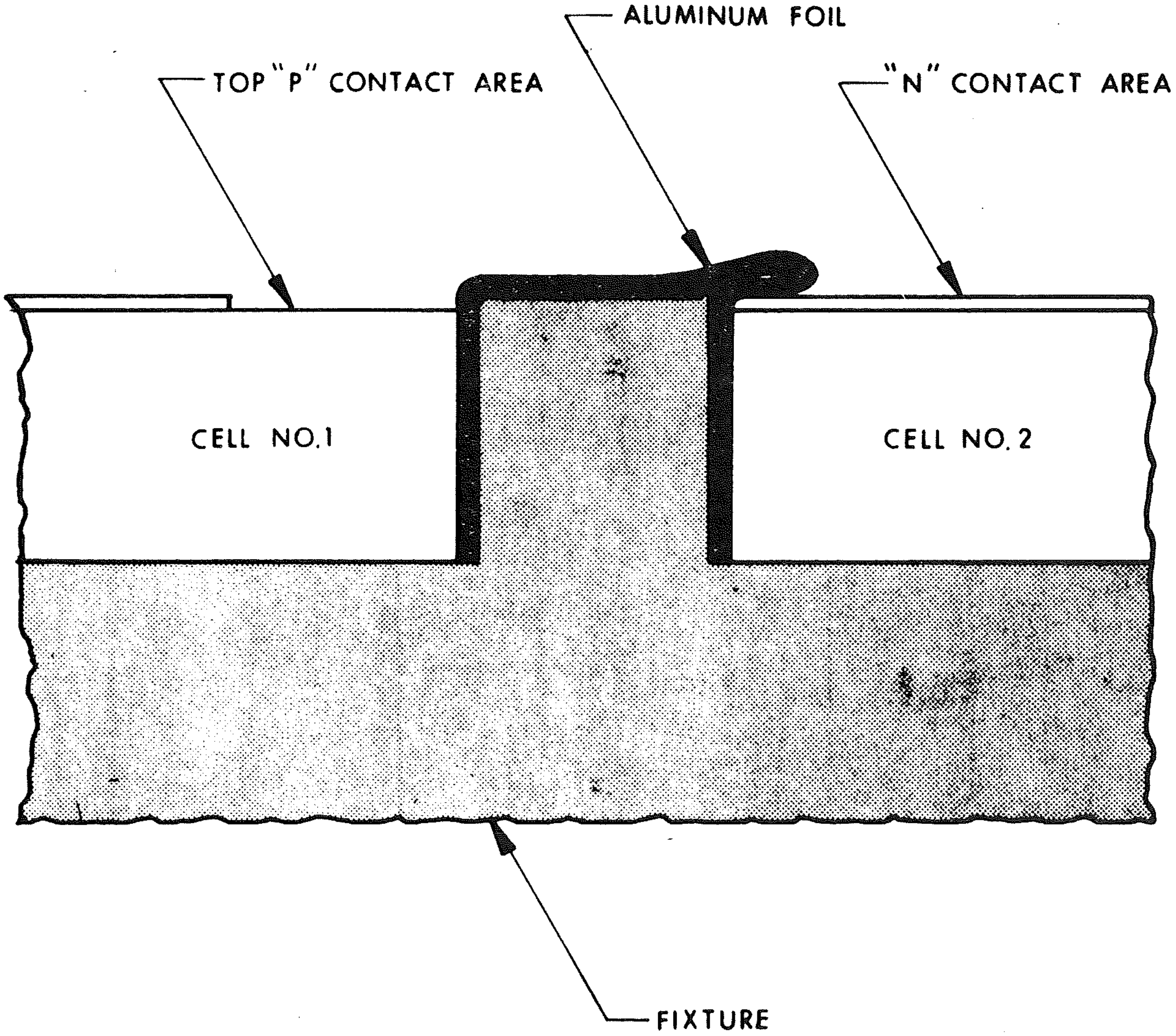

Figure 3-13. Section Through Plating Fixture Showing Foil Position for Series Interconnection Plating

37265

47698

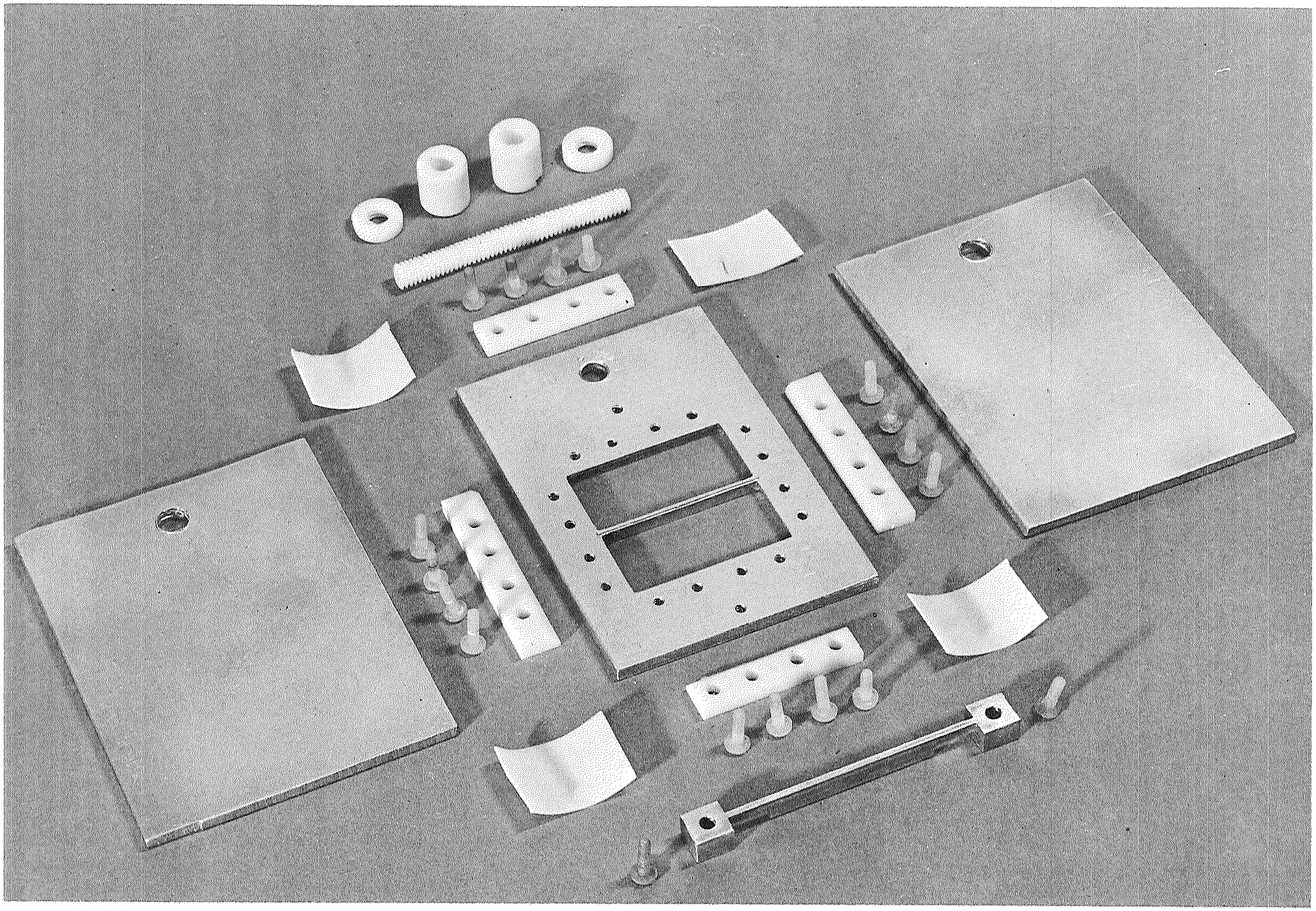

Figure 3-14. Four Cell Plating Fixture, with Anodes

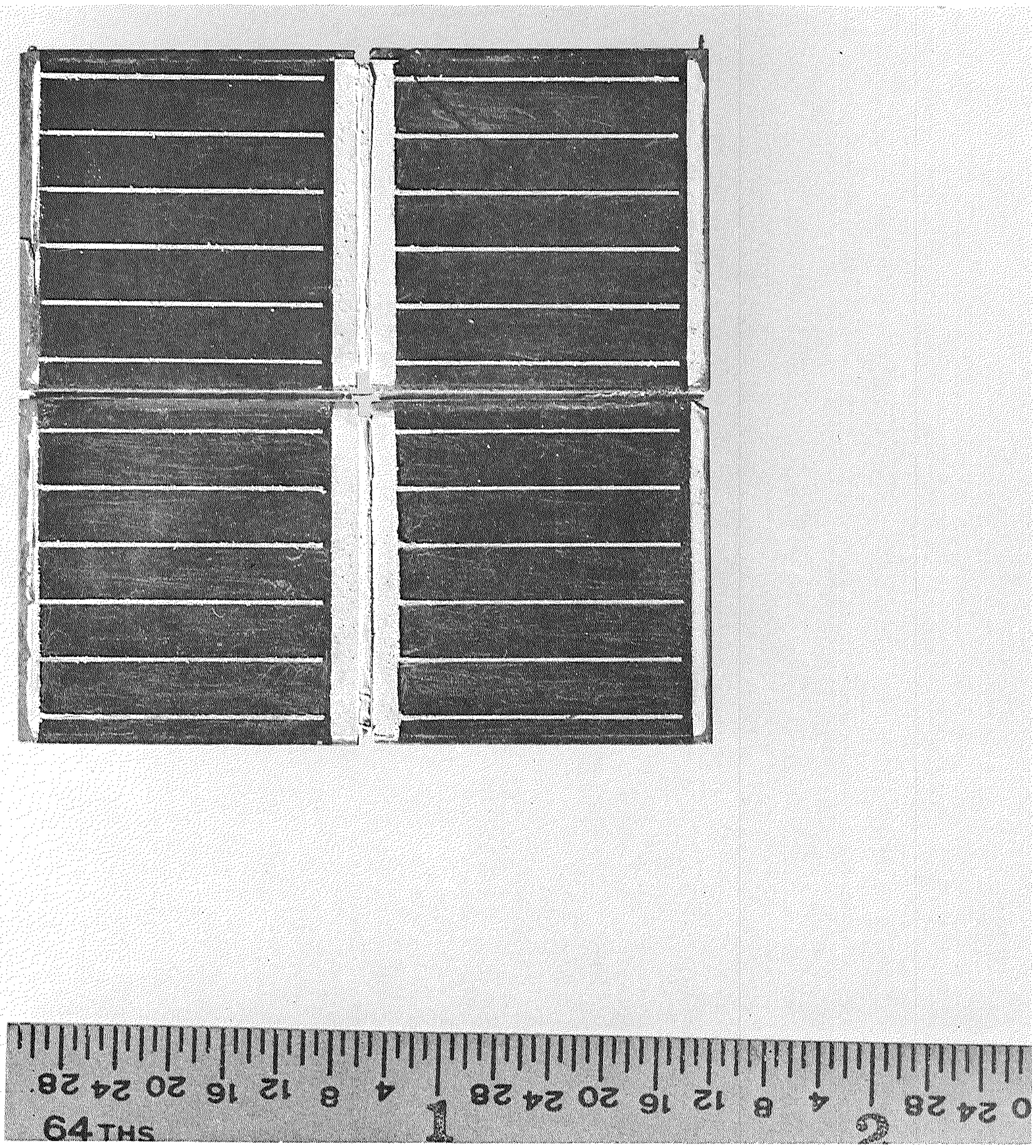

Figure 3-15. Assembled Four Cell Plating Fixture Ready for Plating

SECURITY CLASSIFICATION

UNCLASSIFIED

| ZONE | LTR | REVISIONS DESCRIPTION | DATE | APPROVED |
|---|---|---|---|---|
| | | | | |

NOTES: UNLESS OTHERWISE SPECIFIED

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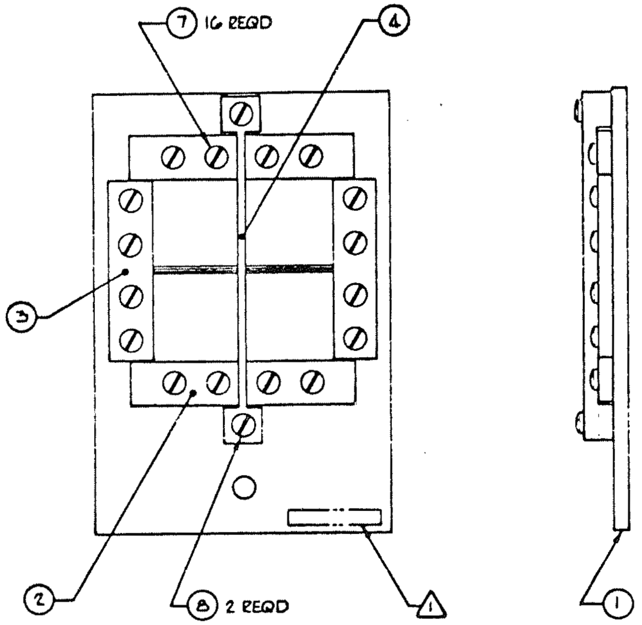

| QTY REQD | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
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| | | | | | | | | | 9 |
| 2 | | | | SCREW, PAN HD. 4-40 UNC×3/8 LG | MOLDED NYLON | MIL-M-20693 COMP A TYPE I | | | 8 |
| 16 | | | | SCREW, PAN HD. 4-40 UNC×1/4 LG | MOLDED NYLON | MIL-M-20693 COMP A TYPE I | | | 7 |
| | | | | | | | | | 6 |
| | | | | | | | | | 5 |
| 1 | | | 4039-117 | DIVIDER | | | | | 4 |
| 2 | | | 4039-116-3 | SUPPORT | | | | | 3 |
| 2 | | | 4039-116-1 | SUPPORT | | | | | 2 |
| 1 | | | 4039-115 | BASE PLATE | | | | | 1 |

LIST OF MATERIALS

| NEXT ASSY | USED ON |
|---|---|
| APPLICATION | |

ON | THRU | PART DASH NO. | NEXT FINAL QTY REQD PER ASSY
EFFECTIVE SERIAL NO.
USAGE DATA
DRAWING LEVEL

UNLESS OTHERWISE NOTED
LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ±
.XXX ± ✓ RMS ±
DO NOT SCALE
MATERIAL
TREATMENT/FINISH
SIMILAR TO
ACT. WT. CALC. WT.

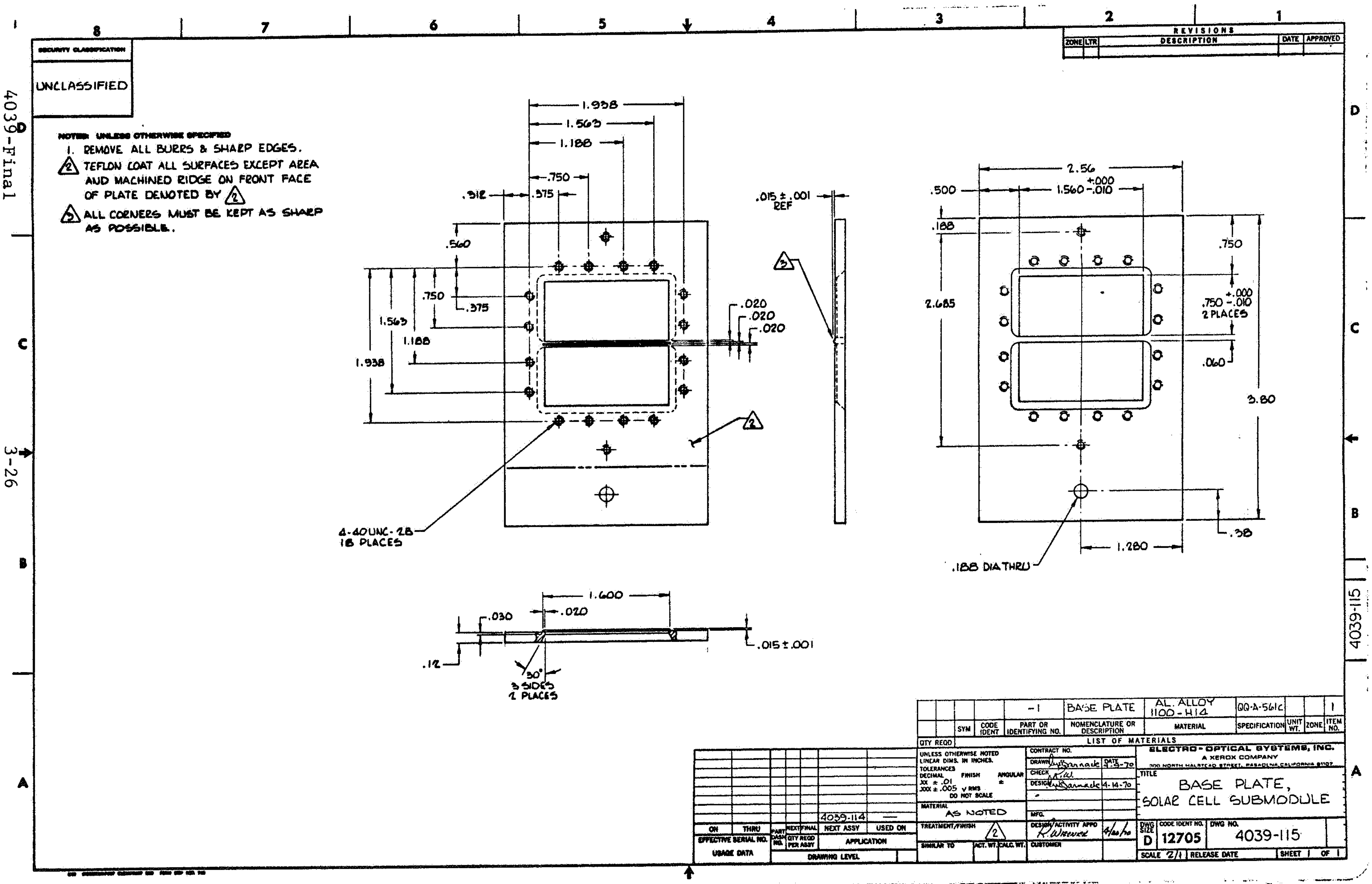
CONTRACT NO.
DRAWN Lymmack DATE 9-F-70
CHECK R.W.
DESIGN Lymmack 4-14-70
MFG.
DESIGN ACTIVITY APPD R. Warner 4/16/70
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
[illegible]

