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LMSC-D573729

Final Report

TRANSPARENT SUPERSTRATE TERRESTRIAL SOLAR CELL MODULE

JPL Contract No. 954653

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FINAL REPORT

TRANSPARENT SUPERSTRATE TERRESTRIAL SOLAR CELL MODULE

Prepared by

Lockheed Missiles & Space Co., Inc.
Under Contract Number 954653

for

Jet Propulsion Laboratory
California Institute of Technology

as part of

Task 4 - Automated Assembly of Arrays

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The JPL Low-Cost Silicon Solar Array Project is funded by ERDA and forms part of the ERDA Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

FOREWORD

This report contains information prepared by the Lockheed Missiles and Space Company under JPL contract. The content is not necessarily endorsed by the Jet Propulsion Laboratory, California Institute of Technology, National Aeronautics and Space Administration or the U.S. Energy Research and Development Administration Division of Solar Energy.

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Cont.)

TABLES

INTRODUCTION

Section 1

INTRODUCTION

This is the final report on the design, development, fabrication, and testing of the Transparent Solar Cell Module Development effort which was performed by Lockheed Missiles & Space Company for JPL under contract 954653 as part of the Energy Research and Development Administration (ERDA) Low-Cost Silicon Solar Array Project from 3 January 1977 through 31 August 1977; Figure 1-1 depicts the major elements and output of the program, namely the design, fabrication, and test of 12 preproduction modules which comply with the requirements of JPL Specification 5-342-1 Rev B. Six of the preproduction modules were retained at LMSC for mechanical and environmental tests prior to shipment and the other six were shipped directly to JPL. Cell performance and material process characteristics were determined by extensive tests and design modifications were made prior to preproduction fabrication. These tests included three cell submodules and two full size engineering modules. Along with hardware and test activity, engineering documentation was prepared and submitted as depicted in Figure 1-1 and in accordance with the program schedule, Figure 1-2. The final report was rescheduled until September 1977 to incorporate results of sunlight testing and repair analysis as reported in Section 4.

A major objective within the program was to gather module development and perform a cost analysis based on mass production quantities of this module. The analysis served the purpose of identifying material and labor intensive features of the module design.

As a result of first fabricating two engineering modules, design and fabrication improvements were made which later resulted in more cost effective preproduction modules and in the identification of cost reduction areas for future mass production of modules. Features of a suggested baseline production module design evolved and estimated costs to produce 5 to 50 kW and 1 mW are presented.

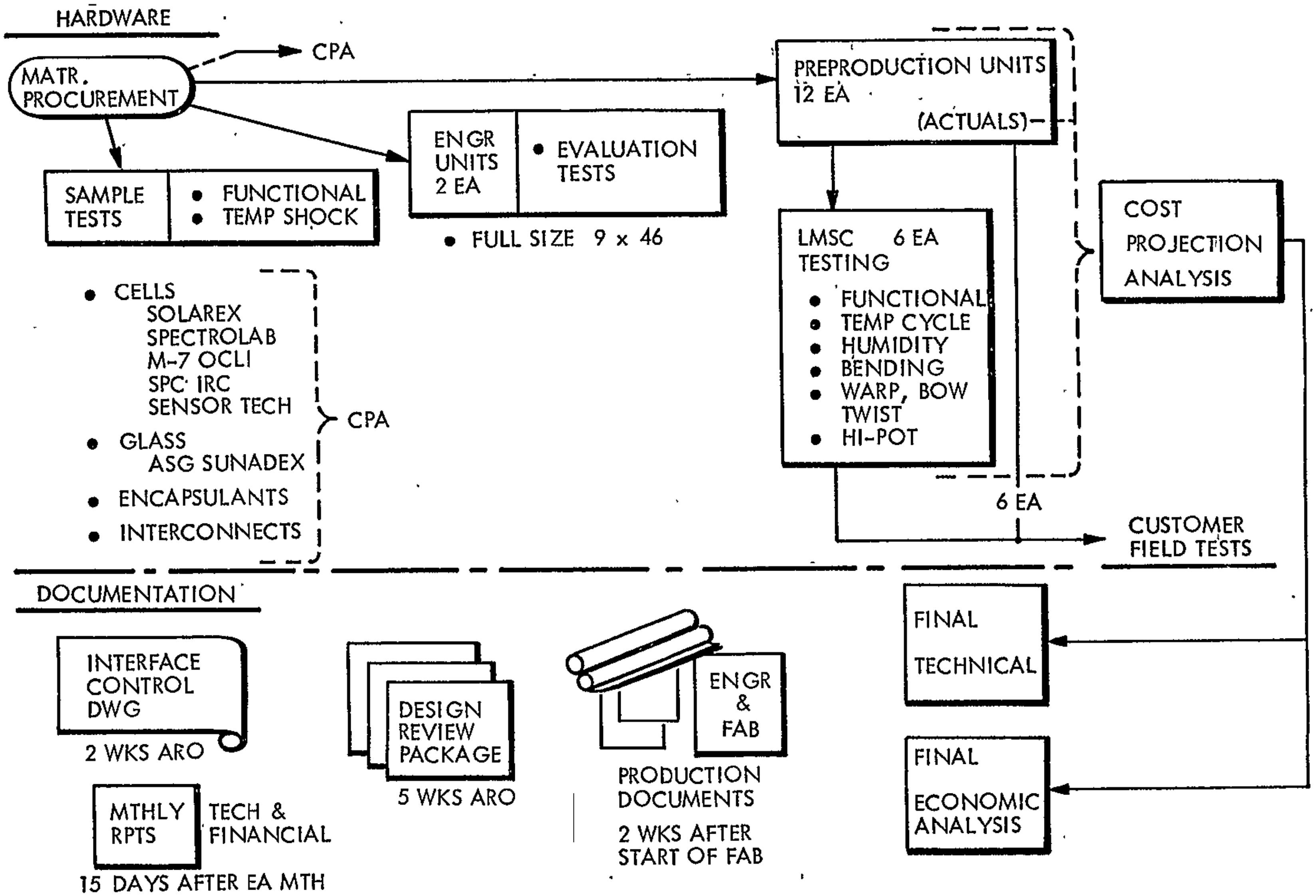

Figure 1-1 Program Element Schematic

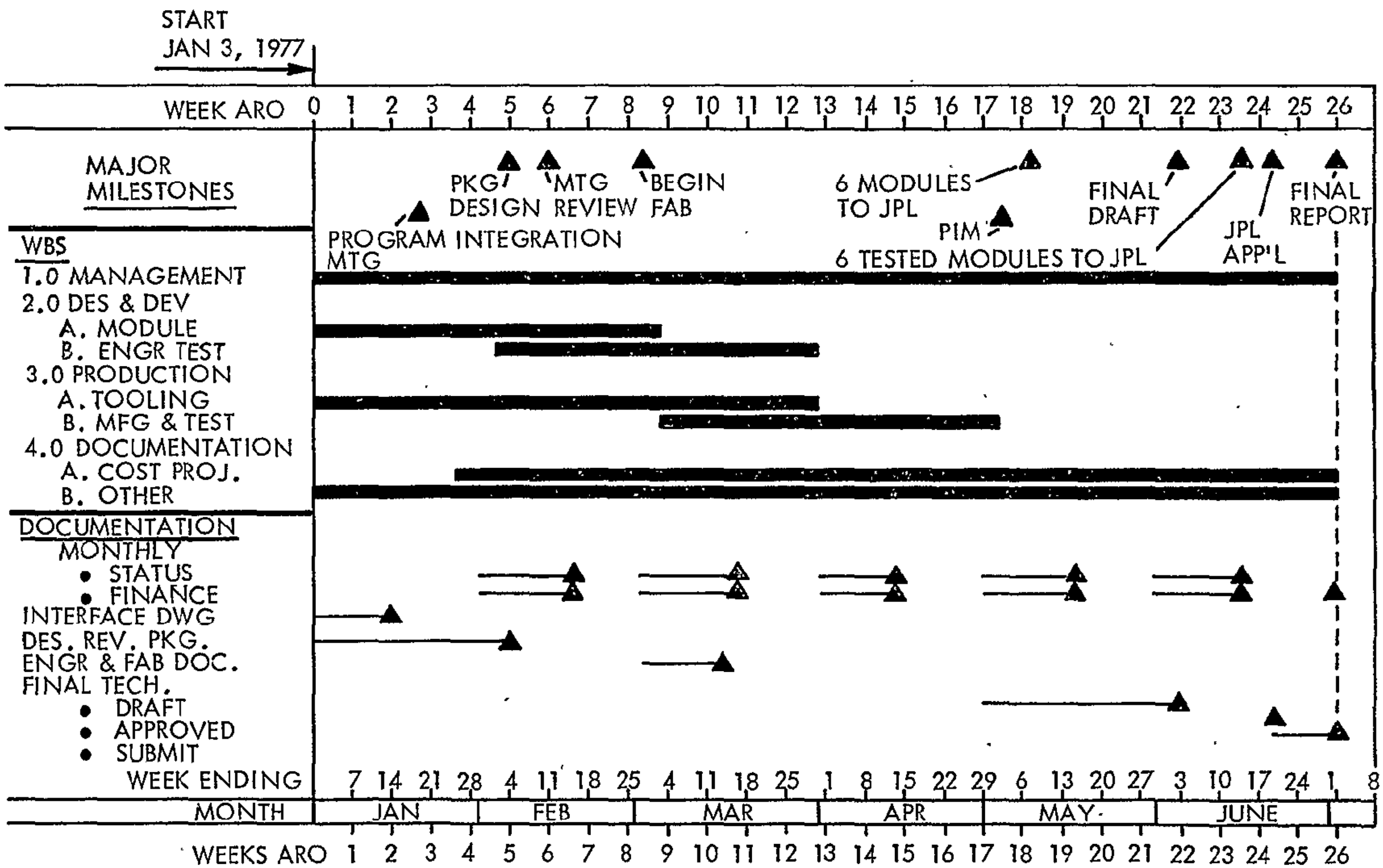

Figure 1-2 Program Schedule and Milestones

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SUMMARY

The mechanical features of the module design incorporate high transmission glass superstrate, custom extruded aluminum side and end rails, a backside center stiffening web which also served as a mounting for two electrical output connectors, and three compliant grommets for mounting the unit into subarray frames.

The electrical portion of the design incorporates 3-inch diameter circular cells from two vendors. Cells from each vendor were used to fabricate half of the modules so side by side comparative testing could occur at JPL and at LMSC. Forty-one cells were interconnected in series using chem-etched in-plane stress relief copper interconnects. The cell strings were mounted to the underside of the cover glass using clear silicone adhesive. The modules fabricated during the program are representative of the general design and of terrestrial cells currently available. Slight modifications of the interconnect, to accommodate the cells with single N bus, is the only significant adaptation from one design to the other.

To assess the value of primed versus unprimed glass, selected modules used no primer and others used two types of silicone primer. Also to gain additional comparative data in this developmental program, two types of encapsulants were used.

Two methods of frame mechanical fastening were assessed, self-drilling tapping screws and blind or pop rivets. Riveting was found to be far superior. It was also found, for mechanical design and assembly, that the program baseline design was quite labor intensive because of high mechanical piece part counts and required fabrication processes. However, as a result of these and other general findings, the following conclusions and recommendations can be stated.

CONCLUSIONS.

1. Cell loading or handling time can be reduced over 50 percent by having an omnidirectional N bus electrode geometry for the solar cells.

2. Water white high transmission glass (0.01 percent iron oxide content) enables cells to produce up to 20 percent more power at AMI. In terms of value added at present prices the high transmission glass costs $.50 more per ft^2 but provides $18 worth of additional power per ft^2. This corresponds to a savings of $3.00 per watt.

3. Glass front surface permits cleaning by normal methods to restore power.

4. Modules that are transparent between cells permit energy throughput and cause lower operating temperatures (and thus more power) than in opaque modules.

5. The technical features of the design have been proved by the module efficiency which averages 9.84 percent (based on cell area) at 60 deg C, 100 mW/cm^2.

6. Developmental design changes which combine mechanical part functions can reduce parts count in modules from 25 to 10. The number of fabrication process steps would be reduced by 50 percent.

7. At maximum projected levels of module production the consumption of key materials (e.g., aluminum, high transmission glass, silicone) is insignificant compared with existing production capacity. No significant material cost reductions are expected from large scale module production. This conclusion, of course, does not apply to the costs of silicon or cell fabrication.

8. Cells need to be handled only one time during the entire fabrication process when combination loading-registration-traveling fixtures are used.

9. The use of glass primers does not improve the adhesion of the cells to the glass for qualification testing survivability. Data does not yet exist to assess lifetime performance of primed and unprimed glass.

10. Blind rivets are more time-cost effective for module frame assembly than self-drilling/tapping screws and represent less of a safety hazard.

11. Practical weight limitations on modules discourage laminated glass designs. Better materials and encapsulation methods are required for environmental protection, particularly moisture absorption.

12. The LMSC module design and assembly tooling and methods accommodates a wide variety of cell configurations and size tolerances. Minor adjustments in the LMSC interconnect design will accommodate most of the existing cell contact configurations although greater savings would result from use of omnidirectional contacts.

RECOMMENDATIONS

1. Additional work should be done on room cure, hard skinning encapsulants. Alternative encapsulation methods such as bonded films should be investigated.
2. Studies should be initiated to determine maximum size solar cell configurations, including handling considerations, shape adaptation for round, sheet, ribbon, etc., and assessing these features for end-use requirements such as current and voltage specifications.
3. An omnidirectional cell electrode design would reduce module fabrication time significantly. Studies of omnidirectional cell electrode design costs weighted against cell indexing flats or optical placement registration mechanisms should be conducted.
4. Solar cells are still, and will be for the near future (until crossovers are reached where scrap out is more cost effective), the most costly elements in a terrestrial module. A program should be conducted to develop nondestructive methods of cost effective refurbishment of modules for cell replacement.
5. For near and intermediate term, testing methods for solar cell characterization in end-item combinations should be developed so that differences in performance due to changes in spectral response and other design dependent phenomena are accounted for when comparing performance of different cells. Comprehensive evaluation cannot be made at the bare cell level. It must be accomplished by side-by-side testing of different cells with identical covers and encapsulants.
6. As module packing factor increases the module temperature will also increase. Studies and development hardware tests should be conducted to determine the maximum feasible packing factor which will give greatest power at lowest temperature.

MODULE DESIGN

Section 2
MODULE DESIGN

2.1 DESIGN DESCRIPTION OF LMSC TERRESTRIAL TRANSPARENT SOLAR CELL MODULE

The LMSC module developed for this contract uses 41 cells which are solder interconnected into a single series string with flat copper interconnects and are bonded to the back of high transmission glass with clear silicone adhesive. The module delivers 20 W electrical at peak solar irradiance (air mass one) at 28 deg C cell temperature. It is supported by an aluminum frame which consists of extruded channel side rails and angle end rails which are used for module mounting and a center web which gives structural rigidity and is used for mounting the electrical connectors and grounding.

Modules are made with two different types of 3-inch diameter solar cells from two different vendors. Spectrolab and Optical Coating Laboratories Inc. (OCLI). This proves the adaptability of the LMSC design, tooling, and assembly methods. Minor changes in interconnect design permit assembly of both types of module in the same tooling. Cells with diameters of 2.93 to 3.005 inches are assembled in the tooling, and minimum spacing of .027 inches between cells is maintained.

The module in Fig. 2.1-1 uses Spectrolab silicon solar cells with texturized surface, anti-reflection coating, and silk-screened contacts. The N contact has redundant collection buses to which redundant interconnect tabs are soldered.

The module in Fig. 2.1-2 uses OCLI silicon solar cells with polished surface, anti-reflection coating and vapor deposited contacts. LMSC modified the interconnect design to provide redundant attachment to the single N bus collector on OCLI cells.

The module cross section shown in Fig. 2.1-3 shows the way the module is assembled. The cell/interconnect/adhesive/glass assembly is fitted into the frame with the foam seal tape in place in the side rails. Then the electrical connectors are attached and

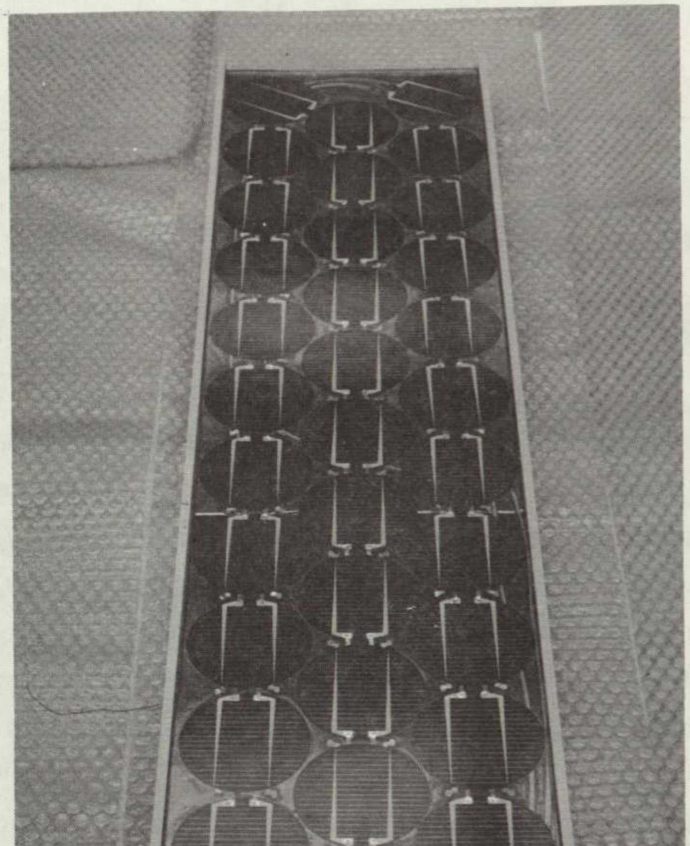

Figure 2.1-1 Engineering Module - Spectrolab Cell

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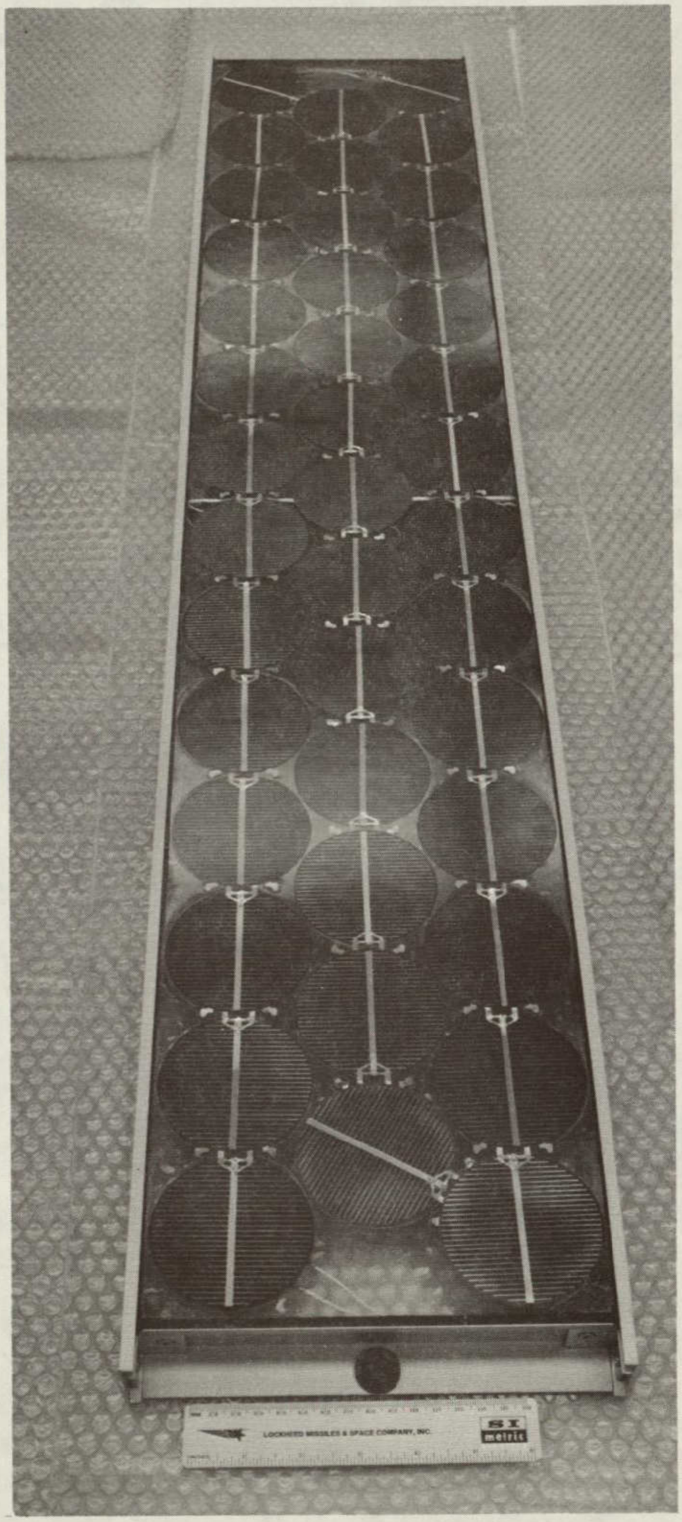

Figure 2.1-2 Engineering Module - OCLI Cell

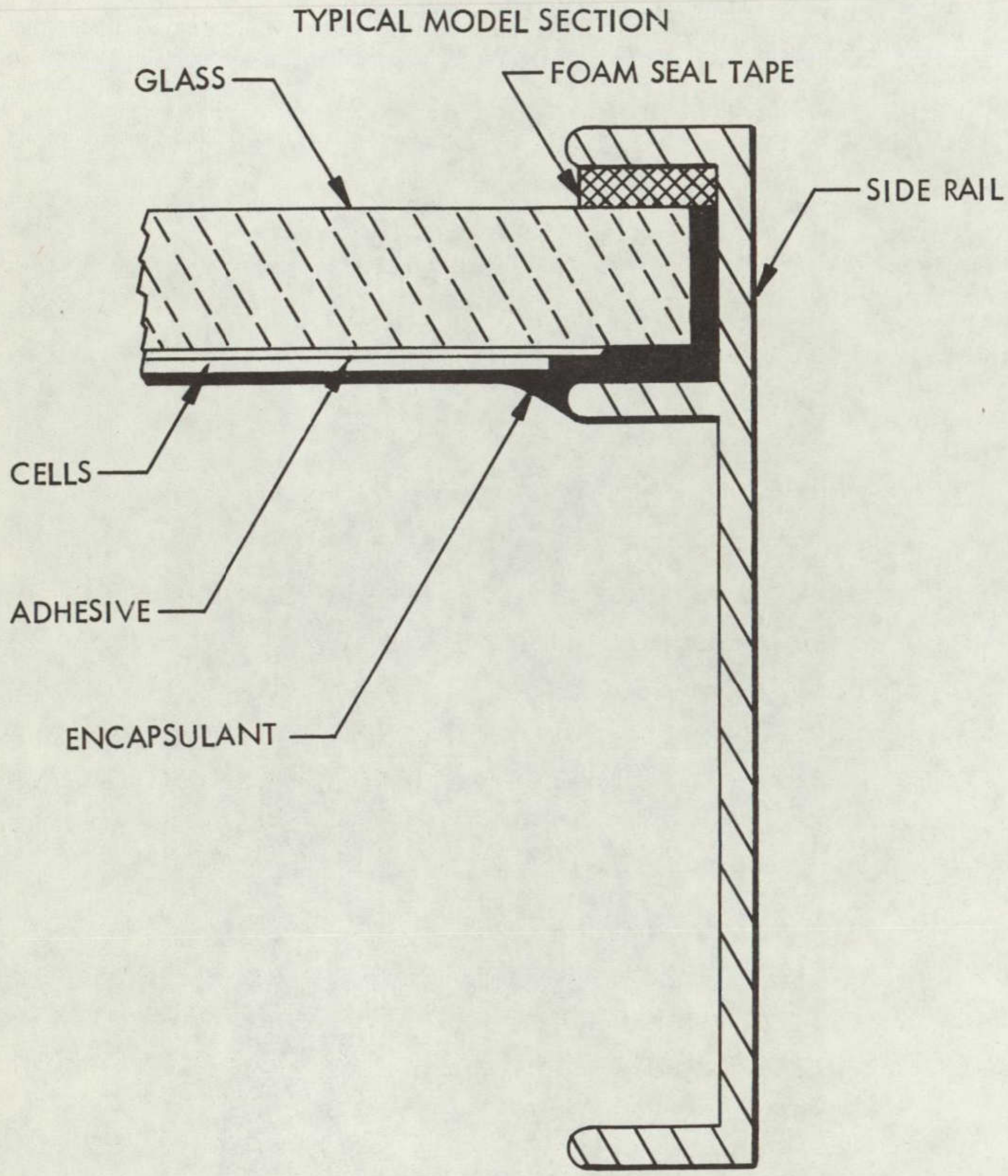

Figure 2.1-3 Typical Section Through Module Siderail

the rails riveted in place. Finally the encapsulant is applied over the back of the module – sealing it from the environment and providing some structural properties to the assembly. Figure 2.1-4 shows the two engineering modules prior to encapsulation.

Electrical Configuration

The electrical connections within the module are totally redundant internally and externally (see Fig. 2.1-5). There are two connections to the solar cells and two conductors to separate pins at the module output connector.

2.2 DESIGN DEVELOPMENT

The LMSC solar cell module design has been developed by merging high efficiency and reliability from aerospace and cost effectiveness from commercial practice. The result shows that these areas are completely compatible – it is cost effective (at least at present) to use the highest efficiency solar cell, the highest transmission (in the cell response region) cover, high transmission cell-to-cover adhesive (applied in vacuum), and transparent encapsulant, and to mount them in a structure which is designed and assembled in much the same way as a window for a mobile home or recreational vehicle.

