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CENTER PUNCHED SOLAR CELL MODULE DEVELOPMENT EFFORT

FINAL REPORT

JUNE 1978

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Xerox Electro-Optical Systems

Pasadena, California 91107

"The JPL Low-Cost Silicon Solar Array Project is sponsored by the U. S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE."

Prepared Under Contract No. 954693 For

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

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CENTER PUNCHED SOLAR CELL MODULE DEVELOPMENT EFFORT

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By

R. E. Ross and W. E. Mortensen

JPL CONTRACT NO. 954693

Xerox Electro-Optical Systems

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SECTION I

INTRODUCTION AND SUMMARY

This report describes the results of an advanced module development program with the objective of providing a low cost solar cell mechanical interconnect design. The design approach, which avoids soldering or welding operations, lends itself to automated assembly techniques thus supporting the Low-Cost Silicon Solar Array Project goals.

During the course of the program, a total of twelve modules were delivered to JPL for qualification testing. The first group of six modules contained aluminum contact cells and the second group of six modules contained silver-titanium-palladium contact cells.

Extensive component and environmental testing by Xerox Electro-Optical Systems at the module level has shown that reliable cell mechanical interconnection can be achieved when utilizing the proper electrical contact materials and pressures. Environmental testing of XEOS modules at JPL, in accordance with the same JPL specification used by XEOS, will be performed and the results will be separately published.

This final report discusses the module design, manufacturing procedure, test program, significant problem areas and solutions, and conclusions and recommendations as formulated and conducted by XEOS.

SECTION 2

MODULE DESIGN

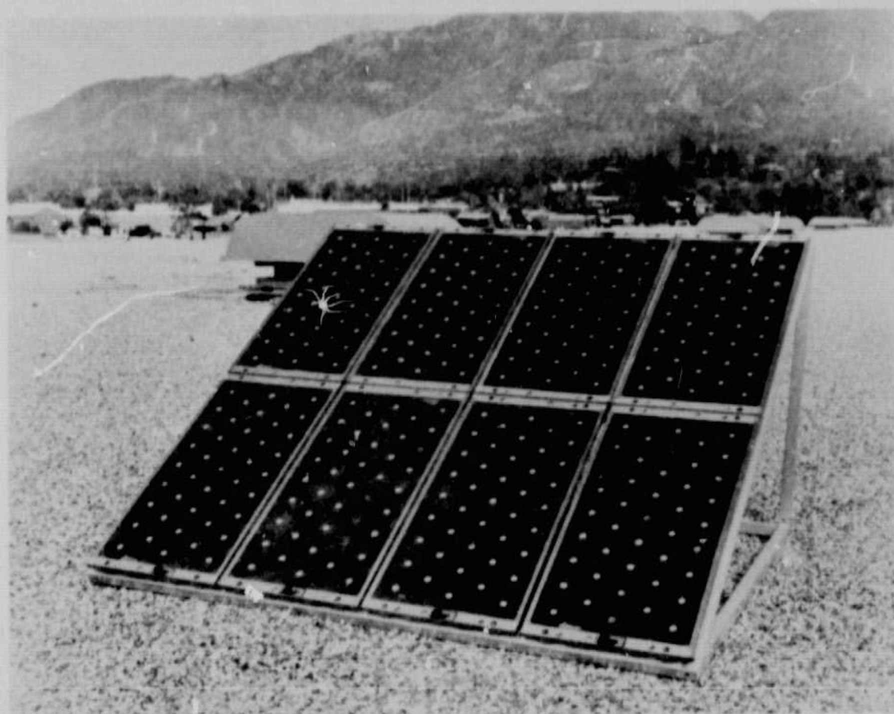
The module design, established at the beginning of the program, consists of 43 silicon solar cells mechanically interconnected in series and encapsulated with silicone rubber utilizing a glass window and aluminum frame structure. The overall module dimensions are presented in Figure A-1 of the Appendix. Eight modules package into a 46 inch by 46 inch subarray as shown in Figure 2-1.

2.1 PACKAGING DESIGN

The module packaging configuration is presented in Figure A-2 of the Appendix. The packaging configuration consists of an extruded aluminum alloy main frame, a double sided printed circuit board-solar cell subassembly bonded to the main frame, annealed soda lime cover glass supported in the main frame by means of a gasket configuration, silicone encapsulate between the cover glass and printed circuit board-solar cell subassembly, and electrical output receptacles (Reference Figure 2-2).

The module main frame (Figure 2-3a) is an anodized 6063-T5 aluminum alloy extrusion chosen for its high corrosion resistance and low cost. The 6063 alloy is utilized extensively in architectural applications.

The double sided circuit board, (Figures 2-3b and A-4) is 0.062 inch in thickness with plated through-holes and tin-lead plating over a nickel strike on all circuitry. The solar cells are retained on the circuit board by a threaded stud and nut arrangement. The beryllium-copper stud configuration, shown in Figure A-3, provides a spring rate controlled load at the solar cell N contact thus controlling the joint clamping force applied in direct compression to the circuit board. The average stud installation force is 5 lbs. such that the N and P contact resistance is minimized under nominal operating conditions. The retained cell-stud configuration is shown in Figure A-2.



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Solar Module Sub Array

Figure 2-1

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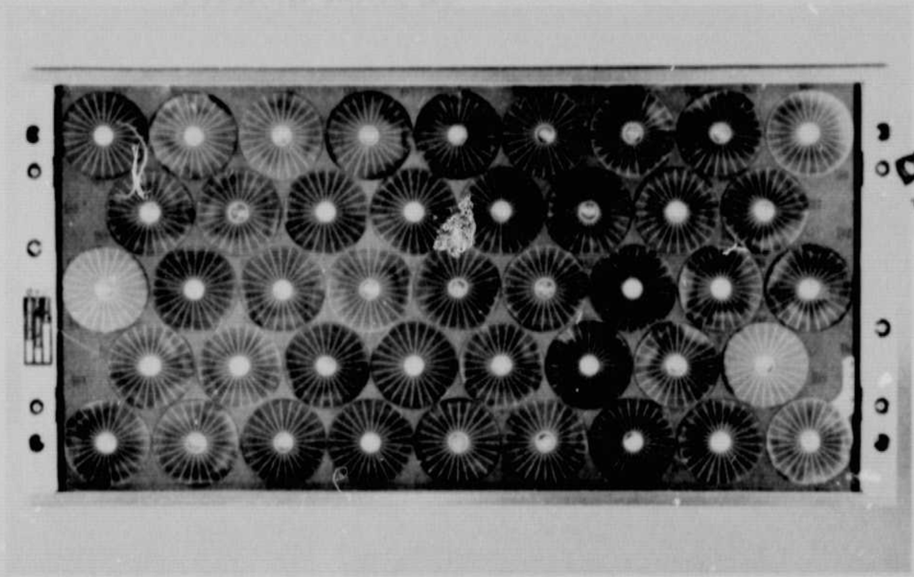