TITLE
FIXTURE ASSEMBLY,
SOLAR CELL SUBMODULE

DWG SIZE D
CODE IDENT NO. 12705
DWG NO. 4039-114
SCALE 2/1
RELEASE DATE
SHEET 1 OF 1

Figure 3-16


UNCLASSIFIED
SECURITY CLASSIFICATION
REVISIONS
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2 TEFLON COAT ALL SURFACES EXCEPT AREA AND MACHINED RIDGE ON FRONT FACE OF PLATE DENOTED BY 2
3 ALL CORNERS MUST BE KEPT AS SHARP AS POSSIBLE.
1.938
1.563
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.750
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.750
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1.563
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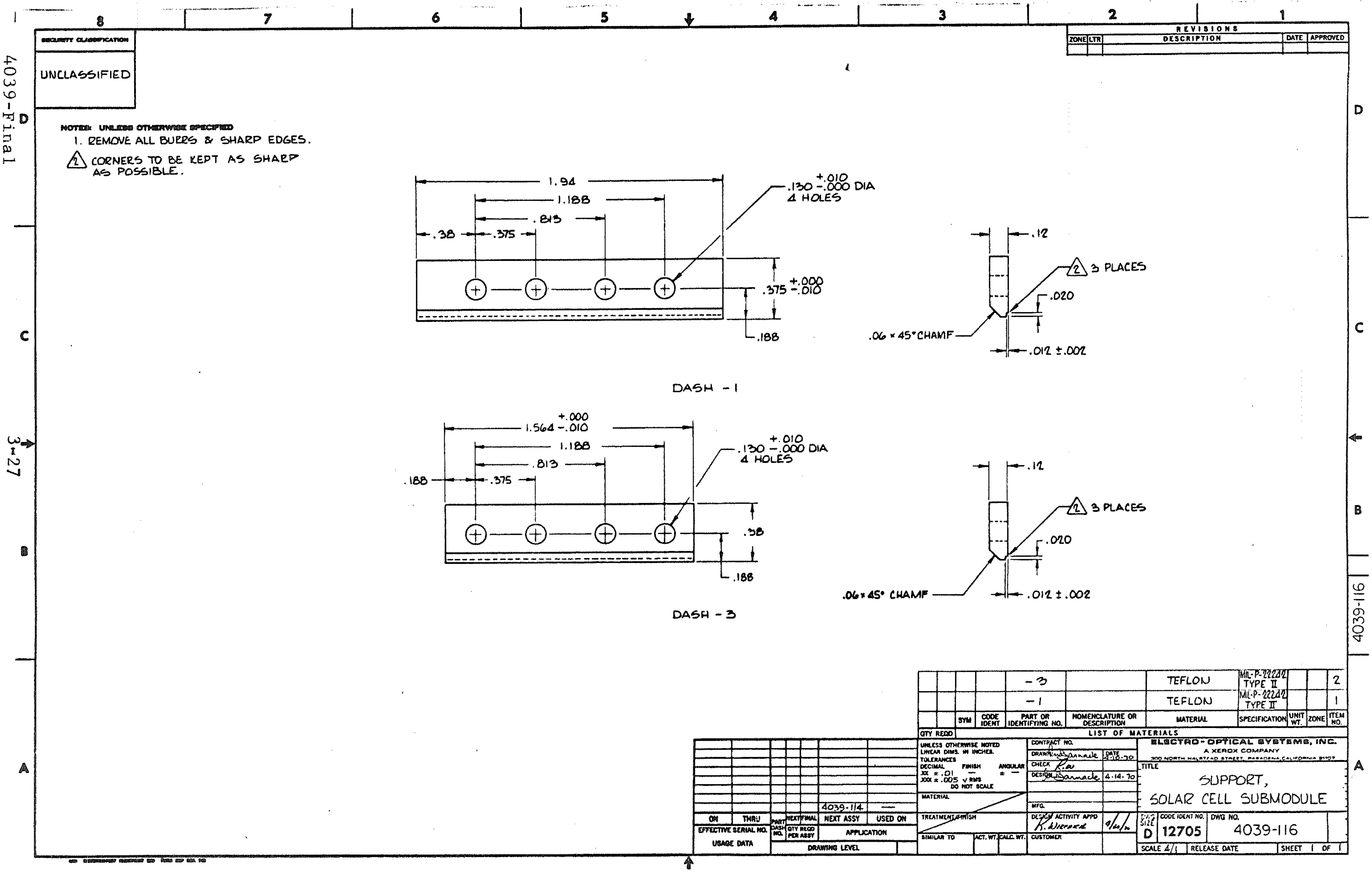
4-40UNC-2B 18 PLACES
2.56
.500
1.560 +.000 -.010
.188
2.685
.750
.750 +.000 -.010 2 PLACES
.060
3.80
.38
1.280
.188 DIA THRU
1.600
.030
.020
.015 ± .001
.12
30°
3 SIDES 2 PLACES
-1
BASE PLATE
AL. ALLOY 1100-H14
QQ-A-561c
1
QTY REQD
SYM
CODE IDENT
PART OR IDENTIFYING NO.
NOMENCLATURE OR DESCRIPTION
MATERIAL
SPECIFICATION
UNIT WT.
ZONE
ITEM NO.
LIST OF MATERIALS
UNLESS OTHERWISE NOTED LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ± .01
.XXX ± .005 √ RMS ±
DO NOT SCALE
MATERIAL
AS NOTED
TREATMENT/FINISH 2
SIMILAR TO
ACT. WT.
CALC. WT.
CONTRACT NO.
DRAWN Barnade DATE 4-9-70
CHECK R.W.
DESIGN Barnade 4-14-70
MFG.
DESIGN ACTIVITY APPD R. Wrenn 4/20/70
CUSTOMER
ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107
TITLE
BASE PLATE, SOLAR CELL SUBMODULE
DWG SIZE D
CODE IDENT NO. 12705
DWG NO. 4039-115
SCALE 2/1
RELEASE DATE
SHEET 1 OF 1
4039-114
NEXT ASSY
USED ON
ON
THRU
EFFECTIVE SERIAL NO.
USAGE DATA
PART DASH NO.
NEXT
FINAL
QTY REQD PER ASSY
APPLICATION
DRAWING LEVEL
4039-115
1 2 3 4 5 6 7 8
A B C D

Figure 3-17


UNCLASSIFIED
NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & SHARP EDGES.
2 CORNERS TO BE KEPT AS SHARP AS POSSIBLE.
1.94
1.188
.813
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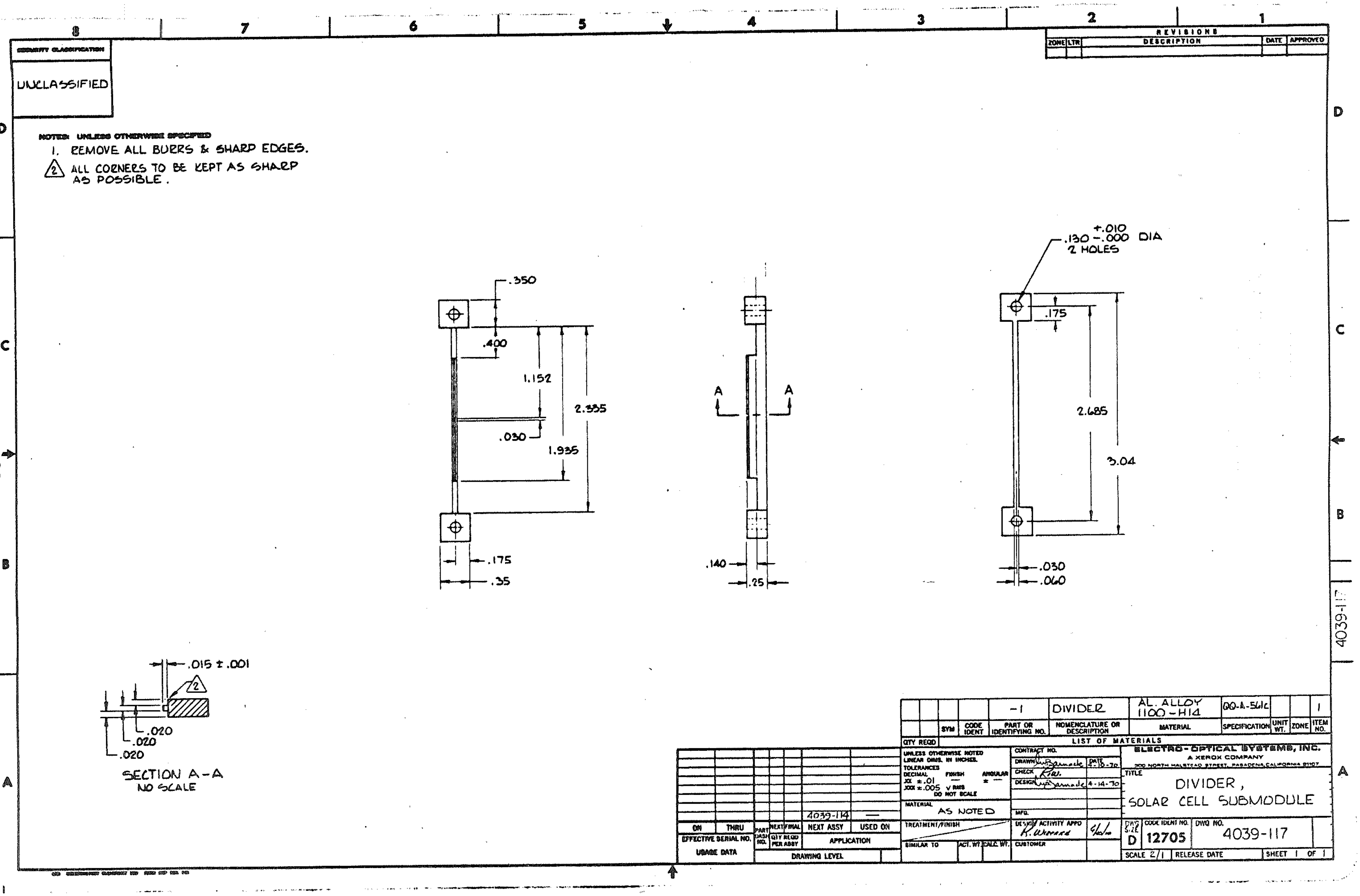
.130 +.010 -.000 DIA 4 HOLES
.375 +.000 -.010
.188
.12
2 3 PLACES
.020
.06 × 45° CHAMF
.012 ±.002
DASH -1
1.564 +.000 -.010
1.188
.813
.188
.375
.130 +.010 -.000 DIA 4 HOLES
.38
.188
.12
2 3 PLACES
.020
.06 × 45° CHAMF
.012 ±.002
DASH -3
4039-116
-3 TEFLON MIL-P-22242 TYPE II 2
-1 TEFLON MIL-P-22242 TYPE II 1
LIST OF MATERIALS
UNLESS OTHERWISE NOTED LINEAR DIMS. IN INCHES.
TOLERANCES DECIMAL .XX ±.01 .XXX ±.005 FINISH √ RMS ANGULAR ± —
DO NOT SCALE
DATE 4-16-70
DESIGN 4-14-70
ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107
TITLE SUPPORT, SOLAR CELL SUBMODULE
DWG SIZE D
CODE IDENT NO. 12705
DWG NO. 4039-116
SCALE 4/1
SHEET 1 OF 1
4039-114

Figure 3-18.


UNCLASSIFIED
NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & SHARP EDGES.
2 ALL CORNERS TO BE KEPT AS SHARP AS POSSIBLE.
REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
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.400
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2.335
.030
1.935
.175
.35
A
A
.140
.25
.130 +.010 -.000 DIA 2 HOLES
.175
2.685
3.04
.030
.060
.015 ± .001
2
.020
.020
.020
SECTION A-A
NO SCALE
-1
DIVIDER
AL. ALLOY 1100-H14
QQ-A-561c
1
QTY REQD
SYM
CODE IDENT
PART OR IDENTIFYING NO.
NOMENCLATURE OR DESCRIPTION
MATERIAL
SPECIFICATION
UNIT WT.
ZONE
ITEM NO.
LIST OF MATERIALS
UNLESS OTHERWISE NOTED LINEAR DIMS. IN INCHES.
TOLERANCES DECIMAL XX ±.01 XXX ±.005
FINISH
ANGULAR ±
DO NOT SCALE
MATERIAL AS NOTED
TREATMENT/FINISH
SIMILAR TO
ACT. WT.
CALC. WT.
CONTRACT NO.
DRAWN Barnade DATE 4-10-70
CHECK Kw.
DESIGN Barnade 4-14-70
MFG.
DESIGN ACTIVITY APPD K. Wheeler 4/16/70
CUSTOMER
ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107
TITLE
DIVIDER, SOLAR CELL SUBMODULE
DWG SIZE D
CODE IDENT NO. 12705
DWG NO. 4039-117
SCALE 2/1
RELEASE DATE
SHEET 1 OF 1
4039-114
NEXT ASSY
USED ON
ON
THRU
EFFECTIVE SERIAL NO.
PART DASH NO.
NEXT
FINAL
QTY REQD PER ASSY
APPLICATION
USAGE DATA
DRAWING LEVEL
4039-117
8
7
6
5
4
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2
1
D
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B
A

Figure 3-19.

### 3.4.2 CONTACT THICKNESS

As described in Section 2 of this report, the optimum contact thickness determined for individual solar cells and for the matrix cells was 0.5 mils. However, to electroplate the interconnector thicker plating must be obtained. This thicker plating is required in the interconnector for two reasons: First, the 0.5 mil interconnected bridge between the cells would be too fragile, and second, as stated earlier, an air gap exists between the fixture and the cell edge which requires a buildup of plating to close. The use of the aluminum foil gasketing reduces the fixture "air gap" on typical plating set-ups to 0 to 1.0 mil; gaps typically being in the 0.5 to 1.0 range. It was empirically determined that a target interconnector thickness of 3.0 mils presented the best interconnection bridging. This thickness is too heavy for the grid lines of the cells. Therefore, a masking technique was developed by which, utilizing Teflon shims, the grid portion of the cells was masked during 80% of the plating time and unmasked for the final 20%, giving a grid line thickness of approximately 0.5 mils. This procedure was used successfully to plate the matrices during Task II.

### 3.4.3 DELETION OF SILICON MONOXIDE COATING

All the individual cells fabricated during the Task I effort of this program had a silicon monoxide (SiO) antireflective coating applied after aluminum plating. One of the goals of Task II was to eliminate the SiO coating, thus eliminating the necessity of removing the diffusion oxide coating from the cell prior to KMER masking, and then reapplying an antireflective coating. This change was desirable as a cost saving and process simplification; since applying SiO coating to a large matrix of cells, as described under Task III, would be difficult.

The use of the phosphor-silicate glass (diffusion oxide) coating, which is naturally deposited on the cell as an antireflection coating during the diffusion process, is not new. This coating was used as the standard antireflective coating for nickel plated n/p solar cells by Hoffman Electronics for approximately two years, and proved quite satisfactory. It was abandoned as an antireflective coating when the evaporated silver-titanium solar cells were developed, only due to mechanical registration problems of the evaporation process.

Test results of five aluminum electroplated top contact solar cells are shown in Table 3-I. The test data were obtained in a tungsten simulator at a light intensity of 100 $mW/cm^2$ and a temperature of 28°C. The test consisted of measuring the $I_{sc}$ of a diffusion glass coated solar cell first; then filtering the cell and remeasuring the $I_{sc}$. The filter was then removed and the adhesive cleaned off the cell; then the diffusion glass coating was etched off the cell with hydrofluoric acid, and the cell was washed and dried and remeasured for $I_{sc}$.