LMSC worked with many organizations during the development of this design. The result is a design which is suitable for production in quantities of 1,000 to 2.5 million if some minor design changes and increased levels of automation are achieved.

Solar cell manufacturers were requested to submit ten solar cells which reflect their best and most likely high volume production cells for the next few years. Those responding were Spectrolab, OCLI, M7 International, Solar Power Corp., Sensor Technology, International Rectifier, and Solarex. Since that time, more terrestrial cell manufacturers have come on line and they will be included in future studies. LMSC selected Spectrolab and OCLI, the two vendors whose cells had the highest output/cost.

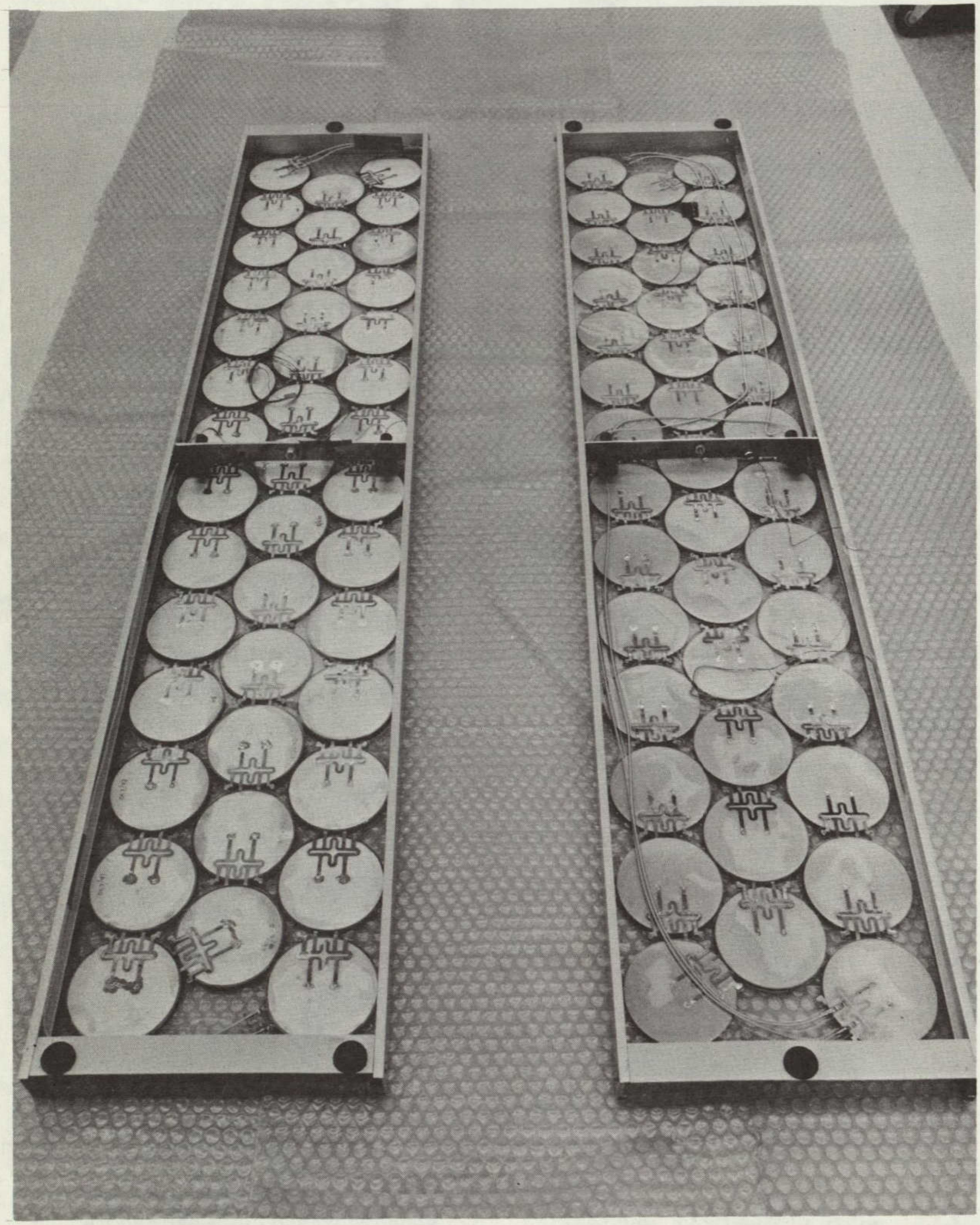

Figure 2.1-4 Rear View of Engineering Modules Prior to Encapsulation

Glass companies were asked to send samples of their "solar product" lines for evaluation on LMSC photovoltaic panels. Respondents were Libbey Owens Ford (LOF), Pittsburg Plate Glass (PPG), and Fourco-who make a low iron glass with total sun spectrum transmittance of 85 to 88 percent, and ASG-with Sunadex which has total sun spectrum transmittance of 90 percent and 97 percent effective transmittance when cells are bonded as in our module.

With the help of Fluorocarbon Corporation, silicone channel extrusions were developed in two configurations. The method selected for module assembly did not permit the use of either extrusion and closed cell vinyl foam tape by 3M was substituted.

Side and end rails on the module were made from custom extrusions developed for this design with assistance from Ametek Pacific Extrusions.

2.2.1 Requirements

The module has been designed to meet requirements of JPL Specification 5-342-1 Rev B with the following features:

(A) Module Shape and Size

The solar cell module is 9 inches in width, 46 inches in length and a maximum of 1.56 inches in thickness, including aluminum fins along the edge of the two 46 inch lengths.

(B) Cover Selection

The solar cells are protected from the terrestrial environment by Sunadex high transmission glass 3/16 inch thick.

(C) Encapsulant/Adhesive Selection

Sylgard 184 silicone adhesive/encapsulant and Dow Corning X1-2577 encapsulant are used.

(D) Electrical Design

The module is capable of providing power greater than specified (minimum output 12 Watts at 15.8V, 60 deg C, AM1, 100 mW/cm^2).

(E) Thermal Design

The module is transparent to sunlight wherever possible to achieve the lowest possible operating temperature. Aluminum side rails along the two long edges are provided to enhance cooling.

(F) Structural Design

The aluminum side rails serve to restrict deflection of the module so the constraints of the mechanical integrity testing are met. A center web prevents deflection at midspan.

(G) Mechanical Interface Design

For the module three mounting points are provided using elastomeric standoffs. The mounting arrangement meets the requirements of the JPL test structure per JPL Dwg. 10081548 with addition of holes to match LMSC modules.

(H) Maintenance

If power is reduced due to accumulated dirt on the cover, recovery is possible by standard window washing methods.

2.2.2 Cell and Module Size Selection

The size and shape of the solar cell have the greatest influence on module shape and size. This program was limited to the commonly available round solar cell sizes 2-1/4 inch (57 mm), 3 inch (76 mm), 3.5 inch (90 mm) and 4 inch (100 mm). These sizes were included in a module size study along with the 40 to 42 cells in series required to provide peak power voltage near 15.8 volts at 60 deg C, AM1, 100 mW/cm^2, and the specified subarray dimensions of 46 x 46 maximum overall (44.5 inch maximum active dimension). This resulted in the selection of 3.0 inch diameter cells nested with 3.12 inch centerline spacing in string dimension and 2.6 inch between string centerlines with glass area of 8.5 x 44.5 as shown in Table 2.2-1.

2.2.2.1 Solar Cell Selection

Solar cell selection was based on a comprehensive series of screening tests which fully characterize the performance of the selected cells.

2.2.2.2 Cell Vendor Selection

Because LMSC is not and does not plan to be a solar cell producer, we objectively evaluate performance of terrestrial cells available at the start of the program from on-line manufacturers under identical conditions. For this contract, sample cells were purchased off the shelf from seven manufacturers and comparatively tested.

Testing and comparisons included bare cell performance at 28 deg and 60 deg C, solderability, size availability, and cost per watt. It is recognized that this method of screening may unduly penalize manufacturers who do not use anti-reflection coatings on their bare cells. A more complete comparison would (if time would have permitted) have included tests on cells after cover bonding.

Cells without A/R coatings usually show significant increases in output when encapsulated while those with A/R coatings do not. For future programs LMSC suggests more thorough testing of cells in the proposed final configuration to more fairly evaluate cell performance. A program for side-by-side and identical cover/encapsulant testing of different solar cells is required to eliminate the performance prediction problems which result from testing cells that have different frequency responses under different configurations. The desirability of this approach was acknowledged by LeRC at the 6th LSSA Project Integration Meeting.

Table 2.2-2 shows the cells which were tested. Figure 2.2-1 shows various sizes and contact configurations typical of cells from different vendors.

TABLE 2.2-1

MODULE DESIGN TRADEOFFS - TERRESTRIAL CELL PERFORMANCE

SOLAR CELL SIZE SELECTION – 3 IN. DIAM

- LOWER PIECE PART HANDLING PLUS BEST AREA EFFICIENCY

CELL ENVELOPE C (INCL LOCATION TOLERANCE)	CELL/ROW CONFIG FOR L = 44.5"	ω MODULE WIDTH MIN (IN)	MODULES PER SUBARRAY	T SPACE BETWEEN MODULES FOR X = 0.25 (IN)	A_m ACTIVE AREA OF CELLS IN MODULE (IN2)	MODULE AREA EFFICIENCY $\frac{A_m}{\omega \times L}$	SUBARRAY AREA EFFICIENCY $\frac{AM}{W \times L}$	CELLS PER MODULE
2.12"	2 ROWS: 21/21	4.24	9	0.37	132	0.70	0.58	42
2.12	2 ROWS NESTED: 21/20	3.95	10	0.15	129	0.73	0.63	41
2.37	3 ROWS: 17/17/17	7.11	6	0.06	160	0.50	0.47	51
3.64	4 ROWS: 12/12/12/12	14.56	3	0.17	339	0.52	0.50	48
3.12	3 ROWS: 14/14/14	9.36	4	1.64	296	0.71	0.58	42
3.12	3 ROWS NESTED: 14/13/14	8.5	5	0.20	290	0.77	0.71	41
4.18	4 ROWS NESTED: 11/10/11/10	15.04	3	(0 FOR X = 0.14)	528	0.79	0.77	42

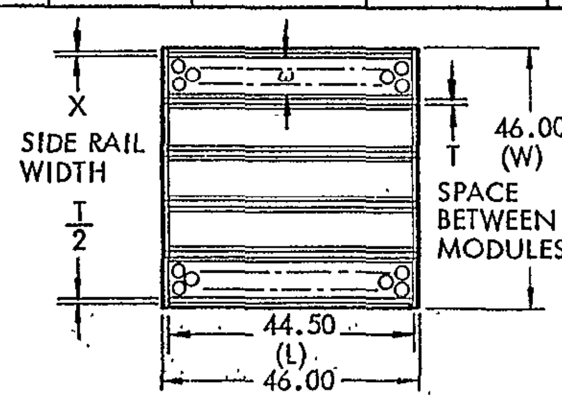

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TABLE 2.2-2
TERRESTRIAL CELL COMPARATIVE SIZE DATA

	Cell Sizes Nom.	Actual (maximum)	Active Area*	in.^{2} (cm^2)
SL	2 in.	2.05	All	3.3 (21.29)
	3 in.	2.96 (later cells are 2.98 in.)	All	6.86 (44.24)
M7	3 in.	3.20	3.0 dia	7.07 (45.61)
SP	90 mm	3.54	3.50	9.62 (62.06)
IR	3 in.**	3.00	All	7.07 (45.61)
IR	2 in.	2.00	1.95	2.99 (19.29)
OC	3 in.	2.98	All	6.97 (44.97)
SX	3 in.	2.97	All	6.93 (44.71)
SX	4 in.	4.06 pts	All	12.70 (81.94)
ST	2 in.	2.15	2.12	3.53 (22.77)

SL = Spectrolab
M7 = M7 International
SP = Solar Power Corporation
IR = International Rectifier Corporation
OC = Optical Coating Laboratories, Inc.
SX = Solarex
ST = Sensor Technology, Inc.

* Active area includes contact but excludes border around cell when present
**Produced by Solar Technology International, purchased by LMSC through IR

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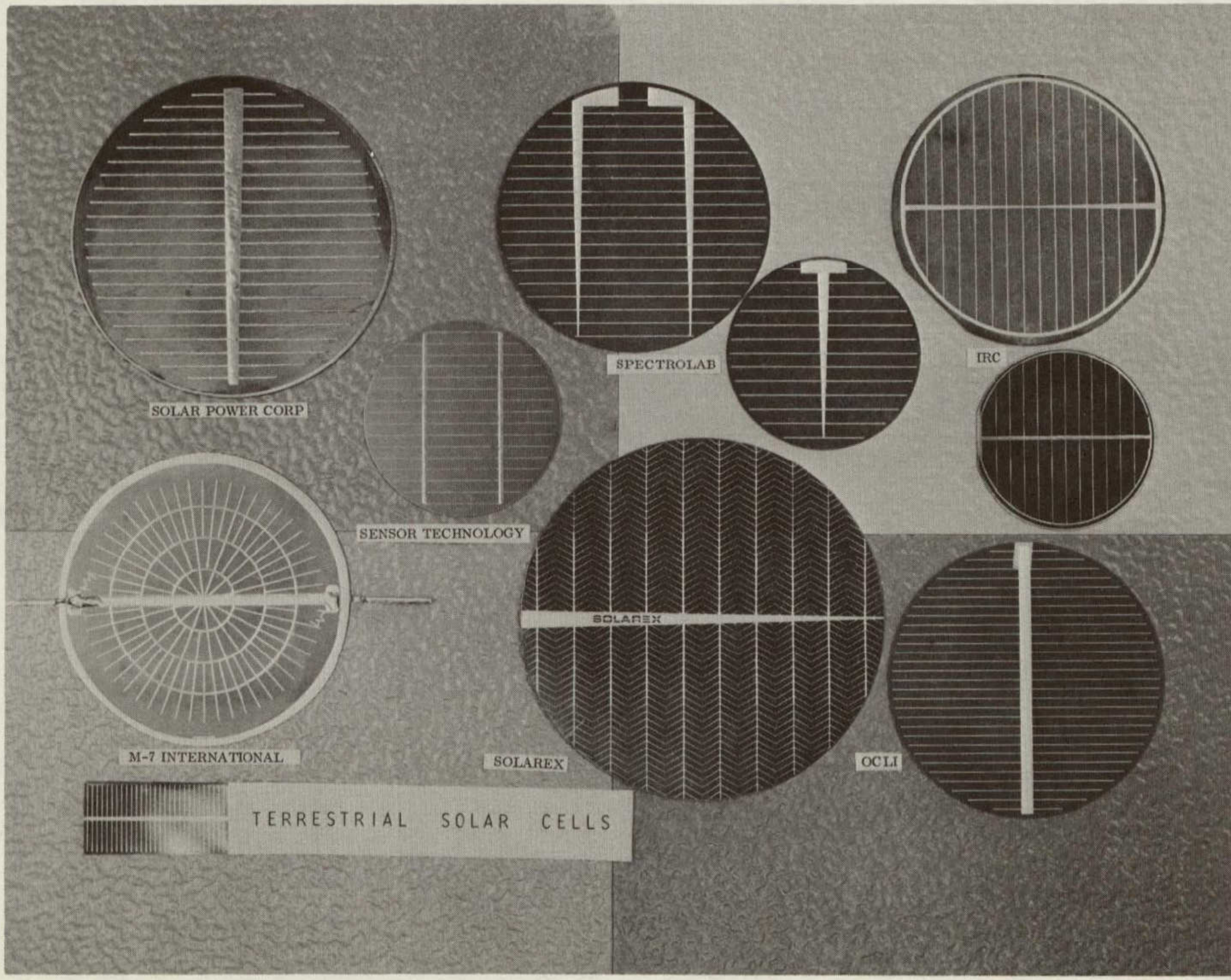

Figure 2.2-1 Terrestrial Solar Cells

Bare cells were tested with X-25 steady state illumination adjusted to give 100 mW/cm^2 per Spectrolab 2 inch diameter standard cells 3001 and 3003 which were calibrated by LeRc.

Current-Voltage (I-V) curves for eight to ten cells of each type were taken at 28 deg C. Then one "average" cell was selected for temperature performance tests in which I-V curves were taken at 28 deg, 40 deg, 60 deg, and 80 deg C.

The results of the bare cell test data are summarized in Table 2.2-3 where I_{sc}, V_{oc}, I_{mp}, V_{mp}, and W_{mp} at 28 deg C and I_{sc}, V_{oc}, I_{mp}, V_{mp}, W_{mp}, I at V = .385* and W at V = .385* at 60 deg C are reported after having been normalized to 3 inch equivalent cell diameter for all cells.

Based on cost and bare cell power output at 60 deg C SL (glassified), SX and OC cells were selected for further testing.

The quantities of cells involved in this program, where only two engineering modules and 12 preproduction modules were assembled, were relatively small. Procurement of cells for a production program would be preceded by cell performance evaluation which accounts for end product output, i.e., cells mounted in segments simulating the design cross-section tested simultaneously under pulse zenon and cross-checked under sunlight to minimize AR, spectral response anomalies.

2.2.2.3 Interconnect Design

In the LMSC module the interconnected cell string is bonded to the backside of the glass cover with Sylgard 184 in vacuum. Then, after curing the 184, an encapsulant is added to seal all components from the environment. Thus the interconnect is fully embedded in the adhesive/encapsulant as well as being soldered to two cells. The functional requirements of the interconnect are as follows:

- Conduct current in redundant paths between cells
- Prevent thermal expansion from causing loading on the contact bonds — planar, torsion, peel
- Prevent shorting of cell junction

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*.385 volts = 15.8 volts (i.e., module voltage at 60 deg C) ÷ 41 cells in series

- Maintain integrity during thermal cycling when embedded in adhesive/encapsulant
- Cover minimum of cell active area

Producibility requirements for the interconnect are as follows:

- Easily automated
- Accommodate large cell tolerances
- Self tooling for accurate contact location on cell

The current and early interconnect designs are shown in Figure 2.2.3-1 with differences noted. These changes resulted from the following considerations:

Thicker and Wider Traces

The copper thickness was increased from 1 oz. to 2 oz. and the trace width was increased from .080 to .105 to reduce the potential for intercell voltage drop and to improve redundancy.

Inboard Tooling Stem

The tooling stem was moved inboard to reduce the possibility that the tooling tab would bend up over edge of cell causing shorting.

Offset P&N Tabs

The P&N tabs were offset to accommodate moving the tooling stem. An additional consideration was to reduce cell shadowing by interconnect on the OCLI version.

Solder in Connect Points Only

Reduces possibility of cell shorting due to solder melting near edge of cell. Reduces solder consumption. In addition, the material can be produced for either stamping or chemical etching of the interconnect in large quantities.

Current thought is that stamping is most feasible for individual interconnects which would be fed in tape form to the module assembly soldering station. The potential for chem-etching appears greatest in forming a complete module of interconnects in one piece. This offers potential for saving labor or automation costs for placing interconnects.

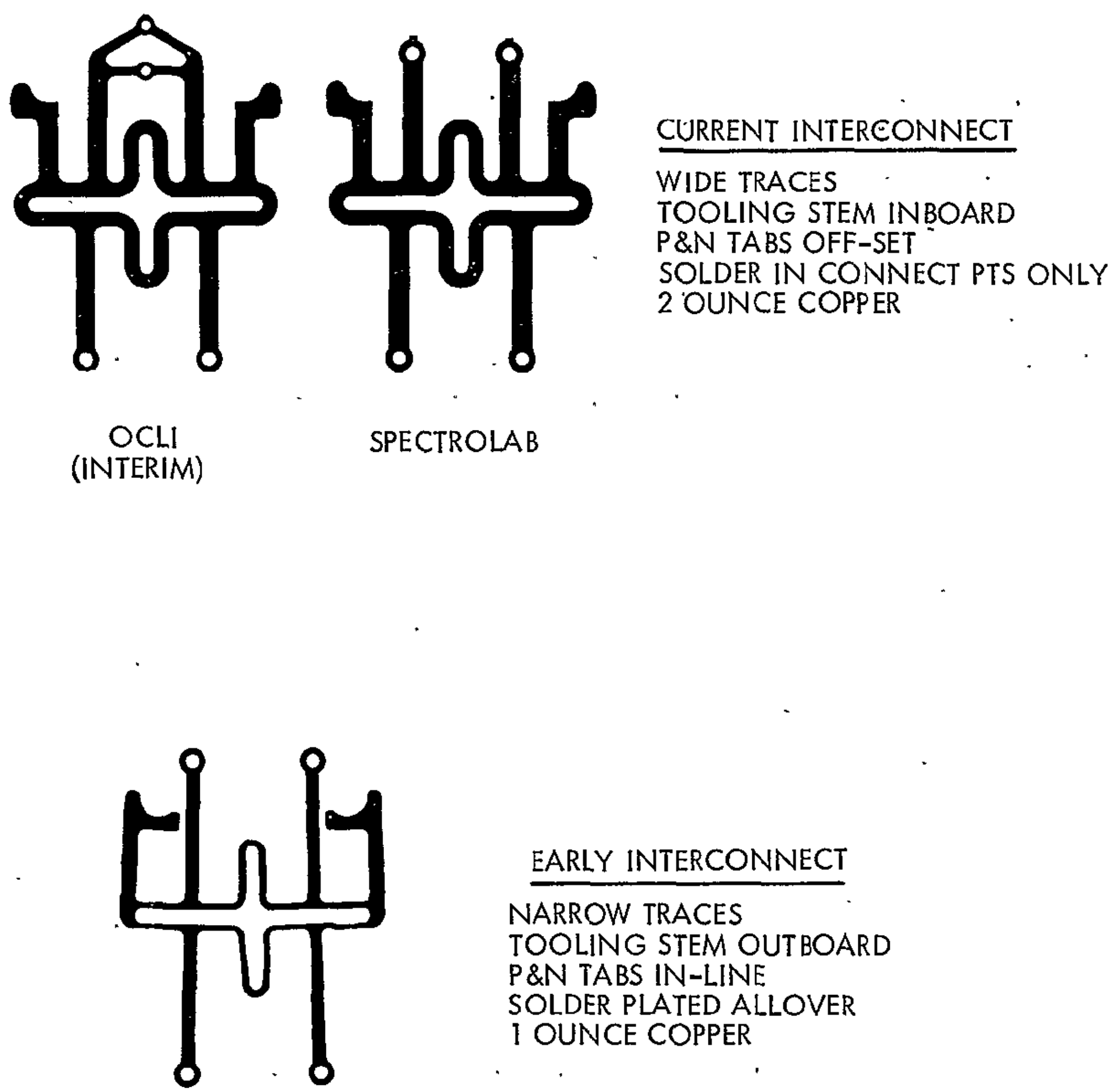

Figure 2.2.3-1 Interconnect Designs

Another area of interest is in the potential design of interconnects for cells with omni-directional contacts. The inter-relationship of all contact and interconnect design features must be considered for optimum module output.

Interconnect-Soldering Evaluation. Solder plated copper interconnects were used to solder three cells in series. These three cell assemblies were used in solderability tests that were performed to determine ease of soldering and the effect of soldering on power output. All cells of the selected types soldered easily. The P contact of Spectrolab cells exhibits a different characteristic during soldering in that it does not fillet. The wetting action of the solder appears to "puddle" in small areas between the cell and interconnect rather than "tinning" the whole area. This apparently does not affect cell performance. Humidity tests with soldered Spectrolab cells showed no degradation.

The three cell modules were then bonded to cover glasses, retested and subjected to 18 rapid thermal cycles from -50 deg to +90 deg C. Problems with operating the test caused some LN_2 to splash onto the modules cracking the untempered coverglass. The cycling was terminated and electrical tests were run. No degradation occurred.

Table 2.2.3.1-1 shows the effect of the process steps and testing on cell output from individual cells through temperature cycling.

These tests proved the concept of in-plane stress relieved interconnects encapsulated in Slygard 184. No module output degradation or contact delamination occurred.

These tests provided sufficient information regarding cell performance to enable selection of OCLI and Spectrolab cells on the basis of cost and output.

Further testing of these cells using redesigned interconnects is described in Section 4.

TABLE 2.2.3.1-1

PROCESSING EFFECTS ON CELL OUTPUT

	Individual Base Cells at 28° C			Base 3 Cell Module at 28° C			Covered 3 Cell Module at 28° C Before Temp. Cycle			After Temp. Cycle			Covered 3 Cell Module at 60° C After Temp. Cycle		
Module	V_{oc}	V_{oc}	V_{oc}	V_{oc}	I_{sc}	W_{mp}	V_{oc}	I_{sc}	W_{mp}	V_{oc}	I_{sc}	W_{mp}	V_{oc}	I_{sc}	W_{mp}
SX a	0.574	0.582	0.580	1.72	1.36	1.56	1.74	1.39	1.58	1.74	1.38	1.56	1.54	1.40	1.37
SX b	0.579	0.578	0.577	1.71	1.35	1.60	1.72	1.36	1.57	1.72	1.40	1.61	1.52	1.42	1.36
SL a				1.71	1.37	1.57	1.73	1.41	1.59	1.73	1.39	1.60	1.53	1.42	1.33
OC a	Interconnect broke and could not be resoldered – prompted new interconnect design*														
OC b				1.73	1.04	1.23	(Cell Broken)*								

*This problem was caused by using an interconnect designed for SL cells on OC modules. It was decided that results of other temperature tests made sufficient to unable selection of OCLI cells on cost basis.