(a) Module Front View

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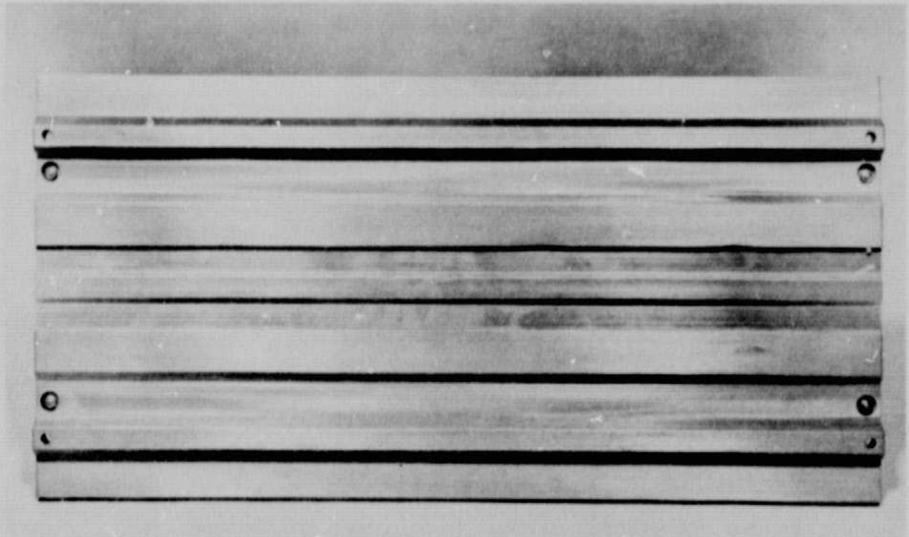

(b) Module Rear View

Figure 2-2

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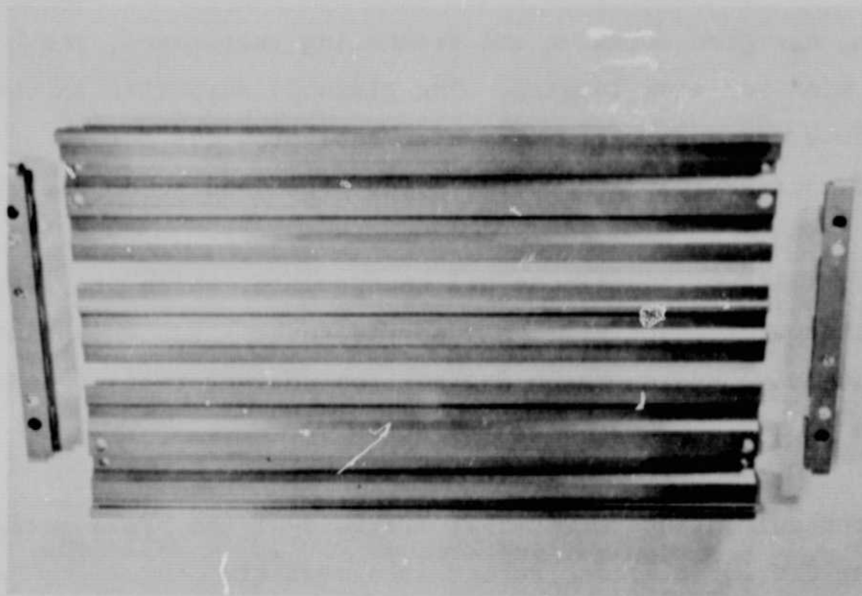

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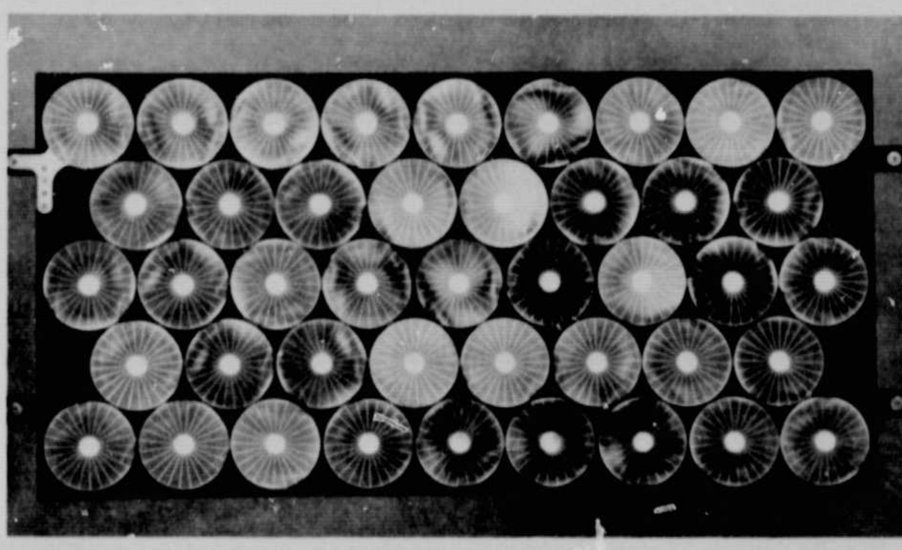
(a) Frame Assembly



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(b) Solar Cell/Printed Curcuit Board Assembly

Figure 2-3

The cover glass configuration is a 0.093 inch thick annealed soda lime plate glass. The soda lime glass does not degrade or darken under solar exposure, has good abrasion and weathering resistance, and has the ability to meet wind and snow loading. The glass is supported in the main frame by a groove and edge seal. The edge seal provides for relative expansion and contraction, and avoids point edge loading on the glass.

The General Electric silicone gel encapsulate, which provides the required thermal conductivity between the cover glass and printed circuit board assembly, has no known degradation characteristics under extended exposure to terrestrial solar radiation.

The electrical output receptacles are gold-plated brass potted in place, utilizing RTV 108 silicone rubber as a sealant.

2.2 ELECTRICAL DESIGN

The solar cell is a circular N/P silicon 2 Ω cm cell, 2.28 inches in diameter with silver-titanium-palladium contact material. The N contact is an annulus about the center hole permitting electrical connection and mechanical attachment in one assembly operation. Symmetrical grid lines radiate from the N contact in a pattern optimized to maximize the cell output.

The interconnection of the circular cells into a series string module is accomplished by means of a double-sided printed circuit board. The cell is mounted to the PC board by means of an N-contact threaded stud and nut as shown on the module assembly drawing.

The head of the contact stud makes the N contact with the top of the cell. The N-contact stud connects with the rear side of the PC board by means of a nut which establishes the clamping force on the mechanical joint and makes electrical contact with the negative trace.

The negative trace to an adjacent cell passes through three plated-through holes to a circular pad located under the P contact of the adjacent cell. This procedure is repeated for each cell to form the series string of the module.

The printed circuitry terminates at two positive and two negative output terminals. The location of these terminals permits a wide variety of series and parallel configurations, within the 46 inch by 46 inch subarray.

The module interconnection may be accomplished by jumper leads and/or cable harnessing depending on array design requirements.

The output terminals are potted receptacles for AMP taper pin connectors which provide easy connection and removal, maximum resistance to vibration and corrosion, and low cost.

The design of the module insures electrical safety. All electrical circuits are housed inside the module with the only access at the recessed output terminals. When connected, the terminals may be protected and sealed with a moisture-proof cap on the harness. When unused the terminal is sealed with a terminal cap.

The 100 megohm insulation to ground is insured by use of insulation materials and proper placement and sealing of the components. The cell area is encapsulated with silicone gel and the rear of the PC board is isolated from the chassis by means of RTV 108. In addition, the aluminum main frame is hard anodized for electrical and environmental protection.

SECTION 3

MODULE MANUFACTURING

3.1 GENERAL

Twelve solar cell modules were manufactured and delivered. Six modules utilized aluminum plated solar cell contacts and six modules utilized silver-titanium-palladium contacts. Module manufacturing was conducted in two phases to support the different cell configurations.

Preproduction module assembly was conducted utilizing a combination of hand tools and an assembly bonding fixture.

Two problems were noted during the assembly effort:

- The aluminum oxide on the aluminum contact solar cells prevented a reliable electrical contact using the existing mechanical stud design. The electrical contact problem was eliminated by use of silver-titanium-palladium contact cells.
- Minor voids developed in the encapsulant during curing due to material shrinkage in an enclosed cavity. It is recommended that the encapsulation approach be modified as discussed in the following section, to reduce cost which should also correct the void problem.