TABLE 3-I

$I_{sc}$ OF TEST CELLS (mA)

| Cell No. | $I_{sc}$ (1) | $I_{sc}$ (2) | $\Delta$ (1-2) | $\Delta$% (1-2) | $I_{sc}$ (3) | $\Delta$ (1-3) | $\Delta$% (1-3) |
|---|---|---|---|---|---|---|---|
| 1 | 97.5 | 105.6 | 8.1 | 8.30 | 114.6 | 17.1 | 17.53 |
| 2 | 100.1 | 106.7 | 6.6 | 6.57 | 113.4 | 13.3 | 13.29 |
| 3 | 103.8 | 111.6 | 7.8 | 7.51 | 118.7 | 14.9 | 14.35 |
| 4 | 100.5 | 107.9 | 7.4 | 7.36 | 114.2 | 13.7 | 13.62 |
| 5 | 99.4 | 106.2 | 6.8 | 6.84 | 116.2 | 16.8 | 16.90 |
| Average % $\Delta$ | | | | 7.34 | | | 15.14 |

(1) $I_{sc}$ of cell with bare 'n' surface

(2) $I_{sc}$ of cell with diffusion glass coating on 'n' surface

(3) $I_{sc}$ of cell with diffusion glass and OCLI filter type B-SCC(400)-FS-C, (12 mil thick) installed with RTV-602 adhesive.

This compares with an average $\Delta I_{sc}$ of 25 individual solar cells fabricated during Task I of 15.4 percent change in $I_{sc}$ as a result of silicon monoxide (AR) coating.

Therefore, while the bare cell to diffusion glass coating percent change averaged only 7.34 percent, this percentage change was increased to 15.14 percent when the cells were filtered, which is comparable to the silicon monoxide (AR) coating previously used.

### 3.4.4 SINTERING

All attempts to sinter electroformed aluminum solar cell interconnected matrices resulted in the 3 to 4 mil aluminum plating peeling from the silicon. The peeled aluminum contacts characteristically pulled chunks of silicon from the cells.

An analysis of the plating thickness versus thermal expansion of silicon and aluminum was performed. It showed that an aluminum plating thickness of approximately 2.5 mils was the limiting thickness for the existing sintering $\Delta T$ of $320-25 = 295^{\circ}C$ or $531^{\circ}F$. This limitation is shown in Fig. 3-20.

Contact pull tests on 5 unsintered cells gave the following results:

| Cell No. | Plating Thickness | Pull Strength (grams) |
|---|---|---|
| 1 | 4 mils | 1500 |
| 2 | 4 mils | 1500 |
| 3 | 4 mils | 1500 |
| 4 | 3 mils | 1250 |
| 5 | 2 mils | 500 |

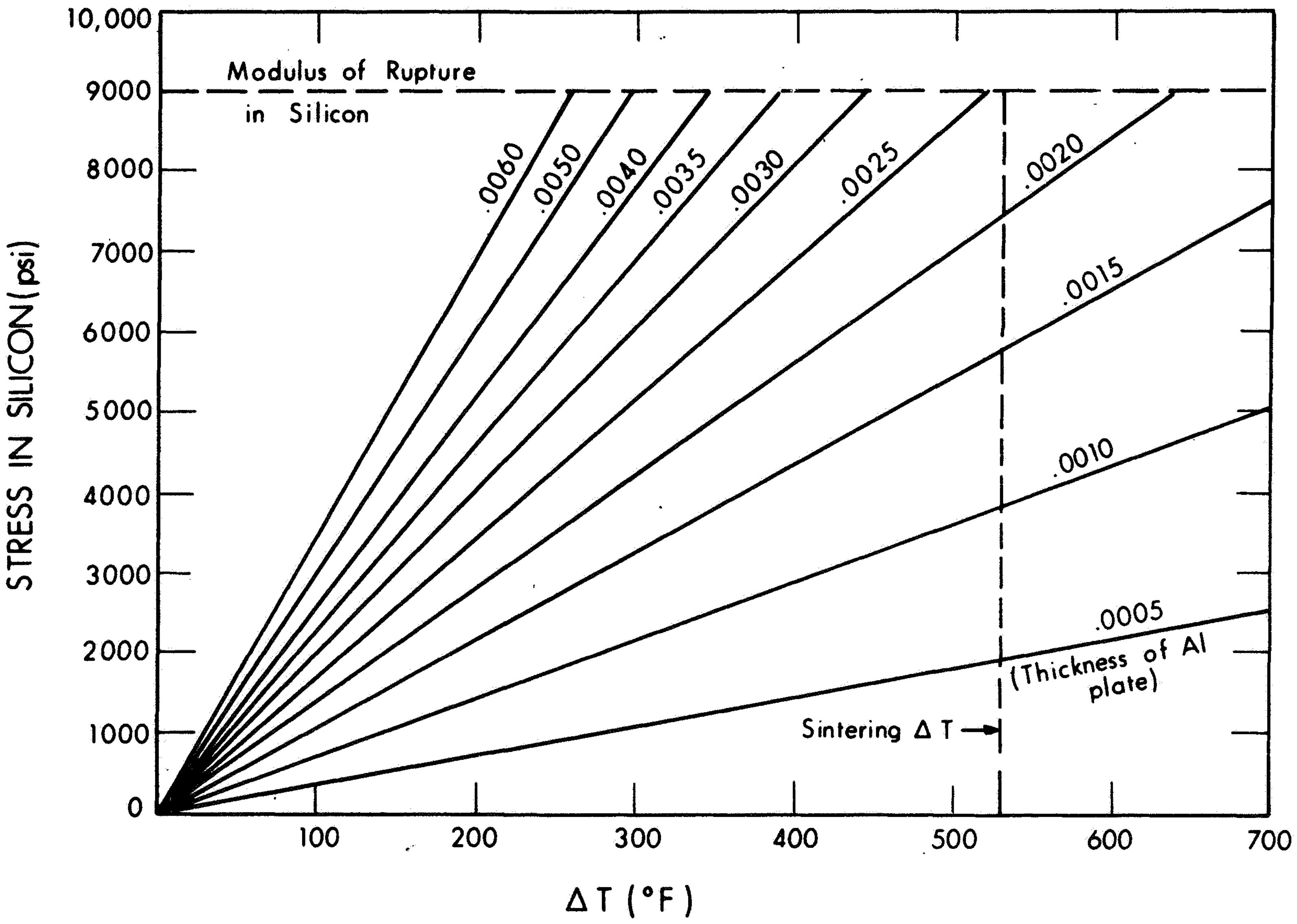


Figure 3-20. Aluminum Plated Thickness versus Silicon Stress With Respect to Temperature

All pull tests were performed on the 'p' contacts using No. 26GA wire soldered to the contact and pulled at right angles to the cell surface until failure.

The sintering operation has been deleted from the matrix process specification. However, EOS believes that additional studies should be made in this area to determine the effects of lower temperature sintering operations.

## 3.5 MATRIX TESTING

The matrix testing as required by the contract was not performed because a sufficient number of four cell matrices could not be prepared within the time and funding limitations of the program.

## 3.6 MATRIX EVALUATION

The fabrication of aluminum electroformed interconnector solar cell matrices has been demonstrated in this program. The complexity of this fabrication technique proved to be more difficult than originally envisioned at the inception of this work. The following evaluation is made with respect to the matrices.

### 3.6.1 EFFECTS ON SOLAR CELL CURRENT VOLTAGE CHARACTERISTICS

A review of the I-V curves of the individual solar cells fabricated in Task I shows that short circuit currents and open circuit voltages of the aluminum plated cells are comparable with conventional n/p evaporated contact solar cells. The power point measurements are significantly lower, due to higher internal series resistance in the cell, causing a soft knee in the curve. This soft knee is typical of a lapped finished plated solar cell; the original nickel plated n/p solar cells had the same problems. The polished surface silver-titanium evaporated and sintered solar cell was in part developed specifically to overcome this problem; therefore, without a polished surface a soft knee in the I-V curve will be typical.

Two additional effects are present in the multicell matrix. First, the matrix requires a top contact cell configuration which reduces the available active area and, consequently, the cells short circuit current potential. Secondly, the inability to sinter the heavier plating on the matrix increases the series resistance which is detrimental to the I-V curve shape. It is possible that further studies may be able to overcome this problem.

### 3.6.2 ARRAY COMPATIBILITY

The series/parallel matrix configuration was designed to be typical of flat mounted conventionally soldered solar cell modules. The cell to cell spacing is 0.020 inch in both series and parallel directions. Task III reviews the design of a 25 cell matrix. This size matrix could be built into solar panel modules or circuits, utilizing existing technology for cell laydown and wiring.

### 3.6.3 RELIABILITY AND POSSIBLE FAILURE MODES

As stated earlier, the test evaluation of the 4-cell matrices could not be performed during this contract. Even if it had, it would have been difficult to accurately assess the overall reliability factors of this matrix design, due to the limited amount of samples and testing data that would have been available. The most common failure mode anticipated would be an interconnection open either by a separated interconnection or a contact delamination, as a result of vibration or thermal cycling.

### 3.6.4 HANDLING AND REWORK

Handling of the electroplated interconnected matrices is more critical than a conventional soldered module, as the electroplated interconnection does not have the flexibility of a conventional soldered interconnection. One of the inherent difficulties is that the electroplated interconnection must originate directly from the cell edge to cell edge, whereas most soldered interconnections have the 'p' side solder attachment point on the back side of the cell away from the edge. This difference allows the solder connector to have considerably more length between attachment points and inherently proves more flexibility.

Rework or replacement of an individual cell in the matrix has not been investigated; however, certain generalizations can be made. Testing of individual cells in the matrix would be easier than on a conventional cell matrix or module due to the fact that the electroformed cells have the top contact configuration. Electrical measurements of individual cells could be made by masking off the other parallel cell in the submodule and probing the cell in question. Replacement of an individual cell in an electroformed matrix could be accomplished by cutting the plated interconnector and inserting a new cell. Interconnecting the new cell could not be made by plating, it would have to be attached by some variation of conventional techniques. The top contact configuration would simplify the attachment to the adjacent cells. This could be done by soldering tabs to the cells or by other attachment methods such as thermal compression bonding, or welding. Further investigation should be made to evaluate these repair techniques.

### 3.6.5 WEIGHT ANALYSIS

A typical 4-cell matrix weight breakdown is as follows:

Weight of four 0.013 thick cell blanks - 1.11 grams
Total matrix weight after plating - 1.50 grams
Weight differential - 0.39 grams
Weight/cell blank - 0.28 grams
Weight/cell including interconnectors - 0.38 grams

Estimated weight of 25 cell, Task III matrix.

$$0.38 \times 25 = 9.50 \text{ grams}$$

The estimated weight of 25 cell, conventional soldered unfiltered matrix is 20.25 grams, utilizing the same thickness cells. The electroplated cell matrix is only 46 percent of the weight of a conventional EOS matrix of 25 (2 x 2 cm) solder coated cells interconnected with a two mil molybdenum interconnector.

### 3.6.6 PRODUCTION COST

Using the 100 cell pilot cost delineated in Section 2 of this report as the base line, the following costs are estimated for simultaneously electroforming four 25-cell matrices as described in Task III.

The time analysis for the electroforming operations:

| | | | Time/Lot (Minutes) |
|---|---|---|---|
| 1. | Degrease blank | - | 15 |
| 2. | Etch blank | - | 10 |
| 3. | Rinse blank | - | 5 |
| 4. | Load 4 fixtures | - | 120 |
| 5. | Load in plating tank | - | 60 |
| 6. | Unload fixture | - | 120 |
| 7. | Wash and dry cells | - | 60 |
| | | | 390 minutes = 6.50 hours |

The cost computed for the total electroforming operation to make 25-cell matrices using diffused blanks is as follows:

| | | | Manhours |
|---|---|---|---|
| 1. | Masking | - | 3.25 hours |
| 2. | Electroforming | - | 6.50 hours |
| 3. | Mechanical inspection | - | 4.00 hours |
| 4. | Electrical test | - | 0.66 hours |
| | | | 14.41 hours |

Cost/Matrix

| | | |
|---|---|---|
| 14.41/4 = 3.60 hours at $3.00/hour | = | $10.80 |
| Overhead at 150 percent | = | 16.20 |
| Blank cost at $2.00 each x 25 | = | 50.00 |
| Miscellaneous materials at $0.10/cell x 25 | = | 2.50 |
| Subtotal | | 79.50 |
| G&A at 15 percent | | 11.93 |
| Subtotal | | 91.43 |
| Profit at 15 percent | | 13.71 |
| Total | | $105.14 |
| Equivalent cost/cell | = | $ 4.21 |
| Cost per cell (Task I) | | 3.41 |
| Cost differential | | $ 0.80 |

This analysis indicates that the matrix can be formed for less than a dollar per cell.

However, it must be understood that these costs are strictly estimates based on a projected pilot production operation of a module as described in the next section under Task III.

# SECTION 4

# TASK III

## 4.1 SUMMARY

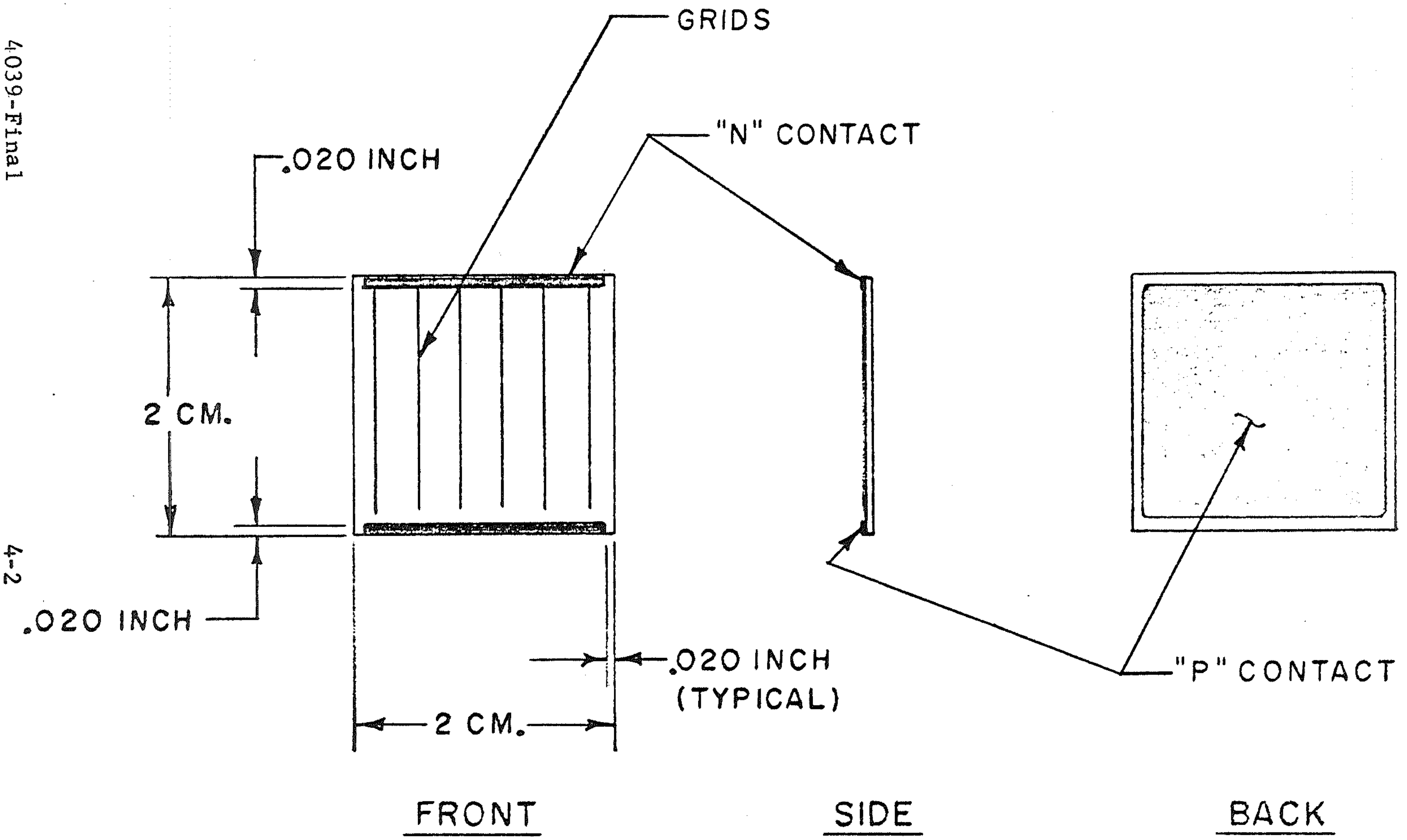
The original scope of Task III was modified to delete the fabrication of 20-cell matrices and changed to the design of a 25-cell matrix and the tooling design for this sized unit.

This section describes in detail the design of a 25-cell matrix, and the plating fixture required to simultaneously electroform the aluminum contacts and interconnections.

## 4.2 MATRIX DESIGN

The solar cells considered for the matrix design are a silicon base n/p type diffused cell, size is 2 x 2 cm, nominal thickness 0.014 inch, base resistivity of 1 to 3 Ω cm. The cell shall contain aluminum contacts of top contact configuration, as depicted in Fig. 4-1. The top contact cell has a modified convential 'n' contact and grid configuration with the addition of a 'p' contact area on the front face of the cell.

