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Low-Cost Solar Array Project

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DOE/JPL-1012-79/1
Distribution Category UC-63b

Environmental Testing of Block II Solar Cell Modules

John S. Griffith

January 1, 1979

Prepared for
U.S. Department of Energy
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

(JPL Publication 79-5)

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ABSTRACT

The results of environmental tests of Block II solar modules are described. Block II was the second large scale procurement of silicon solar cell modules made by the JPL Low-cost Solar Array Project with deliveries in 1977 and early 1978. The results of testing showed that the Block II modules were greatly improved over Block I modules. In several cases it was shown that design improvements were needed to reduce environmental test degradation. These improvements were incorporated during this production run.

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I. INTRODUCTION

This report describes the testing procedures and the results of testing samples of the LSA Project Block II procurement of silicon solar cell modules. Block II modules were procured by the Project for the test and applications projects of the Department of Defense (DOD), the Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL) and the Lewis Research Center (LeRC).

Three separate procurements of solar cell modules have been made for this purpose: Block I was a 58-kW purchase of off-the-shelf module types, with deliveries mainly in 1976; Block II was a 110-kW purchase of modules to uniform design and test requirements, with deliveries mainly in 1977; Block III is the current purchase of 212-kW of modules to Block II design and test requirements but more uniform quality standards, with deliveries mainly in 1978. The next major DOE procurement of solar cell modules will be accomplished via the Albuquerque Operations Office's Program Research and Applications Experiments (Ref. 1).

Module testing reported here is in three main categories

1. Prototype module tests. An initial delivery of prototypes was given qualification tests. Any redesigns or process improvements that were necessary were made before production of modules started.

2. Production sample testing. After every 1 kW of module power was produced, a module was selected at random and given the same qual-type tests to insure the maintenance of acceptable quality.

3. Exploratory testing. Several additional environmental tests were performed which were not required by contract. In some cases, these tests were precursors of future qualification tests, while in other cases they were intended for evaluation of performance in unusual environments or simply for determination of normal performance behavior under specified operating conditions.

In addition to the above environmental tests, several characterization and performance tests were run including measurement of NOCT (Nominal Operating Cell Temperature), thermal coefficients, electrical isolation to ground, current-voltage characteristic (I-V curve), etc. Hail damage and voltage bias-humidity tests were run and reported in references 2 and 3.

II. MODULE DESCRIPTIONS AND SPECIFICATIONS

Modules were procured from four manufacturers for Block II, given the code letters V, W, Y, and Z. A summary of their physical and electrical characteristics is given in Tables 1 and 2. Two versions of the V and W modules were procured and designated VA and VB, WA and WB as described in Table 2. Figures 1 and 2 are front and back photographic views. The performance and test specification is given in Doc. 5-342-1B (Ref. 4). Briefly, the requirements were:

1. Modules shall be designed to fit into a 1.2m x 1.2m (4' x 4') subarray (actually, 1.17m x 1.17m (46" x 46") module group outside dimensions).

2. The 1.2m x 1.2m subarray shall supply at least 60 watts of power at 15.8V, air mass 1 spectrum, 100mW/cm^2 and at 60^{o}C cell temperature.

3. Electrical resistance to ground shall be 100 megohms or greater at 1000Vdc and the module shall withstand a test voltage of 1500Vdc.

4. Modules shall be capable of withstanding a twist of 1 part in 48 which might occur if a field mounting surface was out of flat by that amount.

5. Pass three environmental tests with less than 5% electrical degradation. Mechanical degradation from test exposures must be acceptable per the Inspection System Plan. The following exposures shall be applied with the modules held in a rigid frame.

    a. Temperature Cycling
    50 temperature cycles from ambient to +90^{o}C, to -40^{o}C, and to ambient. Temperature change rate shall not exceed 100^{o}C/hr and each cycle shall be completed in 6 hours or less.

    b. Humidity
    Two days of preconditioning followed by 5 cycles from 23^{o}C to 40.5^{o}C at 90% R.H. per the program pictured in Fig. 3.

    c. Cyclic Pressure Loading (also called wind simulation or mechanical integrity test).
    A pressure load of +2400Pa ($\pm$ 50 pounds/sq ft.) shall be applied uniformly to the front and back surfaces of the modules for 100 cycles.

Table 1. Physical and Electrical Characteristics of Modules
(All power, current, and efficiency values at 100 mW/cm^2)

Item \ Vendor Code	VA	VB	WA	WB	Y	Z
Maximum Power, 28°C, W	10.75	10.95	26.58	30.41	22.06	34.55
Rating Voltage (RV), 60°C, V	15.8	16.5	15.8	15.8	15.8	15.8
Power at 60°C, RV	8.95	9.20	21.78	25.80	18.91	28.75
Power at NOCT*, W	9.85	10.12	24.13	28.5	20.2	31.1
Current at 60°C, RV, A	.567	.558	1.38	1.63	1.20	1.82
Nominal Cell Diameter, mm	54.9	54.9	50.8	50.8	76.2	100.
Nominal Cell Area, mm^2	2364	2364	2027	2027	4560	7854
Number of Cells	42	44	120**	120**	42	40
Module Length, cm	58.17	58.17	116.0	116.0	58.10	116.8
Module Width, cm	28.89	28.89	37.9	37.9	58.10	38.8
Module Thickness						
panel alone, cm	1.52	1.52	3.63	3.63	3.8	4.8
including terminal box, cm	4.55	4.55	3.63	3.63	5.1	4.8
Total Cell Area, m^2	.0994	.1040	.2432	.2432	.1915	.3142
Total Module Area, m^2	.1681	.1681	.4396	.4396	.3376	.4538
Packing Factor	.5913	.619	.5532	.5532	.567	.692
Average Weight, kg	1.66	1.84	5.80	6.19	4.62	7.4
Encapsulated Cell Eff., P_m, 28°C	.108	.105	.109	.125	.115	.110
Encapsulated Cell Eff., 60°C, RV	.090	.089	.090	.106	.099	.092
Module Efficiency, P_m, 28°C	.064	.065	.060	.069	.065	.076
Module Eff., 60°C, RV	.053	.055	.050	.059	.056	.063
Watt/kg, 60°C, RV	5.39	5.0	3.76	4.17	4.13	3.89
Temperature Coefficient, V/°C	- .106	- .111	- .0969	- .0992	- .102	- .0940
Temperature Coefficient, A/°C	.00043	.00043	.00053	.00094	.0013	.000045

*Power at NOCT (Nominal Operating Cell Temperature) computed from Power, 60°C, RV, using coefficients.
**3 strings of 40 series cells in parallel.