Voltage Drop Due to Interconnects. Analysis indicated that, in a 250 volt system where 16 modules would be connected in series with the Design Review Baseline Module, a total voltage drop of 8.822 volts (3.5 percent) could occur. 7.545 volts or 3 percent is attributable to the interconnect using 1 ounce copper with a primary tab width of .080 inches. A new design was developed for a modified interconnect which increased tab width to .109 and, by incorporating 2 ounch copper, increase interconnect thickness from .00128 to .0025. Interconnect thickness is still maintained below 3 mils to ensure flexibility. With this modification total drop is reduced to 4.017 volts or 1.6 percent. Changing interconnect termination wire gauge from 22 to 18 reduced losses approximately 0.72 volts or 0.3 percent.

2.2.2.4 Cell Adhesive

The properties required for the cell to cover adhesive include:

- High transmission of solar energy
- Good adhesion to glass and to the cell
- Ability to cure in large thin unexposed areas (i.e., between cell and glass)
- Low modulus to compensate for high thermal expansion relative to glass and cell (enables stretch to compensate for differential thermal expansion without delaminating).
- Maintains properties over wide temperature range especially low modulus at low temperatures
- Non-ionizing in presence of moisture
- UV stability

Sylgard 184 was selected because it has the best performance of existing known adhesives as well as moderate cost when the amount is controlled during application. Its moisture permeability and tacky surface, however, with its softness and affinity for dirt cause concern regarding durability when used as an encapsulant. This is discussed further in the next section.

To bond the cells to the coverglass the outgassed Sylgard 184 is metered onto the front of the cleaned solar cells. A vacuum is drawn between the cells and cover before they are pressed together. This ensures that no air remains between the cell and cover.

The completed modules were primed in three (3) ways: without primer, with Dow Corning 1200 primer, and with Dow Corning 3-6060 primer. LMSC does not expect any difference in performance between the modules to be caused by the different primers. It is our opinion that the glass cleaning prior to bonding is of more importance to long life performance. However, the fact that selected modules do contain primed surfaces will provide data for comparison should any delaminating occur during the test life of the modules.

2.2.2.5 Encapsulant

Materials considered for module encapsulation included the following:

- Films
  - Mylar
  - Tedlar
  - FEP
  - "Glad"
- Thermal Control Paints
  - White
  - Black
  - Silver
- Fabric/encapsulant combination
- Silicones
  - Dow Corning R4-3117
  - Sylgard 184
  - Dow Corning X1-2577

Preliminary attempts to encapsulate the module with a film resulted in entrapped bubbles between film and cells. This approach should be pursued further because the film offers greater moisture protection than any of the other coatings. Areas which should be investigated are: application of film in vacuum during cell bonding operation, configuring the film as a part of the assembly/soldering tool to remain with cells when bonded, and incorporation of interconnects on film to reduce operations and piece part handling operations.

Thermal control paints and fabric/encapsulant combinations were not used during this contract for encapsulants but they offer interesting possibilities and should be investigated further.

As for silicones, Sylgard 184 can be used but its softness and affinity for dirt cause concern regarding durability in use. This may not be a serious problem because the surface is shielded underneath the module, but the fact that Sylgard 184 must be applied in thick coats or multiple coats to ensure full coverage of protrusions has major cost implications.

Two other Dow Corning materials that can be applied thinner and that have a harder, dust resistant surface were considered.

R4-3117 is currently produced in large quantities and is readily available. It has two major drawbacks: It is expensive ($14.25 per lb) and it hardens with decreasing temperature causing cracking during thermal cycling.

X1-2577 is an experimental material which offers better thermal performance and lower cost (projections estimate $5-8/lb when, and if, material is produced in large quantities) than R4-3117. It may replace R4-3117 if it continues to perform as designed, but it is still in a developmental phase. Modules delivered under this contract are encapsulated with Sylgard 184 and X1-2577 as noted in Section 3 in Table 3.2-1.

The application methods will influence encapsulant selection. It is of primary importance to obtain a uniform coating of all surfaces which will provide desired surface and moisture properties. Special attention is addressed at coating sharp protrusions such as cell edges or interconnect or wire edges which are either wiped clean of encapsulant during application, or are coated so thin that minor abrasion during installation will wipe away protection.

More work in the area of module encapsulation is required in both areas of materials and application methods.

2.2.2.6 Coverglass Selection

Module output is affected by transmission of available solar energy to the cell through the cell cover and adhesive interfaces. The energy available to the cell is not the product of normally reported transmission (Figure 2.2.6-1) of the glass times the solar cell response integrated over the cell response wavelengths. The normally reported transmission values are determined by energy throughput from air-to-glass-to-air. The reflectance values of air to glass and glass to air caused by their indices of refraction are deducted along with the bulk absorption of the glass to give the normal transmission value.

The net energy transmitted to the solar cell in the LMSC module is affected by more interfaces than those discussed above. These additional interfaces have the effect of permitting more net energy to reach the cell. The energy throughput from air to glass to adhesive to cell AR coating to silicon is affected by the respective indices of refraction at each interface. LMSC tested these effects (described further in Section 4):

- By measuring Sunadex transmission in normal (no adhesive interface) way with EG&G spectroradiometer in sunlight (i.e., by measuring spectral irradiance of sun with and without Sunadex in input path, and
- By measuring transmission after bonding (temporarily with uncured 184) Sunadex to the input optics of the EG&G instrument.

The results (see Figure 2.2.6-2) show that the Sunadex transmits 96.5 percent of the sun's energy in the solar response region from 380 to 1150 NM when bonded to the optics while it transmits only 90 percent when positioned in the normal way.

A further check on effects of glass transmission on cell output was made by measuring cell output before and after bonding to different glass types. Cells with identical response were selected, tested, and covered with different glass types. Then their output values were compared with their respective bare cell output. The results in Figure 2.2.6-3 show that the Sunadex covered cell delivers 97 percent after being covered. The cells used in these tests had textured surfaces and SiO sintered AR coatings.

The increased cell output due to the higher transmission results is savings of $3.00 per watt in the cost of cells and glass.

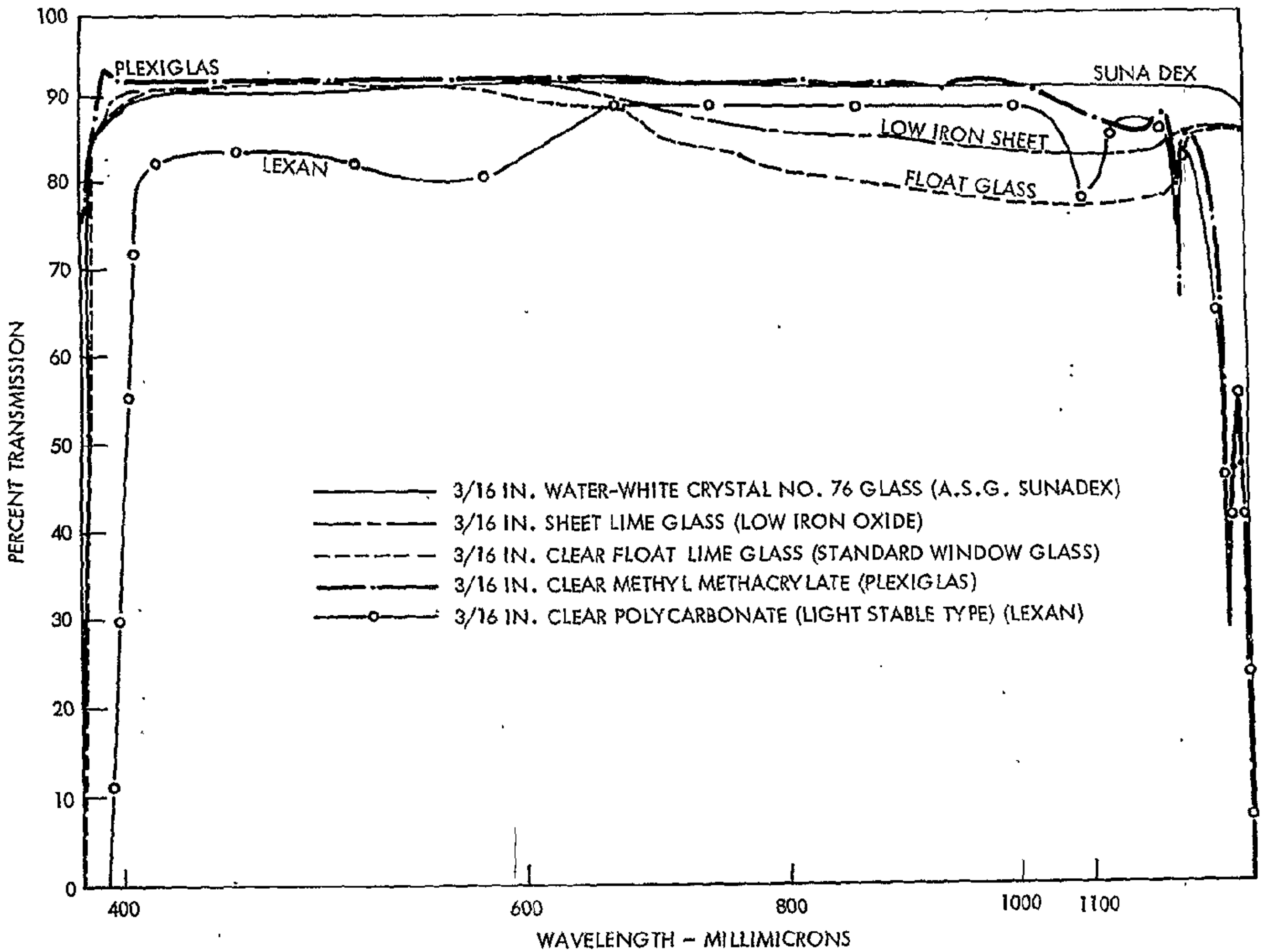

Figure 2.2.6-1 Cover Material Normal Transmission at Air Mass Two*

*ISEC, August 1974, Ft. Collins, Colo., Clarkson & Herbert

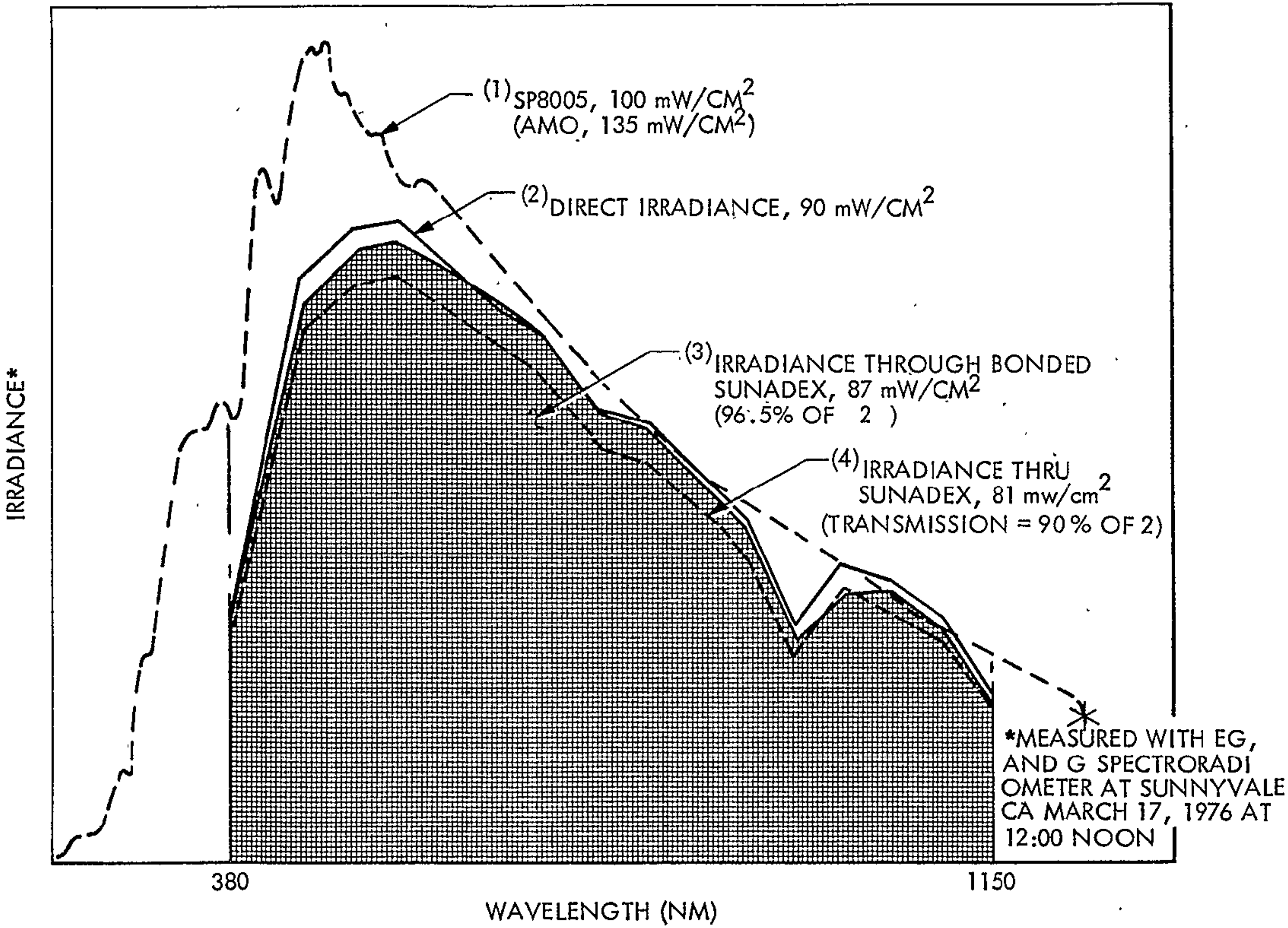

Figure 2.2.6-2 Spectral Transmission of Sunlight Through Sunadex/184

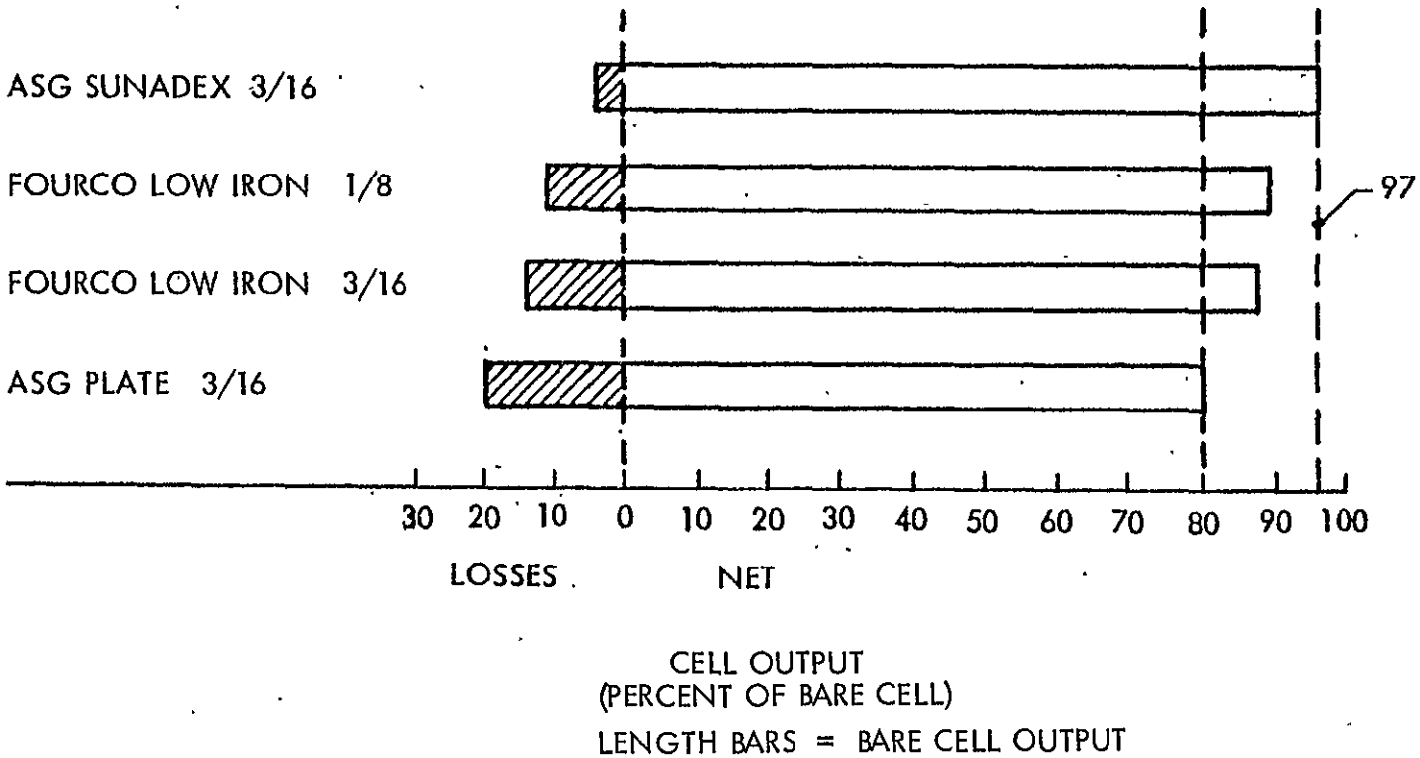

Figure 2.2.6-3 Effect of Cover Transmittance, Adhesive, and Assembly on Cell Output

The measured output of LMSC modules using Sunadex averaged 20.94 Watts at AM1, 100 mW/cm^2, 28 deg C, 18.7 volts. If plate glass were used the output would be 17.27 Watts; for low iron the output would be 18.99 Watts. If we assume that the 41 cells cost $7.50 each or $307.50 we can calculate the cost/watt for each glass type as follows:

Glass Type	Cell Cost $/Module	Glass Cost* $/Module	Watts/ Module	Watts Per Ft^2 Glass	$/Watt**	Value Added Per Ft^2 Over Plate***
High Transmission	307.50	2.55	20.94	7.32	14.81	18.96
Low-iron	307.50	1.60	18.99	6.64	16.28	9.77
Plate	307.50	1.26	17.27	6.04	17.88	-0-

*Based on current purchase prices for 1/8 inch thickness
**Cell + glass cost ÷ Watts/module
***Watts/ft^2/glass minus Watts/ft^2/plate x $/Watt/glass

FABRICATION

Section 3
FABRICATION

The overall fabrication concept for the solar modules was based on a combination of proven methods and new techniques and tooling developed for this program. Due to the small quantity being built (fourteen total), the tooling was kept to a minimum and simple in nature. Where feasible, aerospace fabrication techniques were applied to the terrestrial modules if no cost penalty was apparent. Although the prime purpose of the twelve preproduction units was to prove the assembly processes, much information was learned about the cost drivers that were inherent to the design. The engineering modules were assembled to verify process selection and design integrity. Several changes were incorporated during this phase to improve module performance and simplify production. Although no attempt was made to apply automation directly to the twelve preproduction modules the ability to convert to automatic and/or semi-automatic assembly was a primary factor in the choice of processes and methods.

The assembly area for the fabrication of the engineering modules and the twelve preproduction modules was the solar array clean room in the Electronics Manufacturing Division of LMSC. A clean room environment is not required for the terrestrial modules, but the access to existing facility equipment was best met by utilizing this area. With a larger quantity of modules a dedicated facility would be more conducive to production efficiency. An advantage to the use of the clean room for this contract was the large area pulsed light solar simulator which is located within this facility. Easy access to this test equipment enabled fast turnaround for the assembly of the modules.

Mechanical piece parts were fabricated in a batch mode at an LMSC machine shop located in a nearby area. Final module assembly was performed in an area adjacent to the solar array clean room to reduce the amount of hardware movement.

3.1 PROCESS DEVELOPMENT

Prior to the fabrication of the twelve preproduction modules some development hardware was produced to identify and correct assembly problem areas and design weaknesses.

This development effort fell into three categories, (1) process evaluation, (2) three-cell evaluation modules, and (3) two engineering modules. The process evaluation tasks involved cell solderability, cell-to-cell interconnect fabrication and adhesive application techniques. The primary effort of this process evaluation involved soldering techniques for the terrestrial cells. Although several techniques are known for attaching interconnects to solar cells the use of solder reflow has been the most prominent in recent years and has performed successfully for many years in space. Parallel gap welding is presently a production system used at LMSC on one flight-oriented program but the equipment set-up and monitoring requirements are extensive. Attempts at mechanical attachment are promising but require more development effort to show long term reliability. Other batch processing techniques such as tunnel furnace and infrared soldering approaches were not investigated on this contract due to the few modules to be delivered and the short span to perform.

The use of a heated-tip 35 Watt soldering iron had very good results for both the positive and negative solder connections. To improve on this method for repeatability and to lessen the chance of lifting the negative contact of the cells, a setting of 650 deg F was used on the negative contacts for both OCLI and Spectrolab cells. Due to the increased heat-sinking near the center of the cell a temperature setting of 750 deg F was required for the positive contact solder connections. The pretinned copper interconnects wetted much faster to the OCLI evaporated Ti-Ag contacts than to the screened-on solar paste electrode Spectrolab cells. The use of a mildly activated resin flux (MIL-F-14256 Type RMA) was necessary to induce adequate solder wetting for all solder connections. Flux removal was best achieved by spraying with Freon TMC for approximately 30 seconds.

The adhesive bonding of the interconnected cells to the glass presented the most difficult process problem. Attempts at coating the glass only and applying the cell resulted in unwetted cell areas and the entrapment of numerous bubbles. Coating the cell 100 percent and applying the glass solved the setting problems but not the bubble entrapment. Efforts at coating both cell and glass resulted in similar conditions. Pulling a vacuum on the assembly prior to cure caused considerable cell movement due to expanding bubbles if the glass was on the bottom. With the cell down and the heavier glass on top some bubbles did disperse but not to a satisfactory and repeatable condition.

To resolve the bubble entrapment condition it was necessary to perform the bonding process in a vacuum. To accomplish this a simple two chamber vacuum fixture was made that incorporated a thin membrane as the dividing wall between the chambers. The fixture was used for the two engineering modules and the twelve preproduction modules. The vacuum process eliminated all bubble problems and allowed the Sylgard 184 adhesive to be applied to individual cells.

The adhesive application process was an adaptation of the technique used during the coverslide-to-cell bonding of flight type cells. After the adhesive is mixed (ten parts base to one part catalyst) and degassed,it is loaded into plastic syringes. Adhesive dispensing was then controlled by a varimeter which controls volume by a set pressure and timed shot.

The process for interconnect fabrication was a photo-etch method. The small quantities involved and the need for quick and easy configuration changes favored etching over punching.

The final process area that was investigated was the back-side encapsulation of the modules after the end and side rails have been attached. This encapsulation step was modified several times during the processing of the last six pre-production modules to achieve a hard-skin effect on the back-side of the modules.

After cells are bonded to the coverglass a pool of Sylgard 184 covers the edge of the cell and approximately half of the back. Several approaches were taken to encapsulate the cells and interconnects on the back side of the module. On the six early modules the back was flow coated with an additional layer of Sylgard 184 which was thick enough to level out most of the uneveness.

Several application methods were tested including: (1) trowelling, (2) spraying, (3) multi-coating, (4) brushing, (5) roller coating and (6) film-coating.

Thickness control is inadequate with trowelling, especially around protrusions where the trowell wipes away the coating leaving bare spots.

One of the delivered modules was coated with an additional layer of X1-2577 by "trowelling" it on. Thickness control was inadequate, causing variations in transmission through the backside of the module as evidenced by uneven yellowing.

Spraying appears to be promising. Several tests were run using dilutions of X1-2577 with xylene and toluene at various ratios. Using a venturi gun, the xylene to X1-2577 ratio of 1 to 3 gave the best coverage. However, overspray recirculation caused by spraying into the frame causes frosty deposits on the encapsulant which impede transmission.

Multicoating involves the application of different layers of encapsulant. Brushing causes brush marks and starving around protrusions. Roller coating produces the best conformance and complete coverage of protrusions. Its only drawback is the tendency to entrap small bubbles. This tendency can be reduced by diluting the encapsulant with a suitable solvent. Additional work should be performed in this area.

Film coating was tried by applying a small quantity of adhesive and using a squeegee to apply a thin film of FEP or Saran to the module back. This method caused many bubbles to be entrapped. However, with further development, the bubble problem could possibly be eliminated. Film coat is an encapsulation approach,other than glass lamination, that offers potential for eliminating moisture penetration through the encapsulant.

Problems associated with encapsulation which require further development include: development of application method which uniformly coats all areas of module with thin dielectric coating, and materials development of coating which is moisture resistant (non-ionizing), hard skinned, and transparent to infrared wavelengths.

Potential solutions which require further development to prove viability may include: Composite coating consisting of a thin non woven fiber layer placed over the back of the module followed by roller coating of hard skinning silicone material. Fibers would control encapsulation thickness and prevent starving around protrusions as well as provide further protection against moisture penetration.

3.1.1 Three Cell Evaluation Modules

Three cell modules were fabricated to perform numerous engineering tests including sunlight performance, thermal cycling, and humidity effects. The build-up of these modules allowed tooling concepts to be tried at low risk and minimum cost. Soldering techniques were refined on these modules as well as bonding methods. As these modules had no edge rails some of the design problems of the 41 cell modules were not apparent during the processing of the three cell units.

The soldering fixtures for the engineering modules and the 12 preproduction modules were, in design, similar to the three-cell module fixtures. These fixtures incorporated front and back-side soldering in the same fixture and allowed electrical testing without removing the soldered assembly. Based on earlier process development the adhesive bonding was performed in the two-chamber vacuum fixture. This was the first trial run for the fixture and allowed the bonding of all seven three-cell modules in one operation.

Back side encapsulation of these three-cell modules was performed using Sylgard 184 so no coating problems were encountered on these units.

3.1.2 Engineering Modules

With the processing variations fairly well defined, two engineering modules were fabricated, one with OCLI solar cells and one with Spectrolab solar cells. Due to the single bar negative contact of the OCLI cell a modification to the interconnect configuration was made to add a redundant solder joint. This involved an artwork change and a new photo-template for etching the new design. The interconnect processing was a straight forward photo-etching technique using a dry film negative working photo resist. Final trimming of the individual interconnects from the frame was accomplished by an X-acto knife. Solder coating of the solder area was done by hand dipping into a solder pot. The exception to the solder dipping was in the negative contact area of the OCLI configuration which had to be hand tinned with an iron.