The electroformed interconnected matrix requires the top contact configurated cell; however, it is not restricted to the 2 x 2 cm cell size. Other cell sizes could be utilized; for instance, 2 x 4 cm would be directly applicable to this modular technique.



TOP CONTACT SOLAR CELL

Figure 4-1

The matrix design required has 25 cells, with five cells in parallel and five cells in series. This matrix is depicted in Fig. 4-2, EOS Drawing 4039-120. This matrix is designed to be directly comparable with conventional soldered solar cell flat mounted modules, and has a cell-to-cell spacing of 0.020 inch in the series and parallel directions.

Each cell is interconnected in series to its adjacent cell by a full width electroformed interconnection joining the top contact 'p' bus to the top contact 'n' bus of the second cell. The back contacts are made by a full width electroformed interconnection joining the back 'p' contact of one cell to the back 'p' contact of its adjacent (side) cell.

### 4.2.1 TYPICAL ELECTRICAL ANALYSIS

Assuming a power output of 100 mA at 400 mV per cell the power output of the module would be:

100 mA x 5 = 500 mA = 0.5A

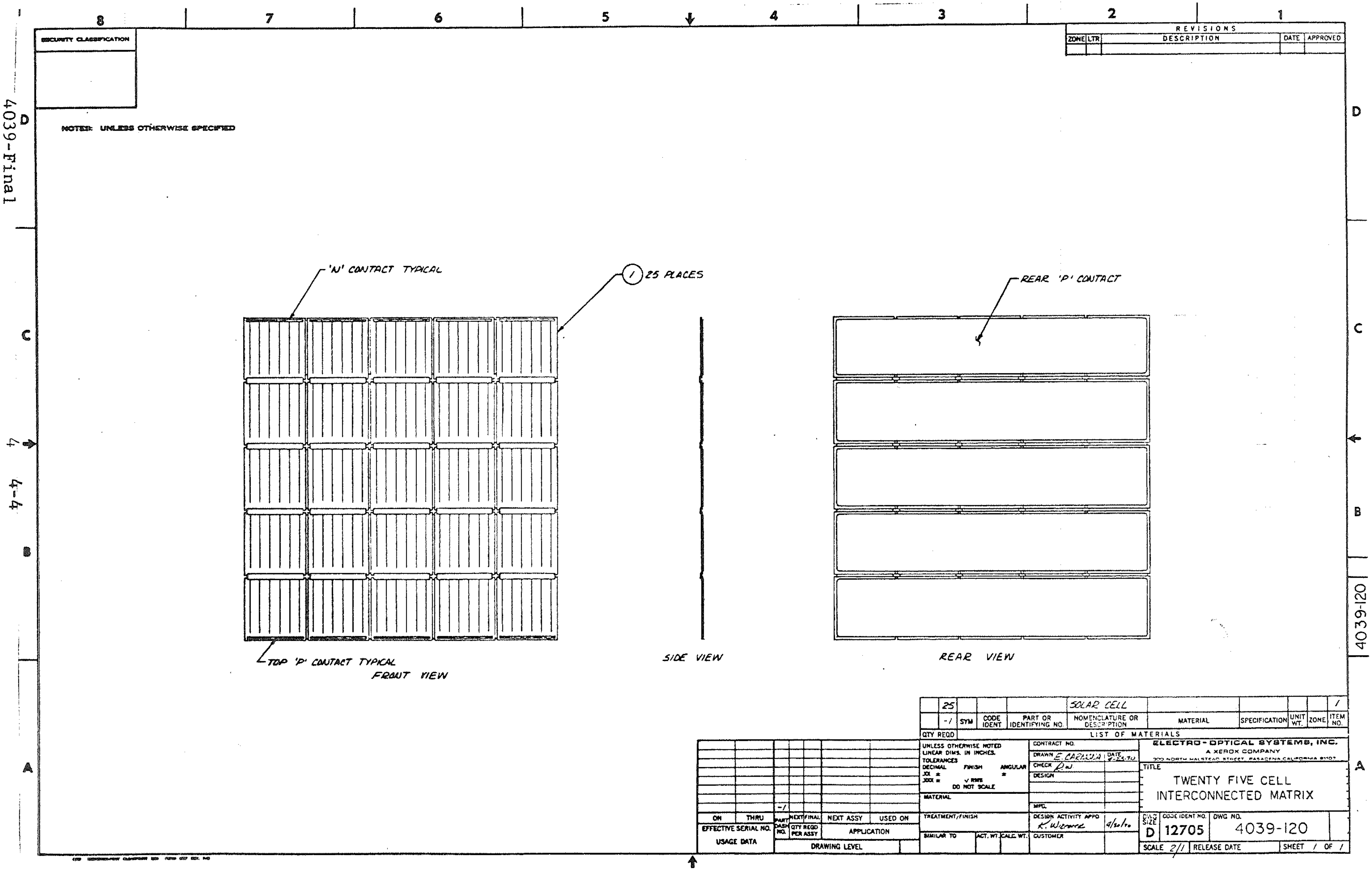
400 mV x 5 = 2000 mV = 2.0V

0.5A x 2.0V = 1.0 watts

The calculated series resistance voltage drop of the interconnectors in the module would be:

Individual interconnector dimensions would give a cross sectional area of:

$0.750 \times 0.003 = 0.00225 \text{ in.}^2$



|  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | 25 |  |  |  | SOLAR CELL |  |  |  |  | 1 |
|  | -1 | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
| QTY REQD | LIST OF MATERIALS |  |  |  |  |  |  |  |  |  |

-1
ON THRU
EFFECTIVE SERIAL NO.
USAGE DATA
PART DASH NO.
NEXT / FINAL
QTY REQD PER ASSY
NEXT ASSY
USED ON
APPLICATION
DRAWING LEVEL

UNLESS OTHERWISE NOTED
LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ± ±
.XXX ± √ RMS
DO NOT SCALE
MATERIAL
TREATMENT/FINISH
SIMILAR TO
ACT. WT.
CALC. WT.

CONTRACT NO.
DRAWN E. CARMAIA DATE 4-23-70
CHECK RW
DESIGN
MFG.
DESIGN ACTIVITY APPD K. Wizrose 4/20/70
CUSTOMER

**ELECTRO-OPTICAL SYSTEMS, INC.**
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA CALIFORNIA 91107

TITLE
TWENTY FIVE CELL
INTERCONNECTED MATRIX

DWG SIZE D
CODE IDENT NO. 12705
DWG NO. 4039-120
SCALE 2/1
RELEASE DATE
SHEET 1 OF 1

Figure 4-2

Total interconnector area for 5 cells

$$0.00225 \times 5 = 0.01125 \text{ in.}^2$$

Interconnector length = 0.020 inch

Total interconnector length for 5 parallel submodules

$$0.020 \times 4 = 0.080 \text{ inch}$$

Resistivity of aluminum ($\rho$)

$$= 2.69\ \mu\Omega\ \text{cm}$$

$$= 1.059\ \mu\Omega\ \text{inch}$$

Interconnector resistance is

$$R = \frac{\rho \ell}{A} = \frac{1.059 \times 10^{-3}\ (0.080)}{0.01125}$$

$$= 7.53 \times 10^{-3}\Omega$$

$$= 0.00753\Omega$$

Interconnector voltage drop in the series direction is:

$$E = IR$$

$$= (0.5)\ (0.00753)$$

$$= 0.003765\text{V}$$

$$= 3.8\ \text{mV}$$

The voltage drop of only 3.8 mV is very low and well within the acceptable voltage drop for a module of this type.

The matrix depicted in Fig. 4-2 will require both 'n' and 'p' electrical end terminations. The type of termination would depend upon the matrix application; however, conventional end terminations could be used, similar to the Mariner solar panel design.

### 4.2.2 ELECTROFORMING TOOLING

The tooling fixture required to electroform the 25-cell matrix is shown in Figs. 4-3, 4-4, 4-5, 4-6, 4-7, 4-8 and 4-9, EOS Drawings 4039-121, 4039-122, 4039-123, 4039-124, 4039-125, 4039-126, and 4039-127, respectively.

The electroforming procedure necessary to fabricate the 25-cell matrix would be very similar to the process used to form the four-cell matrices in Task II. The design of the 25-cell fixture was changed in two areas to accommodate anticipated problems associated with the larger matrix.

First, both the upper and lower cell divider bars, EOS Drawings 4039-124 and 123 (Figs. 4-6 and 4-5), were designed to be removable. This was done primarily so that each bar could be adjusted in position to allow for variances in individual cell sizes. The fixture base plate, EOS Drawing 4039-122 (Fig. 4-4) has a two axis shoulder machined into its face to register the first two rows of cells at right angles. This will maintain the cells in a square configuration on the base plate, and each individual divider bar can then be installed and positioned to minimize the gap clearance between the bar and the cell edge. Aluminum foil gaskets would be used with each divider bar as in the four cell fixture. The removable divider bars would also facilitate fixture repair in the event it became accidently damaged.

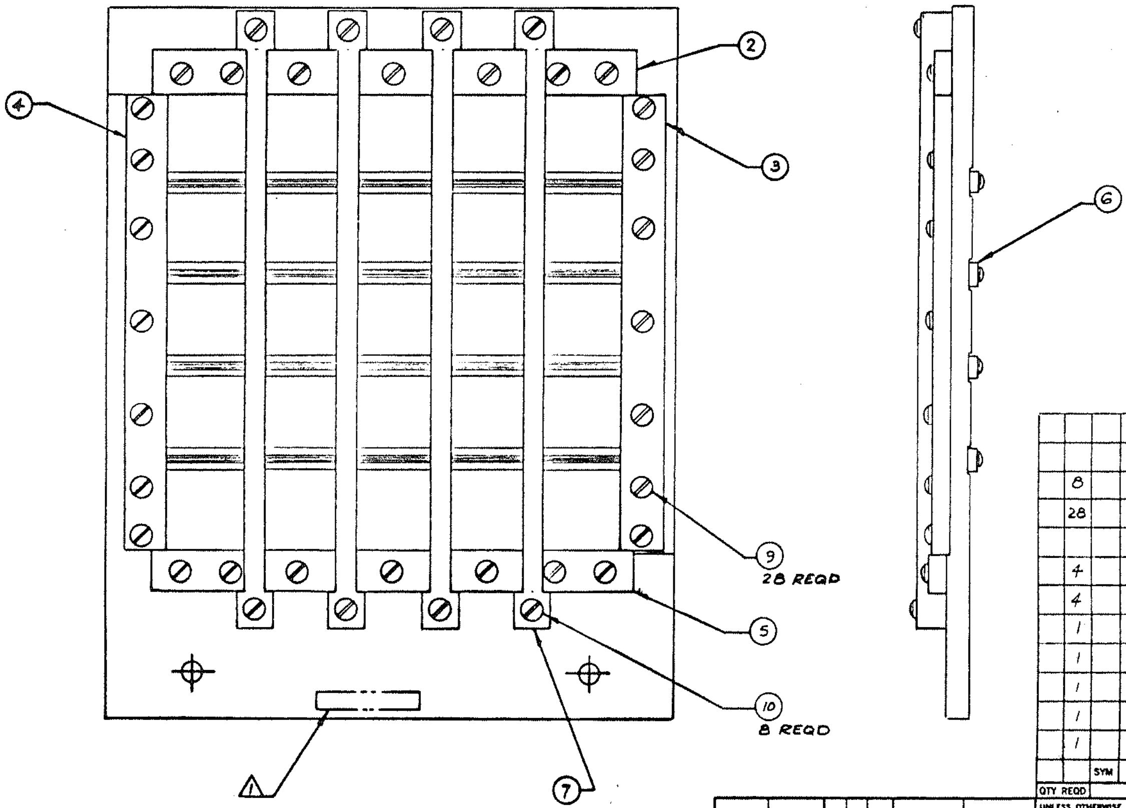
SECURITY CLASSIFICATION

UNCLASSIFIED

| ZONE | LTR | REVISIONS<br>DESCRIPTION | DATE | APPROVED |
|---|---|---|---|---|
| | | | | |

NOTES: UNLESS OTHERWISE SPECIFIED

△1 IDENTIFY WITH ASSEMBLY NO. 12705-4039-121 APPROX WHERE SHOWN WITH 1/8 HIGH GOTHIC CHARACTERS PER EOS STD ST4000-3



| QTY REQD | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | | | | | | | | | |
| 8 | | | | SCREW PAN HD 4-40UNC x 3/8 LG | MOLDED NYLON | MIL-M-20693 COMP A TYPE I | | | 10 |
| 28 | | | | SCREW PAN HD 4-40 UNC x 1/4 LG | MOLDED NYLON | MIL-M-20693 COMP A TYPE I | | | 9 |
| | | | | | | | | | 8 |
| 4 | | | 4039-124-1 | DIVIDER UPPER | | | | | 7 |
| 4 | | | 4039-123-1 | DIVIDER LOWER | | | | | 6 |
| 1 | | | -7 | SUPPORT | | | | | 5 |
| 1 | | | -5 | | | | | | 4 |
| 1 | | | -3 | | | | | | 3 |
| 1 | | | 4039-127-1 | SUPPORT | | | | | 2 |
| 1 | | | 4039-122-1 | BASE | | | | | 1 |

LIST OF MATERIALS

| NEXT ASSY | USED ON |
|---|---|
| APPLICATION | |

ON THRU EFFECTIVE SERIAL NO.
USAGE DATA
PART DASH NO. NEXT FINAL QTY REQD PER ASSY
DRAWING LEVEL

UNLESS OTHERWISE NOTED
LINEAR DIMS. IN INCHES
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ± ±
.XXX ± √ RMS
DO NOT SCALE
MATERIAL
TREATMENT/FINISH
SIMILAR TO ACT. WT. CALC. WT.

CONTRACT NO.
DRAWN DATE 8/27/70
CHECK R.W.
DESIGN
MFG.
DESIGN ACTIVITY APPD
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
FIXTURE ASSEMBLY
SOLAR CELL SUBMODULE

DWG SIZE D
CODE IDENT NO. 12705
DWG NO. 4039-121
SCALE
RELEASE DATE 2/1
SHEET 1 OF 1

4039-121

Figure 4-3

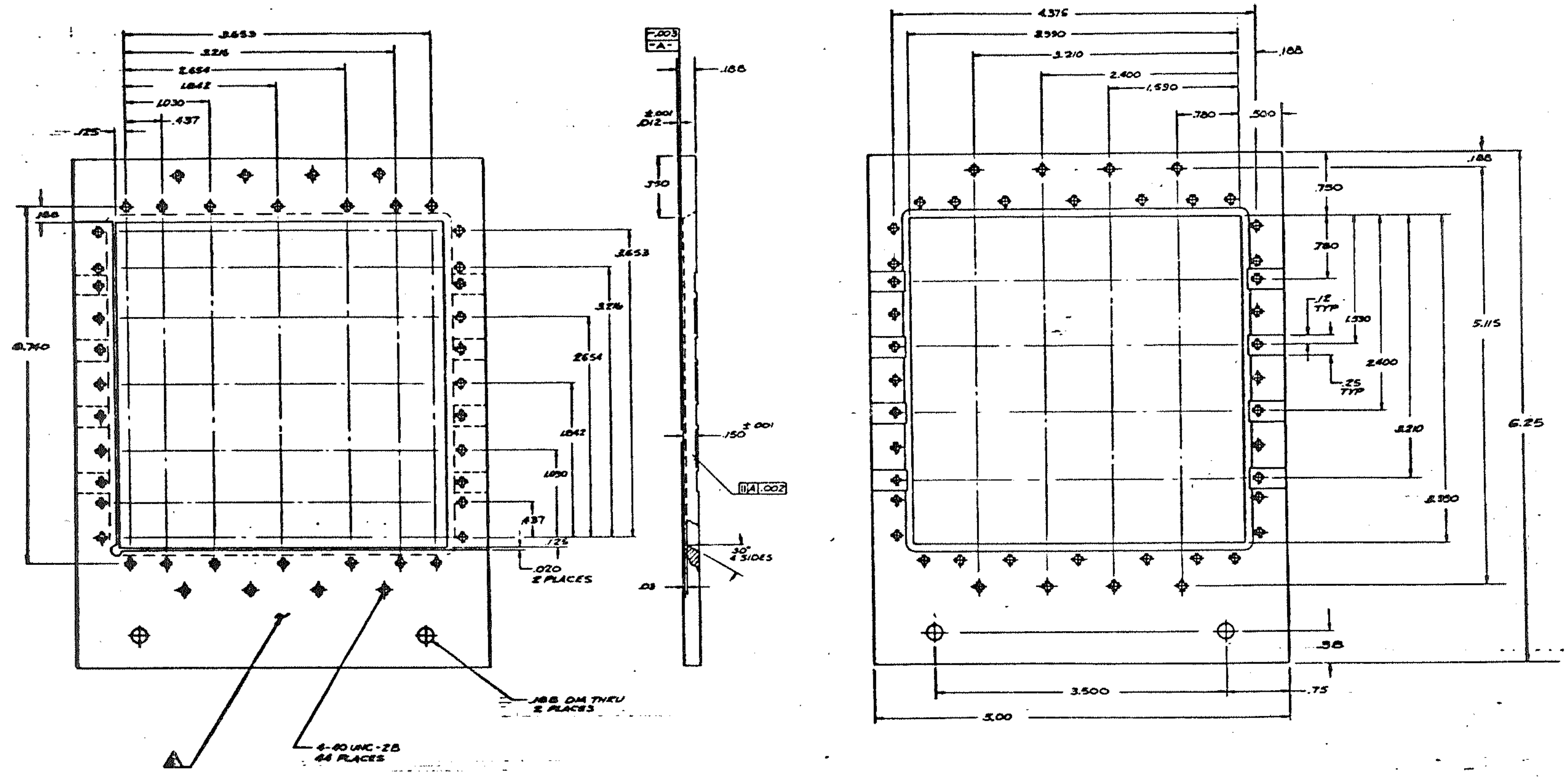
SECURITY CLASSIFICATION

UNCLASSIFIED

REVISIONS

| ZONE | LTR | DESCRIPTION | DATE | APPROVED |
|---|---|---|---|---|

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS AND SHARP EDGES
2. TEFLON COAT ALL SURFACES EXCEPT AREA SHOWN



| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | -1 | BASE PLATE | AL ALLOY 1100-H14 | QQ-A-561C | | 1 |
| QTY REQD | | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. / ZONE | ITEM NO. |

LIST OF MATERIALS

UNLESS OTHERWISE NOTED LINEAR DIMS. IN INCHES
TOLERANCES
DECIMAL .XX ±.01 .XXX ±.005
FINISH 63 √ RMS
ANGULAR ± 1°
DO NOT SCALE

MATERIAL SEE L/M

TREATMENT/FINISH 2

SIMILAR TO | ACT. WT | CALC. WT.