Table 2. Module Descriptions
Structural Characteristics
(From the Top Surface Down)

Item \ Vendor Code	VA and VB*	WA and WB**	Y	Z
Model No. or Drwg.	20-10-1452 G, J, K	022961 G	A-0221	E-10008/D
Top Cover	none	3.2 mm (1/8") float glass	none	Conformal coating DC X1-2577
Encapsulant	RTV 615	PVB, Mylar back sheet	Sylgard 184 or RTV 615	Sylgard 184
Backside Insulating Material	Plastic wire insulating screen	-	Random fiberglass reinforced polyester G 200	Fiberglass/polyester frame
Electrical Feed-through	Black diallyl phthalate threaded inserts	Polysulfide rubber seal around wires	RTV-102 seal around wires entering J-box	

*Type VA
G Mod: 42 cells
Type VB
J Mod: 44 cells
K Mod: Added a thin aluminum sheet below plastic screens.

**W modules had silk screen printed contacts. The WB process was improved over the WA process.

(continued)

Table 2. Module Descriptions (Continuation)
Structural Characteristics
(From the Top Surface Down)

Item \ Vendor Code	VA and VB*	WA and WB**	Y	Z
Output terminations	Screws on back of feedthrough	ITT Cannon Connectors	7x11.4x3.8cm UL box with terminal block	Junction box integral with frame, threaded inserts
Frame	One piece pressed alum. pan with seven stiffening grooves	Frame of 1.6mm alum. material, neoprene gasket	5.08x2.54x.32cm (2x1x1/8") alum angles welded to (3) 2.5x2.5cm (1x1") alum channel cross-members. Four 5.08x.076cm (2"x.030") alum. sheet borders with .64cm (1/4") bent up edge dams, spotwelded to the angles.	Random orientation fiberglass reinforced white polyester

*Type VA
G Mod: 42 cells
Type VB
J Mod: 44 cells
K Mod: Added a thin aluminum sheet below plastic screens.