The solder fixture for the 41 cell modules was designed to accommodate all 41 cells and 42 interconnects in registration at one time. By this approach the cells and interconnects can be loaded in series, soldered, cleaned, the unit functionally tested, and the cell string bonded to the coverglass without any handling loads transmitted to the solder joints. The negative contacts are soldered first. The cover to the fixture is then secured over the cells and the fixture is flipped over exposing the positive contact area. The positive contacts are now soldered again using a controlled temperature soldering iron. For all soldering operations the use of a mildly activated resin flux was required to promote wetting of the solder from the tinned interconnect to the cell nozzle. After the flux was removed from the positive (back-side) solder areas the fixture cover was removed and the negative contact (cell active side) solder areas were cleaned in Freon TMC in a like manner. These operations are shown in sequence in Figures 3.1.2-1 through 3.1.2-4.

To verify electrical integrity the series connected module was next tested at 28 deg C using a pulse light simulator. In a production mode the module would not need to be heated to a precise 28 deg C ±0.1 for this initial test but would be tested at room ambient temperature and corrected to 28 deg C by the readout system. For the two engineering modules and the 12 preproduction modules the 28 deg C controlled temperature was desirable as an engineering data collection point. Figure 3.1.2-5 shows the test set-up for a controlled temperature electrical power output determination using the TRW data console (a Spectrosun data console is also used interchangeably).

After the module had tested satisfactory it was ready for adhesive bonding of the cells to the coverglass. For the two engineering modules there was one to two days delay between the freon clean operation and the cell bonding step. Due to this delay and an additional amount of handling and transporting of the cell strings caused by test process debugging, a reclean of the top-side (bonding side) of the cells with freon TMC was performed to ensure their cleanliness.

The Sylgard 184 adhesive was mixed per the manufacturer's instructions of 10 parts base to one part catalyst. After thorough mixing the adhesive was degassed in a vacuum bell jar for 10 minutes. When degassed the adhesive was transferred to plastic syringes for application to the solar cells. The dispensing equipment was a Vari-meter which can be adjusted for syringe loading pressure and time of dispensing. It is activated by a foot pedal leaving the operator's hands free to handle the syringe and workpiece. The particular settings found to be satisfactory were 20 psi pressure and 1.7 seconds dwell. A pool of adhesive was next dispensed at the center of each cell as shown in Figure 3.1.2-6.

The glass covers were prepared for bonding by hand wiping with a lint-free cloth and Freon TMC. After air drying for 10 minutes the OCLI Engineering module was primed with Dow Corning DC1200 primer and allowed to air dry for 30 minutes. The Spectrolab Engineering Module coverglass was cleaned but not primed.

As shown in Figure 3.1.2-7, the cell-strings still located in the solder fixture are next placed in the two-chamber bonding fixture. The coverglass is then placed over the cells but is not in contact as it rests on stand-off pins above the adhesive coated solar cells. The mating half of the bonding fixture is set in place and a vacuum is pulled in the lower chamber and the upper chamber. After 5 minutes the lower chamber is vented to atmospheric pressure and cells are lifted off the solder fixture and pressed against the coverglass as shown in Figure 3.1.2-8 by the deformation in the fixture center membrane. The bonding fixture is then flipped over and ambient pressure retained against the membrane for an additional 5 minutes (Figure 3.1.2-9). Figures 3.1.2-10 through 3.1.2-12 show the fixture being taken apart after the remaining chamber has been vented to atmosphere and the pressure equalized between the two

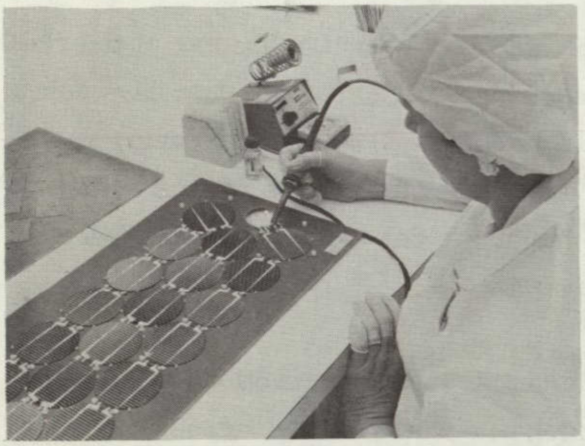

Figure 3.1.2-1 Interconnect "N" Tab Soldering with Cells and Interconnects in Registration Fixture

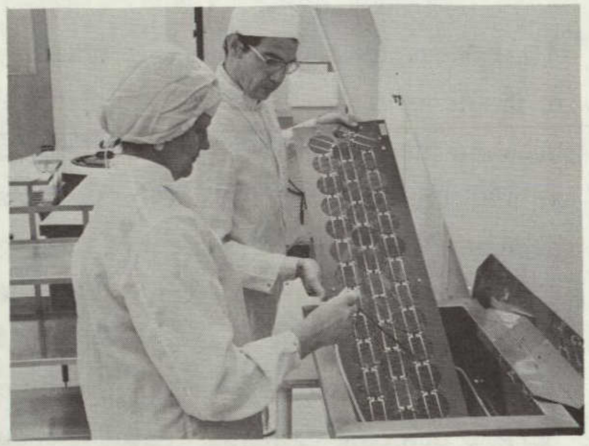

Figure 3.1.2-2 "N" Joint Freon Spray Cleaning

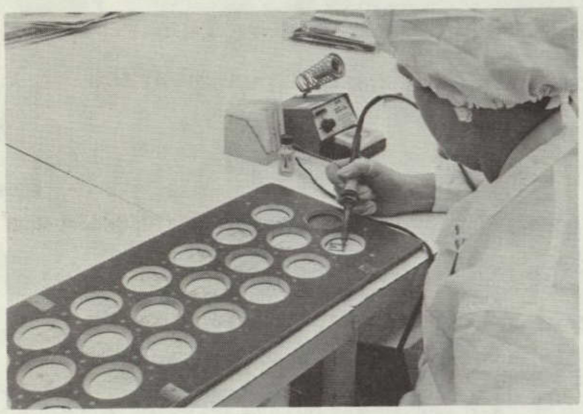

Figure 3.1.2-3 "P" Joint Soldering

Figure 3.1.2-4 "P" Joint Cleaning

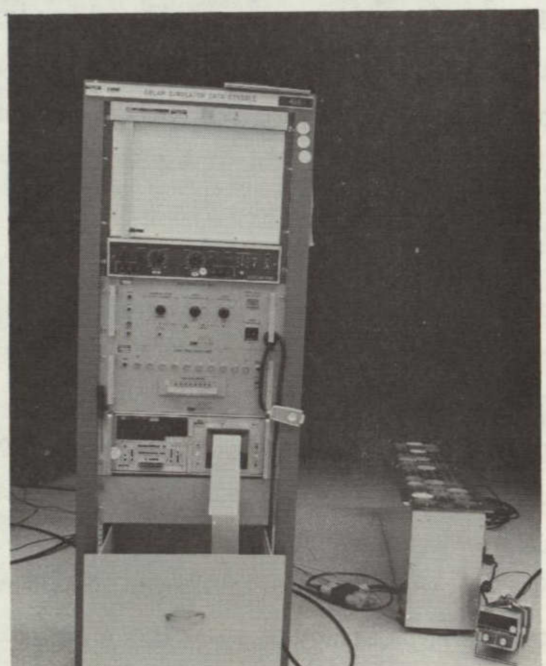

Figure 3.1.2-5 Module String Electrical Test – TRW Data System

Figure 3.1.2-6 Adhesive Application to Cells

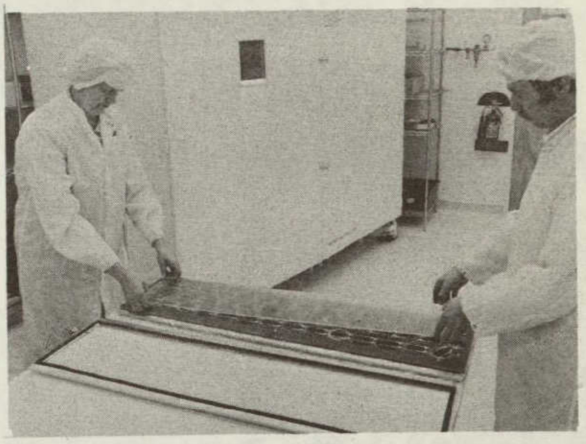

Figure 3.1.2-7 Module String and Glass Loading Into Vacuum Fixture

Figure 3.1.2-8 Application of Ambient Pressure to Fixture Lower Chamber

Figure 3.1.2-9 Fixture Turnover

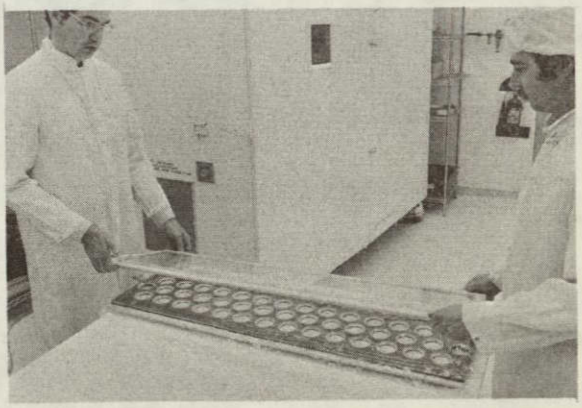

Figure 3.1.2-10 Fixture Disassembly

Figure 3.1.2-11 Fixture Disassembly

Figure 3.1.2-12 Glass/Cell Assembly Liftoff

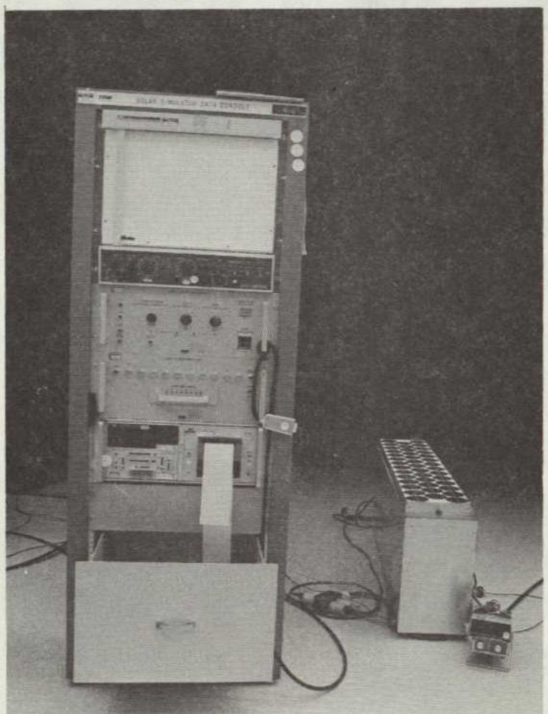

Figure 3.1.2-13 Module Test

place the corner clips were located and one pop rivet was installed at each corner clip interface. In the case of the Spectrolab engineering module the use of self-tapping screws were used but the corner clips had to be drilled at the assembly level which increased cost and resulted in undesirable aluminum chips throughtout the assembly. The Center Connector Assembly was next installed at midpoint of the side rails.

The electrical wiring was routed across the back of the cells on the Spectrolab module but this was changed to side rail routing on the OCLI module to provide uniformity in design and appearance. The electrical connection of the wire leads to the termination tabs on the cells was accomplished by hand soldering. The tabs were cleaned with isopropyl alcohol to remove silicone adhesive and then fluxed and pretinned. After soldering of the lead wires the flux was removed by locally cleaning with alcohol.

The backside encapsulation of the modules was varied in an attempt to obtain a suitable covering. On the Spectrolab engineering module half of the back was flow coated with Sylgard 184 and the other half was coated by trowelling with Dow Corning X1-2577. The X1-2577 was used in an attempt to achieve a hard coat that would allow easy cleaning. The trowel method introduced numerous bubbles and coating thickness was not even.

Other attempts at controlling the back-side thickness were tried on the OCLI module. It was level coated with Sylgard 184 and after cure was coated with several coats of Dow Corning X1-2577. The application methods involved rolling with a hand applicator, brushing by hand and spraying. The rolling and brushing introduced too many bubbles while the spraying created a frosty finish. More work in these areas needs to be done before a final method is selected.

Following final coating and cure the typed identification plate was attached, the module cleaned and readied for final test for power performance testing.

3.2 PRE-PRODUCTION MODULES

Following the completion of the two engineering modules the assembly of the 12 preproduction modules was started. The baseline assembly and process methods were the same as those defined in paragraph 3.1.2, for the engineering modules. Two process area's were altered during the twelve module fabrication in an attempt to gain additional knowledge in the cell bonding area and the backside encapsulation approach. Other than these two processes no changes were incorporated during the build-up of the Preproduction Modules. These variances are tabulated in Table 3.2-1 Module Descriptions where the grouping of the 41 cells in each module is identified.
The first six modules to be produced varied only by the primer for cell to glass-cover bonding. As seen by Table 3.2-1 OCLI modules serialized as -001 had no primer, -002 had a Q3-6060 primer, and -003 a DC 1200 primer. The Spectrolab modules -001 and -002 were primed with DC 1200, serial number -003 was not primed. The backside encapsulation of these six modules was Sylgard 184 adhesive applied as a level coat by pouring it uniformly over the back surface.

The priming sequence for the next six modules was as follows: OCLI module -004 and Spectrolab modules -004 and -005 were not primed for cell bonding while OCLI modules -005 and -006 as well as Spectrolab module -006 received Q3-6060 primer prior to cell bonding.

Various approaches to the backside encapsulation requirement were attempted to obtain a semi-hard yet flexible surface that was easily applied and consistent in appearance. As seen in Table 3.2-1 the coating combinations are varied. OCLI-004 received two roller coats of X1-2577 thinned two to one with xylene. OCLI modules -005 and -006 were first thin coated with Sylgard 184 and after curing roller coated with two coats of thinned X1-2577 in like manner as OCLI-004.

The Spectrolab modules -004, -005 and -006 also received combination of coatings for backside encapsulation. Serial number -004 was spray coated with X1-2577 thinned three to one with xylene followed after cure by a rolled coat of X1-2577 thinned two to one with xylene. Spectrolab -005 had a rolled coat of X1-2577 thinned three to one with xylene followed by a rolled coat thinned two to one. The last unit, Spectrolab 006 was thin coated with Sylgard 184, followed by a sprayed coat of X1-2577 thinned two-to-one and then final coated by roller with X1-2577 thinned two-to-one.

TABLE 3.2-1

TSM 7701 MODULE DESCRIPTIONS

Module ID Dash No. Ser No.	Cell Vendor	Cell Qty in Each Performance Group													Primer On Glass	Encapsulation Material and Sequence
		1	2	3	4	5	6	7	8	9	10	11	12	13		
(Minimum amps* in each group)		1.05	1.07	1.09	1.11	1.13	1.15	1.17	1.19	1.21	1.23	1.25	1.27	1.29		
501-001	OCLI														None	Leveled coat of Sylgard 184
501-002	OCLI								14	17	9	1			Q3-6060	Leveled coat of Sylgard 184
501-003	OCLI						10	14	17						DC 1200	Leveled coat of Sylgard 184
501-004	OCLI			9	1	4	3	← (24 cells not graded by vendor) →							None	2 rolled coats of X1-2577/xylene (2:1)
501-005	OCLI			3	15	10	6	5	1	1					Q3-6060	Thin coat of Sylgard 184 followed by 2 rolled coats of X1-2577/ xylene (2:0)
501-006	OCLI	6	23	12											Q3-6060	Thin coat of Sylgard 184 followed by 2 rolled coats of X1-2577/ xylene (2:1)
501-009	OCLI	← (cells not graded by vendor) →													DC 1200	Leveled coat of Sylgard 184 followed by several coats of X1-2577 rolled, brushed, sprayed, etc.
503-001	Spectrolab									16	15	6	3	1	DC 1200	Leveled coat of Sylgard 184
503-002	Spectrolab					1	18	9	10	3					DC 1200	Leveled coat of Sylgard 184
503-003	Spectrolab								40		1				None	Leveled coat of Sylgard 184
503-004	Spectrolab					6			3	32					None	Sprayed coat of X1-2577/xylene (3:1) followed by rolled coat of X1-2577/xylene (2:1)
503-005	Spectrolab							21			20				None	Rolled coat of X1-2577/xylene (3:1) followed by rolled coat of X1-2577/xylene (2:1)
503-006	Spectrolab			6	6	7	11	3				7	1		Q3-6060	Thin coat of Sylgard 184 followed by sprayed coat of X1-2577/ xylene (2:1) followed by rolled coat of X1-2577/xylene (2:1)
503-009	Spectrolab	2	3	1	1	3	1	9	21						None	Half coated with Sylgard 184· other half with trowelled coat of X1-2577

*Amps reported by vendor at 0.456V, AMI, 100 mW/cm^2, 28^{o}C.

After encapsulation the modules were tested for electrical output as shown in Section 4 in Table 4.2-2.

The outcome of all of these variations was defined by cross comparison after the test cycles. Any process that requires multiple coatings with different material combinations is not desirable from a production aspect. The backside encapsulation requirement and techniques needs additional investigation but it is an area that should be fairly easily resolved with more testing and evaluation.

3.3 FABRICATION AIDS AND TOOLING

Tooling and assembly aids were built to enable repeatable processing where tolerance and process requirements necessitated. Due to the small quantity of units fabricated tooling was kept to a minimum and many of the operations were performed by hand to keep tooling design, make and check out to a low cost factor. The following fixtures and aids were prepared for this contract:

1. Photo templates for etching the OCLI and Spectrolab patterns (quantity one each).
2. The Cell/Interconnect Registration Tool (CIRT) which is a solder fixture for maintaining cell-to-cell registration and interconnect location during soldering operations (quantity of three each).
3. Cover for CIRT which allows flipping the solder fixture during soldering of the positive contact (quantity of one each).
4. Two Stage Transparent Vacuum Fixture (2STVF) for bonding cells to coverglass (quantity of one each).

TESTS

Section 4
TESTS

Extensive tests were performed early in the program to make component and design selections and performance predictions. In addition to the cell selection tests described in Section 2, a second set of 3-cell modules using Spectrolab and OCLI cells, redesigned interconnects, and assembled in the same manner as the full scale modules was tested extensively. Those tests and the full module tests are described in this section. The tests on the engineering modules are described, in particular the tests which determined module temperature performance.

4.1 INITIAL EVALUATION TESTING

In addition to the cell screening tests described in Section 2, several tests were run to predict and verify module performance under environmental extremes.

Seven 3-cell modules were made and tested extensively to evaluate component and module performance under environmental test exposure. They were also used to verify the advanced concepts for tooling and assembly processes which were later adapted for use on full size engineering and preproduction modules.

Tooling and Assembly Process Verification

The three cells for each module were interconnected on the cell/interconnect registration tool (CIRT) which holds the cells and interconnects in registration during soldering and flux cleaning. For module assembly the tool incorporated additional features of glass support during evacuation prior to cell bonding and provision for pressing the cells into the adhesive against the glass in vacuum. All seven 3-cell modules were successfully bonded in the same tool which was later used for full size modules.

Bare to Covered Module Output

Prior to bonding, with the 3-cell module remaining in the CIRT, the output was measured using the X25 set to 100 mW/cm^2 per LeRC Standard SL No. 2. After bonding the same test was repeated. The results are reported in Table 4.1-1 after adjustment to reflect performance of full size modules. Note that in every case there was a net increase in output after cover bonding. These results are compared with full size module tests later in this report.

Three-Cell Module Thermal Cycling Tests

To provide confirmation of the interconnect and encapsulant performance under extreme thermal cycling, 3-cell modules were exposed to 50 quick cycles from -50 deg C to +90 deg C with average cycle time of 30 minutes. This cycle time is very rapid compared with expected operating conditions. It was used to give the modules very severe thermal expansion/contraction. Modules were tested before and after the cycling and showed no delamination or electrical degradation. Results shown in Table 4.1-2 indicates

Table 4.1-1

PREDICTED EFFECTS OF ENCAPSULATION ON MODULE POWER BASED ON 3 CELL MODULE TESTS

	Max Power at 28°C		Power at 15.8V 60°C		Δ%
	Bare	Encaps	Bare	Encaps	
OLC1					
OC010203 Bare	20.5 W at 18.86 V		17.63		
OC010203 Encaps/184		22.27 at 18.86 V		18.31	+3.8
OCE1E2E3 Bare	20.64 W at 19.13 V		17.49		
OCE1E2E3 Encaps/184		21.32 W at 19.41 V		18.04	+3.1
OCE4E5E6 Bare	20.09 W at 18.17 V		17.08		
OCE4E5E6 Encaps/184		21.18 W at 18.45 V		17.77	+4.0
OCL1 Average/184			17.35	18.04	+3.63
SPECTROLAB					
SL384041 Bare	20.77 W at 17.90 V		17.36		
SL384041 Encaps/184		21.46 W at 18.17 V		18.31	+5.8
SL515253 Bare	19.95 W at 17.36 V		16.54		
SL515253 Encaps/184		20.64 W at 17.63		17.08	+3.2
SL484950 Bare	20.23 W at 17.63 V		17.22		
SL484950 Encaps/184		21.59 W at 18.17 V		18.45	+7.1
Spectrolab Average/184			17.04	17.94	+5.4

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Table 4.1-2

PREDICTED EFFECTS OF THERMAL CYCLING ON MODULE POWER
(BASED ON 3 CELL MODULE TESTS)

	Max Power at 28°C		Power at 15.8 V 60°C		Δ% at 60°C
	Before	After	Before	After	
OCLI					
OC010203	22.27	22.55	18.58	18.86	+1.6
OCE1E2E3	21.86	22.54	18.45	19.27	+4.4
OCE4E5E6	21.59	21.73	18.45	18.72	+1.5
SPECTROLAB					
SL384041	21.59	22.00	18.31	18.31	+0
SL515253	20.64	20.22	17.22	16.8	-2.4
SL484950	21.32	21.32	17.63	18.45	+4.6
SL345	17.63	18.45	14.35	14.76	+2.9

some increase in power following thermal cycling. It has been LMSC's experience that this apparent increase is transitory and that after a period of 2 or more weeks the modules will "anneal at room temperature" and show no net increase due to temperature cycling. The data indicate, however, that thermal cycling has not caused a significant change (particularly decrease) in performance.

Comparison of Steady State and Pulsed Simulators

Following thermal cycling the 3-cell modules were tested under both X-25 Steady state xenon and LAPSS (pulsed xenon) simulators to compare performance under the two lamps. The LAPSS was set per Standard SL No. 2 which was calibrated by both LeRC and JPL. X-25 was set per Standard SL No. 1 which was calibrated by LeRC. Data from curves produced for 3-cell module OCE4E5E6 are compared in Table 4.1-3.

Note that there is good correlation between V_{oc} on the tests which indicates that cell temperature is the same. In I_{sc}, however, the 3 percent difference between 1.29a and 1.33a in the two setups results from the combined effects of different standards, and different spectral content of the lights; and some room temp annealing during the 3 days between tests.

The pulsed simulator will be used exclusively for full size module tests.

Humidity Test

A humidity cycle test using identical cycle rates and times shown in Figure 2 of JPL 5-342-1 was run in the same chamber which was used later for full sized modules. Automatic programming cams developed for this program were used to verify their performance.

In addition to 3-cell modules OC010203 and SL345, samples included standard-mounted Spectrolab cells No. 4 and 66 which are bonded and encapsulated under Fourco Low Iron glass, 3 inch diameter bare Spectrolab cells Nos. 12 and 22, 2 inch diameter Spectrolab nonglassified cells NG No. 2 and NG No. 1, and glassified cells G No. 1 and G No. 2.

Table 4.1-3

COMPARISON OF X-25 AND LAPSS DATA ON 3 CELL MODULE

	3 Cell Module Output 28°C Performance Data	
	LAPSS	X-25
I_{sc}	1.29	1.33
V_{oc}	1.73	1.72
Maximum Power		
I_{mp}	1.17	1.18
V_{mp}	1.30	1.35
W_{mp}	1.525	1.593
Power Point*	1.37V	
I	1.11	1.16
W	1.521	1.588

*Corresponds to 18.7 volts at 28°C which relates to 15.8V specified at 60°C by the estimated cell temperature coefficient.

The encapsulated cells Nos. 4 and 66 showed no change in performance after humidity exposure. Bare 3 inch diameter cells Nos. 12 and 22 showed no change in I_{sc} or V_{oc} but softening of the knee caused reduction of maximum power by 4 to 6 percent at 28 deg C and 4 percent at 60 deg C. Comparison of glassified and nonglassified cell performance following humidity cycles shows average peak power reduction for glassified cells of 3.6 percent at 28 deg C and 1.5 percent at 60 deg C while nonglassified cells show reductions of 3.4 percent and 2.6 percent, respectively. As relates to short term humidity testing, no dominant advantages in power output occur with glassification.

Sunlight Temperature Stability Tests

Several of the 3-cell modules which were already exposed to thermal cycling were subsequently used in sunlight temperature stability tests which showed that the transparent module delivers approximately 50 percent more power due to lower operating temperature than opaque modules.

4.1.1 Sunadex Transmission Measurement

The measurement of glass transmission in the normal way includes measuring the difference in irradiance from a light source with the glass in the light path. LMSC used sunlight as the light source to measure the spectral transmission of Sunadex. Curve (1) in Figure 4.1-1 shows the direct irradiance of sunlight as measured with EG&G Spectroradiometer Model 580/585. Curve (4) shows the transmitted irradiance through Sunadex. This is the normal method for measuring transmission. The integrated area under curve (4) is 90 percent of curve (2), and this agrees with the advertised transmission value of Sunadex.