CONTRACT NO.
DRAWN DY DATE 2-24-70
CHECK [illegible]
DESIGN
ENGR.
DESIGN ACTIVITY APPD R. Wynne [illegible]
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY

TITLE
BASE PLATE
SOLAR CELL SUBMODULE

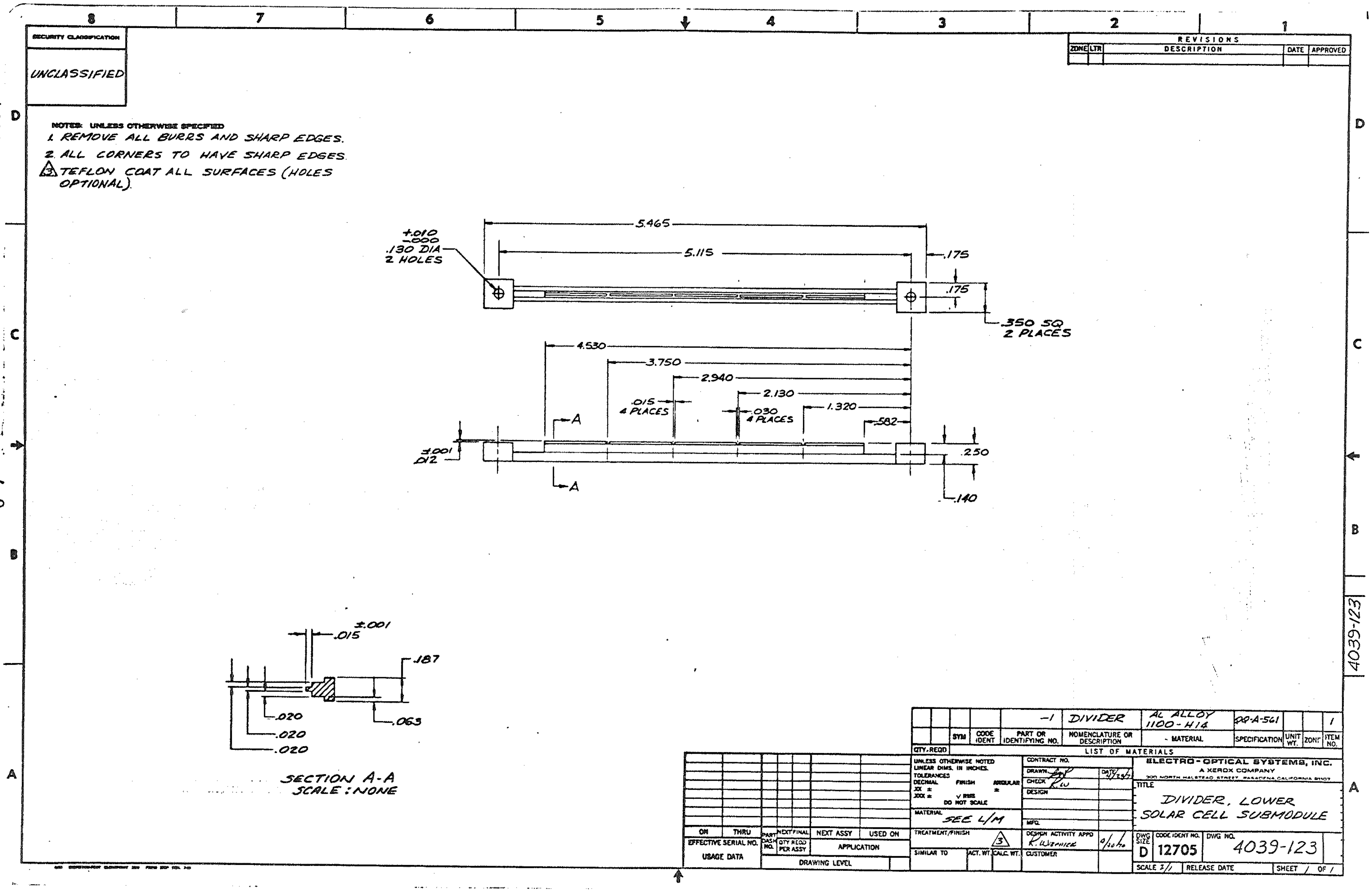
DWG SIZE E | CODE IDENT NO. 12705 | DWG NO. 4039-122

SCALE 2/1 | RELEASE DATE | SHEET 1 OF 1

| | | | | | |
|---|---|---|---|---|---|
| SN | THRU | PART DASH NO. | MODEL/FINAL QTY REQD PER ASSY | NEXT ASSY | USED ON |
| EFFECTIVE SERIAL NO. | | | | APPLICATION | |
| SERIES DATA | | DRAWING LEVEL | | | |

4039-122

Figure 4-4



NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS AND SHARP EDGES.
2. ALL CORNERS TO HAVE SHARP EDGES.
3. TEFLON COAT ALL SURFACES (HOLES OPTIONAL).

| QTY. REQD | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
|---|---|---|---|---|---|---|---|---|---|
| | | | -1 | DIVIDER | AL ALLOY 1100-H14 | QQ-A-561 | | | 1 |

LIST OF MATERIALS

UNLESS OTHERWISE NOTED
LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ± ±
.XXX ± √ RMS
DO NOT SCALE

MATERIAL SEE L/M
TREATMENT/FINISH 3
SIMILAR TO
ACT. WT.
CALC. WT.

CONTRACT NO.
DRAWN DATE 4/29/70
CHECK
DESIGN
MFG.
DESIGN ACTIVITY APPD K. Wzhnick 4/30/70
CUSTOMER

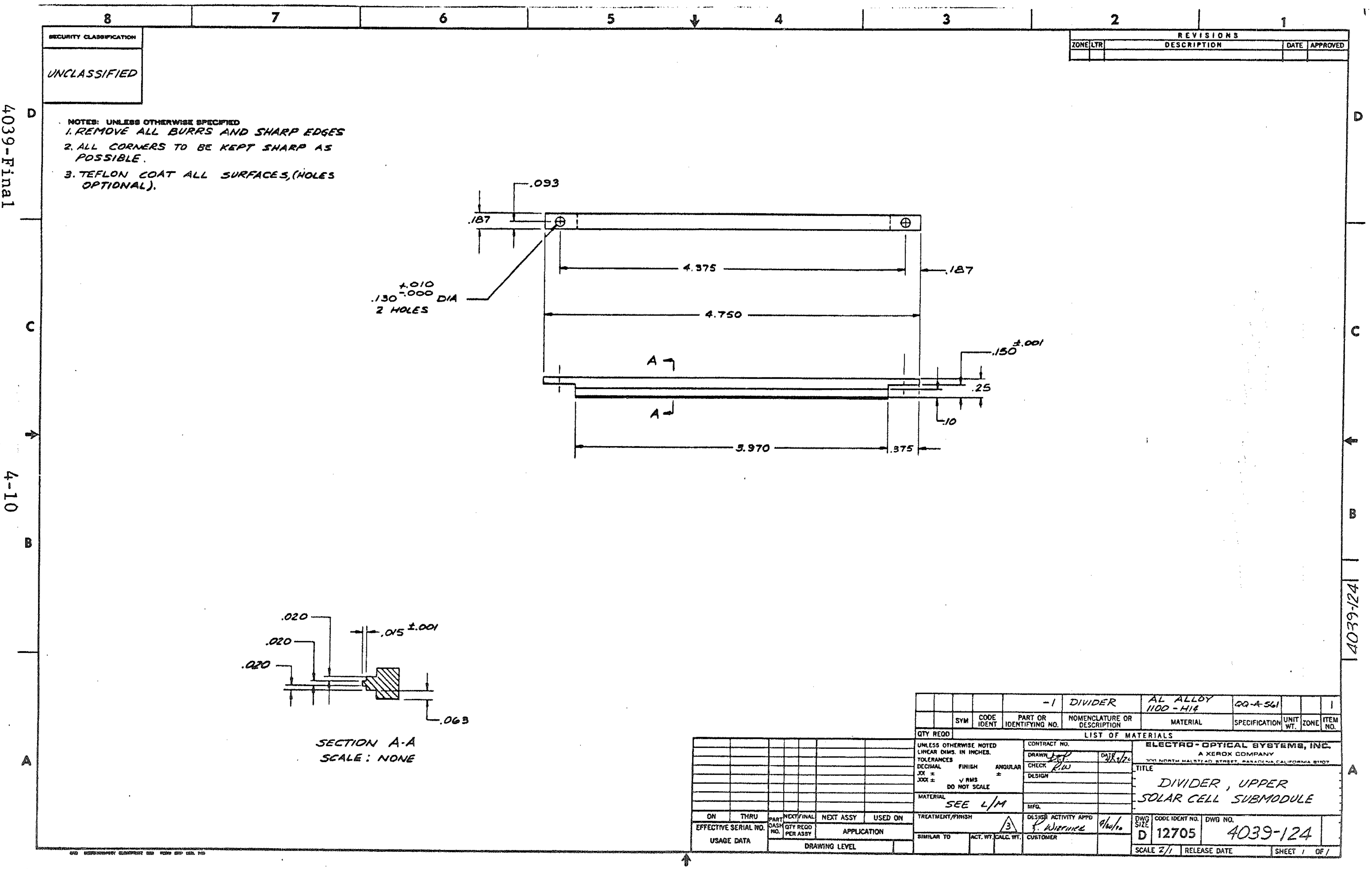
ON THRU
EFFECTIVE SERIAL NO.
USAGE DATA
PART DASH NO.
NEXT FINAL QTY REQD PER ASSY
NEXT ASSY
USED ON
APPLICATION
DRAWING LEVEL

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
DIVIDER, LOWER
SOLAR CELL SUBMODULE

DWG SIZE D
CODE IDENT NO. 12705
DWG NO. 4039-123
SCALE 2/1
RELEASE DATE
SHEET 1 OF 1

Figure 4-5


8
7
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D
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B
A
SECURITY CLASSIFICATION
UNCLASSIFIED
REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS AND SHARP EDGES
2. ALL CORNERS TO BE KEPT SHARP AS POSSIBLE.
3. TEFLON COAT ALL SURFACES, (HOLES OPTIONAL).
.093
.187
4.375
.187
.130 +.010 -.000 DIA
2 HOLES
4.750
A
A
.150 ±.001
.25
.10
3.970
.375
.020
.020
.020
.015 ±.001
.063
SECTION A-A
SCALE: NONE
-1
DIVIDER
AL ALLOY 1100 - H14
QQ-A-561
1
QTY REQD
SYM
CODE IDENT
PART OR IDENTIFYING NO.
NOMENCLATURE OR DESCRIPTION
MATERIAL
SPECIFICATION
UNIT WT.
ZONE
ITEM NO.
LIST OF MATERIALS
UNLESS OTHERWISE NOTED LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL
FINISH
ANGULAR
.XX ±
.XXX ±
√ RMS
±
DO NOT SCALE
MATERIAL
SEE L/M
TREATMENT/FINISH
3
SIMILAR TO
ACT. WT.
CALC. WT.
CONTRACT NO.
DRAWN
DATE
CHECK
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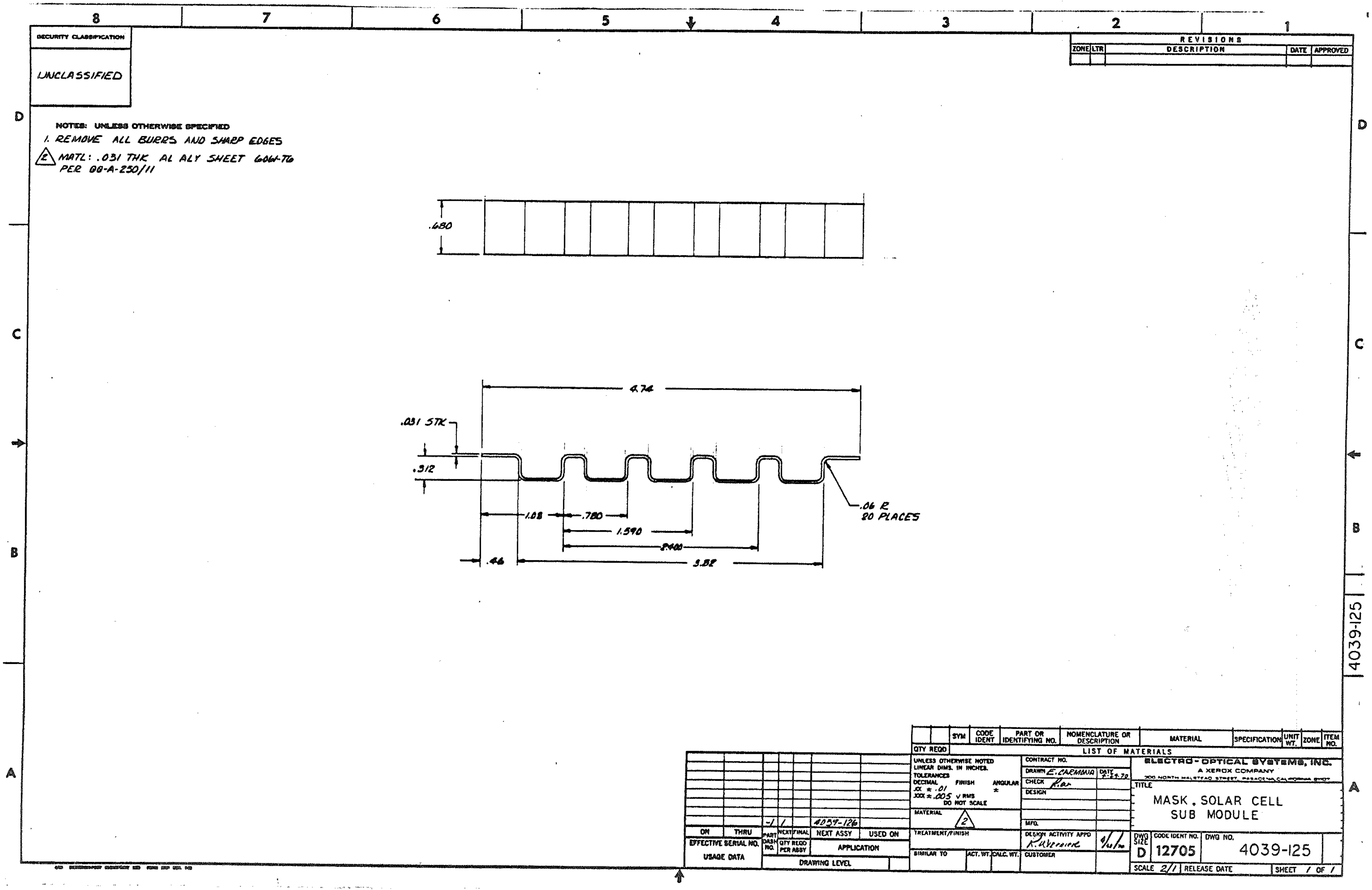
DESIGN
MFG.
DESIGN ACTIVITY APPD
P. Wierince
9/10/70
CUSTOMER
ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107
TITLE
DIVIDER, UPPER SOLAR CELL SUBMODULE
DWG SIZE
D
CODE IDENT NO.
12705
DWG NO.
4039-124
SCALE 2/1
RELEASE DATE
SHEET 1 OF 1
ON
THRU
PART DASH NO.
NEXT
FINAL
QTY REQD PER ASSY
NEXT ASSY
USED ON
EFFECTIVE SERIAL NO.
APPLICATION
USAGE DATA
DRAWING LEVEL
4039-124

Figure 4-6



SECURITY CLASSIFICATION

UNCLASSIFIED

| REVISIONS | | | | |
|---|---|---|---|---|
| ZONE | LTR | DESCRIPTION | DATE | APPROVED |

NOTES: UNLESS OTHERWISE SPECIFIED

1. REMOVE ALL BURRS AND SHARP EDGES
2. MATL: .031 THK AL ALY SHEET 6061-T6 PER QQ-A-250/11

| | | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
|---|---|---|---|---|---|---|---|---|---|---|
| QTY REQD | | LIST OF MATERIALS | | | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | -1 | 1 | | 4039-126 | |
| ON | THRU | PART DASH NO. | NEXT | FINAL | NEXT ASSY | USED ON |
| EFFECTIVE SERIAL NO. | | | QTY REQD PER ASSY | | APPLICATION | |
| USAGE DATA | | DRAWING LEVEL | | | | |

UNLESS OTHERWISE NOTED LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ± .01 ±
.XXX ± .005 √ RMS
DO NOT SCALE

MATERIAL 2

TREATMENT/FINISH

SIMILAR TO | ACT. WT. | CALC. WT.