3.2 COST REDUCTION RECOMMENDATIONS

The present frame, glass and printed circuit board represents a two year old design. As the result of information gained from the assembly of these modules and investigation into low-cost approaches, the following recommendations can be made:

1. Eliminate the expensive P-C board and connect the cells using copper straps between the mechanical studs. The front glass will provide the mounting surface support presently provided by the P-C board.

2. Eliminate the rear frame extrusion and replace with a simple edge frame.

3. Conformal coat the cells, interconnect straps, and studs for safety and environmental protection.

Implementation of these recommendations would simplify the assembly process and reduce the unit costs.

SECTION 4

TEST PROGRAM

The test program consisted of development and preproduction testing including electrical performance, thermal cycling, humidity, electrical, and mechanical integrity testing. The results of the test program are discussed in the following sections.

4.1 DEVELOPMENT TESTING

Development tests included cell characteristics, cell contact methods, and encapsulation techniques and materials. Sample circuit boards with various fastener and cell interface configurations were tested with Ag-Ti-Pd contact cells providing a reliable low resistance mechanical interconnect. A summary of the development tests conducted is presented in Table 4-1.

4.2 PREPRODUCTION MODULE TESTING

The six solar modules with aluminum contact cells were tested for electrical performance and environmental effects per JPL Environmental Test Specification 5-342-1-B. The six silver-titanium-palladium contact cell modules were electrical performance tested only. Electrical performance testing utilized the XEOS xenon arc solar simulator. This simulator was designed to provide air mass zero solar irradiation. Air mass one intensity was attained by reducing power input to the simulator as measured by the JPL AM1 standard cell.

The thermal cycling and humidity tests used XEOS chambers and equipment. A test fixture was designed and built to implement the mechanical integrity testing.

Table 4-1

Development Test Summary

Test Item	
Aluminum contact solar cells.	Unsatisfactory Electrical contact unreliable in a thermal cycling environment.
Push nut-stud cell fastener.	Unsatisfactory Push nut unable to maintain sufficient contact pressure on cell.
Flat circuit board pad for rear cell contact.	Unsatisfactory Insufficient contact pressure for reliable electrical contact.
Threaded stud with nut as cell fastener.	Satisfactory Sufficient contact pressure is obtainable. Cell able to withstand considerable contact compression loading. Lock-tite on threads required to maintain pressure under thermal cycling.
Threaded stud with locking nut as cell fastener.	Unsatisfactory Excessive installation torque required.
Ring contact washer on rear contact of cell.	Satisfactory Sufficient contact pressure provides repeatable low resistance contact on rear of cell.
Ag-Ti-Pd contact solar cells.	Satisfactory Contact is compatible with the mechanical fastener. Degradation $< 5\%$ after 60 thermal cycles on an open board.
Aluminum contact solar cells with conductive epoxy at contact interface.	Unsatisfactory Aluminum contact unreliable after thermal cycling.

4.2.1 Electrical Performance Testing

Electrical testing was performed in accordance with Section II A-1 and 2 of JPL Specification 5-342-1. The individual cells were tested and graded into 10 mA groups by the cell manufacturer. The lot mean of the delivered cells was 580 mA for the aluminum contact cells and 680 mA for the silver-titanium-palladium contact cells.

The assembled modules were tested under the XEOS xenon solar simulator. The modules were tested at 100 mW/cm^2 and 28°C. The measured electrical performance of the six Ag-Ti-Pd contact cell modules at 28°C and 100 mW/cm^2 illumination intensity is presented in Figure 4-1.

Figure 4-2 compares to the measured performance with the predicted module performance at AM1, 100 mW/cm^2 solar insolation, and a 60°C cell temperature. Figure 4-3 shows the predicted performance range of the assembled subarray for the same operating conditions as Figure 4-2.

Statistical analysis, assuming a large sample of modules, shows that that probability of eight randomly selected modules in a subarray providing less than the minimum specified average power is approximately 1×10^{-7}. The distribution of the preproduction modules with respect to the normal distribution of the maximum power for a large quantity of modules is shown in Figure 4-4.

4.2.2 Thermal Cycling Test

Six modules with aluminum contact cells were mounted in a single rack for thermal cycling. The modules were subjected to 50 cycles with cell temperature ranging from -40° to +90°C.

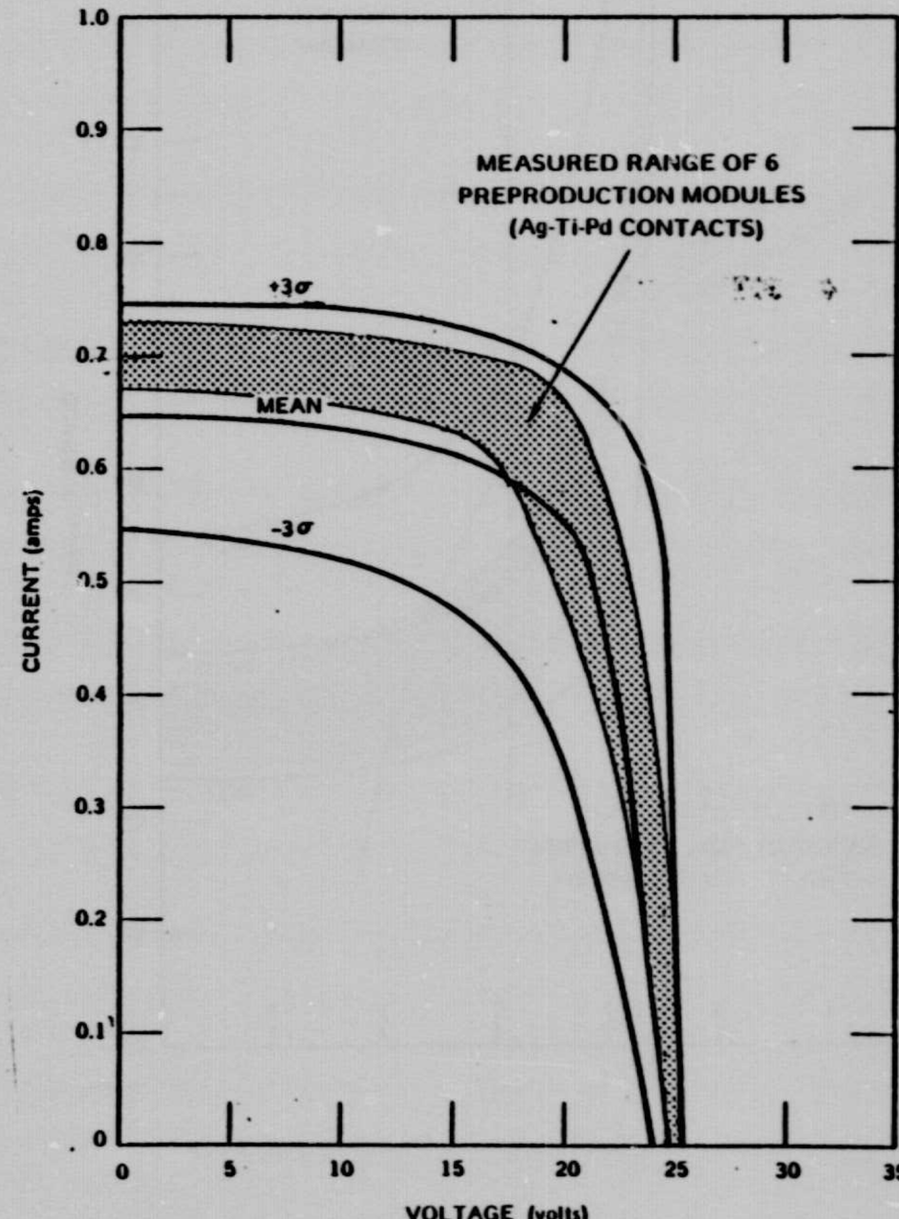

Figure 4-1

Module Performance at $100\ mW/cm^2$ AM1 28^oC Including Assembly Losses Anticipated and Actual