But the normal transmission value does not represent the energy throughput that the solar cells will see on LMSC modules because the back side reflection is reduced by the cell adhesive. Therefore, to more closely simulate the energy throughput for spectral irradiance measurement, Sunadex was bonded directly to the EG&G optics with uncured Sylgard 184 adhesive. Curve (4) shows the measured spectral distribution. The integrated area under curve (4) is 96.5 percent of curve (2); and this agrees with the 97 percent of bare cell output which was measured using the X-25 simulator after cells were covered with Sunadex.

Curves (1) and (5) in Figure 4.1-1 show the AMO spectral irradiance per SP8005 and the measured irradiance of the LMSC X-25 set to 100 mW/cm^2 respectively.

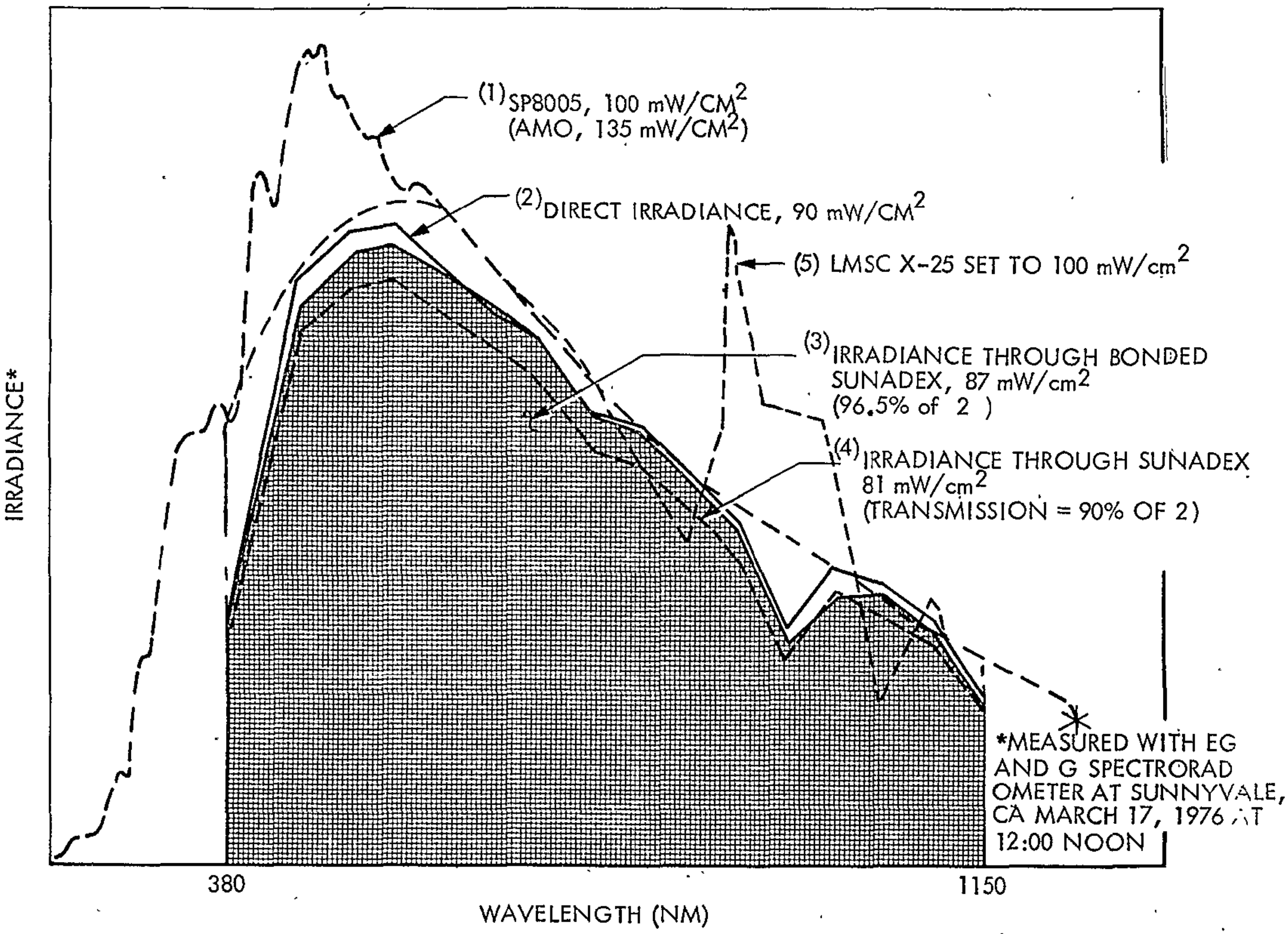

Figure 4.1-1 Spectral Irradiance Measured by Spectroradiometer

4.1.2 Solar Cell Measurement

As discussed in paragraph 2.2 the bare solar cell screening consisted of: (1) measuring I-V curves of several cells from each vendor, (2) selecting a typical cell of temperature performance measurements, and (3) comparing cell performance and cost (as shown in Table 2.2-3) and selecting cells for the contract. Figure 4.1-2 shows a typical set of 28 deg C curves which was run at AMI, 100 mW/cm^2 per bare standard No. 3003 (LMSC later changed to encapsulated Standard SL No. 2). Note that all but one cell from this vendor exceeded the minimum specified output and that Cell No. 15 was selected for temperature performance measurements as shown in Figure 4.1-3.

Standard Cells. The LMSC encapsulated Spectrolab standard for terrestrial testing is designated as SL No. 2. Another Standard, SL No. 1, is identical and it is used as a backup standard.

Standard No. 2 has been calibrated by LeRC on steady state xenon (Figure 4.1-4) and by JPL on pulsed xenon (Figure 4.1-5). Temperature performance of Standards No. 1 and No. 2 as measured using the X-25 simulator is shown in Figure 4.1-6.

Fabrication of SL No. 1 and SL No. 2

3 inch SL Cell	–	selected from average cells of 70 produced in early 1976
Sylgard 184	–	encapsulant and adhesive (~ 0.010 between cell and glass)
ASG Sunadex	–	3/16 inch thick high transmission glass "Lightly diffusing rolled water-white crystal"
Thermocouple	–	Copper Constantan (5 mil dia) soldered to back of cell with leads to terminal board
Terminal Board	–	6 terminals 2 for thermocouple 2 for current 2 for voltage

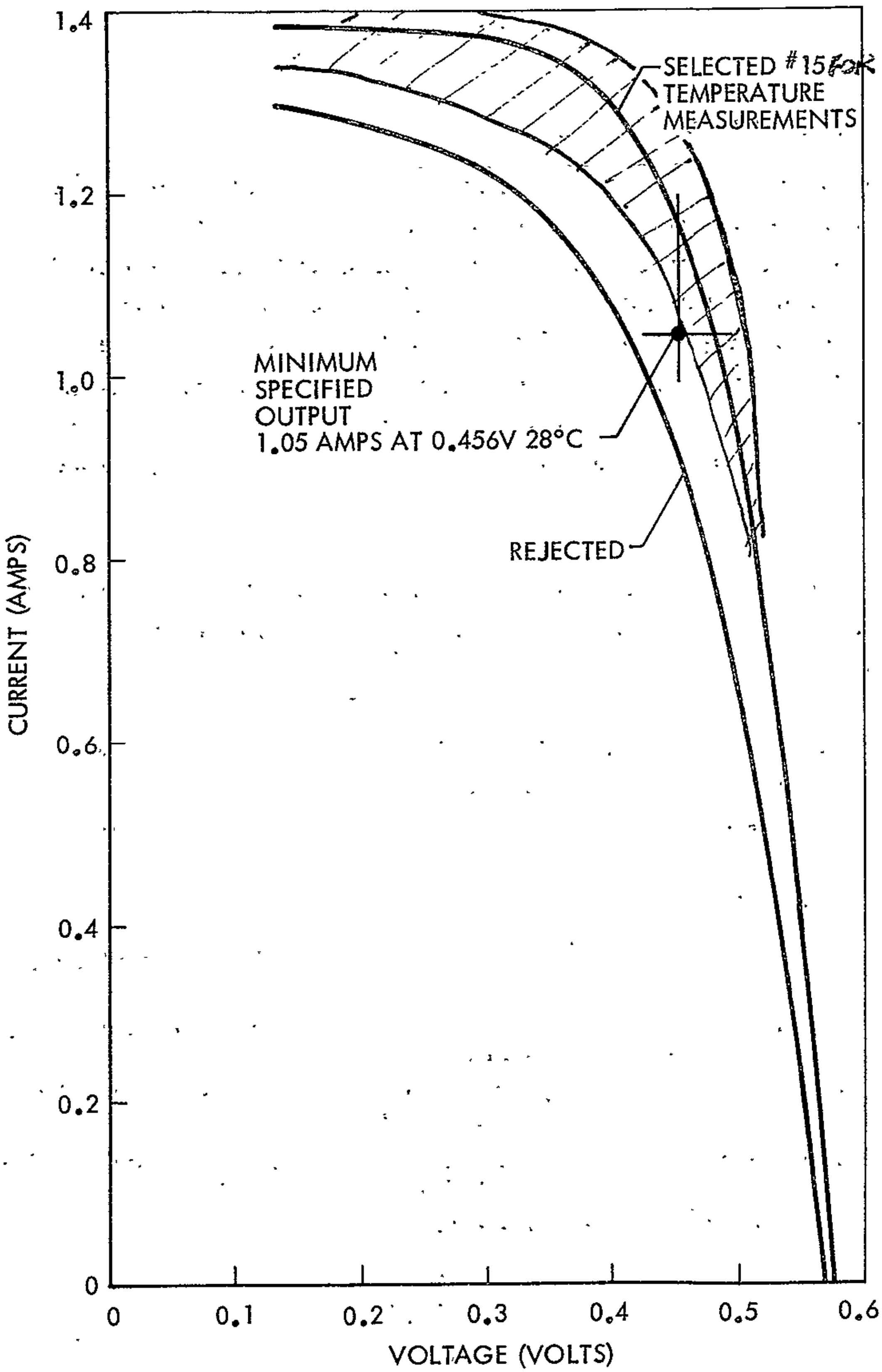

Figure 4.1-2 Typical 28°C Bare Solar Cell Screening Test Results

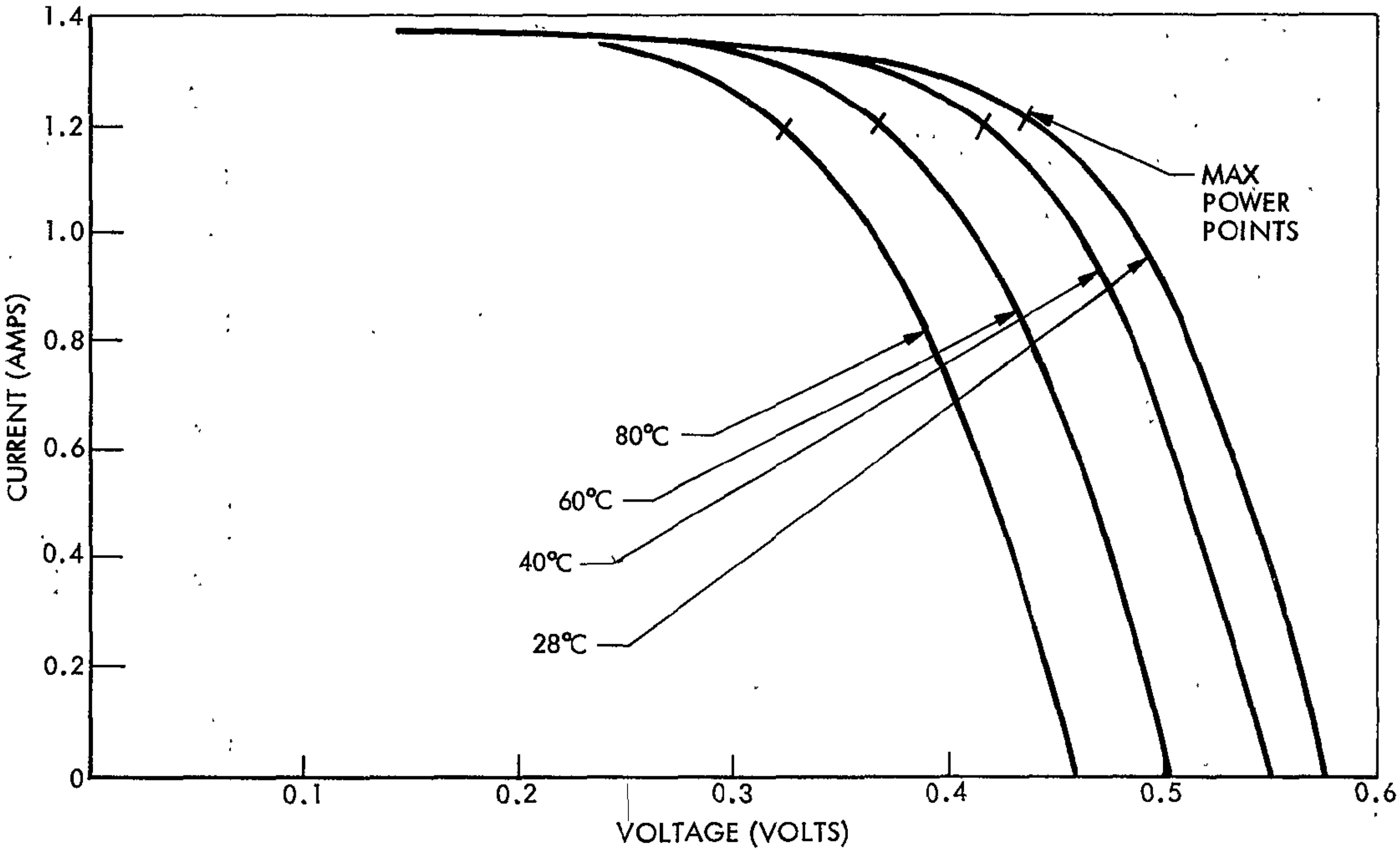

Fig. 4.1-3 Typical Selected Bare Cell Temperature Performance

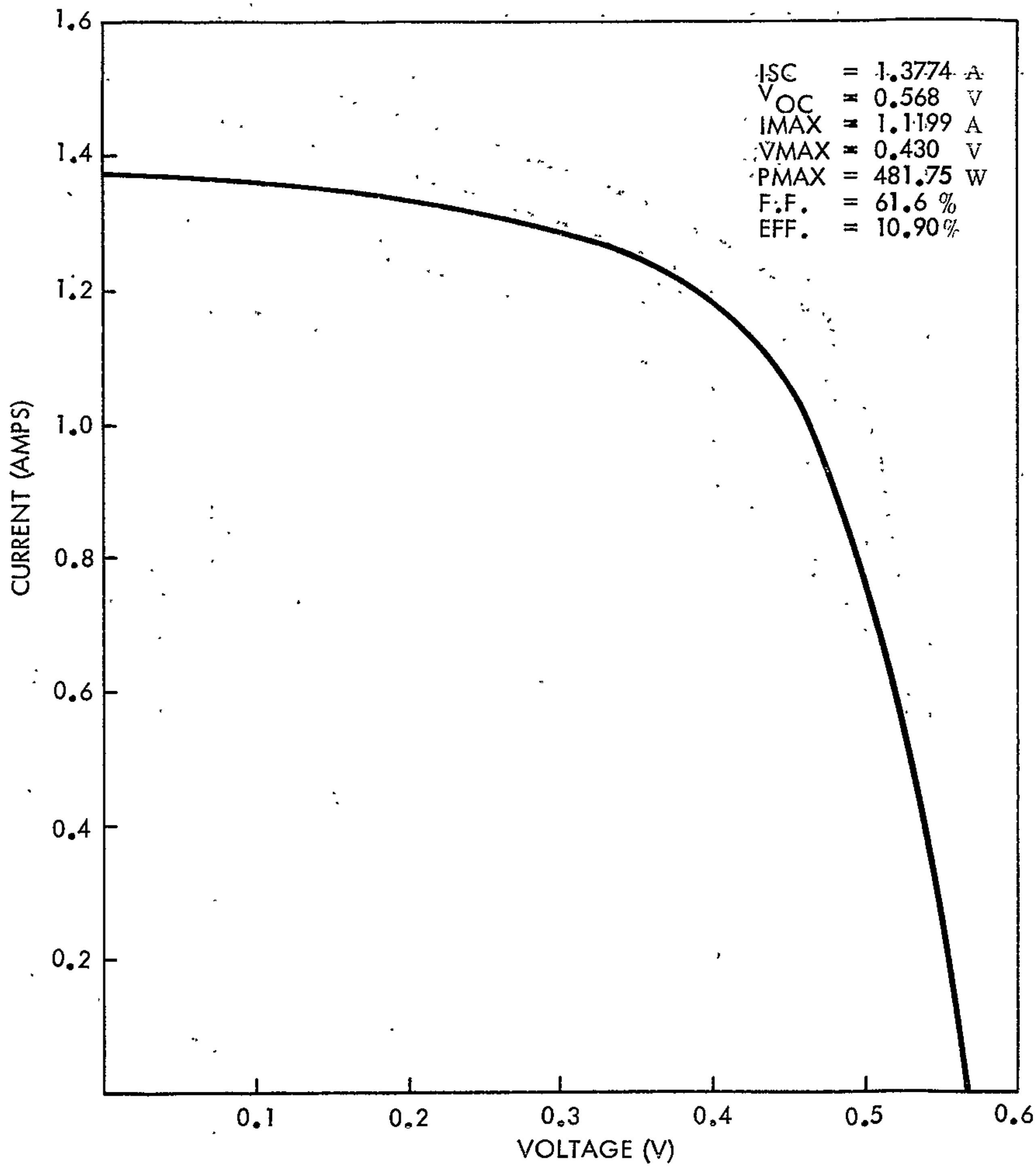

Figure 4.1-4 LERC Calibration Standard SL #2 at AMI, 28°C Steady State Xenon Simulator

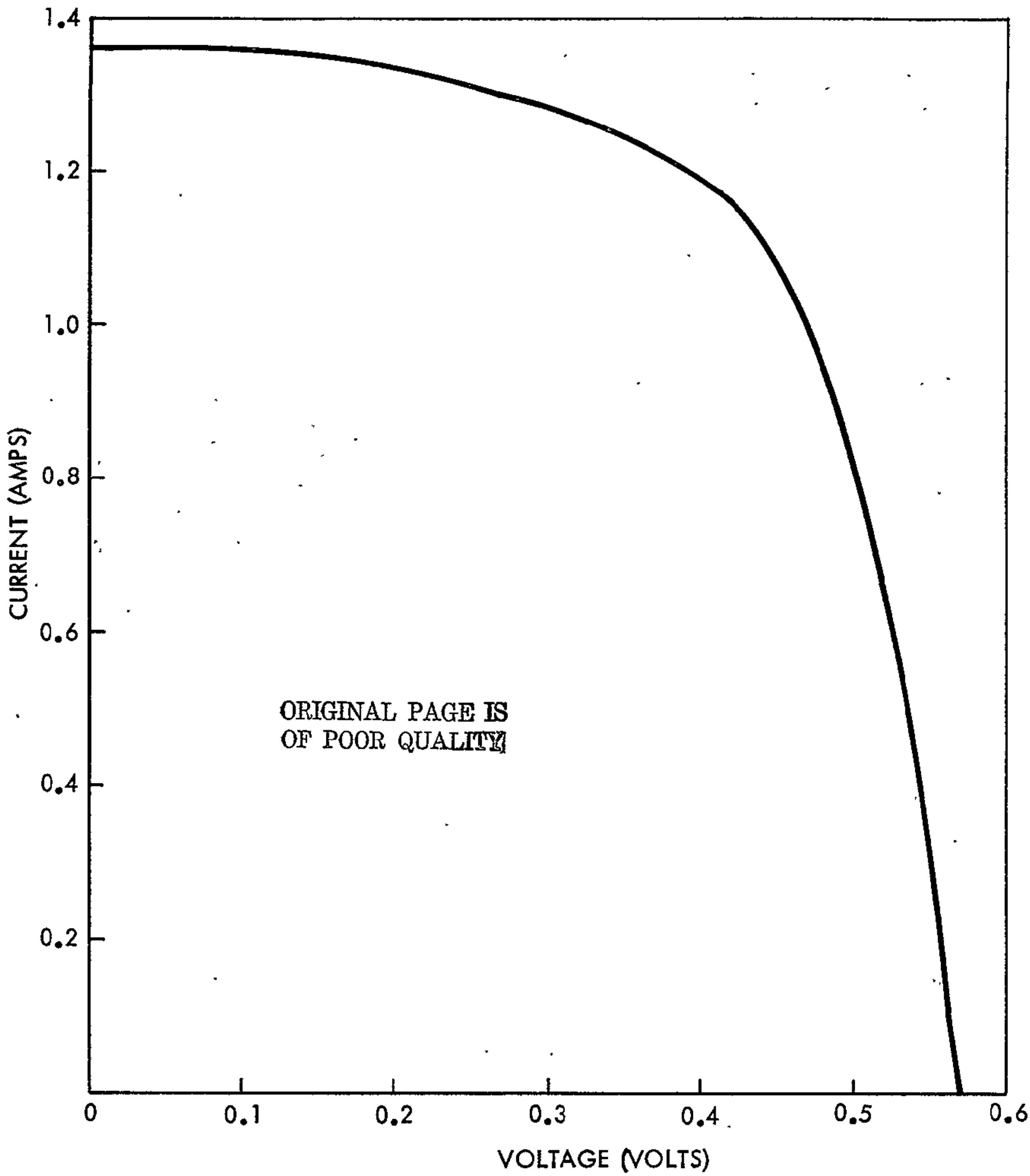

Figure 4.1-5 JPL Calibration of Standard SL #2 at AMI, 28°C Xenon Pulsed Simulator

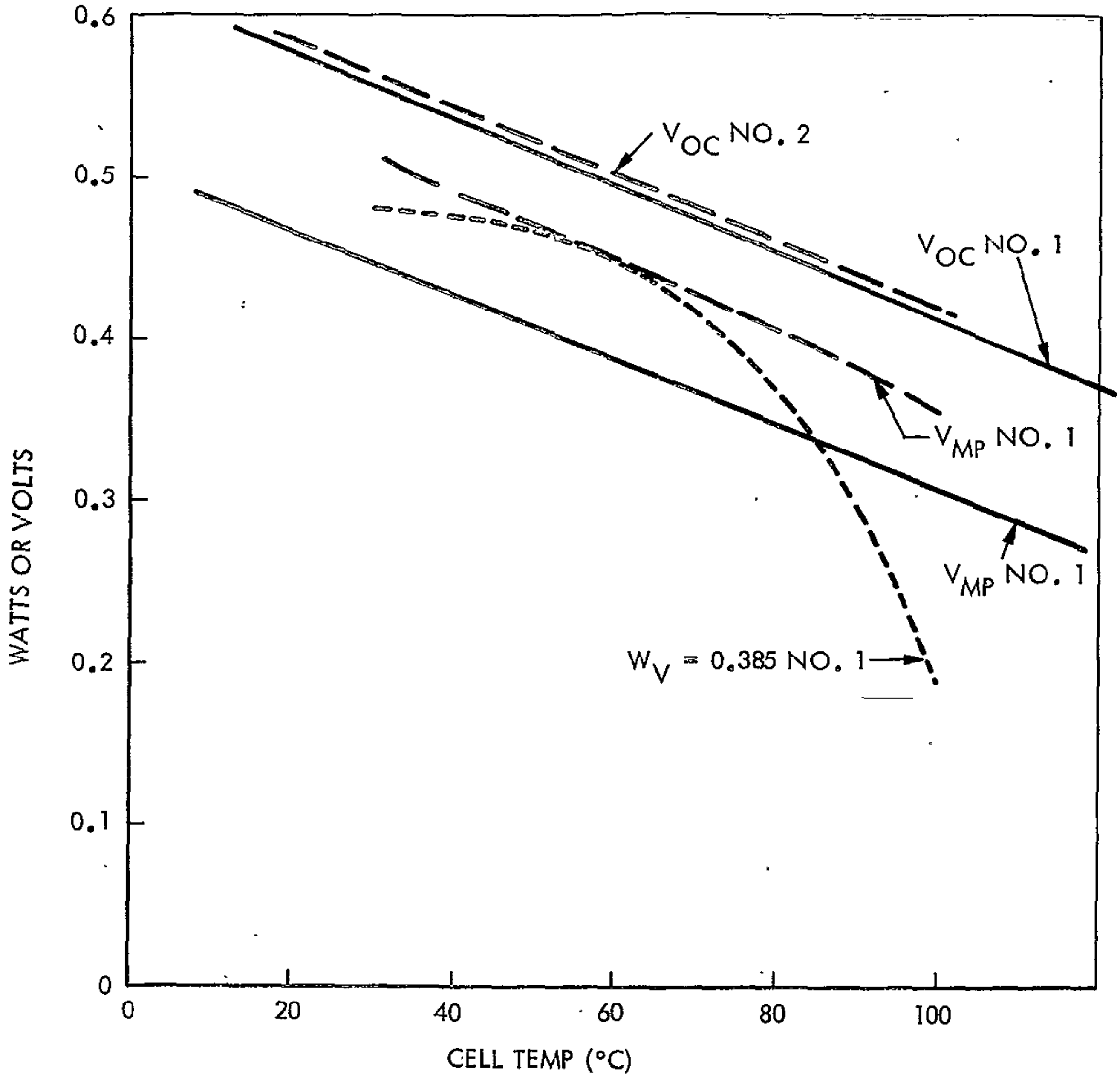

Figure 4.1-6 Temperature Coefficient Encapsulated Standards SL #1 & 2 (X-25 Simulator)

Interconnects	—	Flat lead soldered to contact – round wire to terminal – encapsulated in RTV
Edge Channels	—	3/8 x 3/8 x 1/16 aluminum channel on two sides
Grommet	—	Silicone rubber grommet between glass and edge channels

Standard materials and assembly methods were similar to proposed module design so that its performance would also be similar to a proposed module performance.