CONTRACT NO.
DRAWN E. CARMONA DATE 7-24-70
CHECK R.ar
DESIGN
MFG.
DESIGN ACTIVITY APPD R.Wernick 4/10/70
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
MASK, SOLAR CELL
SUB MODULE

| DWG SIZE | CODE IDENT NO. | DWG NO. |
|---|---|---|
| D | 12705 | 4039-125 |

SCALE 2/1 RELEASE DATE SHEET 1 OF 1

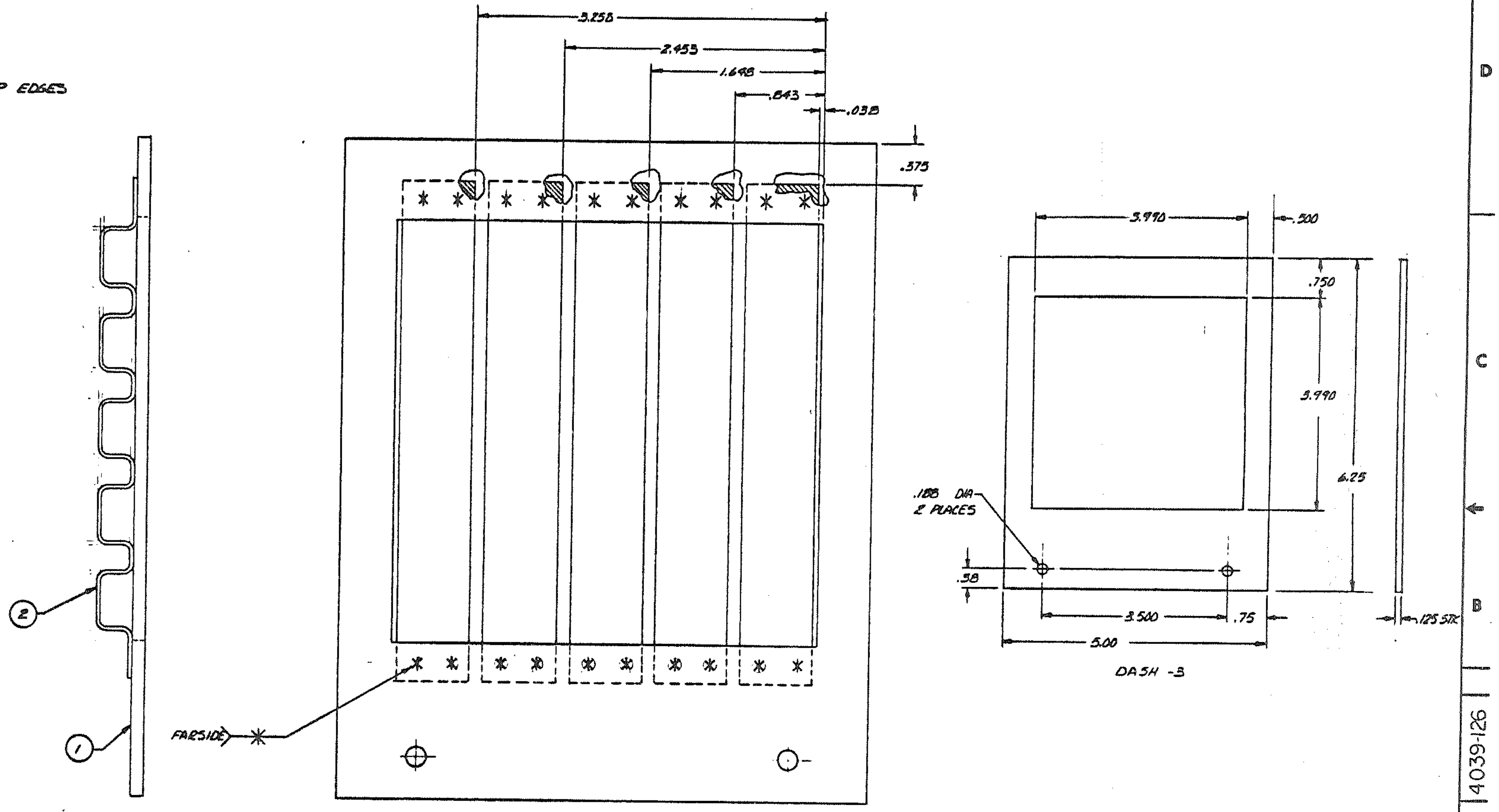
Figure 4-7

SECURITY CLASSIFICATION

UNCLASSIFIED

| REVISIONS | | | | |
|---|---|---|---|---|
| ZONE | LTR | DESCRIPTION | DATE | APPROVED |

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS AND SHARP EDGES



| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 5 | | | 4039-125 | MASK | | | | | 2 |
| | 1 | | | -3 | FRAME, MASK | .125 THK AL ALY SHEET 6061-T6 PER QQ-A-250/11 | | | | 1 |
| | -1 | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
| QTY REQD | LIST OF MATERIALS | | | | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | -1 | 1 | | | |
| ON | THRU | PART DASH NO. | NEXT | FINAL | NEXT ASSY | USED ON |
| EFFECTIVE SERIAL NO. | | | QTY REQD PER ASSY | | APPLICATION | |
| USAGE DATA | | DRAWING LEVEL | | | | |

UNLESS OTHERWISE NOTED
LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
XX ± .01 ±
XXX ± .005 √ RMS
DO NOT SCALE

MATERIAL

TREATMENT/FINISH

SIMILAR TO | ACT. WT | CALC. WT.

CONTRACT NO.
DRAWN E. CARMONA DATE 4-17-70
CHECK R.W.
DESIGN
MFG.
DESIGN ACTIVITY APPD R. Wiseman
CUSTOMER

**ELECTRO-OPTICAL SYSTEMS, INC.**
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
MASK SUBASSY, SOLAR CELL
SUBMODULE

DWG SIZE D | CODE IDENT NO. 12705 | DWG NO. 4039-126

SCALE 2/1 | RELEASE DATE | SHEET 1 OF 1

4039-126

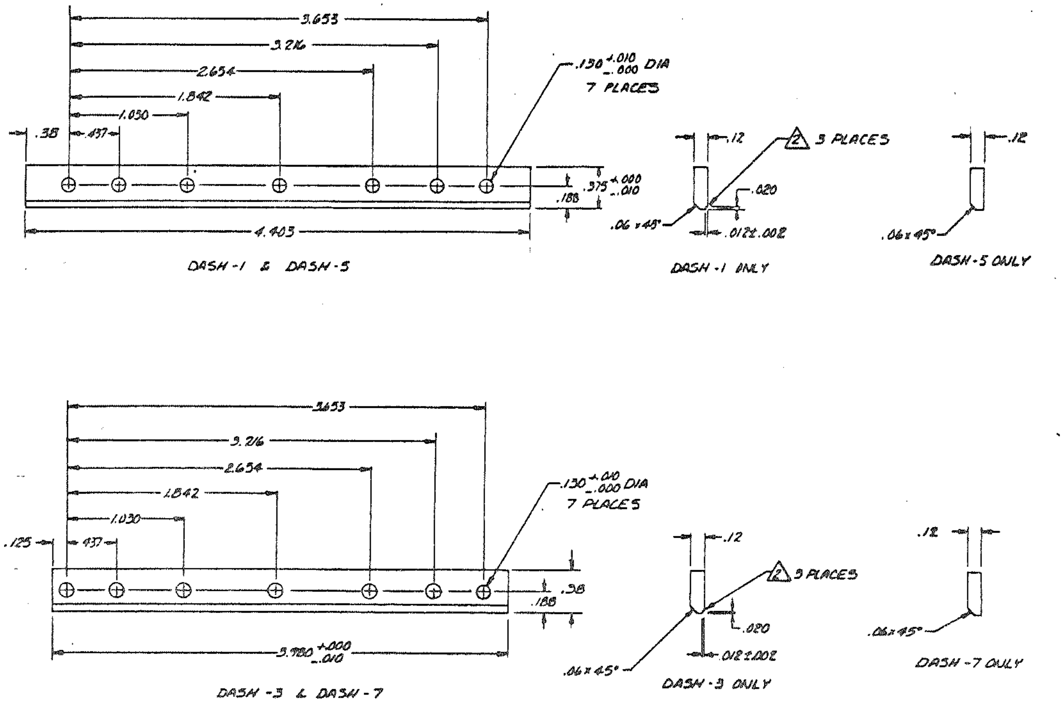
Figure 4-8

SECURITY CLASSIFICATION

UNCLASSIFIED

| REVISIONS | | | | |
|---|---|---|---|---|
| ZONE | LTR | DESCRIPTION | DATE | APPROVED |
| | | | | |

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS AND SHARP EDGES
2 CORNERS TO BE KEPT AS SHARP AS POSSIBLE



| | | SYM | CODE IDENT | PART OR IDENTIFYING NO. | NOMENCLATURE OR DESCRIPTION | MATERIAL | SPECIFICATION | UNIT WT. | ZONE | ITEM NO. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | -7 | | TEFLON | MIL-P-22242 TYPE II | | | 4 |
| | | | | -5 | | TEFLON | MIL-P-22242 TYPE II | | | 3 |
| | | | | -3 | | TEFLON | MIL-P-22242 TYPE II | | | 2 |
| | | | | -1 | | TEFLON | MIL-P-22242 TYPE II | | | 1 |

QTY REQD — LIST OF MATERIALS

| | | | | | | |
|---|---|---|---|---|---|---|
| ON | THRU | PART DASH NO. | NEXT | FINAL | NEXT ASSY | USED ON |
| EFFECTIVE SERIAL NO. | | QTY REQD PER ASSY | | | APPLICATION | |
| USAGE DATA | | DRAWING LEVEL | | | | |

UNLESS OTHERWISE NOTED
LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL FINISH ANGULAR
.XX ± ±
.XXX ± √ RMS
DO NOT SCALE
MATERIAL
TREATMENT/FINISH
SIMILAR TO
ACT. WT.
CALC. WT.

CONTRACT NO.
DRAWN E. CARMONA DATE 7-22-70
CHECK
DESIGN
MFG.
DESIGN ACTIVITY APPD R. Wheeard
CUSTOMER

ELECTRO-OPTICAL SYSTEMS, INC.
A XEROX COMPANY
300 NORTH HALSTEAD STREET, PASADENA, CALIFORNIA 91107

TITLE
SUPPORT,
SOLAR CELL SUBMODULE

DWG SIZE D
CODE IDENT NO. 12705
DWG NO. 4039-127
SCALE 2/1
RELEASE DATE
SHEET 1 OF 1

4039-127

Figure 4-9

Secondly, the fixture incorporated a metal mask subassembly, EOS Drawing No. 4039-126 (Fig. 4-8), to mask the grid lines to prevent over plating; in place of the individual Teflon masks used on the four-cell fixture. The one-piece mask design would facilitate installation and registration to the fixture.

EOS is confident, based upon the experience gained under Task II of this program, that the 25-cell fixture described herein would produce electroplated solar cell matrices. EOS is not in a position to predict the yield of usable matrices that would be fabricated by the electroforming process as that would for the most part be subject to the matrices end usage requirements.

# SECTION 5

# RECOMMENDATIONS

The work accomplished in this program has established the feasibility of aluminum electroplated single cells, and aluminum electroformed solar cell interconnections.

While this work covered a broad scope of preliminary research and development into aluminum electroplated silicon solar cells and interconnected matrices, EOS recommends further study in the following areas.

## 5.1 INDIVIDUAL CELLS

a. Tests of radiation tolerance of cells

b. Investigation of high temperature operating characteristics

c. Investigation of methods of preventing aluminum contacts from air oxidation

d. Investigation of optional means of interconnecting aluminum plated cells such as high temperature solder, thermal compression bonding, and ultrasonic welding.

e. Evaluation of pilot line production feasibility, with detail analysis of expected production electrical and mechanical yields, and cell costs.

## 5.2 MATRICES

a. Perform matrix testing program to evaluate the electroformed matrices.

b. Investigate and develop rework and repair procedures for the matrix.

c. Investigate antireflection coatings for matrices, possible use of spray-on coating for terrestrial applications.

d. Investigate and develop interconnection methods for matrix-to-matrix wiring.

e. Evaluation of pilot line production feasibility, with detailed analysis of expected production electrical and mechanical yields, and matrix costs.

## 5.3 GENERAL

Perform a performance/cost effectiveness evaluation of both single and matrix aluminum electroplated solar cells, specifically for low cost large volume terrestial power applications.

# SECTION 6

# CONCLUSION

This study sponsored by JPL has resulted in a significant step in the state of the art of silicon solar cell fabrication. The primary manufacturing technique of silicon N/P solar cell today utilizes evaporated silver-titanium contacts; this method supplanted the previously used electrolis nickel plated contacts.

This study has demonstrated for the first time in the solar cell industry the feasibility of and the actual fabrication of aluminum electroplated silicon solderless solar cells. The cells fabricated in this R&D study shows a wide variance in output efficiencies as reflected by the data shown in this report. This variance can be attributed to problems associated with developing a new process. The fact that cells of efficiencies comparable to silver-titanium cells were produced indicates that the aluminum electroplating process has the potential to produce cells competitive with conventional solar cells.

The primary goal of this study was to demonstrate feasibility of interconnecting silicon solar cells with electroformed aluminum, while simultaneously electroplating the aluminum contacts on the cell. This was accomplished under Task II of this study. While this study showed that electroformed interconnected matrices are possible, additional development is required to make the matrices competitive power-wise with conventional space solar cell assemblies. Techniques to achieve matching and cell replacement are some of the areas for further investigations. EOS believes that this process has its best advantage in low cost nominally powered terrestrial applications.

# APPENDIX A

## CONTACT THICKNESS VERSUS RESISTANCE CALCULATIONS

# APPENDIX A

## CONTACT THICKNESS VERSUS RESISTANCE CALCULATIONS

For the straight grid line contact, a conservative estimate of the voltage drop can be made by using the following assumptions:

(1) The current collected by one grid line (total of six) is $\frac{140 \text{ mA}}{6}$ or 23.3 mA.

(2) The voltage drop is calculated at the midlength of the grid line.

The voltage drop is related to the thickness by the following equations:

$$E_G = I R_G$$

$$R_G = \frac{\rho \ell}{Wt}$$

where

$\rho$ = resistivity of Al

$\ell$ = length of grid

W = width of grid

t = thickness of grid

For l = 0.95 cm,

w = 0.015 cm,

$\rho$ = $2.62 \times 10^{-6}$ ohm-cm, and

I = $2.33 \times 10^{-2}$ A,

$$E_G = \frac{I \rho \ell}{wt} = \frac{(2.33 \times 10^{-2})\ (2.62 \times 10^{-6})\ (0.95)}{(0.015)\ (t)}$$

$$E_G = \frac{3.87 \times 10^{-6}}{t}$$

At 0.001 in. or 0.0025 cm, the voltage drop is 1.55 mV, and the values of $E_G$ corresponding to other thickness are as follows:

| t(in.) | $E_G$ (mV) |
|---|---|
| 0.001 | 1.55 |
| 0.0005 | 8.75 |
| 0.0001 | 15.5 |

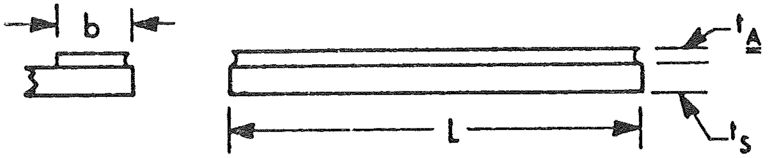
For practical purposes, both a pore-free continuous layer of aluminum and an acceptable resistance are obtained when the electrodeposited layer is approximately 0.00125 cm.