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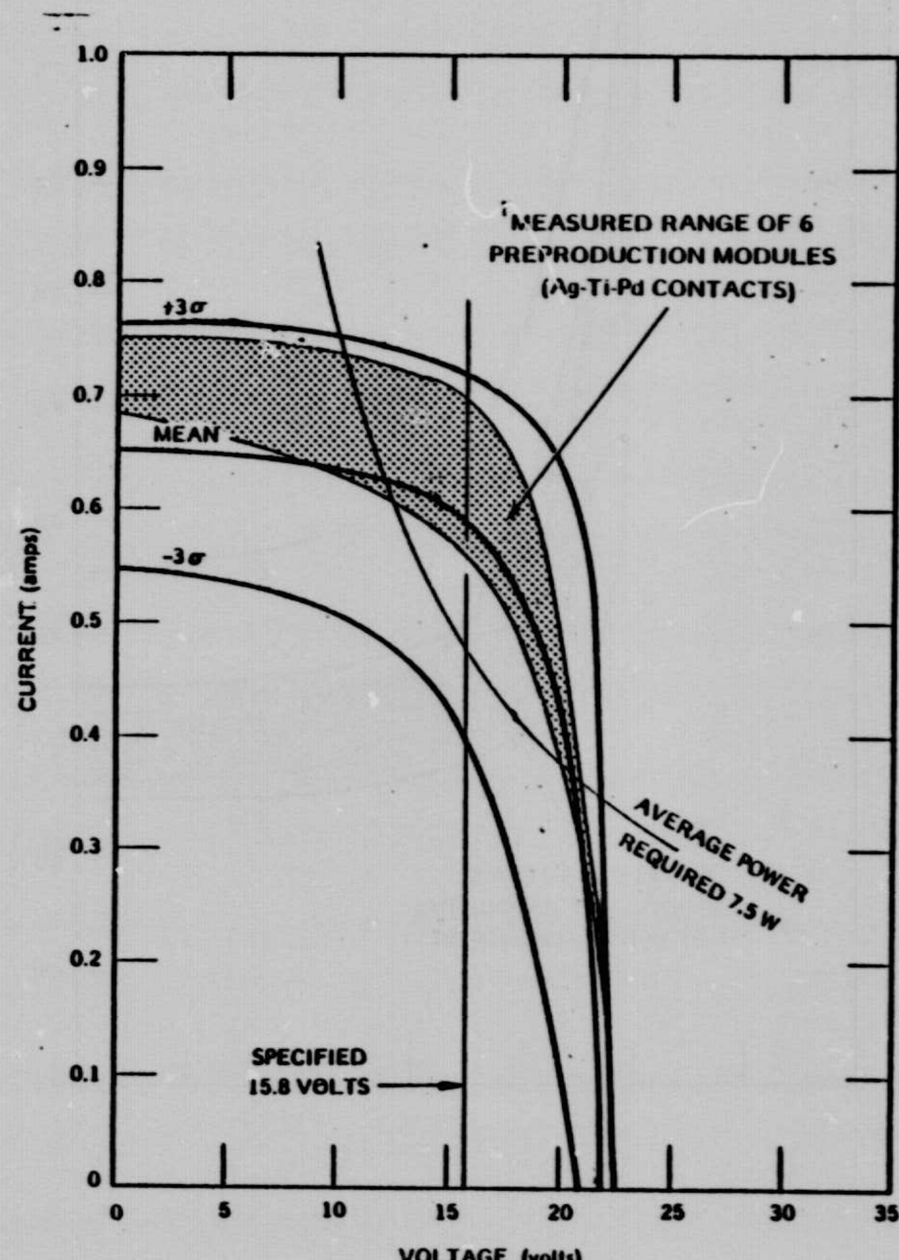

Figure 4-2
Module Performance at the Specified Operation Conditions of 100 mW/cm^2, 60^oC, AM1

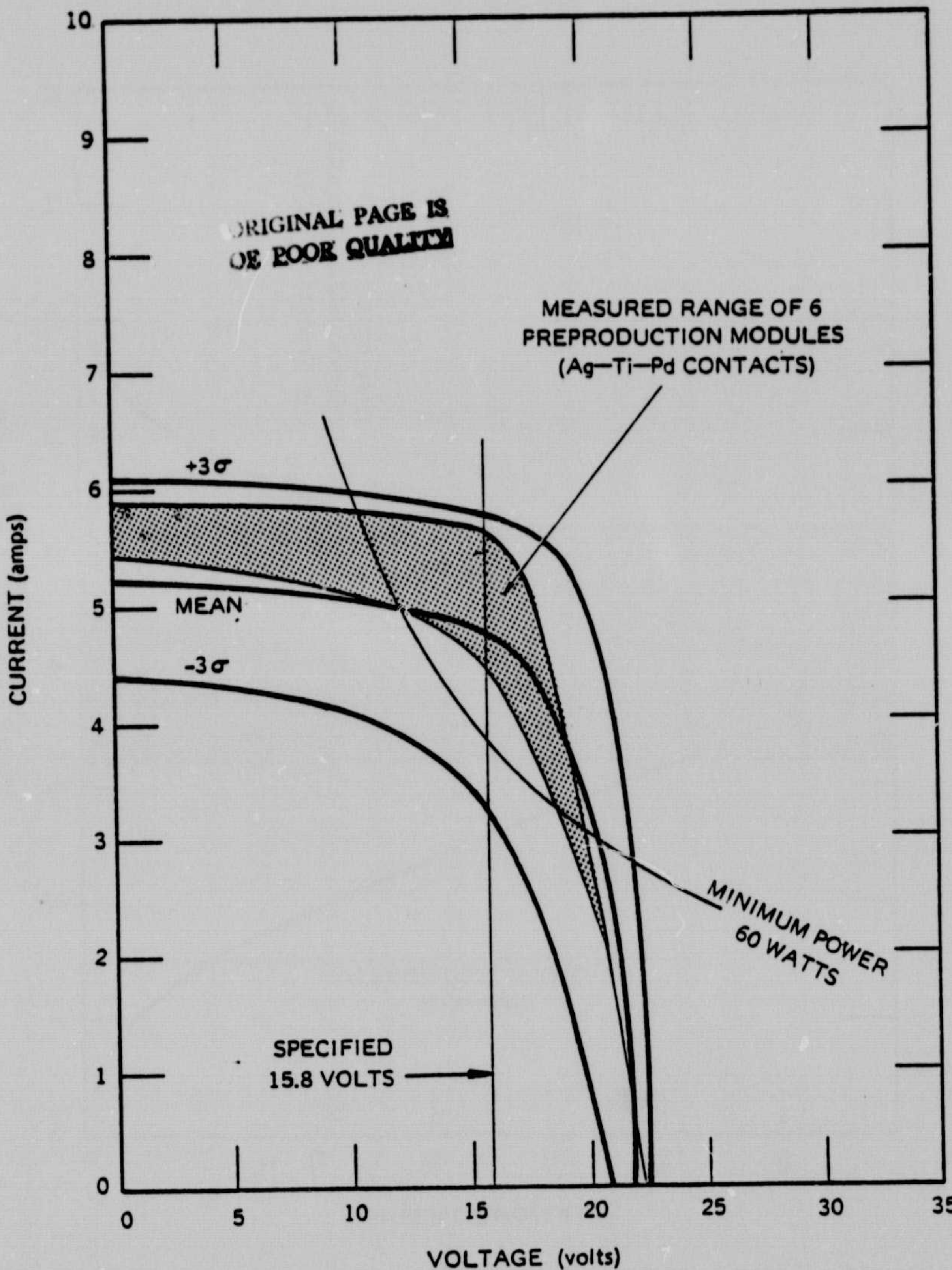

Figure 4-3. Subarray Performance at the Specified Operating Conditions of 100 mW/cm^2, $60^{\circ}C$, AM1