**W modules had silk screen printed contacts. The WB process was improved over the WA process.

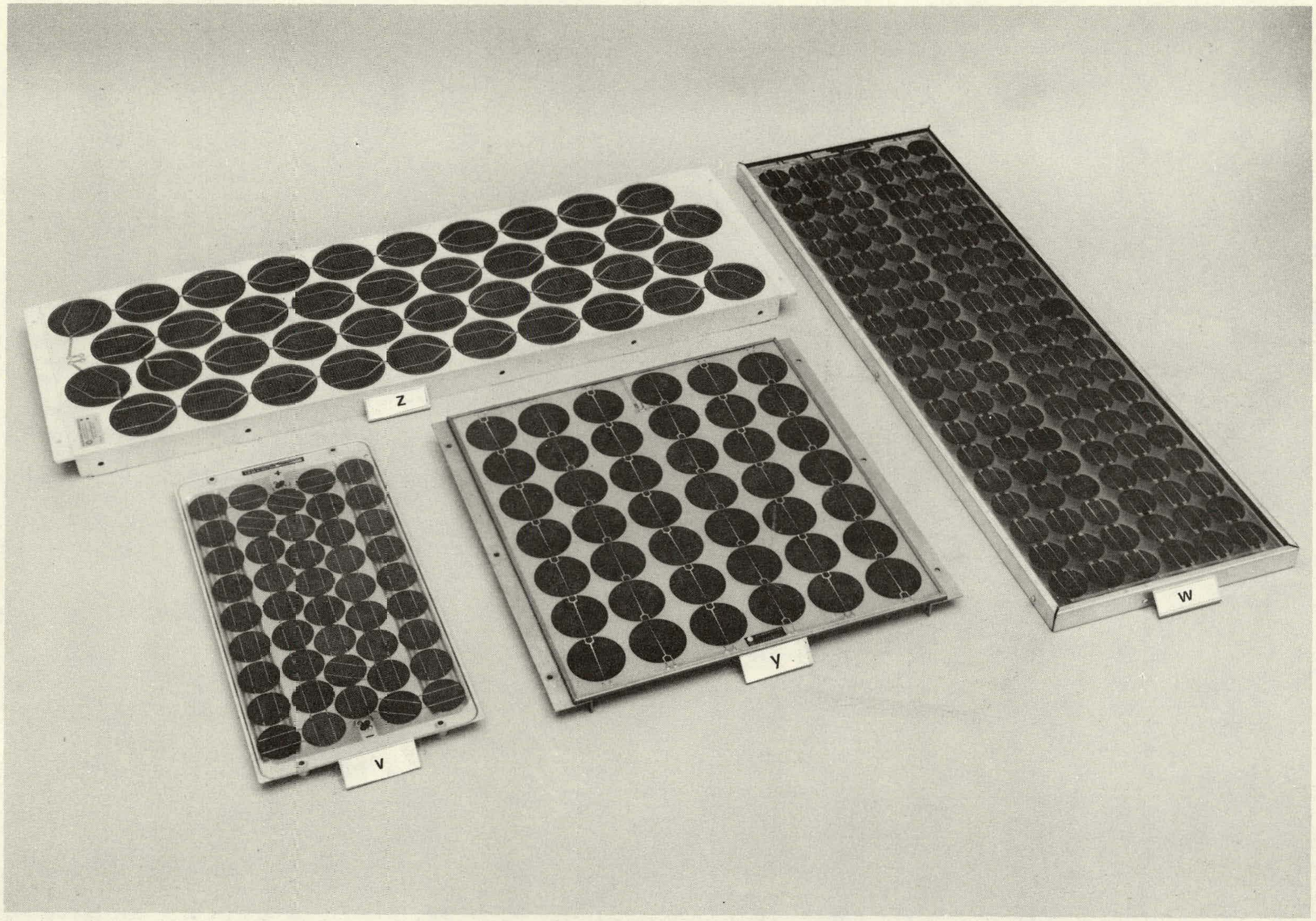

Figure 1. Block II Modules, Front View

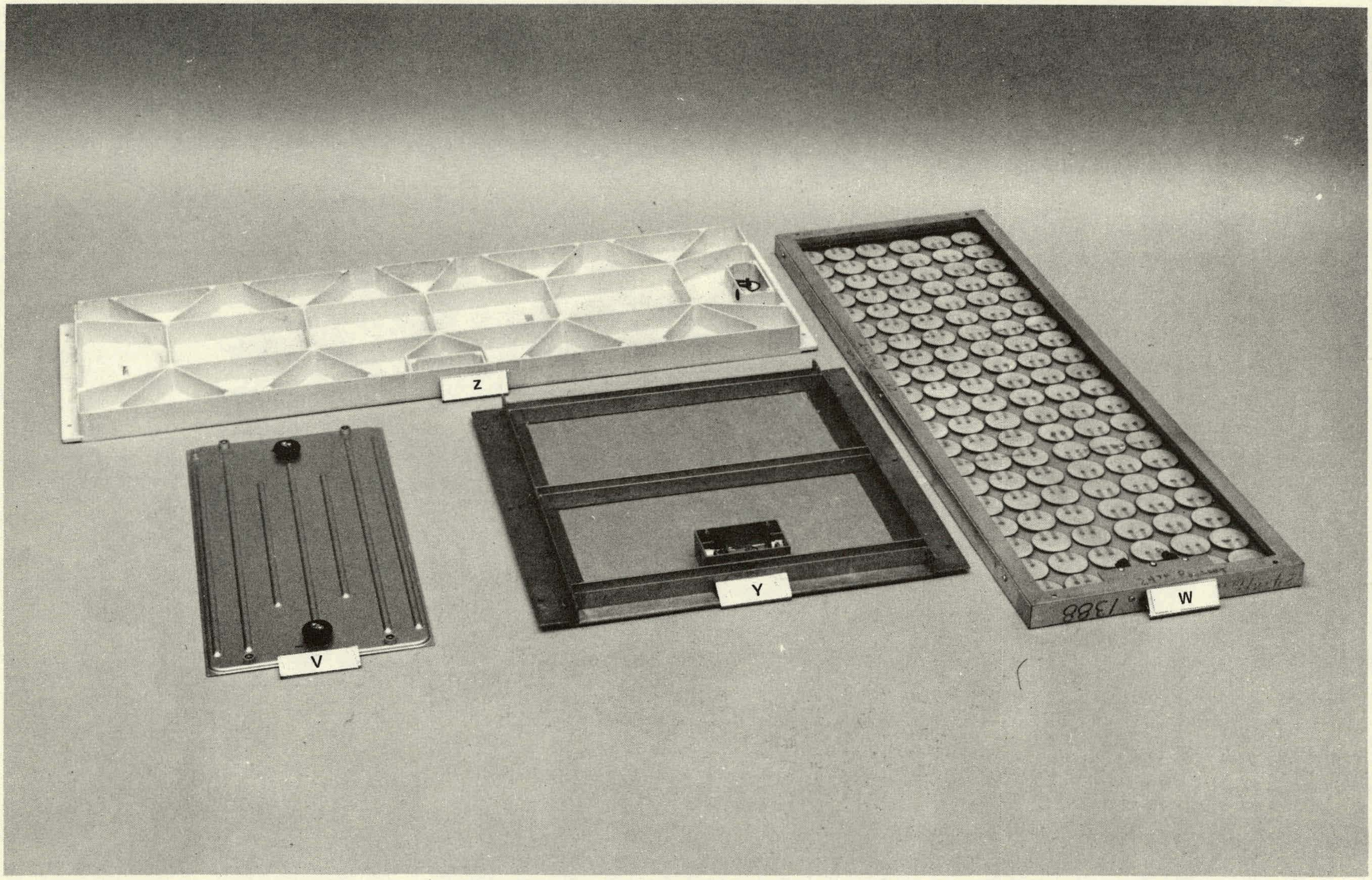

Figure 2. Block II Modules, Rear View

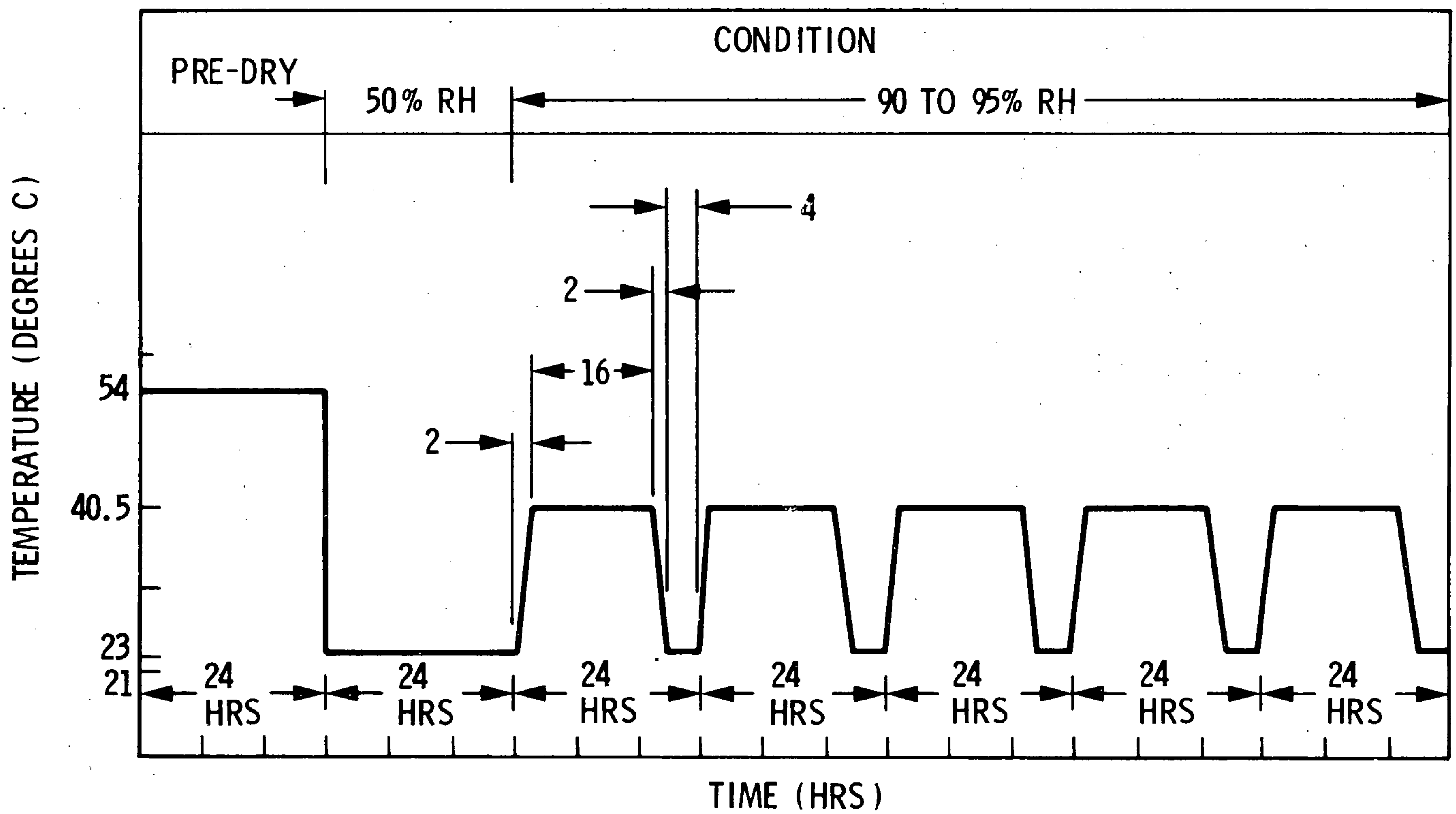

Figure 3. Humidity Cycle Test (Suitable Procedures for Accomplishing This Test Are Described in MIL-STD-810C, Method 507.1, Procedure V.)

III. THERMAL CHARACTERISTICS OF MODULES

There were two thermal characteristics measured for each type of module - the NOCT (Nominal Operating Cell Temperature) and the temperature coefficients for voltage and current.

A. Nominal Operating Cell Temperature (NOCT)

NOCT is defined as the module cell temperature at $80 mW/cm^2$, 20^oC air temperature, 1 m/s wind speed, module surface normal to the sun's rays, open back & open circuited. The method is described in Appendix A of JPL report 5101-76 (Ref. 5). The NOCT of the modules were determined to be

V	42.9^oC
W	41.1
Y	47.1
Z	46.0

B. Temperature Coefficients For Voltage And Current

Electrical output of photovoltaic modules decreases with temperature. Typically, the power output of a module operating at a NOCT of about 45^oC will be about 10% lower than under laboratory test conditions. The procurement specification for Block II, Document 5-342-1B, Section II, requires the rating of modules at 60^oC and 15.8V*.

The 60^oC power output can either be measured directly with every module controlled to 60^oC or by the determination of the average temperature coefficients from a small group of modules. At JPL, the coefficients of a small group of modules from each manufacturer were measured and averaged. In fact, two methods of coefficient measurement were performed at JPL.

1. The primary method used was as described in Doc. 5-342-1B, Section II, A2. The 60^oC and OTC (Optional Test Conditions at JPL = 28^oC) I-V curves were matched at V' and I' near the knee as shown in Fig. 4C. The shifts in the I and V axes divided by the temperature difference (32^oC) yielded the coefficients $\Delta V/\Delta T$ and $\Delta I/\Delta T$. The averaged coefficients for 10 or more of each type of module were used in rating subsequent modules at JPL. These data were also made available to each manufacturer (Table 3). Although this method provided a value for rated power from an OTC IV curve, it was not useful for computation of other 60^oC power values except in the vicinity of the knee.