# APPENDIX B

# THERMAL STRESS IN ALUMINUM-SILICON BOND

# APPENDIX B

## THERMAL STRESS IN ALUMINUM-SILICON BOND



35454

Coefficients of thermal expansion:

$\alpha_{aluminum}$ = $13.1 \times 10^{-6}$ in./in. °F

$\alpha_{silicon}$ = $1.8 \times 10^{-6}$ in./in. °F

Modulus of elasticity

$E_{aluminum}$ = $9.0 \times 10^{6}$ psi (electroformed)

$E_{silicon}$ = $15.5 \times 10^{6}$ psi

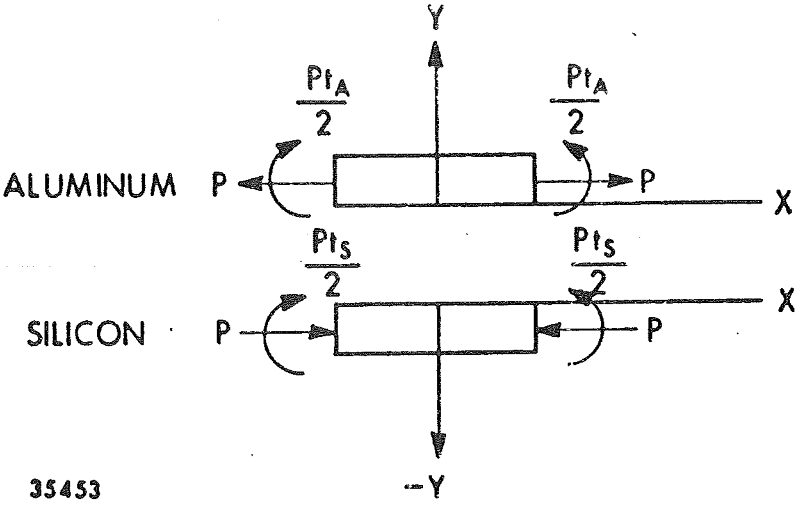
Derivation of equation for stress at bondline

Define $\Delta T = T - T_{AMB}$

$T_{AMB}$ = temperature during plating °F

$T$ = temperature (independent variable) °F

Free-Body Diagrams



The axial displacements are

$$\mu_{AL}\ (y) = \alpha_{AL}\ \Delta T + \frac{P}{E_{AL}\ t_A b} - \frac{1}{\rho 1}\left(y - \frac{t_{A1}}{2}\right) \tag{1}$$

$$\mu_{S1}\ (y) = \alpha_{S1}\ \Delta T - \frac{P}{E_{S1}\ t_S\ b} - \frac{1}{\rho 2}\left(y + \frac{t_{S1}}{2}\right) \tag{2}$$

Where,

$$\frac{1}{\rho 1} = \frac{M}{E_{AL}\ I_{AL}} = \frac{P\ t_{AL}}{2\ E_{A1}\left(\frac{1}{12}\ b\ t_{AL}{}^{3}\right)} = \frac{6\ P}{E_{A1}\ b\ t_{AL}{}^{2}} \tag{3}$$

$$\frac{1}{\rho 2} = \frac{M}{E_{S1}\ I_{S1}} = \frac{P\ t_{S1}}{2\ E_{S1}\left(\frac{1}{12}\ b\ t_{S1}{}^{3}\right)} = \frac{6\ P}{E_{S1}\ b\ t_{S1}{}^{2}} \tag{4}$$

At $y = 0\ \mu_{AL}\ (y) \equiv \mu_{S1}\ (y)$

$$\therefore\ \alpha_{AL}\ \Delta T + \frac{}{E_A\ t_A\ b} + \frac{t_A}{2\rho 1} = \alpha_{S1}\ \Delta T - \frac{P}{E_{S1}\ t_S\ b} - \frac{t_S}{2\rho 2} \tag{5}$$

Substituting (3) and (4) in (5) and solving for P gives

$$P\left(\frac{1}{E_A\ t_A\ b}+\frac{1}{E_S\ t_S\ b}\right) = (\alpha_{S1}-\alpha_{AL})\ \Delta T - 3P\left(\frac{1}{E_{AL}\ t_{AL}\ b}+\frac{1}{E_{S1}\ t_S\ b}\right)$$

$$P = \frac{(\alpha_{S1}-\alpha_{AL})\ \Delta T}{4\left(\frac{1}{E_A\ t_A\ b}+\frac{1}{E_S\ T_S\ b}\right)}$$

Stress at the bondline (aluminum side tension)

$$S = \frac{P}{A}+\frac{Mc}{I}$$

$$= \frac{P}{t_A\ b}+\frac{P\ t_A\ (t_A/2)}{2\left(\frac{1}{12}\ b\ t_A{}^3\right)}$$

$$S = \frac{P}{t_A\ b}+\frac{3\ P}{t_A\ b}$$

$$S = 4\ \frac{P}{t_A\ b} = \frac{4}{t_A\ b}\ \frac{(\alpha_{S1}-\alpha_{AL})\ \Delta T}{4\left(\frac{1}{E_A\ t_A\ b}+\frac{1}{E_s\ t_s\ b}\right)}$$

$$S = \frac{(\alpha_{S1}-\alpha_{AL})\ \Delta T}{\frac{1}{E_{AL}}+\left(\frac{t_{AL}}{t_s}\right)\frac{1}{E_{S1}}} = \frac{(\alpha_{S1}-\alpha_{AL})\ \Delta T\ E_{A1}}{1+\left(\frac{t_{A1}}{t_s}\right)\frac{E_{AL}}{E_{S1}}}$$

Evaluating (S) for the previously specified values for E, and $\alpha$

$$S = \frac{-11.3\ \Delta T}{0.11111+\left(\frac{t_{AL}}{t_S}\right)\ 0.06451} = \frac{-101.7\ \Delta T}{1+\left(\frac{t_{AL}}{t_{S1}}\right)\ (0.58064)}$$

Silicon side

$$S = \frac{-11.3\ \Delta T\ E_S}{\frac{t_S\ E_S}{t_A\ E_A}+1} = \frac{-175.4\ \ \Delta T}{1.72222\left(\frac{t_S}{t_A}\right)+1}$$

During the thermal shock cycling, the $\Delta T$ encountered is $388^{o}F$. The tension on the aluminum is

$$S = \frac{-101.7\ (388)}{1 + (0.018)(.58064)} = -39{,}100 \text{ psi.}$$

The aluminum will yield under this tension. The failure of the aluminum-silicon bond is prevented, however, by the stretching of the aluminum.

The elongation of the aluminum, including extension in the plastic region, must be:

$$\mu_{AL} = \alpha_{AL}\,\Delta T + \frac{P}{E_{AL}t_{A}b} + \frac{1}{\rho 1}\,\frac{t_{AL}}{2}$$

where

$$\frac{1}{\rho 1} = \frac{GP}{E_{AL}b\ t_{AL}^{2}}$$

$$P = \frac{(\alpha_{S1}-\alpha_{AL})\ \Delta T}{4\left(\frac{1}{E_{A}t_{A}b} + \frac{1}{E_{S}t_{S}b}\right)}$$

$$\mu_{AL}\ (y = o) = \alpha_{A1}\,\Delta T + \frac{P}{E_{A1}\ t_{A1}b} + \frac{GP}{2E_{AL}b\ t_{A1}}$$

$$\mu_{AL}\ (y = o) = \alpha_{A1}\,\Delta T + \frac{AP}{E_{A1}\ t_{A1}b}$$

$$= \alpha_{A1}\,\Delta T + \frac{(\alpha_{S1} - \alpha_{A1}\ \Delta T}{1 + \frac{E_{A1}\ t_{A1}}{E_{S1}\ t_{S1}}}$$

$$= \left[ \frac{\alpha/AL + \frac{E_{AL}}{E_{S1}} \frac{t_{AL}}{t_{SL}} \alpha_{AL} + \alpha_{S1} - \alpha/AL}{1 + \frac{E_{A1}}{E_{Si}} \frac{t_{A1}}{t_{Si}}} \right] \Delta T$$

$$\mu_{AL} = \left[ \frac{\left( \frac{E_{AL}}{E_{S1}} \frac{t_{AL}}{t_{S1}} \right) \alpha_{AL} + \alpha_{S1}}{1 + \frac{E_{A1}}{E_{Si}} \frac{t_{AL}}{t_{Si}}} \right] \Delta T$$

for

$$\frac{t_{AL}}{t_{S1}} \ll 1$$

$$\mu_{AL} = \alpha_{S1} \Delta T$$

$$\mu_{AL} = 2.8 \times 10^{-6} \Delta T$$

Exact solution for

$t_{AL} = 0.0005$ in.

$t_{S1} = 0.015$ in.

$E_{AL} = 9.0 \times 10^{6}$ psi

$E_{S1} = 15.5 \times 10^{6}$ psi

$\alpha_{AL} = 13.1 \times 10^{-6}$ in./in. $^{o}$F

$\alpha_{S1} = 1.8 \times 10^{-6}$ in./in. $^{o}$F

$$\mu_{AL} = \left[ \frac{(0.01935)(13.1) + 1.8}{1 + 0.01935} \right] \Delta T \times 10^{-6}$$

$$\mu_{AL} = 2.0 \times 10^{-6} \Delta T$$

% elongation required $= 2.0 \times 10^{-4} \Delta T$

and at $\Delta T = 388^{o}$F

% elongation required $= 2.0 \times 10^{-4} \times 388 = 0.1\%$.

# APPENDIX C

## EOS DOCUMENT 4039-MP-I

CONTRACT JPL 952485

# MATERIAL AND PROCESS SPECIFICATIONS FOR ELECTROFORMED ALUMINUM CONTACT SOLAR CELLS

Prepared for

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California
Attention: Mr. Mark Beckstrom

EOS Document 4039-MP-I
Contract JPL 952485

Prepared by
K. Lui

K. Lui

Approved by

J. Davis

Jack Davis, Vice President
Manager, Aerospace Systems Division

## 1.0 SCOPE

1.1 This specification provides a detailed procedure for the preparation of and the requirements for processing and inspection of electroformed aluminum contact solar cell.

## 2.0 APPLICABLE DOCUMENTS

2.1 The following documents forms a part of this specification to the extent specified herein.

2.1.1 Specifications governing the silicon water material and the material required to formulate the aluminum electroplating bath shall be as stipulated or approved by the procuring activity.

## 3.0 REQUIREMENTS

### 3.1 Materials

a) Diffused silicon wafer 2x2x0.035 cm.
b) Aluminum plating solution
Aluminum chloride 3.4 molar lithium aluminum hydride 0.3 molar in anhydrous diethyl ether.
c) Plating fixture
d) Plating test cell
e) Buffered oxide etchant (electronic grade)
f) Stripping solution A-30 (electronic grade)
g) De-ionized water (DI $H_2O$)
h) Isopropanol (electronic grade)
i) Trichlorethylene (electronic grade)
j) Acetone (electronic grade)
k) Dry nitrogen
l) Hydrofluoric acid (HF electronic grade)
m) Sulfuric acid
n) Nitric acid
o) Hydrochloric acid
p) Methyl alcohol (Me OH electronic grade)
q) Kodak metal etch resist
r) Kodak metal etch resist thinner
s) Solar cell mask
t) Aluminum oxide 500 grit
u) Silicon monoxide - optical grade

v) Finger cots
w) Teflon tweezers
x) 100, 150 ml beakers
y) Edge etching fixture

3.2 Equipment

a) Ultrasonic cleaner
b) Tube furnace
c) Skinner syringe with millipore filter
d) Cell Spinner
e) Bake oven
f) Graduate
g) G.E. sunlamp
h) Jet spray can
i) Yellow room
j) Dry box
k) Vacuum oven
l) Vacuum pump
m) Temperature bridge
n) Vacuum system (Veeco, VE 400)
o) Boonton DC meter 95A
p) Narrow band pass filter 5890A
q) 20X microscope
r) Hot plate
s) DC power supply
t) Fume hood
u) Four point probe
v) Solar simulator

4.0 PROCEDURE

4.1 Photoresist Masking Procedure

4.1.1 Inspect for damage (chips, scratches). Perform sheet resistance measurement on a 10% sample size.

4.1.2 Load into Teflon holders (using finger cots and/or fiberglass-filled Teflon tweezers), and place in 150 ml beakers.

4.1.3 Wash cells ultrasonically (Sonic Systems Model 901) <u>3 times each</u> for <u>3 minutes each</u> in:

a) Isopropanol (Electronic grade, B & A Code 2758).
b) Trichloroethylene (Electronic grade, B & A Code 2787).
c) Acetone (Electronic grade B & A Code 2750).

4.1.4 Blow dry with dry compressed nitrogen.

4.1.5 Etch in HF (Electronic grade, B.A. Code 2753) 5 minutes to remove $P_2O_5$. Rinse 3 times ($H_2O$ DI).

4.1.6 Boil cells in $H_2SO_4$ for 15 minutes (Removes hard-to-remove organic materials.) Rinse 3 times in DI $H_2O$.

4.1.7 Boil cells in $HNO_3$ for 10 minutes. (Leaves surface very clean and hydrophilic). Rinse 3 times in DI $H_2O$.

4.1.8 Rinse 3 times in MeOH. (Electronic grade, B.A. Code 2757).

4.1.9 Heat in furnace at 800°C for 3 minutes. (Removes OH groups from oxide surface and promotes adhesion.)

4.1.10 Mix 5 parts KMER in graduate (Kodak Metal Etch Resist) to 1 part KMER thinner. Shake graduate.

4.1.11 Put KMER mixture in Skinner syringe which has built-in millipore filter. Put cell on spinner and squeeze KMER from syringe on to surface. Spin at 2500 RPM for 15 seconds.

4.1.12 Bake in 100°C oven for 20 minutes.

4.1.13 Put cell in registry fixture and align cell to mask. Expose pattern using G.E. sunlamp 9 inches away for 2 minutes.

4.1.14 Have a 100 cc Pyrex beaker containing KMER developer. Put cell in developer for 3 minutes. Have a jet spray can containing KMER developer and give the cell a quick spray (about 15 sec.). Have another jet spray can containing DI $H_2O$. Spray cell for about 1 minute. Blow dry using jet spray can.

4.1.15 Bake in vacuum oven set at 185°C for 2 hrs. Don't pull vacuum.

4.1.16 Inspect each cell for any discrepancies in the photoresist pattern using a 10X microscope.

4.1.17 Store wafers in a dessicator until ready for plating operation.

## 4.2 Aluminum Electroplating Procedure

### 4.2.1 Preplating Treatment of Masked Silicon Wafer

4.2.1.1 Hand lap 'P' side of cell using wet 500 grit aluminum oxide, or sandblast 'P' side of cell. Rinse well using DI $H_2O$ and dry.

4.2.1.2 Etch the masked water in 8:1 $NH_4$-HF buffered etchant for five minutes. Rinse in DI $H_2O$ and dry.

4.2.1.3 Place the wafer onto the plating fixture with the 'N' side contacting the fixture. Install the teflon hold-down plate and gently turn down the holding screws. Attach the plating fixture which is the cathode and the two aluminum anodes to their respective positions on the test cell lid.

4.2.1.4 Place and screw down this lid assembly into the plating test cell previously filled with the aluminum plating solution. This operation is to be done in a dry box with a dry nitrogen atmosphere since the plating solution is water reactive.

### 4.2.2 Electrodeposition of Aluminum

4.2.2.1 Connect electrical leads from a DC power supply to the respective electrodes of the plating test cell. Set current value at 50 mA, (current density of 15 A/sq.ft.) and turn on power and plate for thirty minutes. Since the plating is being done in a static bath, occasional shaking of the test cell is necessary to dislodge the bubbles from the wafer formed during the plating process.

### 4.2.3 Post Plating Procedure

4.2.3.1 Unscrew and remove the lid assembly from the test cell, performing this step in the dry box. Cap the test cell and save for subsequent platings. Remove the lid assembly from the dry box and rinse off the residual plating solution with distilled water. Disassemble the plating fixture and carefully remove the plated cell. Rinse the cell thoroughly with distilled water.

### 4.2.4 Stripping the Photoresist

4.2.4.1 Heat 100 ml of B & A stripping solution A-30 to 100°C in a Petri dish. Immerse the plated cell into the stripper for ten minutes to remove the KMER photoresist. Rinse off the stripper thoroughly using distilled water. Rinse with isopropyl alcohol and dry.

### 4.2.5 Edge Etching

4.2.5.1 Place cells in the edge etching fixture and immerse in a 50% HCl solution for one hour. Rinse the fixture with distilled water. Remove cells from the fixture and rinse with distilled water and then isopropyl alcohol.

### 4.2.6 Sintering of the Contacts

4.2.6.1 Preheat vacuum oven to 75°C. Place the plated cells inside and pull a vacuum of 30 in Hg for one hour. Remove from oven and cool.

4.2.6.2 Preheat the tube furnace to 320°C and start nitrogen purge. Place the cell in a ceramic boat and insert into the tube furnace and sinter for ten minutes. Remove the boat from the furnace and cool.

### 4.2.7 SiO Coating

4.2.7.1 Ultrasonically wash cells 3 times each for 3 minutes each:

a. Trichloroethylene (electronic grade).
b. Isopropanol (electronic grade).
c. Blow dry with clean, dry compressed $N_2$.