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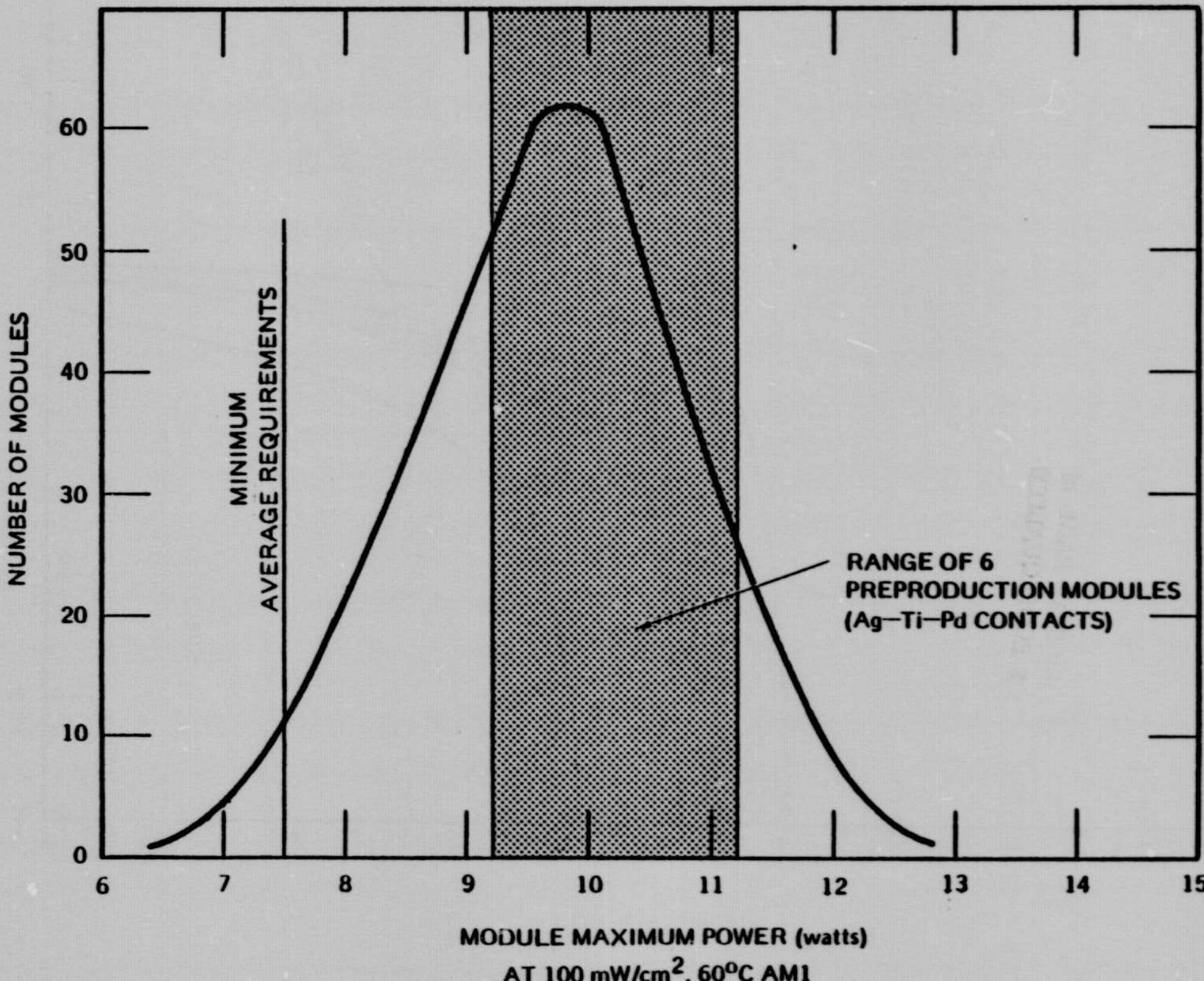

Figure 4-4. Distribution of Number of Modules with Respect to Maximum Power

Chamber temperature rate of change during each cycle was 90 $\pm 10^{\circ}$C/hour. These modules then underwent an electrical performance test and were inspected for delamination, cracks, and other discrepancies following the cycling. No cracks were observed or measured electrically. Some delamination did occur between the glass and the encapsulant system. Electrical performance degradation was observed due to increased electrical resistance at the aluminum contacts.

4.2.3 Humidity Test

Following the thermal cycle test, the six aluminum contact cell modules were humidity tested. The panels were mounted in the same rack and in the same chamber used for the thermal cycle tests. The modules were tested for five cycles of humidity per the JPL specification.

Each module was inspected for damage and given an electrical performance test and high voltage test within one hour of completion of the humidity test. No degradation from the humidity test was detected.

4.2.4 Mechanical Integrity Test

The mechanical integrity test consisted of a cyclic uniform pressure load of 50 psf applied to the module surface. The load was cycled from positive to negative loading 100 times, as defined in the JPL test specification.

During the cyclic loading test, the modules were supported at the four design support points in a rigid fixture. The 50 psf pressure loading was applied to the modules by pressurizing alternate compartments adjacent to the front and back module surfaces, separated by a bladder as shown in Figure 4-5. The pressure cycling was controlled by a solenoid operated, three-way valve which alternately