4.2 MODULE TESTING

A comprehensive series of tests was performed on the engineering and preproduction modules, as listed in Table 4.2-1.

The electrical output of the modules from bare cell to preshipment is shown in Table 4.2-2. There was a 1.5 percent reduction in the overall average 60 deg C output of the six delivered modules after all of the environmental tests were completed at LMSC.

4.2.1 Engineering Module Tests

The principal testing effort on the engineering modules was directed to determining the temperature performance of the modules and relating that to bare cell performance. During the early bare cell performance tests the temperature dependence of cell voltage was measured on individual cells. Using that data and the specified module performance voltage of 15.8 volts at 60 deg C power points were established at 18.7, 17.6, 15.8, and 14.2 volts for 28 deg C, 40 deg C, 60 deg C, and 80 deg C respectively. Specifications to cell vendors required minimum current to be measured at 0.456V at 28 deg C (i.e., 18.7 volts ÷ 41 cells in series). This assumed a constant slope of the temperature voltage curve through 0.385V (i.e., 15.8 V ÷ 41 cells) of -2.2 millivolts per deg C). (Predicted module V_{OC} temperature coefficient using this method would be -90 mV/deg C.) The actual measurements for bare cells and engineering modules are shown in Table 4.2.1-1. Note that the slope is less than predicted at -80 and -84 millivolts/deg C for SL and OC modules respectively.

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Table 4.2-1

ENGINEERING AND PRE-PRODUCTION MODULE TESTING

			Applicable Modules				
			Engr. Test (2)	Prod Untested (6)	Prod LMSC Tested (6)	Major Test Equipment	New Equipment Required
A.	Temp-Elec Performance	Determine STC 1-V which ensures req'd 1-V at 60°C	X			LAPSS	Fixture/ Module Heater
B.	STC-Elec Performance	1-V at STC (12 Watts/ Module at 15.8V, 60°C)	X	X	X	LAPSS	Fixture/ Module Heater
C.	Thermal Stability	Stable temp in sunlight to verify anal	X				
D.	Temperature Cycling	-40°C to 90°C at rate ≤100°C/Hr, cycle time≤ 6 Hr, 50 Cycles			X	CONRAD temp humidity chamber	Module mounting frame
E.	Humidity	Per Figure 2 of Spec STC elect performance within 1 hr			X	CONRAD temp humidity chamber	Module mounting frame
F.	Mechanical Integrity	100 cycles equiv to ±50 psf x 5/8 at midspan			X	Test frame & bellows assy	Test frame & bellows assy
G.	Warp, Bow, Twist	Withstand 1/4 in. per ft of warp, bow, twist			X		Fixture
H.	Voltage Withstanding test	Withstand 1500 VDC for 1 minute, 15 amp current limit. 500 VDC/ sec, in 3 steps of 500 VDC at 15 sec intervals. Hold at 1500 VDC for 1 minute			X	Insulation tester	None
I.	Insulation Resistance	Minimum resistance isolation to grd. 100 megohm at ±1000 VDC			X	Megommeter	None

TABLE 4.2-2

MODULE ELECTRICAL PERFORMANCE

MODULE NO.	MODULE OUTPUT AT AMI 100 mW/CM^2, 28°C, 18.7 VOLTS										MODULE OUTPUT AT AMI 100 mW/CM^2, 60°C, 15.8 VOLTS							
	BARE MODULE		PRE-TEST (ENCAPS)		AFTER TEMP CYC		AFTER HUMIDITY		AFTER MECHANI-CAL LOADING		PRE-TEST (ENCAPS)		AFTER TEMP CYC		AFTER HUMIDITY		AFTER MECHANI-CAL LOADING	
	I	W	I	W	I	W	I	W	I	W	I	W	I	W	I	W	I	W
501-001	NOT RUN		1.05	19.69							1.12	17.77						
501-002	1.10	20.57	1.14	21.27							1.17	18.47						
501-003	1.08	20.19	1.13	21.13							1.17	18.47						
501-004	1.02	19.07	1.05	19.69	1.04	19.39	1.03	19.26	1.05	19.64	1.11	17.54	1.08	17.06	1.03	16.27	1.09	17.22
501-005	1.07	20.00	← NOT RUN →								← NOT RUN →							
501-006	1.04	19.35	1.07	19.99	1.00	18.70	1.06	19.82	1.04	19.45	1.09	17.22	1.01	15.96	1.06	16.75	1.06	16.75
501-009	1.08	20.19	1.08	20.10	1.12	20.94	1.11	20.76	1.12	20.94	1.06	16.75	1.14	18.01	1.13	17.85	1.15	18.17
501 AVG	–	19.89	–	20.31	–	19.68	–	19.95	–	20.01	–	17.70	–	17.01	–	16.96	–	17.38
503-001	1.14	21.39	1.18	20.07							1.22	19.28						
503-002	1.10	20.55	1.14	21.32							1.17	18.43						
503-003	1.12	20.94	1.15	21.43							1.19	18.88						
503-004	1.13	21.19	1.14	21.40	1.14	21.28	1.16	21.69	1.16	21.69	1.19	18.76	1.16	18.33	1.17	18.49	1.17	18.49
503-005	1.14	21.22	1.16	21.68	1.16	21.69	1.16	21.69	1.16	21.69	1.18	18.64	1.17	18.41	1.17	18.49	1.17	18.49
503-006	1.10	20.63	1.11	20.80	1.13	21.07	1.11	20.76	1.12	20.92	1.14	17.98	1.12	17.70	1.13	17.85	1.16	18.33
503-009	← NOT RUN →								1.15	21.51	← NOT RUN →						1.16	18.33
503 AVG	–	20.98	–	21.11	–	21.35	–	21.38	–	21.45	–	18.66	–	18.15	–	18.28	–	18.40
O'ALL AVG	–	20.44	–	20.71	–	20.52	–	20.67	–	20.73	–	18.18	–	17.58	–	17.62	–	17.90

NOTE: W VALUES ARE ACCURATE; SOME I VALUES ARE ROUNDED OFF.

TYPICAL MODULE (503-005)

Table 4.2.1-1

SPECTROLAB AND OCLI BARE CELL AND ENGINEERING MODULE TEMPERATURE COEFFICIENT DATA

SL bare cell temperature coefficient

					Voltage/Temperature Coefficient
Temperature (°C)	28	40	60	80	
V_{oc}	0.574	0.547	0.502	0.458	-2.2 mV/°C

SL Engineering Module temperature coefficient

Temperature	28	40	60	80	
V_{oc}	23.8	22.8	21.2	19.6	-80 mV/°C

OC Bare Cell temperature coefficient

Temperature	28	40	60	80	
V_{oc}	0.581	0.561	0.515	0.472	-2.10 mV/°C

OC Engineering Module temperature coefficient

Temperature	28	40	60	
V_{oc}	23.8	22.7	21.1	-84 mV/°C

Tables 4.2.1-2 and 4.2.1-3 show OCLI and Spectrolab temperature performance data respectively and Figures 4.2.1-1 and 4.2.1-2 show respective IV curves.

Spectrolab data includes a sunlight test during which the module temperature stabilized at 40 deg C. No measurement of total flux was made during the sunlight test, although the Standard cell SL No. 1 had I_{sc} of 1.35 amps and V_{oc} of 0.542 volts.

Table 4.2.1-2

OCLI ENGINEERING MODULE TEMPERATURE PERFORMANCE DATA.

	28°C	40°C	60°C
VOC	23.8	22.7	21.1
ISC	1.20	1.20	1.20
IMP(1)	1.12	1.10	1.14
VMP	18.2	17.3	15.0
WMP	20.38	19.03	17.1
VPP(2)	18.6	17.6	15.8
IPP	1.08	1.07	1.06
WPP	20.0	18.83	16.75

(1) Maximum power

(2) Specified power point at voltage noted

Table 4.2.1-3

SPECTROLAB ENGINEERING MODULE TEMPERATURE PERFORMANCE DATA

	28°C	40°C	(40° in Sunlight)	60°C	80°C
V_{oc}	23.82	22.81	(22.6)	21.19	19.62
I_{sc}	1.30	1.31	(1.34)	1.31	1.31
V_{pp} (1)	18.7	17.7	(17.6)	15.8	14.16
I_{pp}	1.15	1.15	(1.16)	1.15	1.16
W_{pp}	21.51	20.26	(20.42)	18.17	16.42

(1) Specified power point at voltage noted

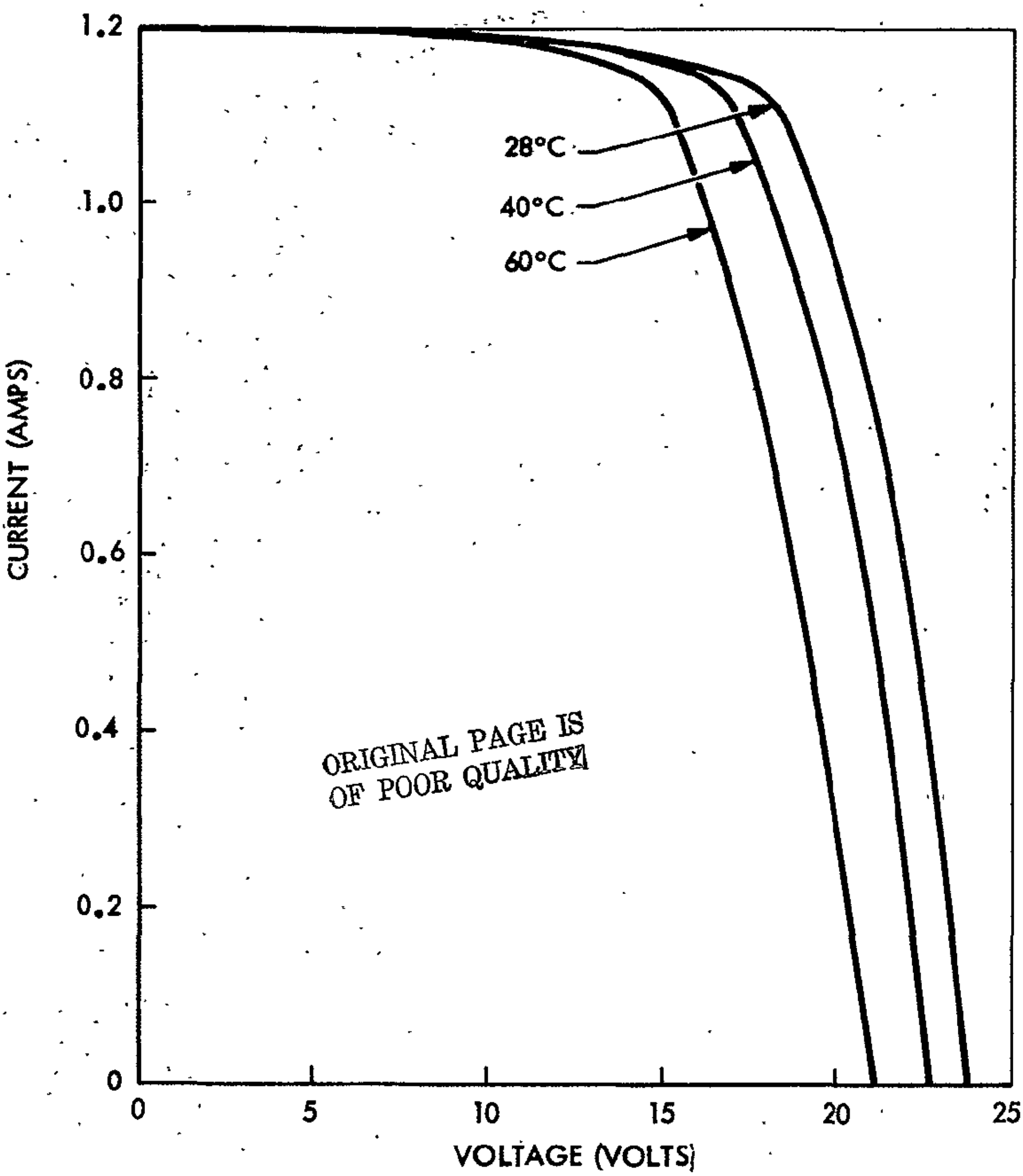

Figure 4.2.1-1 Temperature Effect on IV Curves For OCLI Engineering Module

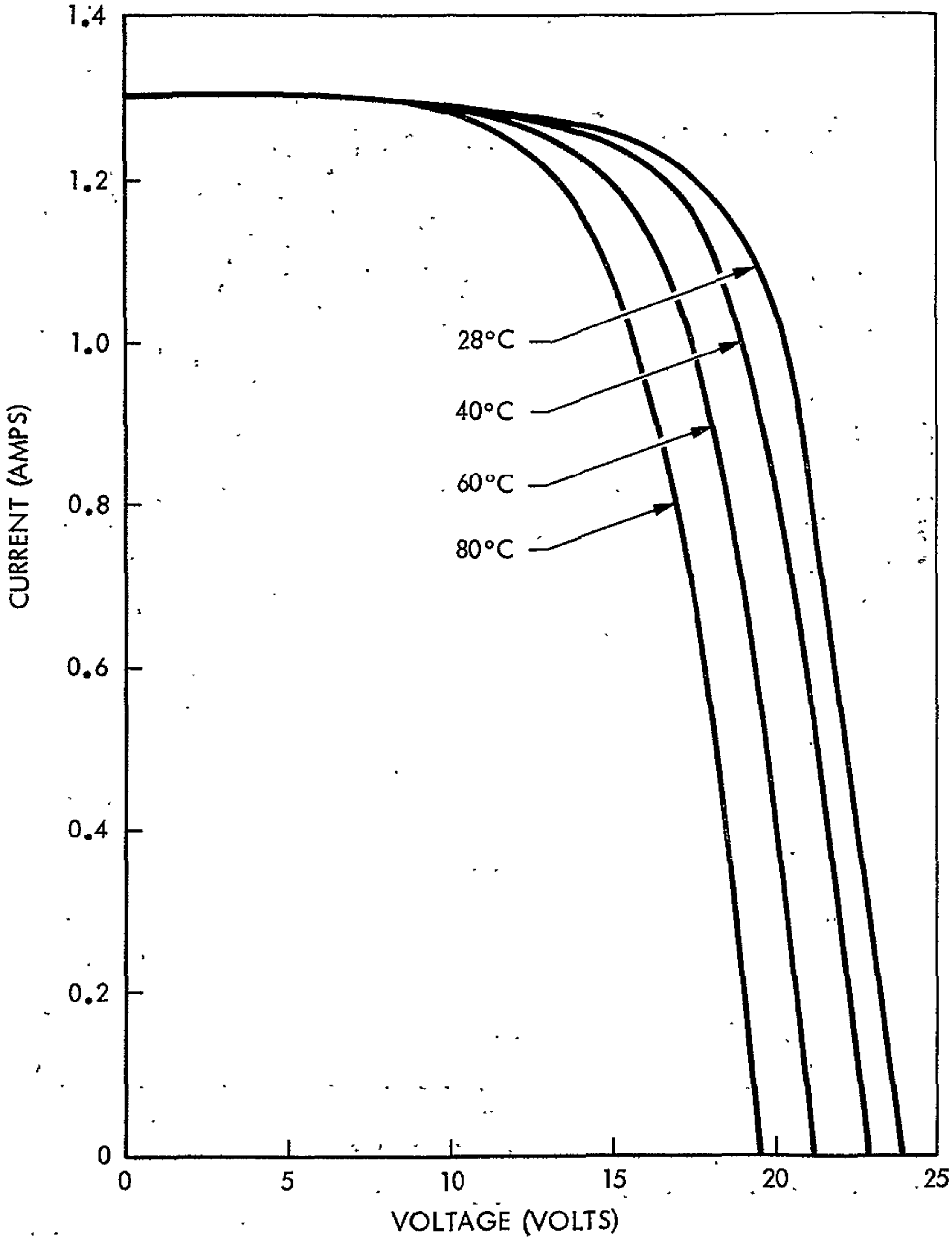

Figure 4.2.1-2 Temperature Effect on IV Curves For Spectrolab Engineering Module

4.2.2 Preproduction Module Tests

At the module level, electrical output was measured on the 41-cell assemblies before and after bonding to the glass cover. Table 4.2.2-1 lists the current and power at 18.7 V for the six preproduction modules at 28 deg C. On average, there was a 2.5 percent increase in current and a 3.1 percent increase in power at 18.7 volts following bonding of the cell assembly to its cover. This is in general agreement with the single cell and 3-cell module data.

Due to the low output of OC-005 during the pretemperature cycle electrical test, it was removed and OC-009 (engineering module) was put in its place.

Table 4.2.2-1

COMPARISON OF MODULE OUTPUT BEFORE AND AFTER COVERING

	Bare		Covered	
	I at 18.7 V	W at 18.7 V	I at 18.7 V	W at 18.7 V
SL-001	1.14	21.32	1.18	22.25
SL-002	1.10	20.57	1.14	20.94
SL-003	1.12	20.94	1.15	21.43
SL-004	1.15	21.51	1.14	21.39
SL-005	1.18	20.07	1.16	21.69
SL-006	1.10	20.57	1.11	20 76
OC-001	Not Run		1.05*	19.60*
OC-002	1.10	20.57	1.14	21.30
OC-003	1.08	20.20	1.13	21.10
OC-004	1.02	19.10	1.05	19.60
OC-005	1.07*	20.01*	Low	Low
OC-006	1.04	19.35	1.07	20.01
AVERAGES (10 Modules)	1.10	20.42	1.127	21.05

*Not included in average

The test sequence for the six environmental test modules is shown in Figure 4.2.2-1.

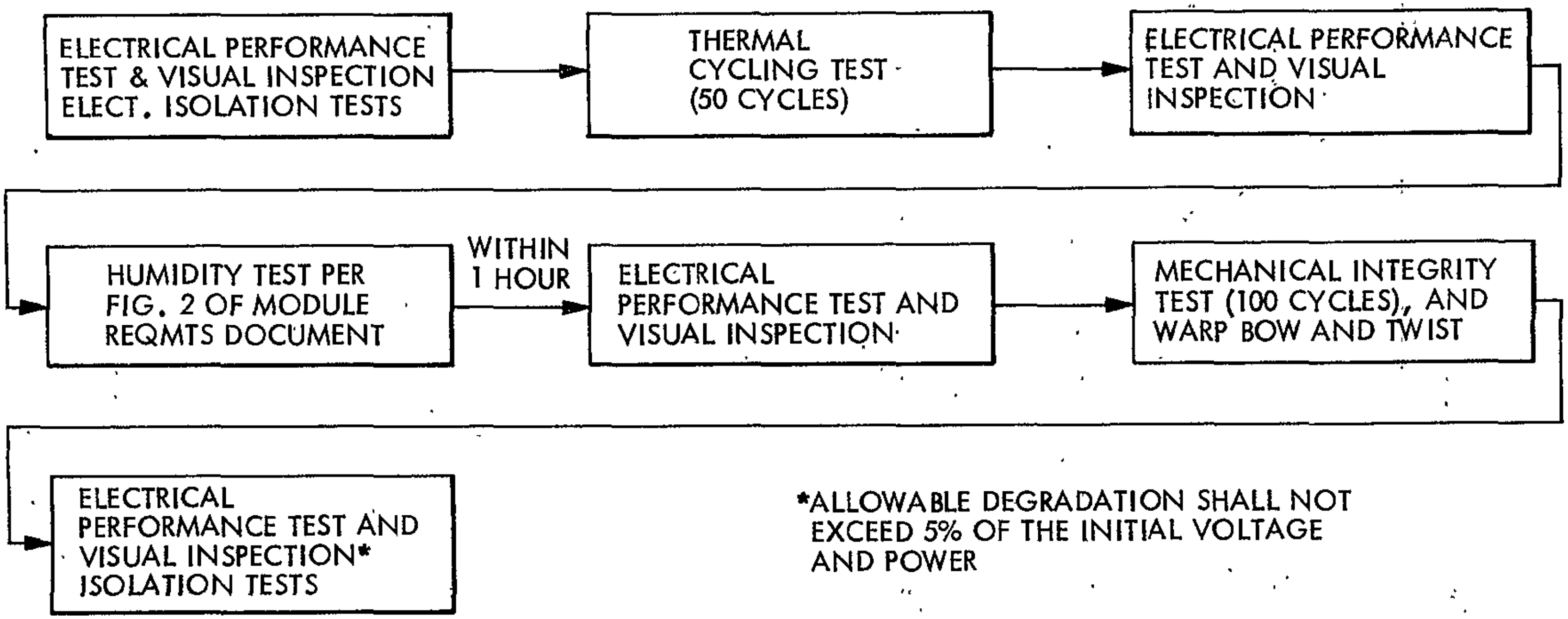

Figure 4.2.2-1 Test Sequence for Environmental Test Modules

Electrical Output Tests. The module electrical output measurements were made using LMSC's Large Area Pulsed Solar Simulator (LAPSS), used for testing all of LMSC's production solar arrays. The LAPSS provides a uniform, spectrally balanced pulse of light to the test object and, during the pulse, electronically loads the module and collects, conditions and records the data. Voltage/current (I-V) data can be printed on a teletypewriter and/or plotted on an x-y plotter.

A fixture, shown in Figure 4.2.2-2 was used in conjunction with the test console, Figure 4.2.2-3, to heat modules to desired test temperatures and for locating the modules under the LAPSS.

Electrical Isolation Tests. The two isolation tests, the insulation resistance and voltage withstanding tests, were made on the engineering and preproduction modules after final assembly. The measured values greatly exceeded requirements on all the modules. The measured resistances varied from 3000 to over 100,000 megohms (>100 MΩ required), and the leakage current at the 500, 1000, and 1500 VDC test voltages was always below 1 microamp (<15 μA required). These tests were run again on the environmental test modules after the last environmental test. The instruments used were a Freed Model 1620C Megohmmeter and a Telemet Model 35T01 Insulation Tester.

Temperature Cycling Test. This test was completed with no visible or significant measured degradation to any of the six modules.