4.2.7.2 Handling only with finger cots and/or glass-filled Teflon tweezers, load into evaporation fixture and tighten holders. Make sure holder covers collector stripe but does not shade any active area of cell.

4.2.7.3 Install in vacuum system (Veeco, VE 400).

4.2.7.4 Evacuate to a better vacuum than $5 \times 10^{-6}$ torr.

4.2.7.5 Heat cells to 200°C with fixture heater (to drive off organics) and turn off to allow to cool (approximately 15 minutes).

4.2.7.6 When cells are approximately 100°C, begin heating SiO source (R.D. Mathis S.O. 25).

4.2.7.7 Raise source current to approximately 250 amps with shutter closed.

4.2.7.8 Noting short circuit current of monitor cell, open shutter quickly (1 sec.) when pressure in bell jar falls below $1 \times 10^{-6}$ torr.

4.2.7.9 Monitor short circuit current during evaporation. When current peaks (about 1 min.) close shutter quickly (1 sec.).

The monitor for each batch of 7 cells is one of the cells whose output is being monitored with a Boonton DC Meter No. 95A. The output of the cell is run through a 1 ohm resistor and the Boonton Meter measures the current flow. The cell is illuminated with a tungsten light source passed through a narrow bandpass filter (centered at 5890Å).

4.2.7.10 Cool source and cells while maintaining vacuum (for about 20 minutes).

4.2.7.11 Remove and inspect for flaws.

4.2.7.12 Store in container for electrical testing.

## 5.0 QUALITY ASSURANCE PROVISIONS

### 5.1 Inspection Responsibility

5.1.1 The supplier is responsible for the performance of all inspection requirements as specified herein. Except otherwise specified, the supplier may utilize his own or any other inspection facilities and services acceptable to JPL.

### 5.2 Classification of Tests

5.2.1 All tests of this specification are classified as in process or acceptance tests, for which the necessary sampling techniques, examination procedures, and methods of testing are specified in this section.

### 5.3 In Process Tests

5.3.1 Sheet Resistance Measurement

In testing for the diffused sheet resistivity a four point probe method shall be employed using a head similar to a model "B" manufactured by the Fell Co., Ltd. Readings shall be taken at the center of the "N" cell face at $77^{\circ}F \pm 2^{\circ}F$. The sheet resistance acceptable value shall be 34 ± 12 ohms/sq.

### 5.4 Acceptance Tests

5.4.1 Electrical Performance

The power output of all cells shall be measured at standard AMO test conditions, at a temperature of $28 \pm 1^{\circ}C$. The completed cells shall be capable of meeting all the following performance criteria, under the environmental conditions specified with a total electrical degradation of not more than five percent (5%).

5.4.2 Cell Contact Strength

Cells shall be capable of withstanding a tape pull test on both cell faces, utilizing Scotch No. 810 "Magic Transparent Tape", with no electrical or mechanical degradation. Cells must be capable of withstanding a 2000 gram pull test on both "P" and "N" contacts when a wire or ribbon is attached to the contact and the force is applied in a direction perpendicular to the cell face. The type of wire or ribbon to be used, and the method of attachment, is subject to JPL approval.

5.4.3 Temperature and Humidity

The cells shall be placed in a test chamber and the air temperature and humidity lowered to 5°C and greater than ninety-five percent (95%), respectively. The air temperature shall then be lowered to 0°C. The cells shall soak at this temperature for four (4) hours. The air temperature and humidity shall then be raised to 125°C and greater than ninety-five percent (95%)respectively. The cells shall soak at this temperature for thirty (30) days. At the completion of this test, the cells shall conform to the requirements of 5.4.1 and 5.4.2.

5.4.4 Thermal Shock

The cells shall be subjected to twenty (20) temperature cycles between the extremes of 200°C and -196°C. The cells shall remain at the extremes for a minimum of one (1) hour. The temperature rate of change shall be no less than 100°C per minute. At the completion of the test, the cells shall conform to the requirements of 5.4.1 and 5.4.2.

5.4.5 Vacuum-Temperature

The cells shall be tested in a vacuum chamber and the pressure of $10^{-5}$ mm Hg or less. The cell temperature shall be maintained at -125°C for four (4) hours and 125°C for twelve (12) days. Upon completion of the test, the cells shall be tested for satisfactory operation and shall conform to the requirements of 5.4.1 and 5.4.2.

5.4.6 Shape Factor

The change in current from the short circuit current point to the current at 400 millivolts shall be less than 2.0 milliamperes.

5.4.7 High Temperature

The cells shall be placed in a chamber and the temperature raised to 200°C and shall remain at this temperature for a period of one hundred sixty-eight (168) hours. Upon completion of this period, the cells shall be allowed to return to ambient room temperature and shall conform with the requirements of 5.4.1 and 5.4.2.

5.4.8 Storage

The cells shall be capable of being stored at a humidity and temperature of ninety-five percent (95%) and 100°C, respectively for a period of time in excess of one (1) year after which the cells shall conform with the requirements of 5.4.1 and 5.4.2.

5.4.9 Low Temperature

The cells shall be placed in a chamber and the temperature reduced to -196° for a period of one hundred sixty-eight (168) hours. The cells shall then be allowed to return to ambient room temperature, and shall conform with the requirements of 5.4.1 and 5.4.2.

# APPENDIX D

EOS DOCUMENT 4039-MP-II

CONTRACT JPL 952485

# MATERIAL AND PROCESS SPECIFICATIONS FOR ELECTROFORMED ALUMINUM INTERCONNECTION OF SOLAR CELLS

Prepared for

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EOS Document 4039-MP-II
Contract JPL 952485

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## 1.0 SCOPE

1.1 This specification provides a detailed procedure for the preparation of and the requirements for the processing of electroformed aluminum interconnected solar cells.

## 2.0 APPLICABLE DOCUMENTS

2.1 The following documents form a part of this specification to the extent specified herein.

(None)

## 3.0 REQUIREMENTS

### 3.1 Materials

a) Diffused N/P type silicon wafer 2x2x0.035 cm., resistivity 34 ± 12 Ω/□
b) Aluminum plating solution
   Aluminum chloride 3.4 molar lithium aluminum hydride 0.3 molar in anhydrous diethyl ether.
c) Buffered oxide etchant (8:1 $NH_4$-HF)
d) KMER stripping solution A-30 (electronic grade)
e) Distrilled water ($H_2O$)
f) Trichlorethylene (electronic grade)
g) Acetone (electronic grade)
h) Dry nitrogen
i) Sulfuric acid ($H_2SO_4$)
j) Methyl alcohol (Me OH electronic grade)
k) Kodak metal etch resist (KMER)
l) Kodak metal etch resist thinner
m) Kodak metal etch resist developer
n) One mil aluminum sheet stock
o) Finger cots
p) Dextilose paper

3.2 Equipment

a) Plating fixture EOS No. 4039-114
b) Ultrasonic cleaner
c) Skinner syringe with millipore filter
d) Cell spinner
e) Bake Oven
f) Graduate
g) G.E. sunlamp (275 watt)
h) Jet spray can
i) Yellow room
j) Dry box
k) 10X microscope
l) Hot plate
m) DC power supply (1 amp rating)
n) Fume hood
o) Solar simulator
p) Solar cell KMER mask and registration fixture
q) Teflon tweezers
r) 100, 150 ml beakers
s) Teflon cell holding fixture rack
t) Dessicator jar
u) Sandblaster, S.S. White Industrial Air Brasive Unit, Model C or equivalent
v) Scissors
w) Orange stick
x) 0.020 Teflon sheet stock
y) Anodes (type 1100 aluminum)

## 4.0 PROCEDURE

### 4.1 Photoresist Masking Procedure

4.1.1 Visually inspect cells for damage (chips, scratches).

4.1.2 Boil cells in $H_2SO_4$ for 15 minutes. Rinse three times in distilled $H_2O$.

NOTE: The following paragraph 4 operations to be done in yellow room:

4.1.3 Load into Teflon holders (using finger cots and/or fiberglass filled Teflon tweezers), and place in 150 ml beakers.

4.1.4 Wash cells ultrasonically (Sonic Systems Model 901) for 3 minutes in trichlorethylene (electronic grade, B&A Code 2787).

4.1.5 Blow dry with dry compressed nitrogen.

4.1.6 Mix 5 parts KMER in graduate (Kodak Metal Etch Resist) to 1 part KMER thinner. Shake graduate.

4.1.7 Put KMER mixture in Skinner syringe which has built-in millipore filter. Put cell on spinner and squeeze KMER from syringe on to surface. Spin at 2500 RPM for 15 seconds.

4.1.8 Bake in 100°C oven for 20 minutes.

4.1.9 Put cell in registry fixture and align cell to mask. Expose pattern using G.E. sunlamp 9 inches away for 2 minutes.

4.1.10 Have a 100 cc Pyrex beaker containing KMER developer. Put cell in developer for 3 minutes. Have a jet spray can containing KMER developer and give the cell a quick spary (about 15 seconds). Dip cell in beaker of MeOH (electronic grade, B.A. Code 2757) while cell is still wet with KMER developer and blow dry using jet spray can.

4.1.11 Bake in oven set at 185°C for 2 hours.

4.1.12 Inspect each cell for any discrepancies in the photoresist pattern using a 10X microscope. Any cell with discontinuous contact patterns should be rejected. Strip KMER per 5.4 and recoat.

4.1.13 Store wafers in a dessicator until ready for plating operation.

## 5.0 ALUMINUM ELECTROPLATING PROCEDURE

### 5.1 Preplating Treatment of Masked Silicon Wafers

5.1.1 Sandblast 'P' side of cells to remove all traces of diffusion coating. Rinse well using distilled $H_2O$ and dry.

5.1.2 Etch the masked wafers in 8:1 $NH_4$-HF buffered etchant for five minutes. Rinse in distilled $H_2O$ and dry.

5.1.3 Place fixture on clean sheet of dextilose paper with cell divider (mandrel) bar up, and at right angle to operator. Carefully cut aluminum 1 mill sheet stock approximately 1/2 by 1 1/2 inches. Place aluminum gasket shim on fixture divider bar and wrap shim over bar.

5.1.4 Place KMER coated cell blanks on fixture, 'N' side down. Position cell blanks with grid lines parallel to divider bar and with 'N' contact areas to one side of fixture, locate cells in approximate final position. Install all four Teflon hold down bars over cell edges and gently tighten nylon holding screws. Trim a second aluminum gasket shim and place in position on removal divider bar per paragraph 5.1.3. Carefully place removable divider bar on fixture, locating bar madrel between cells, gently tighten hold down screws.

5.1.5 Place fixture under microscope and position all four cells tightly against divider bars, and final tighten all hold down screws. Inspect parallel aluminum shim and flatten to fixture divider bar with orange stick, inspect series aluminum shim and fold over 'N' contact edge of cells with orange stick. Trim excess aluminum shim stock from reverse sides of cells.

5.1.6 Cut four pieces of 0.020 Teflon sheet stock approximately 3/4 x 1 inch, and fit into pockets of fixture to cover grid line area of cells. Attach the assembled plating fixture, which is the cathode, to the two aluminum anodes. Each anode should be type 1100 aluminum, solid, and the same size of the plating fixture base. Anodes should be spaced 1/2 inch from the cell faces. Anodes may be attached to fixture base with Teflon bolt or equivalent.

5.1.7 Place the assembly into the plating test cell previously two-thirds filled with the aluminum plating solution. This operation is to be done in a dry box with a dry nitrogen atmosphere since the plating solution is water reactive.

5.2 Electrodeposition of Aluminum

5.2.1 Connect electrical leads from a DC power supply to the respective electrodes of the plating fixture. (Reference Figure 1.) Set current value at 600 mA for 4-cell fixture, (current density of 15 A/sq.ft.) Turn on power and plate for a total of five hours. At the end of 4 1/2 hours, remove four Teflon sheet grid masks from fixture with Teflon tweezers. Do not interupt plating current, or remove fixture from plating solution. Since the plating is being done in a static bath, occasional shaking of the test cell is necessary to dislodge the bubbles from the wafer formed during the plating process.

5.3 Post Plating Procedure

5.3.1 Remove the plating fixture from the test cell, performing this step in the dry box. Cap the test cell and save for subsequent platings. Remove the plating fixture assembly from the dry box and rinse off the residual plating solution with distilled water. Disassemble the plating fixture and carefully remove the plated cells. Rinse the cells thoroughly with distilled water, acetone and dry.

5.3.2 Place four cell matrix under microscope and using Teflon tweezers carefully remove all aluminum shims.

5.4 Stripping the Photoresist

5.4.1 Heat 100 ml of KMER stripping solution A-30 to 100°C in a Petri dish on a hot plate under a fume hood. Immerse the plated cell matrix into the stripper for ten minutes to remove the KMER photoresist. Remove matrix from Petri dish and rinse off the stripper thoroughly using distilled water. Rinse with acetone and dry.

## 6.0 ELECTRICAL PERFORMANCE

6.1 The power output of all aluminum interconnected solar cells shall be measured at standard AMO test conditions at a temperature of 28 ± 1°C.

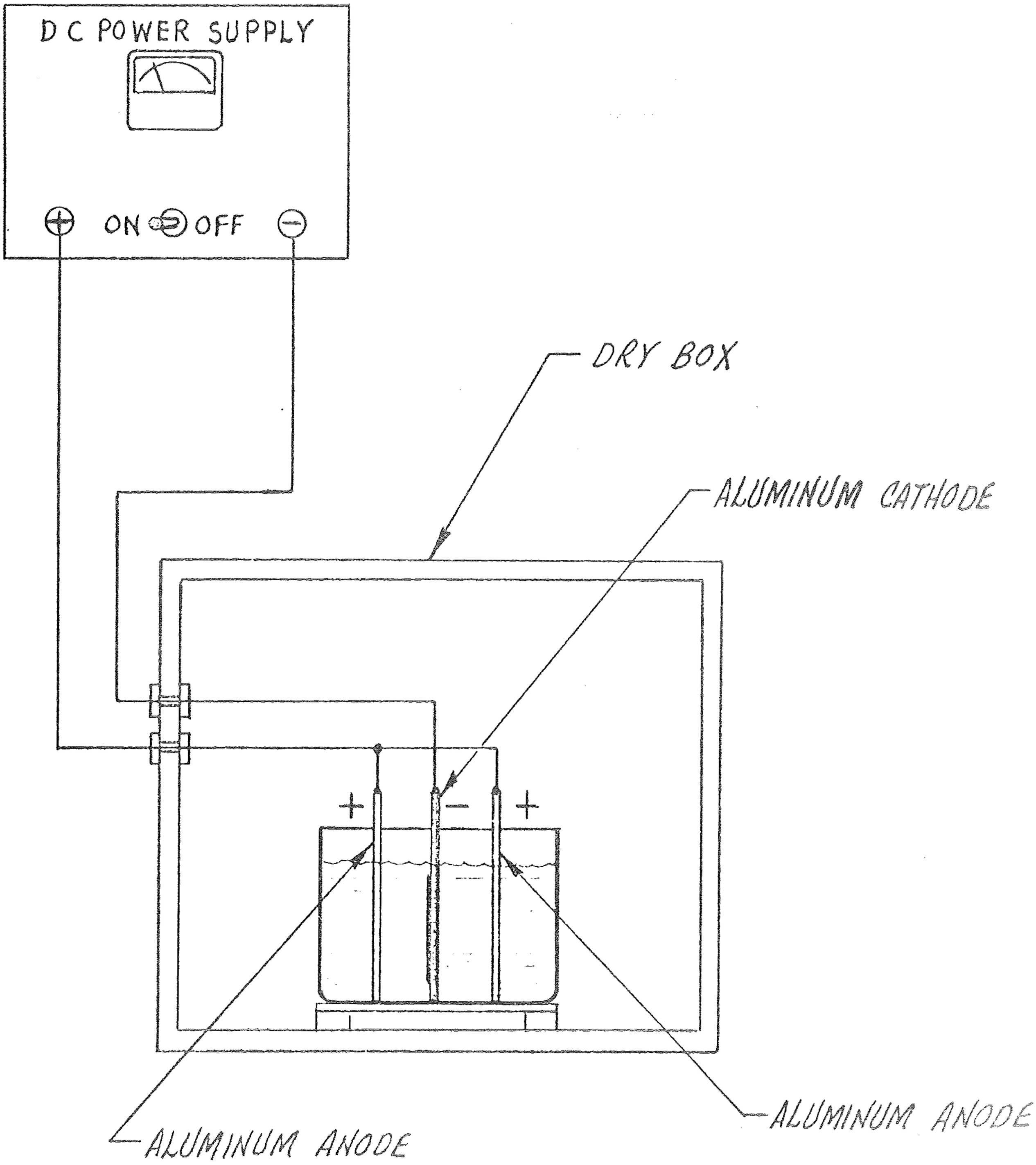

FIGURE 1

ELECTROPLATING WIRING DIAGRAM

**ELECTRO-OPTICAL SYSTEMS**

A XEROX COMPANY

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