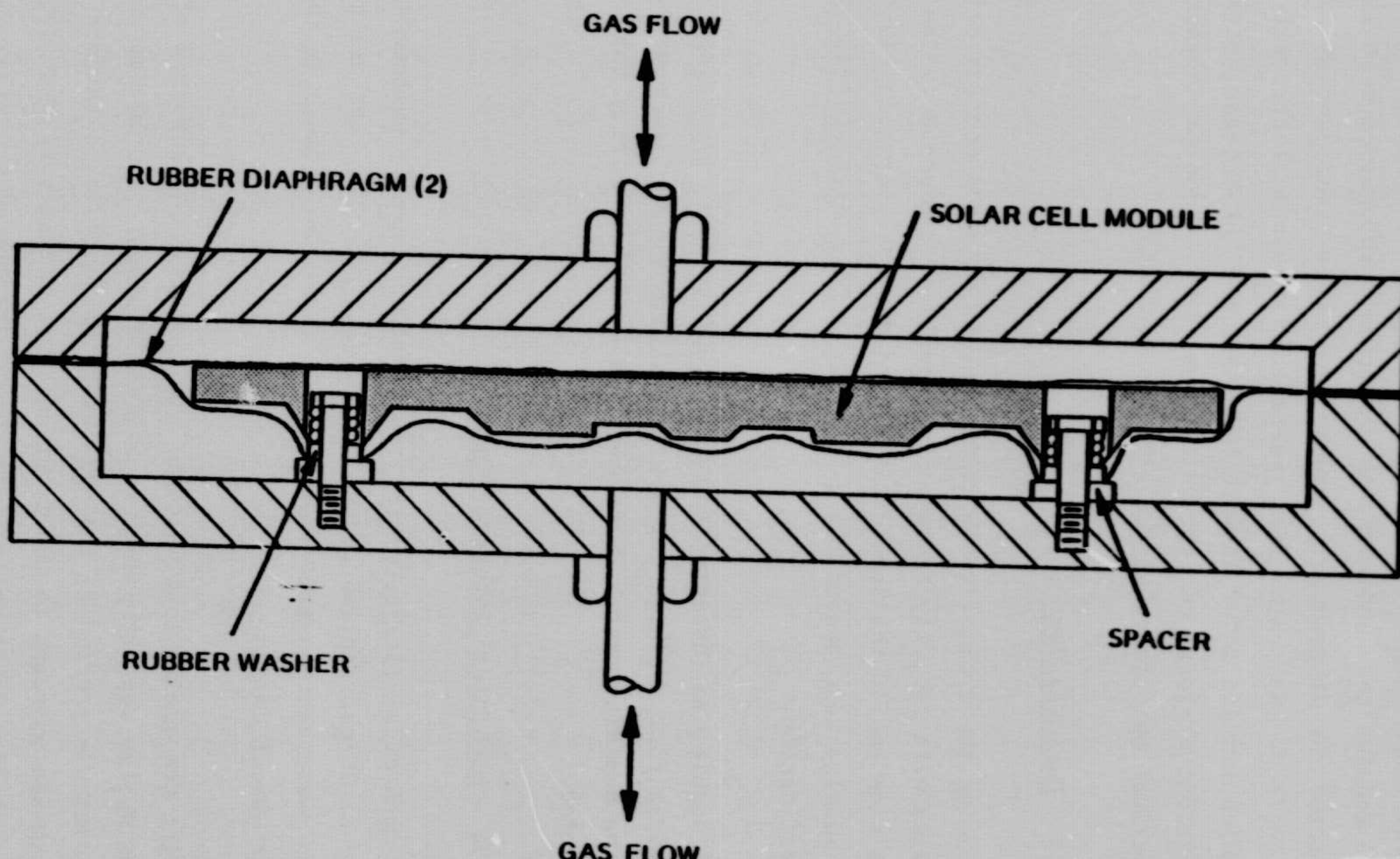

Figure 4-5. Mechanical Integrity Test Configuration

cycled the pressure compartments from atmosphere to a line pressure of 0.347 psig. The pressure loading was maintained on the module for a minimum of one minute to simulate wind gust loading.

No mechanical failures were detected.

SECTION 5

PROBLEM AREAS AND SOLUTIONS

Two significant problems developed during the module assembly: poor electrical connection to aluminum contact cells and the degrading effect of encapsulation adhesive on the mechanical contact electrical interface.

Problem #1:

Extensive component and module testing has shown that reliable cell mechanical interconnection is difficult to achieve when utilizing aluminum contact cells. The aluminum oxide on the surface of the cell contact causes an intermittent electrical connection between the interconnect and the cell after thermal cycling. Tests with various cleaning methods and conductive epoxys failed to reliably overcome the oxide layer.

Solution #1:

The elimination of the aluminum at the electrical interface, i.e., utilization of a Ag-Ti-Pd contact, provided a reliable electrical contact. The same cell and connector design was used, with only a change in the cell contact material to eliminate the aluminum oxide layer. Component tests consistently showed good electrical connections.

Problem #2:

Due to the current packaging design it was necessary to use a partial vacuum during the injection of the silicone rubber encapsulate. This process can force encapsulant into the electrical interface between the cell and the stud to create electrical instability problems and sometimes an open circuit. The low viscosity of the encapsulate and the pressure of the vacuum process causes flow between the cell contact and the stud.

Solution #2:

Modification of the packaging design (see Section 3.2) such that encaplusation can be accomplished without pulling a vacuum on the module. Elimination of the rear frame extrusion and P-C board will allow a gravity-flow application of the encapsulate. This will reduce the pressure of the encapsulate on the stud/cell interface.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

This development program has proven that the mechanical contact concept can be reliably assembled and will pass the environmental requirements of JPL Specification 5-342-1. A summary of significant findings include:

a. A threaded stud (versus a push nut) is required to maintain sufficient contact pressure.

b. The center-hole cell will withstand significant compression loading in this configuration.

c. The back contact interface requires a localized area contact to provide the required pressure distribution.

d. Reliable cell mechanical interconnection is difficult to achieve when utilizing aluminum contact material.

e. The module cost in a production environment can be significantly reduced by simplifying the packaging design.

The recommendation of XEOS is to continue development of the mechanical cell interconnect with these main tasks:

a. Simplify the packaging design by eliminating the circuit board and rear frame.

b. Modify the encapsulation process to prevent the flow of encapsulant into the electrical interface between the cell and the stud.

c. Investigate automated assembly techniques using the cell and stud configuration.

APPENDIX

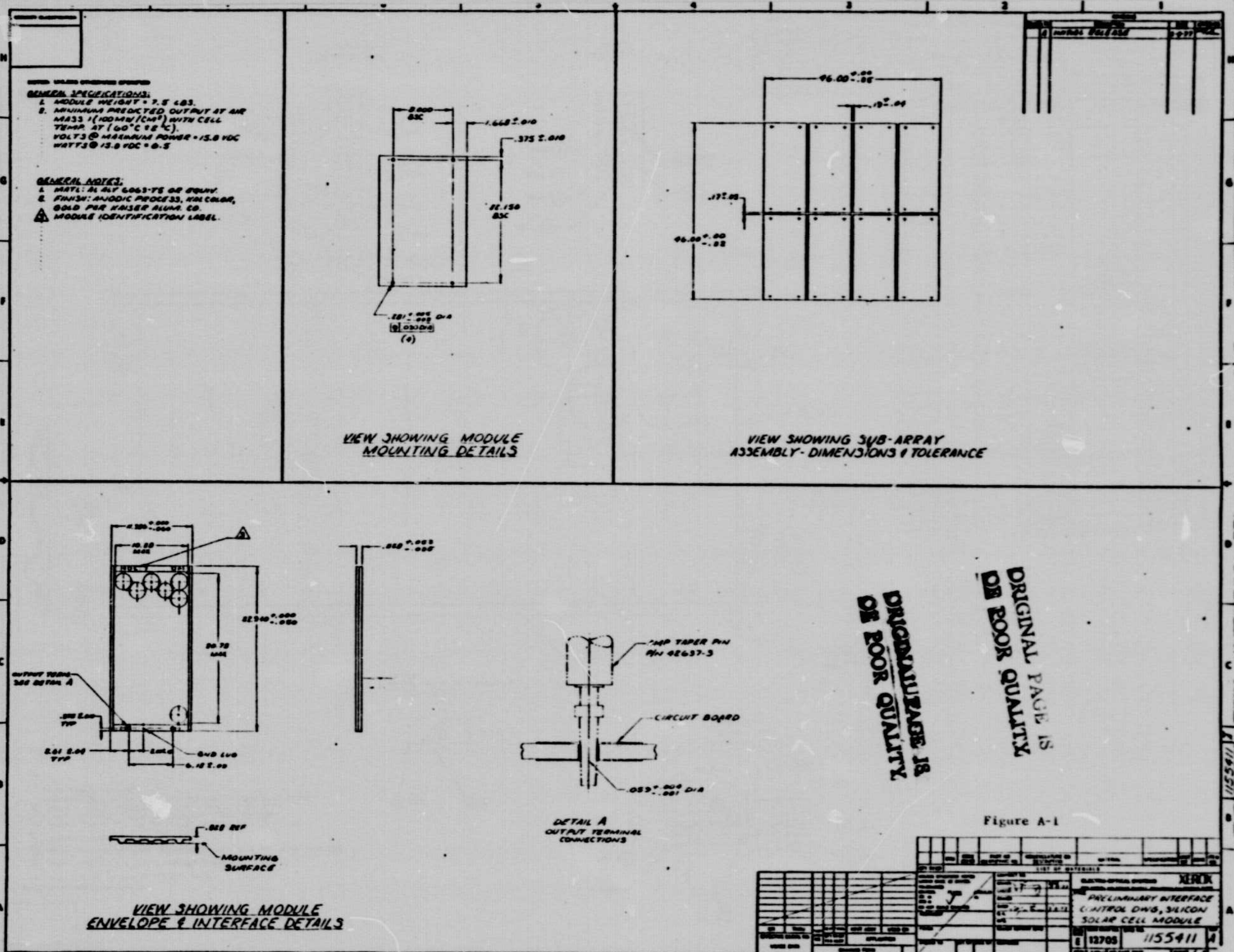
GENERAL SPECIFICATIONS:
1. MODULE WEIGHT = 7.5 LBS.
2. MINIMUM PREDICTED OUTPUT AT AIR MASS 1 (100MW/CM²) WITH CELL TEMP. AT (60°C ±2°C).
VOLTS @ MAXIMUM POWER = 15.8 VDC
WATTS @ 15.8 VDC = 6.5
GENERAL NOTES:
1. MAT'L: AL ALY 6063-T5 OR EQUIV.
2. FINISH: ANODIC PROCESS, KALCOLOR, GOLD PER KAISER ALUM. CO.
3 MODULE IDENTIFICATION LABEL.
VIEW SHOWING MODULE MOUNTING DETAILS
VIEW SHOWING SUB-ARRAY ASSEMBLY - DIMENSIONS & TOLERANCE
VIEW SHOWING MODULE ENVELOPE & INTERFACE DETAILS
DETAIL A
OUTPUT TERMINAL CONNECTIONS
AMP TAPER PIN
P/N 42657-3
CIRCUIT BOARD
GND LUG
MOUNTING SURFACE
XEROX
PRELIMINARY INTERFACE CONTROL DWG, SILICON SOLAR CELL MODULE
13705
1155411
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Figure A-1