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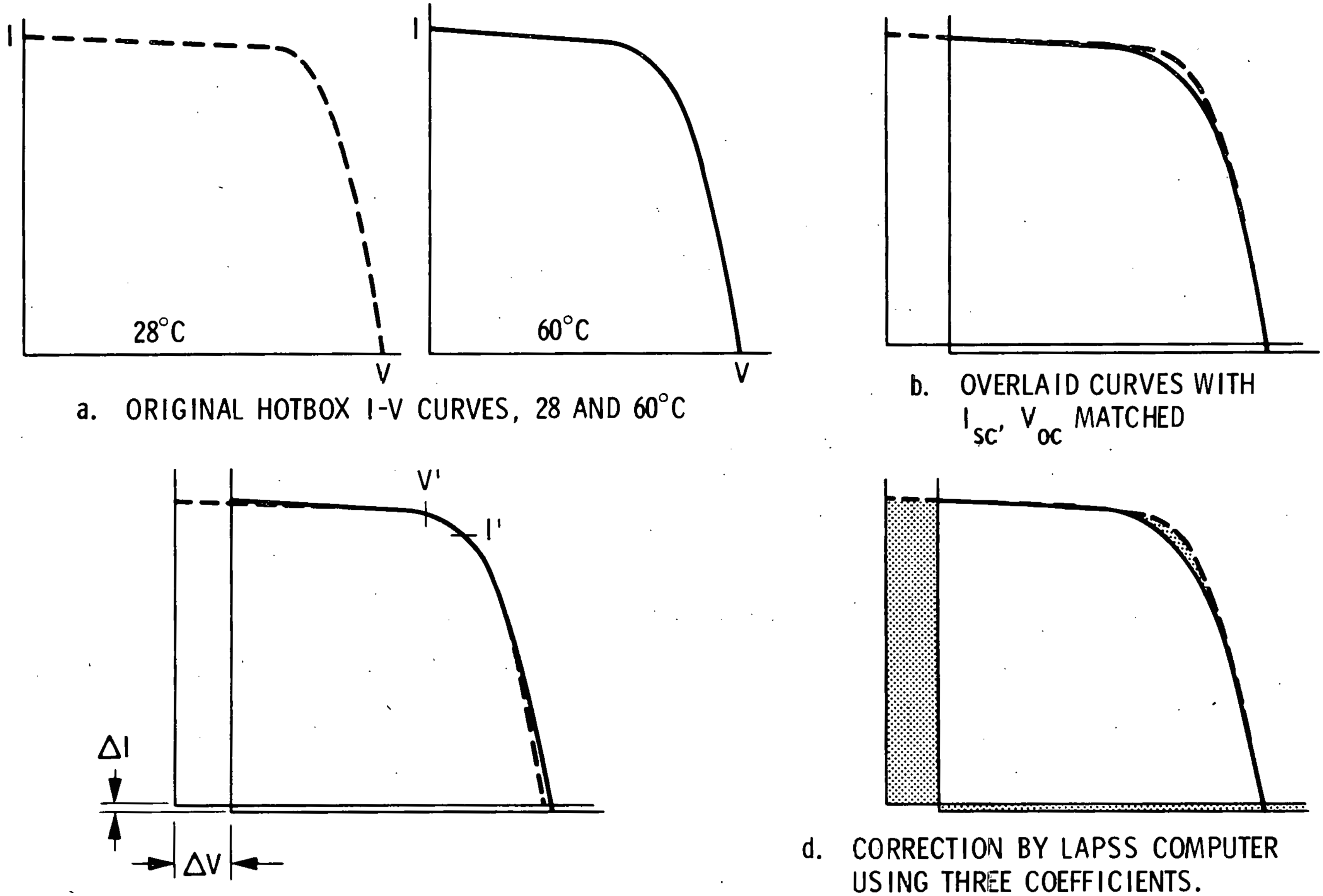
*16.5V for Vendor V, type B modules.



a. ORIGINAL HOTBOX I-V CURVES, 28 AND 60°C

b. OVERLAID CURVES WITH I_{sc}, V_{oc} MATCHED

c. CURVES MATCHED PER DOC 5-342-1B

d. CORRECTION BY LAPSS COMPUTER USING THREE COEFFICIENTS. ADJUSTMENTS OF 28°C CURVE FOR VOLTAGE CURRENT AND SERIES RESISTANCE IS SHOWN BY SHADED AREAS

Figure 4. Temperature Coefficient Determination

2. The LAPSS method uses three coefficients, voltage, current, and R_s. The series resistance coefficient R_s, compensates for the change in resistance of a module operating at high temperature (See Fig. 4d). The coefficients are used in the LAPSS computer program as described in Appendix A. This method provides a complete IV curve from the LAPSS corrected to 60°C with the test made at ambient.*

The LAPSS method is considered to be more accurate because the coefficients are computed from the LAPSS printouts. The IV curve overlay method is subject to the additional errors of the X-Y plotter. However, the overlay method is more generally used at JPL since it provides a standard method of comparison with the manufacturers' data. No manufacturer during Block II procurement used the LAPSS method.

Table 3. Temperature Coefficients of Block II Modules

Vendor	Module Sample Size	Rating Voltage	Voltage Coefficient $\Delta V/\Delta T$, V/°C	Current Coefficient $\Delta I/\Delta T$, ma/°C
VA	10	15.8	-0.106	0.043
VB	20	16.5	-0.111	0.043
WA	15	15.8	-0.0969	0.53
WB	11	15.8	-0.0992	0.94
Y	10	15.8	-0.102	1.30
Z	12	15.8	-0.094	0.045

* In addition to a corrected IV curve at 60°C, the LAPSS is used to provide a standard curve at 28°C. The latter contains only a small temperature correction, normally from an ambient of about 21° to 25°C. The 28°C IV curves are used also as a basis for measurement of any electrical degradation after environmental tests.

IV. QUALIFICATION TESTING

Qualification testing as used in this report refers to the tests required in the procurement specification, Document 5-342-1B, Section III A and Section II C. These tests were applied to the initial shipments of Block II prototype modules as well as to production samples chosen at the completion of each kilowatt of power delivered. The test flow for prototype modules is shown in Fig. 5. Test flow for production samples was the same except that thermal coefficients were not measured.

A. Test Procedures

The three major tests, temperature cycling, humidity, and mechanical integrity (also called cyclic pressure loading or wind simulation) were done with modules mounted in a test frame, JPL Drawing 10081548. Modules were mounted in the frame, bolts were torqued to the proper values, and tests run. Modules weren't demounted until the three tests were completed.

These tests are summarized in Table 4 and described in more detail below

1. Temperature cycling (+90°C, -40°C, 50 cycles)
   The temperature cycles were on a 4 hour basis. Temperature change program was 100°C/hr. There was about a 39 minute dwell time both with chamber air at 92.5°C and at -42.5°C. The additional 2.5°C was necessary to provide a ΔT to bring the individual modules to +90 and -40°C ±2°C in 39 minutes.

2. Humidity Cycling (+23°C to +40.5°C, 90%RH, 5 cycles).
   This test was run according to MIL STD 810C, Method 507.1, Procedure V (Fig. 3). After two days of preconditioning, five cycles (one per day) were run from 23°C to 40.5°C.

3. Mechanical Integrity (±2400 Pa (±50 pounds/sq. ft.), 100 cycles).
   The pressure loading was applied in a special fixture described in Section IV B with an overall cycle time of about one minute.