The test as specified in Test Requirements, Rev B, consisted of 50 cycles from ambient to 90 deg C, then down to -40 deg C, and back to ambient. A 3-hour cycle was selected (Figure 4.2.2-4), without any dwell at the extreme temperatures. This resulted in nominal chamber temperature change rates of 86-2/3 deg C per hour. A Conrad Temperature/Humidity Class A chamber (Model F0-64C-70S) was used. The six modules were mounted on an aluminum frame to simulate being installed in the field. The test setup is pictured in Figure 4.2.2-5. A continuity test circuit was connected as shown schematically in Figure 4.2.2-6. A dark forward current of approximately 0.6 amps was passed through each module, and the voltage drops

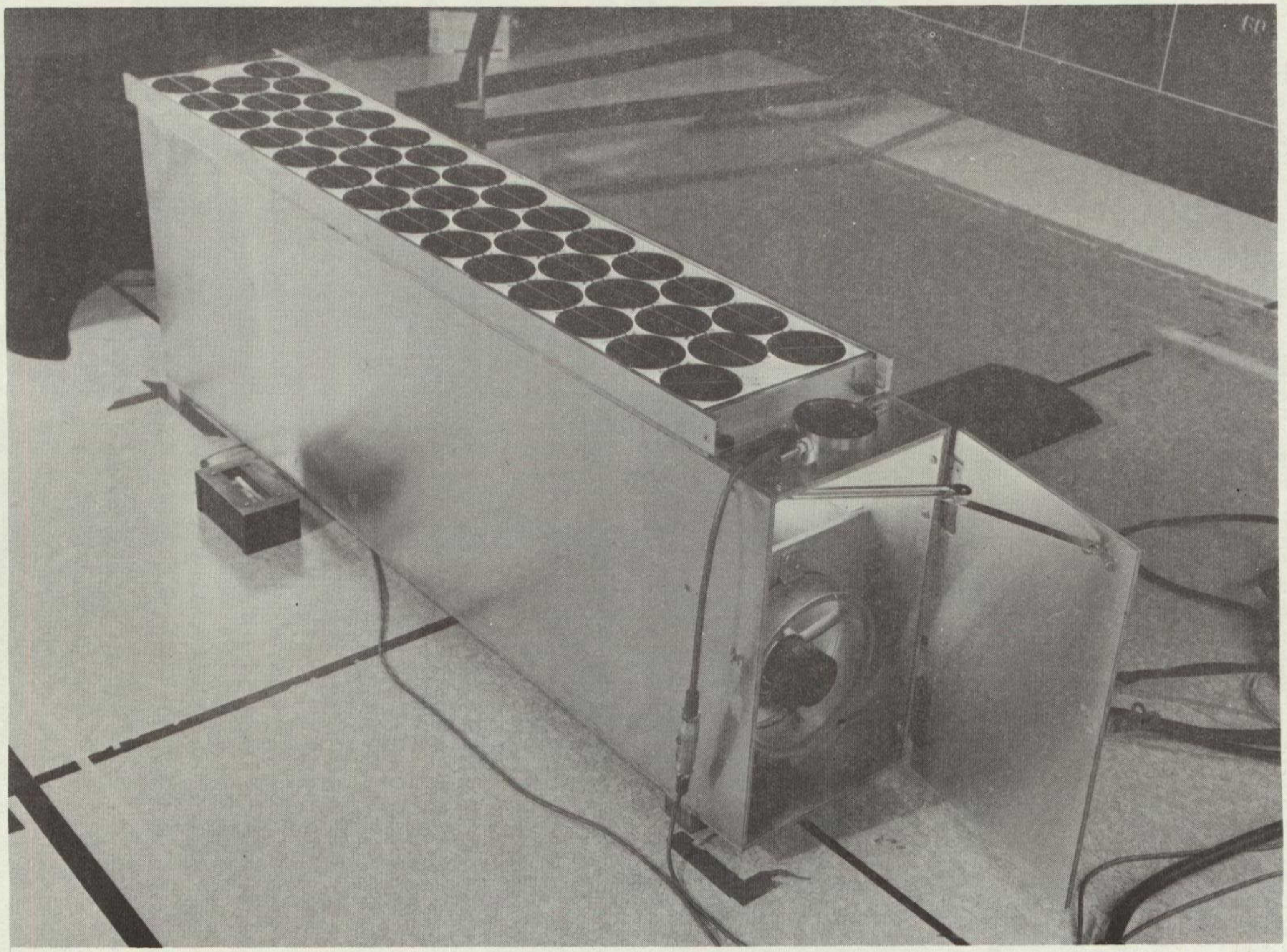

Figure 4.2.2-2 Electrical Output Temperature Control Test Fixture

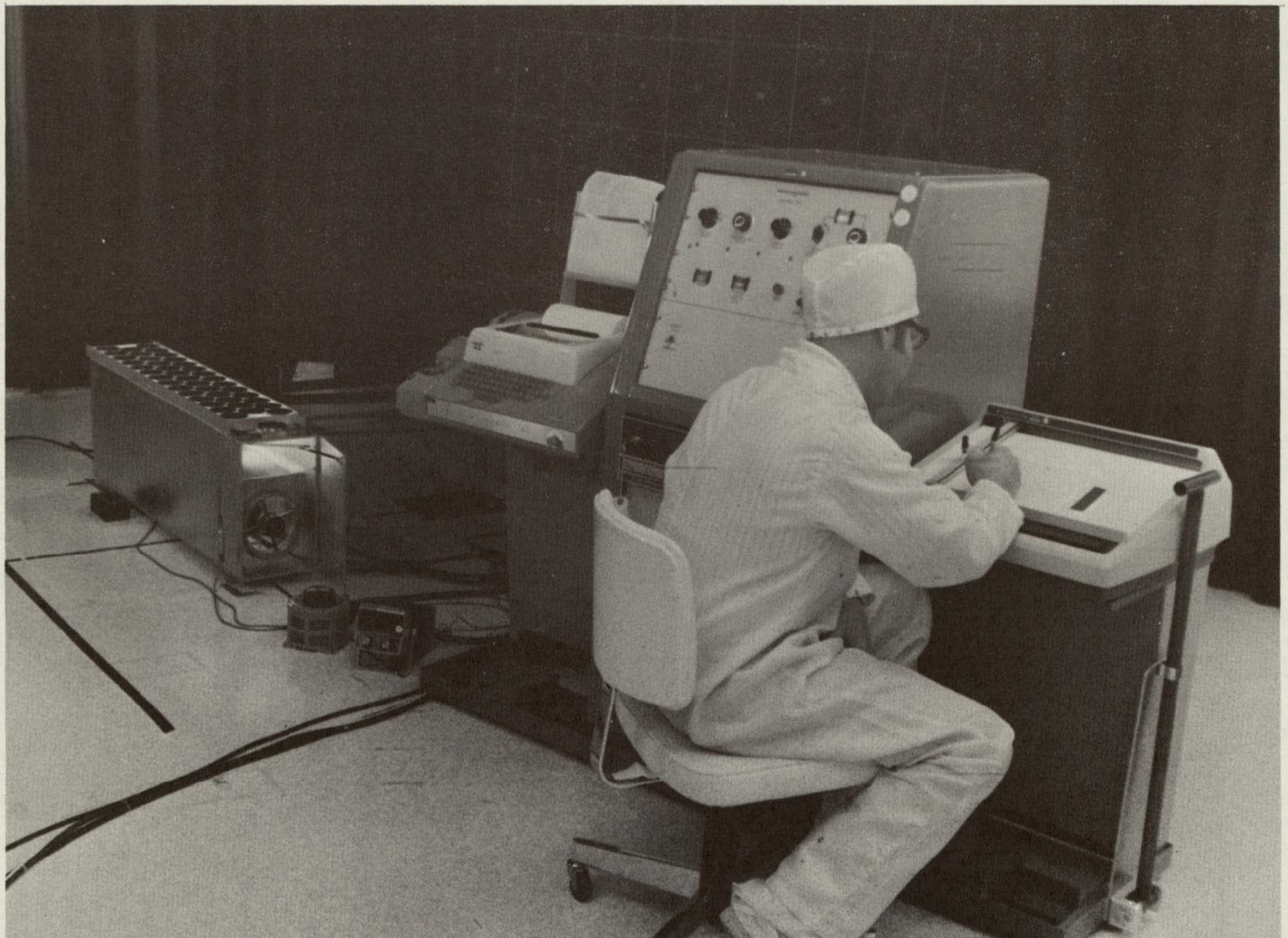

Fig. 4.2.2-3 Electrical Output Test Setup – Spectrosun Console

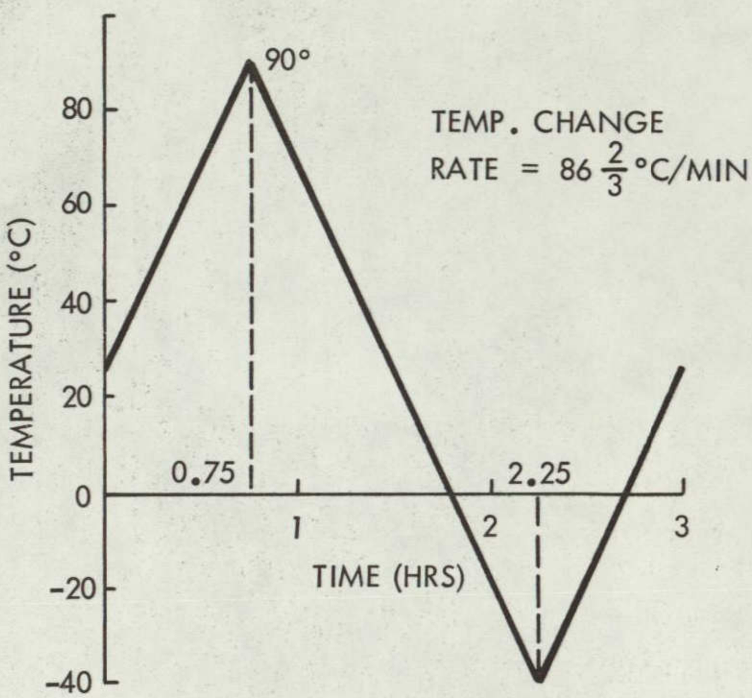

Figure 4.2.2-4 Temperature Cycle Profile

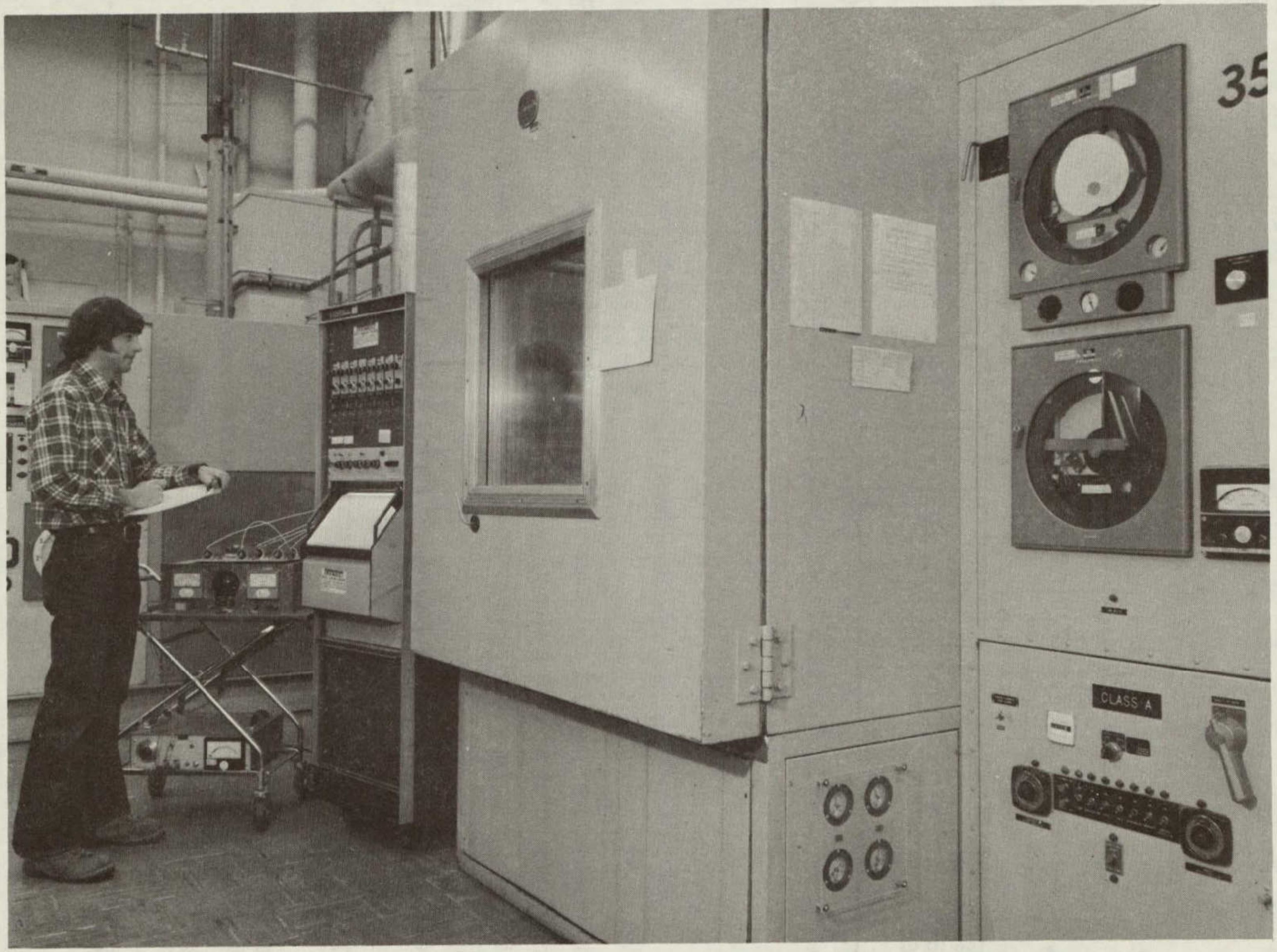

Figure 4.2.2-5 Temperature Test Setup

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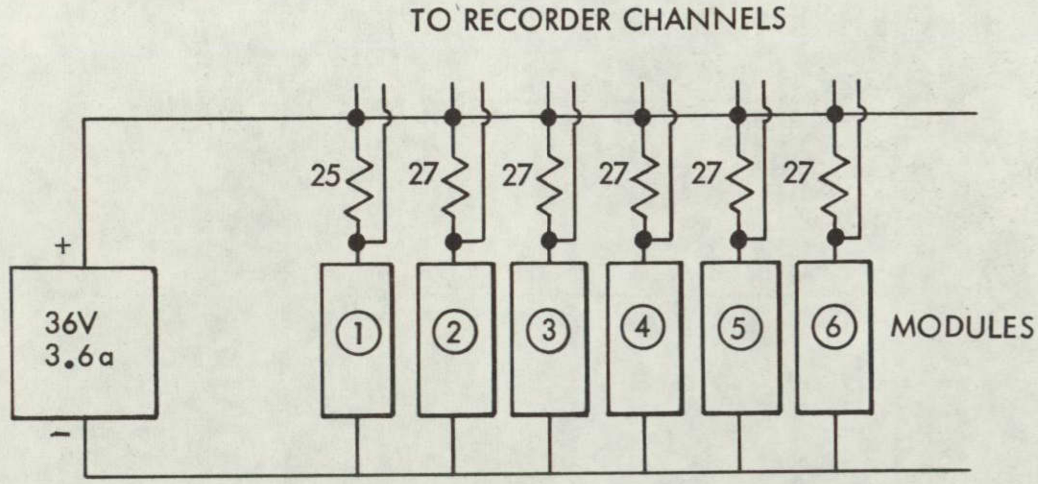

Fig. 4.2.2-6 Continuity Test Circuitry

across the resistors in series with each module were recorded. If an open circuit had occurred in any module, even a momentary one, the voltage drop across the resistor in series with that panel would have dropped to zero and the strip chart recorder (Varian Status 3 electrostatic recorder, 8 channel), would have indicated the open circuit. In addition, twice daily the resistance across each panel with the dc current flowing was measured with a Keithly Model 503 milliohmeter. This measurement was made to determine if there was any degradation in the module circuit conductivity.

The results of the temperature cycling test are given in Tables 4.2.2-2 and 4.2.2-3. The OCLI engineering module (OC-009) had been substituted for preproduction module OC-005 due to the latter's low output after cover bonding. Table 4.2.2-2 shows the percent change in power output after cycling. Table 4.2.2-3 is a tabulation of the results of the visual inspection after the cyling test. There were no circuit discontinuities or degradation of circuit conductivity during the temperature cycling test.

Table 4.2.2-3

VISUAL EXAMINATION DATA

	SL-004	SL-005	SL-006	OC-004	OC-006	OC-009
Initial	← See Text →					
After Temperature Cycling Test	Cracks around edges. Delamination around edges and on 25 cells	Cracks in encapsulant along edges. Apparent spot delamination on 30 cells	Dendritic spots on 4 cells. A few cracks in encapsulant along edges	A few cloudy areas on edges, away from cells	Dendritic spots on 8 cells. A few cracks and delamination along edges	Cracks in thick encapsulant, mostly around interconnect
After Humidity Test	← Not Inspected →					
After Mechanical Integrity and Warp, Bow & Twist Test	← Same Comments Apply As Listed Above →					Delamination is visible in areas around cracks

Humidity. Figure 4.2.2-7 shows the required humidity test cycle.

The Conrad chamber was used again with the six modules mounted on the frame. The continuity test circuit was used to show any open that might occur, and daily measurements of panel resistance were taken.

The modules completed the test with no changes to the circuit continuity or resistance. The post-test electrical output data are given in Table 4.2-2.

Mechanical Integrity. To simulate wind loading on the modules, a load equivalent to ±50 psf was applied to the module for 100 cycles. A line load of ± 90 lb at center-span was substituted for a uniform loading. This is equal to 5/8 of the product of module area and 50 psf.

Two modules, tested together, were positioned face-to-face about 30 inches apart and connected by a hydraulic actuator, load cell, universal joints and vacuum hold-down plates. A Data Trak programmer was set up to apply the ±90 lb maximum load over a 10-second cycle, shown in Figure 4.2.2-8, for 100 cycles.

Each module flexed approximately 7/16ths inch in both directions under the loading. There were no visible changes to the modules as a result of the cyclic loading.

Warp, Bow and Twist. For the warp, bow, and twist test, a pair of fixtures shown in Figure 4.2.2-9 were made. These were bolted onto the two ends of a module and deformed as depicted in the figure to produce warp, bow, and twist moments. The amount of warp is measured on the scale on each fixture. To determine bow, the angles at which the fixtures are rotated can be measured and applied in the equation. Twist is determined by laying the assembly on a flat surface and, after twisting, measuring the distance that one end of a fixture is above the surface.

All eight (two engineering development and six environmental test) modules were tested in warp and twist. The bow test was not done because the flexure during the mechanical integrity test was much greater than would have been experienced in the

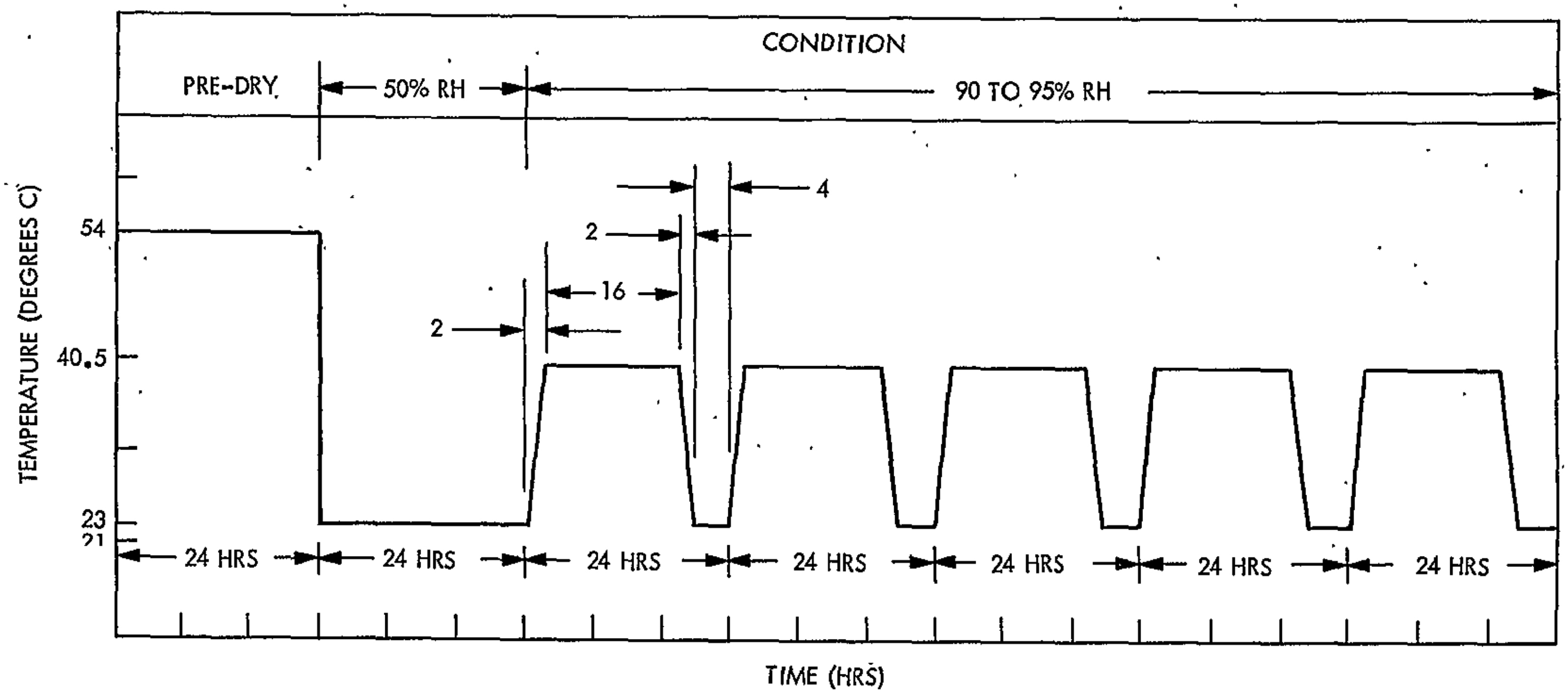

Figure 4.2.2-7 · Humidity Cycle Test

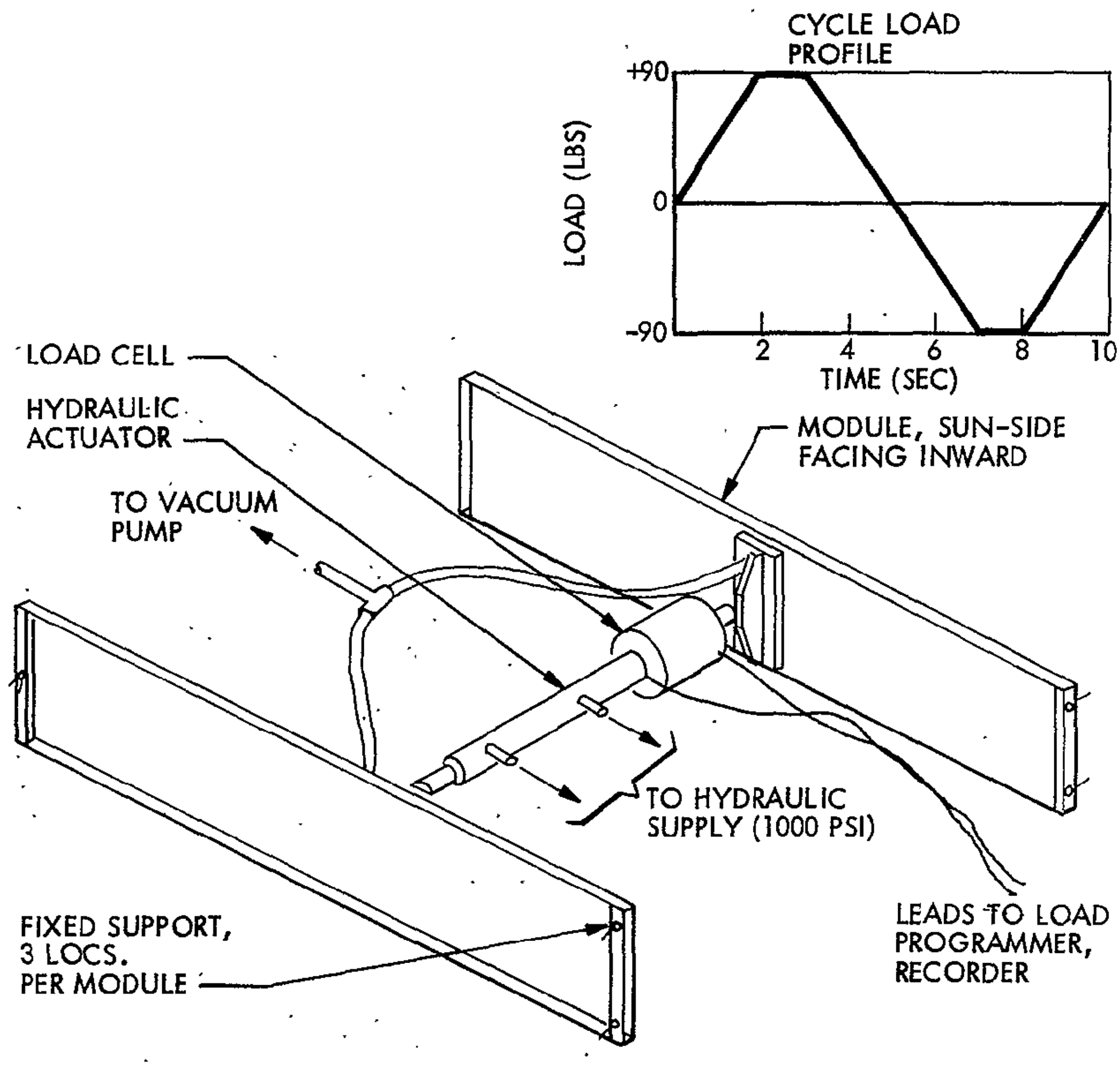

Figure 4.2.2-8 Mechanical Integrity Test Assembly

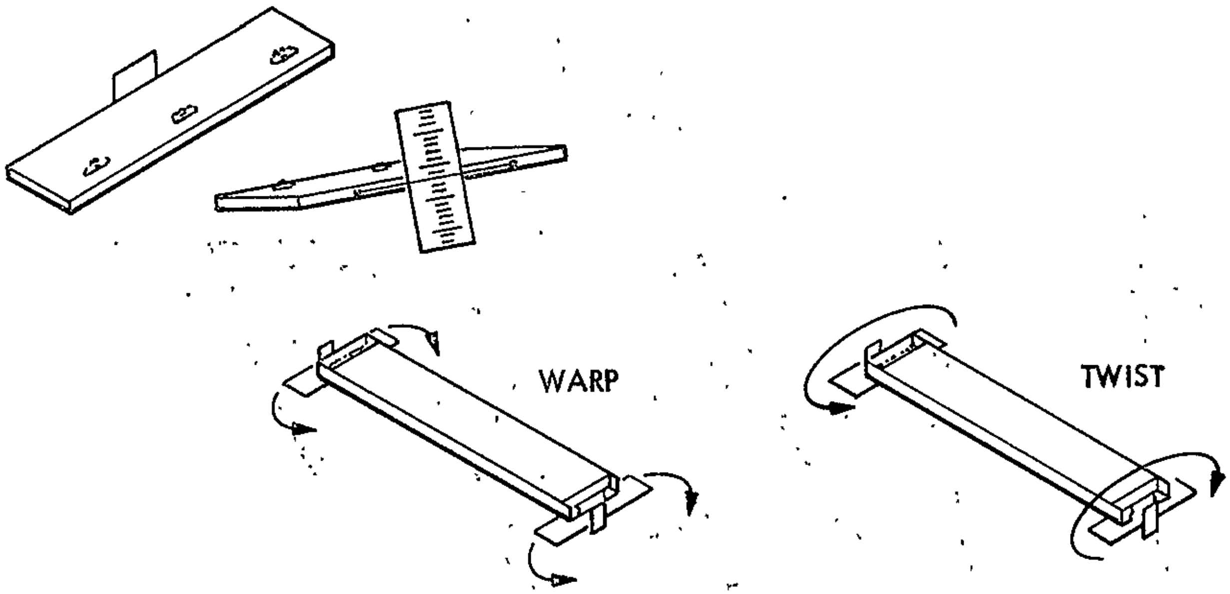

Figure 4.2.2-9 Warp, Bow and Twist Fixture

bow test. The rubber grommets provided approximately half of the flexibility during the warp and twist loadings, the remainder being provided by the module glass and frame. The test procedure included warp in both directions, twist in both directions, and all combinations of warp and twist. The twist applied was a total of 1/2-inch per foot (one end, of one 12-inch long fixture raised 1/2-inch from a flat surface (table) while the other end of the module was held down on the surface), thus equalling a 1/4-inch per foot twist at both ends.

The modules easily passed this test. There were no visible changes to the modules as a result of the test, and no cracking, creaking or other sounds during the test indicating relative movement of the parts (which could lead to wear or fatigue failure).

The electrical output of the modules after the mechanical integrity and warp and twist tests and also the percent degradation in output after all the environmental tests are shown in Table 4.2-2.