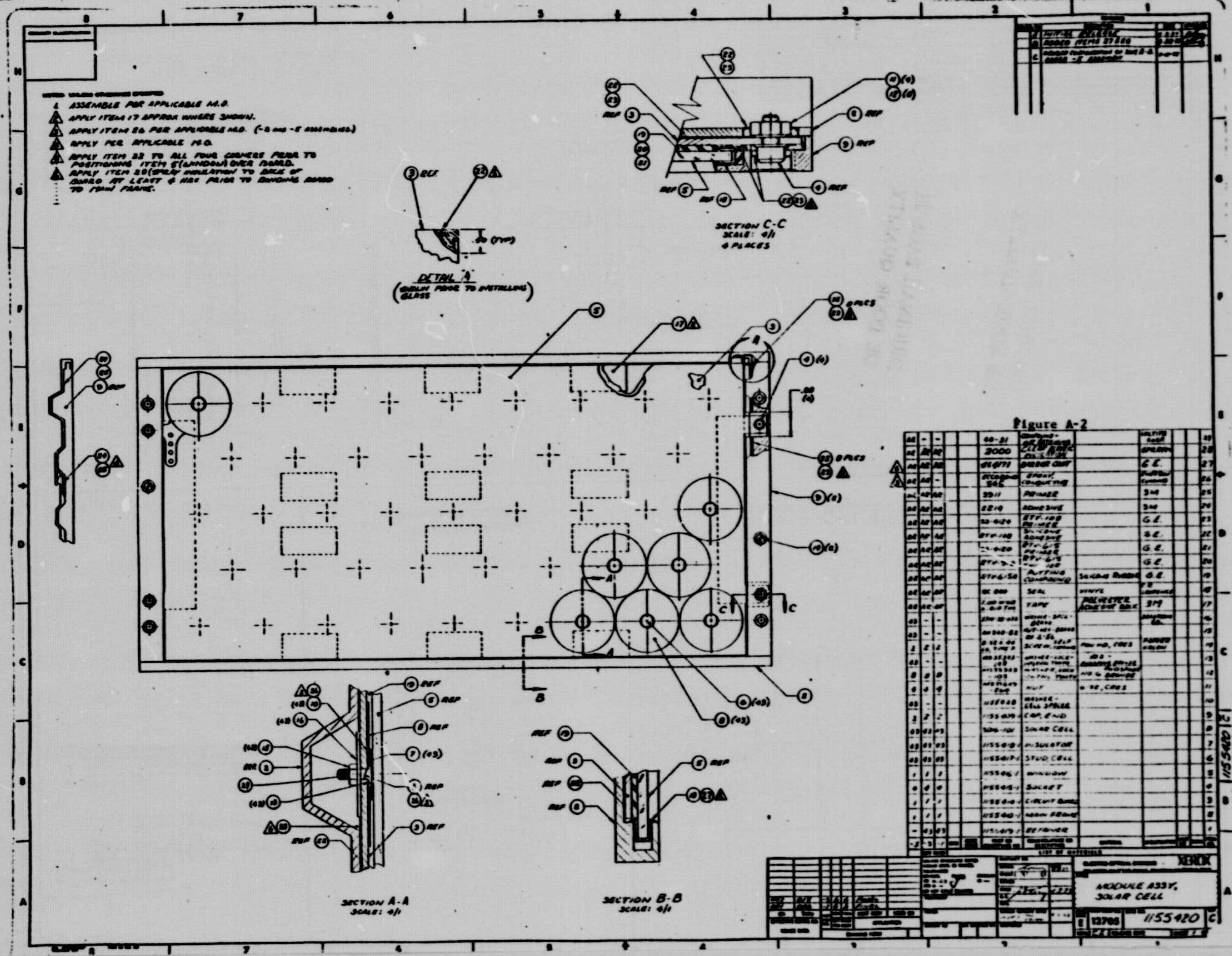
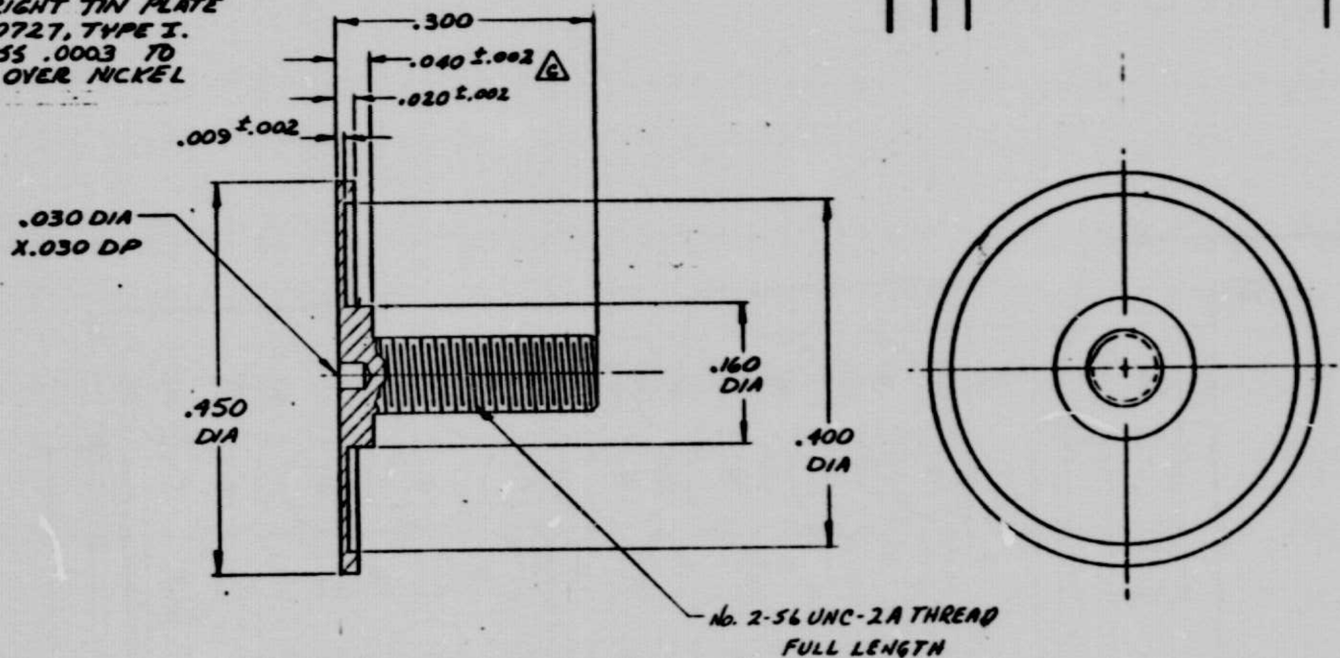