4. Electrical Performance
   Electrical performance before and after each test was measured in the Large Area Pulsed Solar Simulator (LAPSS), Fig. 6. Electrical degradation from test exposures was determined by comparison of the pretest and post-test maximum power from the module at 28°C. The LAPSS computer corrected the ambient data (generally, 21°C to 25°C) to 28°C for all modules, by use of LAPSS temperature coefficients.

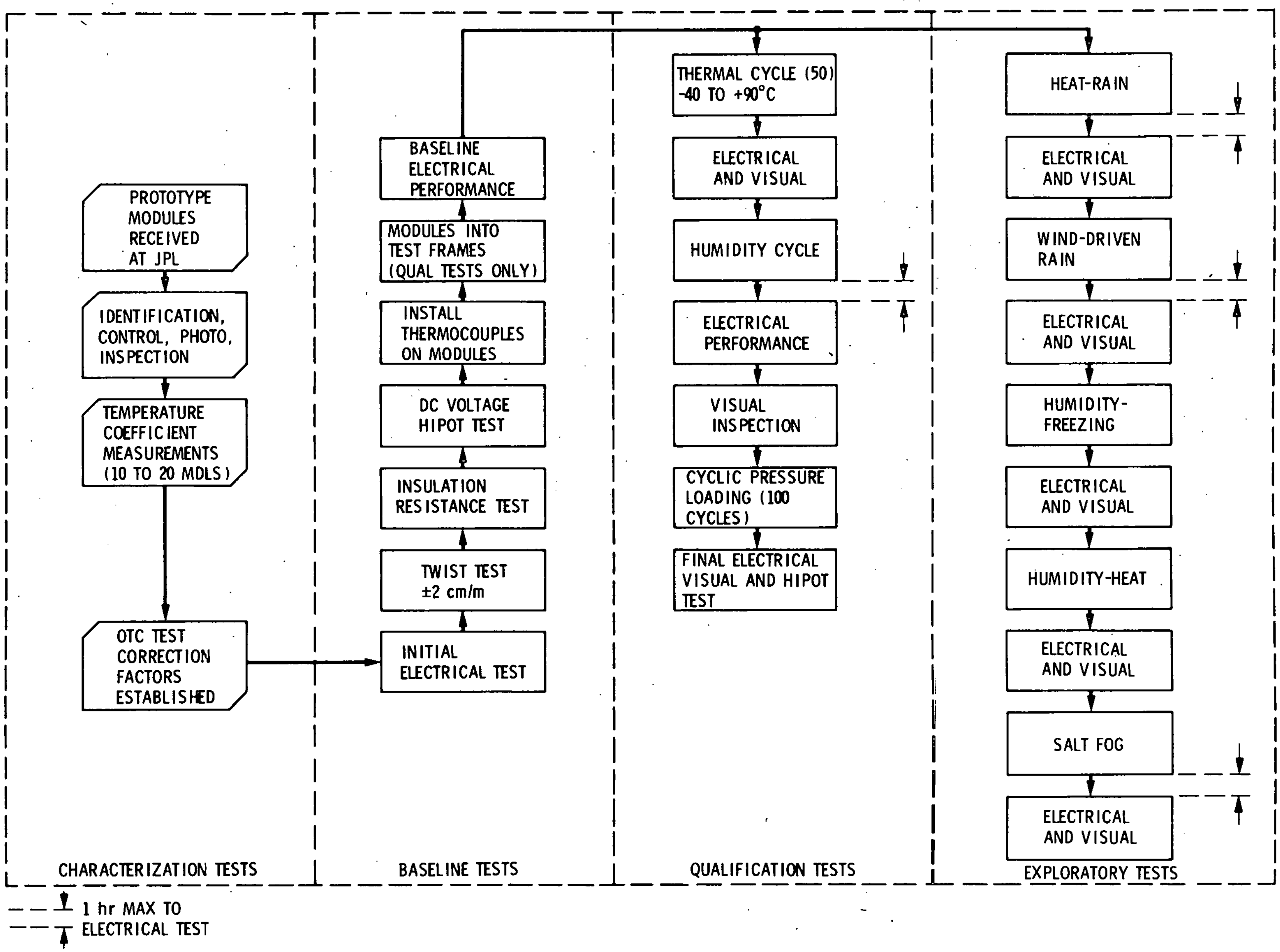


Figure 5. Prototype Module Test Flow at JPL

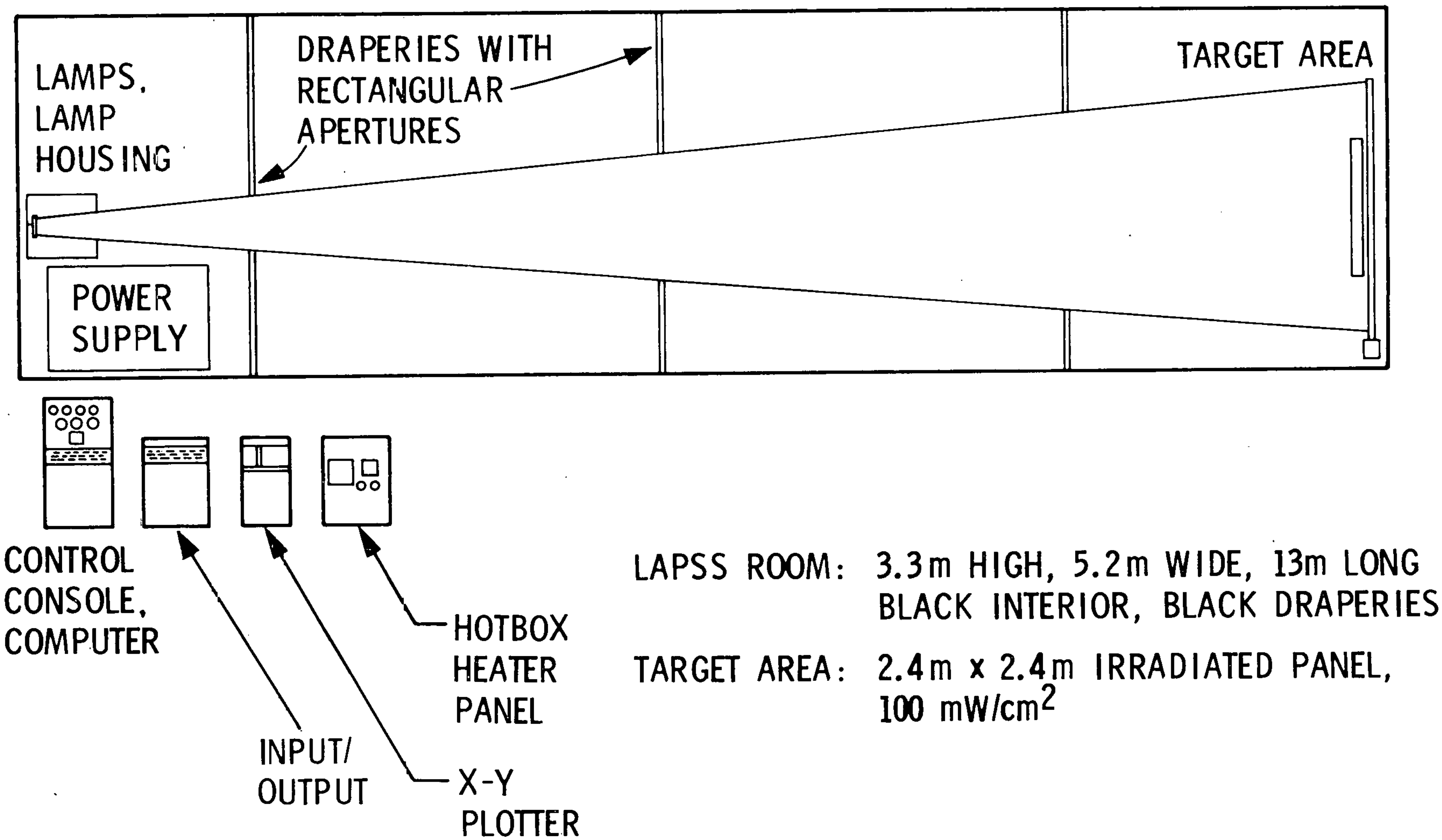


Figure 6. Sketch of the LAPSS (Large Area Pulsed Solar Simulator)

Table 4. Required Environmental Qualification Tests

Tests	Environmental Test Levels
Temperature cycling	+90°C, -40°C, 100°C/hr, 50 cycles
Humidity cycling	+40°C, +23°C, 90% RH, 24 hr/cycle 5 Cycles
Mechanical integrity (cyclic pressure loading)	±2400 Pa (±50 lb/ft^2), 100 cycles.
Warped mounting surface	±2 cm/m (±1/4" per ft).
Electrical isolation	Leakage current <15 uA @ 1500 Vdc, $\geq$ 100 megohms resistance @ 1000 Vdc.

5. Electrical Isolation Tests
   These two tests, insulation resistance and voltage withstanding, were performed per Doc. 5-342-1B, Section III A2. A megohm bridge was used to measure resistance at 1000 Vdc between the cell string and the frame. A hipot tester was used to check for breakdown (15µA or more) at voltage steps of 500, 1000, and 1500 Vdc. Only modules with exposed metal structure were required to meet these tests.

6. Warped Mounting Surface (Twist Test)
   This requirement from Doc. 5-342-1B, Section II C1 was done by mounting the module to a fixture that permitted one corner to be raised and lowered by one part in forty-eight (1/4 inch per foot). This operation is shown in Fig. 7.

B. Equipment and Facilities

A list of the facilities used during Block II qualification testing is given in Table 5. The temperature and humidity exposures of the 1.2 x 1.2m (4 x 4 foot) subarrays were done off-lab because at that time there were no chambers available of sufficient size at JPL. These tests were run at Wyle Lab, Norco, Calif; Lockheed-California Co. at their Rye Canyon Facility near Burbank, Calif.; and at Convair/General Dynamics, San Diego. Most of the tests were performed at Convair.

Module receiving, identification, inspection, electrical testing, electrical isolation tests, twist tests, and installation in subarray frames were done at Bldg. 248 at the Jet Propulsion Laboratory in Pasadena, California. Mechanical integrity tests (cyclic pressure loading) were done in Bldg. 144 of the same facility.