Thermal Analysis/Design

Thermal analysis was conducted to determine the theoretical still-air panel temperature with this panel horizontal, at 45 deg, and vertical.

The analysis shows a temperature of the cell of 56 deg C, 54 deg C and 53 deg C for the three conditions.

The base line for this calculation was:

1. Solar Insolation — 100 mW/cm^2
2. Convective cooling to — 23 deg C Air
3. Radiation to — 23 deg C Sink

The still air analytical temperatures are the most conservative (highest) temperature condition. Further thermal analysis and testing should be done to determine more realistic temperature levels for the cells.

The following test was conducted to correlate test data to actual solar exposure, but was not instrumented for thermal data.

A panel was tested in the air, exposed to solar flux at Sunnyvale. This test was conducted on April 18, 1977 and resulted in an average panel temperature of 40 deg C. This test was conducted at 1:45 p.m., after the panel was exposed to solar flux for more than 2 hours. The weather data was clear sky, 5–15 mph wind, and an air temperature of 19 deg C. The 40 deg C temperature level is significant by lower than would be predicted with still air analysis and shows the effect of slight winds.

Diagnostic Testing and Repair of Module 501-005

During the module fabrication span module 501-005 was tested at the string level (bare) and produced an acceptable output characteristics of 1.07 amps at 18.7 volts, 28°C, AM 1. However, when it was tested after encapsulation it delivered only .57 amps at 18.7 volts, Figure 4.2.2-10.

The module was checked cell by cell and the center cell in the string was found to have a low current output. An I-V curve was rerun with the low cell bypassed, 40 cells in series, and except for an expected reduction in V_{OC}, general current characteristics were recovered. The low performing cell was electrically isolated and tested on the module. The I-V curve showed that the cell had degraded over 50% in power output. It exhibited, however, a normal curve shape with no indications of characteristic internal shunting or high resistance. This would imply a cracked cell or a discontinuity in the main surface electrode collector bar; however, these conditions were not discernable using magnified visual examinations of the front and the back of the cell.

Cell Removal

The encapsulant and adhesive were carefully excised from the back and perimeter of the degraded cell in preparation for removal of the cell. Three cell modules from early evaluation tests were used as practice samples to evaluate a variety of potential techniques for non destructive cell removal. The methods used and the general results are summarized in Table 4.2.2.4.

Two mil thick stainless steel shim stock, .30 in. wide, inserted under the edge of the cell, was found to be the most effective device for separating the adhesive bond line on the samples. This method was initiated on module 501-005. It was found that on the end of the cell opposite of the interconnect tabs that the bond line was less than 2 mils thick and it was impossible to insert the shim stock. On the tab end the bond line was 4.5 mils thick and excavation of the bond line was started. Then a 3 mil stainless steel wire was worked under the tab end and "walked" back and forth through the adhesive in "cheese cutter" fashion. The intention was to carefully work the wire through the

TABLE 4.2.2-4

CELL REMOVAL METHODS

METHOD	COMMENTS
1. Heated Nichrome Wire, 3 mil thick 2. Heated Nichrome Ribbon, 3 mil thick	Heated by passing electric current through. Difficult to handle with electrode holders. Temp did not enhance cutting feature.
3. Braided No. 40 Polyethelene Suture	Too thick
4. Silicone Stripper	Inserted around perimeter of cell with 25 ga. needle. Would soften adhesive to limited depth only.
5. Flat-Tapered Spatula	Too thick
6. 3 Mil Stainless Steel Wire	Limited tensile strength but possible "draw through" if bond line thick enough
7. 2 Mil Stainless Steel Shim Stock	Most promising method

major area between the cell and the glass. The Sylgard 184 adhesive had completely cured and excellent adhesion between the cell and the glass was evident. Because of this high strength adhesion, the minimal thickness of the bond line and the bending stress induced by the removal procedure, a segment of the cell broke away and it was concluded that the remaining portion of the cell could not be removed in one piece with this method. The balance of the cell was moved destructively.

Module Repair and Conclusions

The module was repaired by bonding in and encapsulating a replacement cell in the center position. Electrical performance was restored as is indicated in Figure 4.2.2-10. From the standpoint of minimal use of the relatively expensive Sylgard 184 adhesive, enhancing transmission through adhesive, and minimizing bond line thickness to reduce thermal coefficient stresses, the selected assembly method works excellently but it doesn't lend itself to non destructive cell removal. In this particular case, cell removal would have been desireable to allow further cell diagnostic testing.

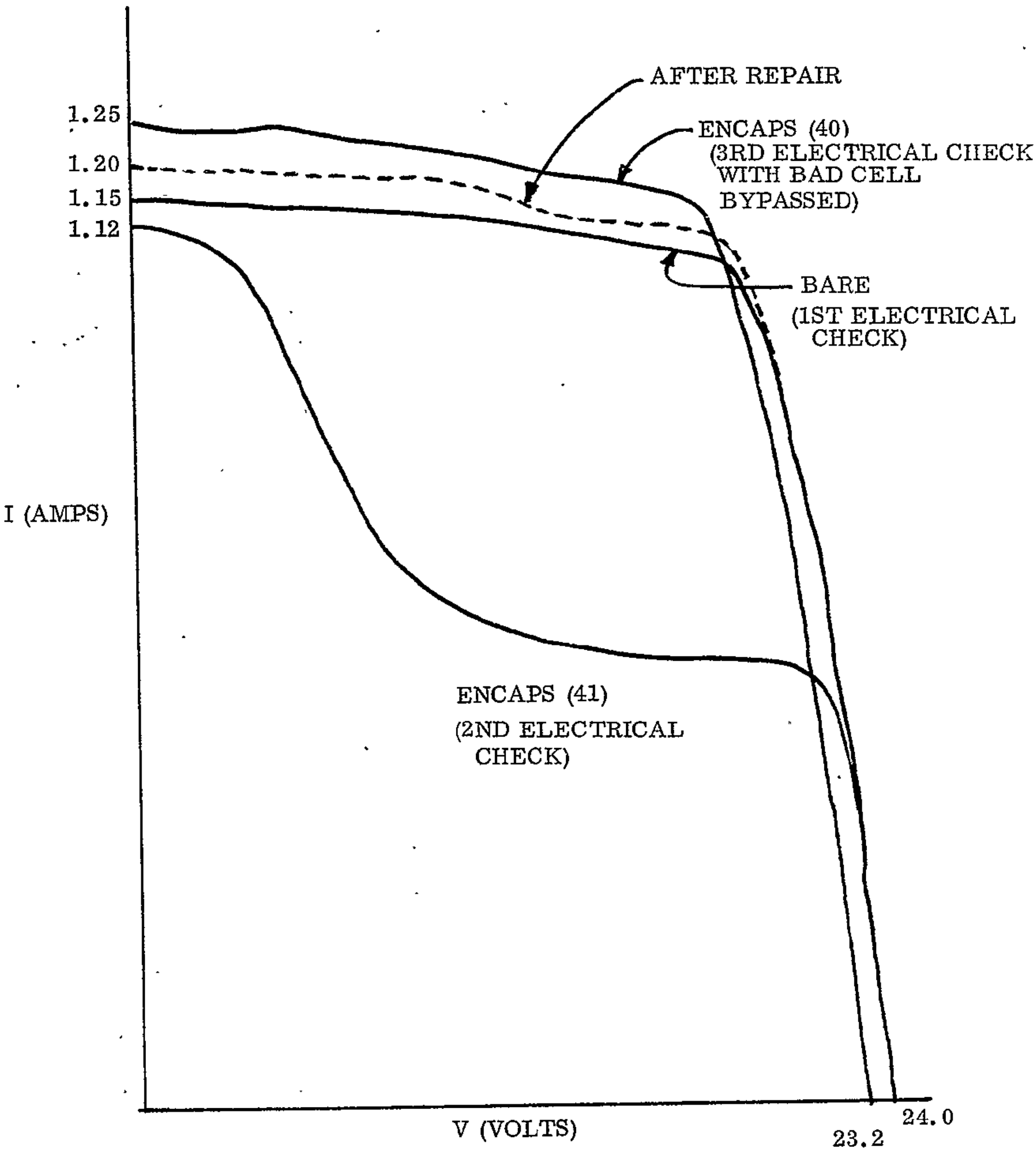

Figure 4.2.2-10 I-V Curves of Module 501-005 Before and After Repair (28°C)

Sunlight Testing of Module 503-009

Module 503-009 was installed in the LMSC Palo Alto sunlight test facility for 30 days beginning 4 August. It was positioned so that it was normal to the sun at solar noon.

Module 503-009 is the same as the other modules except that it is encapsulated with two types of encapsulant. One end is encapsulated with Sylgard 184; the other with Dow Corning X1-2577.

This test was run to compare the temperature of the two encapsulants, and to measure module performance after 30 day exposure in sunlight.

The LMSC Palo Alto sunlight test facility is fully instrumented as an approved weather station and it meets National Bureau of Standards requirements for evaluation testing of solar collectors. Weather conditions monitored for this test included:

1) Total Radiation - Eppley 180° pyranometer (I, w/m^2)
2) Diffuse Radiation - Spectrolab 180° pyranometer with direct shield
3) Temperature (T_{amb}, °C)
4) Wind Velocity (mph)

Module conditions monitored during test:

1) Temperature of Sylgard 184 - copper-constantan thermocouple located under encapsulant in clear area between cells in center of upper end of module (T_{upper}, °C)
2) Temperature of X1-2577- same as 1) except lower end of module (Tlower, °C)
3) Temperature of cell - same as 1) and 2) except thermocouple bonded to back of middle cell (T_{middle} °C)
4) Module Voltage - open circuit voltage at module output terminals (Vmodule, Volts)

Standard cell #67 conditions monitored during the test included:

1) Voltage across a 0.5 ohm shunting resistor (E_{STD}, MV) from which was calculated the standard cell output current (I_{std}, amp).

2) Cell temperature from thermocouple which is soldered to back of cell (T_{STD}, °C)

Although the module was mounted from 4 August, full data was recorded after installation of instrumentation for 11 August through 2 September.

In-situ I-V curves were not made during this test. The instrumentation required could not be installed in time.

Table 4.2.2-5 shows the data for 31 August, a typical day. It shows negligible temperature difference between the two encapsulants (T_{upper} and T_{lower}). It shows that the cell temperature is 2 to 5°C higher than the encapsulant/glass and 10 to 28°C higher than ambient air. Wind speed from 0900 to 1550 was 2 miles per hour average with gusts to 5 mph; after 1550 wind speed was 6 mph avg with gusts to 15 mph. Diffuse radiation was approximately 7.5% of total on 31 August.

Electrical performance after the test was:

At 28°C:

I_{sc} 1.29 amp, V_{oc} 23.8 volts, W 21.37 watts at V = 18.7

And at 60°C:

I_{sc} 1.30 amp, V_{oc} 21.3 volts, W 18.17 watts at V = 15.8

The power performance after the test shows little reduction in output from pre-test values which were 21.51 and 18.33 watts.

The 60°C power at 15.8 volts is a change of -0.9% from earlier test as shown in Table. 4.2-2.

TABLE 4.2.2-5

DATA FOR 31 AUGUST DURING 503-009 MODULE OUTDOOR TEST

Date	Time	E_{STD} (MV)	I_{STD}* (Amp)	T_{STD} (°C)	V_{Module} SL-009	T_{Lower} (°C)	T_{Upper} (°C)	$I_{(W/m^2)}$ **	T_{Amb} (°C)	T_{Middle} (°C)
8-31-77	0900	164.0	.33	23.6	22.38	24.6	24.2	337.2	17.8	25.3
Day 243	1000	382.0	.76	33.4	22.34	36.3	36.2	608.7	20.1	38.4
	1100	432.6	.86	40.6	21.84	44.3	44.7	799.4	23.3	47.6
	1200	448.6	.89	43.4	21.62	48.7	48.3	933.9	24.0	52.0
	1300	455.3	.91	42.6	21.72	48.1	47.1	984.7	25.1	51.6
	1400	449.8	.89	44.8	21.53	50.0	49.2	964.2	26.7	53.1
	1500	435.3	.87	45.2	21.40	49.7	50.3	851.1	28.7	52.8
	1600	410.9	.82	37.3	22.03	40.7	40.9	702.4	26.3	43.6
	1700	310.1	.62	32.9	22.19	35.2	35.2	491.3	26.0	36.9

* calculated

** insolation (calculated from pyronometer data)

COST PROJECTIONS

Section 5
COST PROJECTIONS: 5 TO 50 kW AND 1 mW

5.1 COST REDUCTION RECOMMENDATIONS

Readily apparent methods of cost reduction relate to reduction of piece parts and reduction of process steps associated with a specific design. An area that is not subject to piece parts reduction, however, is a mandatory minimum amount of solar cells and interconnects necessary to achieve specified module voltage. In sizing a subarray or total terrestrial array system, module count reductions can occur by having cells in parallel and/or larger cells than the 3-inch diameter cells which were baseline for this program. But even in this case size and weight limitations pertaining to the module design requirements set limits on how few "big paralleled" cells could be used. For instance JPL specifications 5101-16 indicates a practical handling limit of 48 inches on width and 50 pounds on weight. Increasing cell size to minimize piece parts count, handling, etc. also has upper limits due to (1) cost attrition factors associated with breakage, i.e., better to use more lower cost, less damage-susceptible, smaller cells than fewer, larger, expensive, damage prone, big cells,(2) a crossover is reached where the necessary give-away for current collection grids on a large cell seriously impacts cell active area, and (3) while it is not part of this study, it is noted that smaller cells can be made thinner which means more cell area is produced per kilogram of silicon — the most expensive item in array production. In light of these considerations, cost reduction recommendations will not be made at this time related to reducing solar cell quantity. It is recommended, however, that studies be initiated to develop parametric data on maximum practical cell sizes and shapes from an integrated maximum module width, length, weight, and voltage standpoint. The value of developing ingots 5 or more inches in diameter or X ft^2 sheet silicon is questionable if their use factors are impractical.

There are many ancilliary components in the baseline module design which, either by quantity, method of production used or subsequent processes to which they are subjected, are labor intensive. There are also materials and components whose cost/watt is significantly high relative to completed module cost. Some of these factors as they relate to the baseline preproduction modules built on this program are summarized in Tables 5.1-1 and -2.

Table 5.1-1, actuals for mechanical piece parts fabrication, summarizes the time required for fabrication of the side rails, end rails, corner angles and center web. It was not within the cost or schedule scope of this program to use large batch, semi-automated or automated methods of building piece parts, therefore, most of the work was done by hand. In the case of the parts listed in the table, 15 kits or module sets of parts were built, actual time required for each item-function was recorded, and this raw data were factored to items required for one module. The value of this table or similar summaries is to nail down the labor intensive functions. Note that deburring took 19.6 percent of the time and that marking and drilling holes took 51 percent of the time. Obviously then for production runs tumble deburring would be used which would decrease this factor from .196 to less than .05. To reduce mark-drill intensiveness, production runs of identical parts could be produced using machine punch/shear methods resulting in similar reductions in time to produce. This is borne out by noting that the lowest percentage of total time for any single function was 0.6 percent for shearing the aluminum raw stock to net dimensions for the center webs.

Another primary area where cost reduction can be effected is by using a fabrication method that reduces process functions on any single part. An example of this is the interconnect. Etching an interconnect network for an entire module may be cost effective; however, for automated assembly for solar cell interconnection roll-to-roll punched interconnects are very promising. Process functions can be reduced from 10 to 3, and time to produce 41 interconnects for a module is reduced 98.2 percent from 57 minutes per module to 1.05 minutes. This is illustrated in Table 5.1-2.

To determine whether this reduction is valid requires a comparison of the time required to place and solder 41 individual interconnects with the time required to place, solder, and punch out a single interconnect network.

TABLE 5.1-1

ACTUAL TIME FOR MECHANICAL PIECE PARTS FABRICATION

Function →	Setup	Cut to Length	Deburr	Holes – Mark	Holes – Drill	Final Deburr	Bend Flanges	Item Total
Tool –								
• Hand			File	Punch		Reamer	Brake	
• Power		Saw			Drill Press			
Side Rails –	(2 ea)							
Time (Min.)	0.53	1.60	2.47	1.67	3.00	2.00		11.27 Min.
% Item Time	4.7	14.2	21.9	14.8	26.6	17.7		
% Total Time	1.0	3.2	4.9	3.3	6.0	4.0		
End Rails –	(2 ea)							
Time (Min.)	0.40	1.00	3.00	3.20	2.67	0.53		10.8
% Item Time	3.7	9.6	27.8	29.6	24.7	4.9		
% Total Time	0.8	2.0	6.0	6.4	5.3	1.0		
Corner Angles –								
Time (Min.)	0.67	4.00	2.67	6.00	4.00	0.67		18.01
% Item Time	3.7	22.2	14.8	33.3	22.2	3.7		
% Total Time	1.3	8.0	5.3	12.0	8.0	1.3		
Center Web –	(1 ea)	Shear						
Time (Min.)	0.33	0.33	1.67	1.00	4.00	0.67	2.0	10.00
% Item Time	3.3	3.3	16.7	10.00	40.00	6.7	20.0	
%Total Time	0.6	0.6	3.3	2.0	8.0	1.3	4.0	
Function Total								
Minutes	1.93	6.93	9.81	11.87	13.67	3.87		
% of Total	3.9	13.8	19.6	23.7	27.3	7.7		
Total for One Module								50.08 Min.

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TABLE 5.1-2

ACTUAL TIME FOR ELECTRICAL PIECE PARTS FABRICATION-INTERCONNECT

		FUNCTION AND ASSOCIATED TIME (MIN)											
	Qty	Cut Sheet	Clean	Apply Resist	Expose	Develop	Etch	Strip Resist	Final Trim	Solder Dip	Package	Method A	Total Time
Time (Min)	10/Sheet	0.1	0.3	0.5	2.0	0.5	0.5	2.0	2.5	4.0	1.5		13.9
Time	Module (4.1X)	0.41	1.23	2.05	8.2	2.05	2.05	8.2	10.3	16.4	6.2		57 Min. per Module
% Total Time		0.7	2.2	3.6	14.4	3.6	3.6	14.4	17.9	28.8	10.8		
Function	→	1 Load Roll					2 Punch				3 Package	B	
Time Min.		0.6					0.25				0.2		1.05 Min. per Module

5.2 PRODUCTION BASELINE DESIGN

A production module that requires only 10 parts (as compared with the current 25 parts) in addition to cells and interconnects could be produced by applying cost reduction recommendations and design improvements based on improved understanding of the design, assembly, and test of modules learned during this contract.

Table 5.2-1 shows the material requirements of such a baseline production module.

TABLE 5.2-1
MODULE MATERIAL REQUIREMENTS

COMPONENT	MATERIAL	FORM	QTY/MODULE	SPECIFICATION
Cover	Glass	Tempered Sheet 1/8 in. thick	2.7 ft^2	>96% transmission in solar cell response wave-lengths when bonded to cell
Frame	Aluminum	Extruded Shape	2.3 lb	
Adhesive and Encapsulant	Silicon	2 Part Liquid	90 gm	>91% transmission
Connectors	Purchased		2 each	JPL
Fasteners	Purchased	"pop" Rivets	2 each	
Wire	Stranded Copper	18 ga	5 ft	Exterior UL 1018
Nameplate	Purchased		1	
Interconnect	Copper/ Solder	2 oz. Sheet	0.06 lb	
Expendibles	–	–	Production Volume Dependent	

5.3 COST PROJECTIONS

In addition to reduction in parts count, the labor learning curve is a factor which reduces module costs. Figure 5.3-1 shows the total labor required to produce solar modules. Note that the reduction in times labeled manual and manual with automatic tool assist is due to experience gained during this contract.

Projections for 50 kW and 1mW are estimates based on different levels of automation. Batch automation includes partially automated equipment with manual monitoring and parts transfer.

Cost projections for 5 to 50 kW and 1 mW module production are shown in Table 5.3-1. Cell and material costs are based on quotes obtained during this contract. Cell costs are based on purchase price if ordered in 1977; these prices should be reduced when effects of improved cell production resulting from JPL programs are applicable.

For 5 to 50 kW quantities the cost per watt is reduced only by application of tooling improvements and batch automation equipment which reduce labor. For 1 mW, reductions occur mostly due to cell cost but improved automation also reduces labor.

No overhead profit or burden has been included in the cost projection in Table 5.3-1.

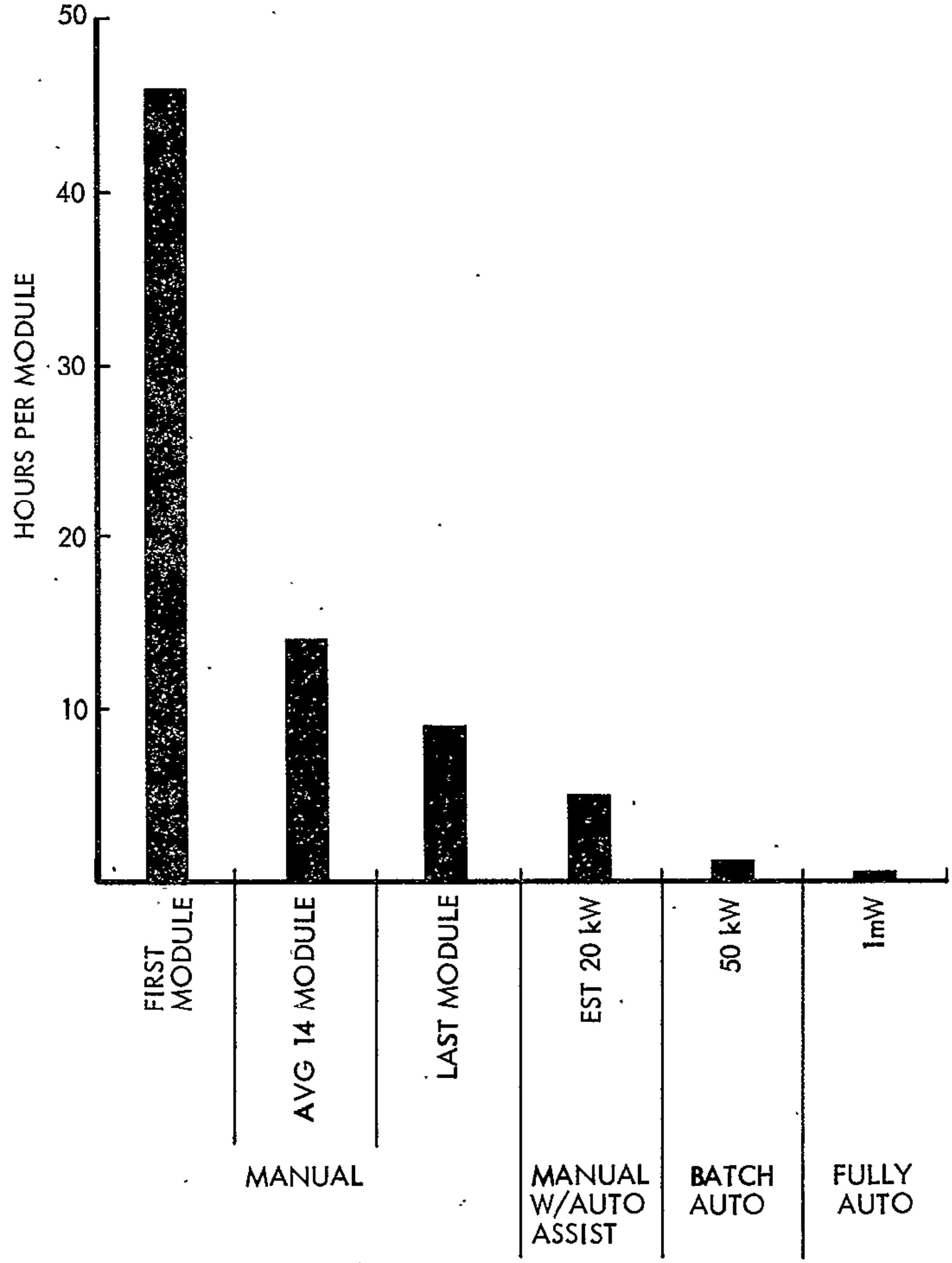

Figure 5.3-1. Labor Learning Curve

TABLE 5.3-1

QTY VS COST PROJECTIONS

kW		5	10	15	20	25	30	35	40	45	50	1 mW
Module Qty		250	500	750	1000	1250	1500	1750	2000	2250	2500	50,000
Materials												
MTL (except cells)	$/Module	12.65	12.60	12.55	12.505	12.49	12.48	12.44	12.40	12.36	12.32	9.18
	$/Watt	.633	.630	.628	.626	.624	.623	.622	.620	.618	.616	.459
Cells	$/Module	307.50	307.50	307.50	307.50	307.50	307.50	307.50	307.50	307.50	307.50	118.40
	$/Watt	15.38	15.38	15.38	15.38	15.38	15.38	15.38	15.38	15.38	15.38	7.70
Labor	Hours/Module	8.6	8.6	8.6	5.0	5.0	5.0	5.0	5.0	5.0		
Manual	$/Watt	3.87	3.87	3.87	2.25	2.25	2.25	2.25	2.25	2.25		
	(at $9/Hr)				← Tooling Augmented →							
Batch Automated	Hours/Module										.14	
	$/Watt										.06	
(Auto machines manual transfer)	(at $9/Hr)											
Fully Automated	Hours/Module											.017
	$/Watt											.008
	(at $9/Hr)											
Consumables & Machine Maintenance	$/Watt	.15	.15	.15	.08	.08	.08	.08	.08	.08	.06	.01
Non-Recurring												
Capital (Mach, engr, inst, floor space and start up)	$ Total	141K	141K	141K	170K	170K	170K	170K	170K	170K	357K	544K
Total $/Watt	$/Watt	20.03	20.03	20.03	18.34	18.34	18.34	18.34	18.34	18.34	16.12	8.18