SECTION C-C
SCALE: 4/1
4 PLACES
DETAIL A
SECTION A-A
SCALE: 4/1
SECTION B-B
SCALE: 4/1
XEROX
MODULE ASSY,
SOLAR CELL
1155420

Figure A-2

ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	INITIAL RELEASE	3-30-77	
	B	ADDED No. 2-56 THREAD	7-13-77	
	C	.040±.002 DIM. WAS .026±.010	12-1-77	

NOTES: UNLESS OTHERWISE SPECIFIED
1. REMOVE ALL BURRS & SHARP EDGES.
2. FINISH : BRIGHT TIN PLATE PER MIL-T-10727, TYPE I. MIN. THICKNESS .0003 TO BE APPLIED OVER NICKEL STRIKE.



1155417 C

Figure A-3

QTY REQD	SYM	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	UNIT WT.	ZONE	ITEM NO.
			-1	STUD	BERYLLIUM COPPER ALLOY 10 HT	CA-175			1

LIST OF MATERIALS

NEXT ASSY	USED ON	PART DASH NO.	QTY REQD NEXT	QTY REQD FINAL
1155420-1		-1	43	

EFFECTIVE SERIAL NO. (ON / THRU) — USAGE DATA — APPLICATION

DRAWING FORM

UNLESS OTHERWISE NOTED LINEAR DIMS. IN INCHES.
TOLERANCES
DECIMAL: XX ± -; XXX ± .010
FINISH: 125√
ANGULAR: ± 2°
DO NOT SCALE DRAWING
TREATMENT
FINISH: 2
SIMILAR TO | ACT. WT. | CALC. WT.

CONTRACT NO.
DRAWN — DATE 3-28-77
CHECK
DESIGN
ENGR
Q.A.
MFG.
DESIGN ACTIVITY APPD
CUSTOMER

ELECTRO-OPTICAL SYSTEMS
A XEROX COMPANY
300 EAST FOOTHILL BOULEVARD, PASADENA, CALIFORNIA

TITLE: STUD, CELL - SOLAR CELL MODULE

DWG SIZE	CODE IDENT NO.	DWG NO.	REV
C	12705	1155417	C

SCALE 10/1 | RELEASE DATE | SHEET 1 OF 1

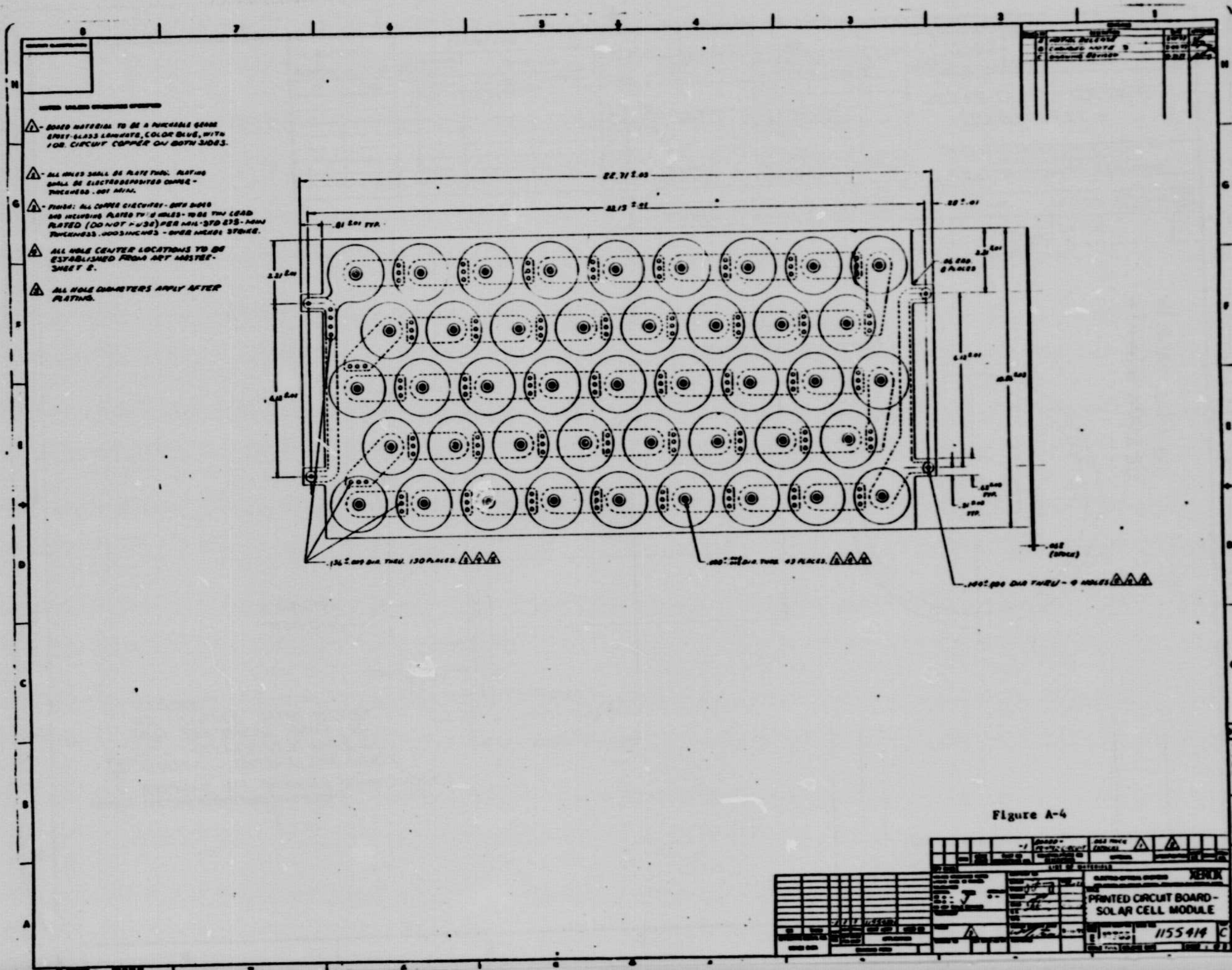


Figure A-4