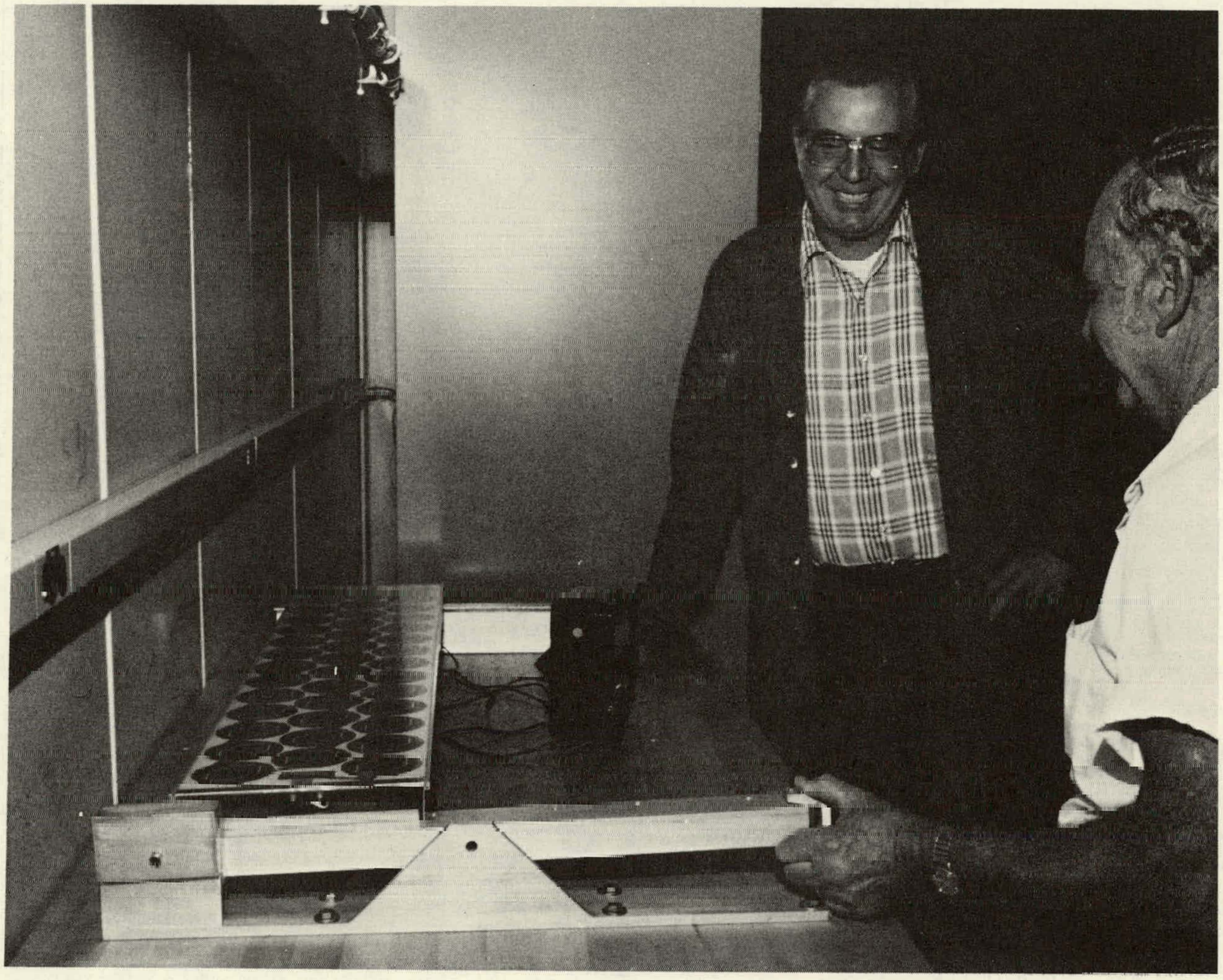


Figure 7. Twist Test Equipment

Table 5. Equipment and Test Specifications

Test	Location	Description of Equipment	Specification (Para. from Doc. 5-342-1B)	Brief Test Description
Subarray Test Frame for Modules		Dwg 10081548	III.A.3	Rigid frame required
Electrical Tests	Bld. 248	Spectrolab LAPSS	II.A.1,2	
Insulation Tests	Bld. 248	a. Megohm bridge, General Radio type 1644A b. Hipot tester, Hipotronics Model HD115	II.A.3; III.A.2	100 megohms at 1000 V, withstand 1500 V
Warped Frame Test	Bld. 248	Dwg. 10082087	II.C.1	±2cm/m deflection of one corner
Temperature Cycling	Convair, San Diego	Temperature-humidity chamber, American Research, 2.4 x 2.4 x 4.8m	III.A.3.a	-40° to +90°C, 100°C/hr, 50 cycles
Humidity Cycling	Convair, San Diego	Temperature-humidity chamber, American Research, 2.4 x 2.4 x 4.8m	III.A.3.b	23°C to 40.5°C every 24 hrs, 90-95 R.H., 5 cycles
Mechanical Integrity	Bld. 144	Dwgs. 10082088 10082110 10082484 10082557	III.A.3.c	±2400 Pa, 100 cycles

The mechanical integrity fixture was developed especially for this test to induce uniform peak pressure loads across the surface of the modules of 2400 pascals. A schematic of this device is shown in Fig. 8. The subarray was held, sandwich-fashion, between two stiffened aluminum sheets covered with a 0.4-mm (1/64-in.) neoprene sheet. The rubber diaphragms were slack to insure that the air pressure was transmitted uniformly to the subarray. A flush bearing surface for each diaphragm was provided by filling all of the spaces and non-uniformities in the modules with foam rubber until the foam was flush (less 5mm) with the subarray frame. The apparatus provided automatic alternating front and back side pressure loading. The applied load was quite uniform (±10%) as measured by linear indicators mounted on a bar across the test frame that sensed module frame deflections. The entire system is shown in Fig. 9.

The air pressure cycling was done by a pneumatic system on a separate stand. Two regulators reduced shop air from line pressure to about 2600 Pa (10-1/2 inches of water). Two loading valves and two exhaust valves alternately pressurized each side of the fixture. The valve controller was a motor-driven shaft with a series of cams and switches. Relief valves were used to prevent overpressurizing. However, as an extra precaution, the air supply lines to the fixture had vents installed in them that were immersed in a can of water that was only 28 cm high precluding excessive pressure buildup.

Other minor tests required were insulation and module flexure tests with equipment as listed in Table 5. The flexure test equipment is shown in Figure 7.

Electrical performance tests were done with a Spectrolab LAPSS (Large Area Pulsed Solar Simulator), Fig. 6. A special non-reflective room 5.2 m wide and 13 m long was used for these tests. The walls, floors, and ceilings were black. Three sets of draperies were hung at various points along the length of the room. Rectangular openings in the draperies further baffled reflections. The light source was two small xenon-filled lamps in a lamp housing at one end of the room. The target area where the cells, modules, or subarrays to be tested were mounted was at the other end of the room. The lamps' power supply was a large capacitor bank. The system computer controlled the entire test sequence from the charging of the capacitor, to flash, to data printout. The flash was approximately 3 milliseconds long. The data were taken in 1 to 2 ms. An electronic load (ramp voltage) was applied during data acquisition. Forty or more current measurements were taken at various voltage values and stored. Data were converted to engineering units for printout and were plotted also. The computer normalized the data to the desired irradiance by comparison with the short circuit current of a calibrated reference cell also mounted in the target area. Thus, if 100 mW/cm^2 data were desired, the lamp controls were set to supply approximately this value; the computer corrected for any differences in the actual setting as well as variations during the pulse. The extremely fast response of silicon solar cells permitted the use of this type of system.

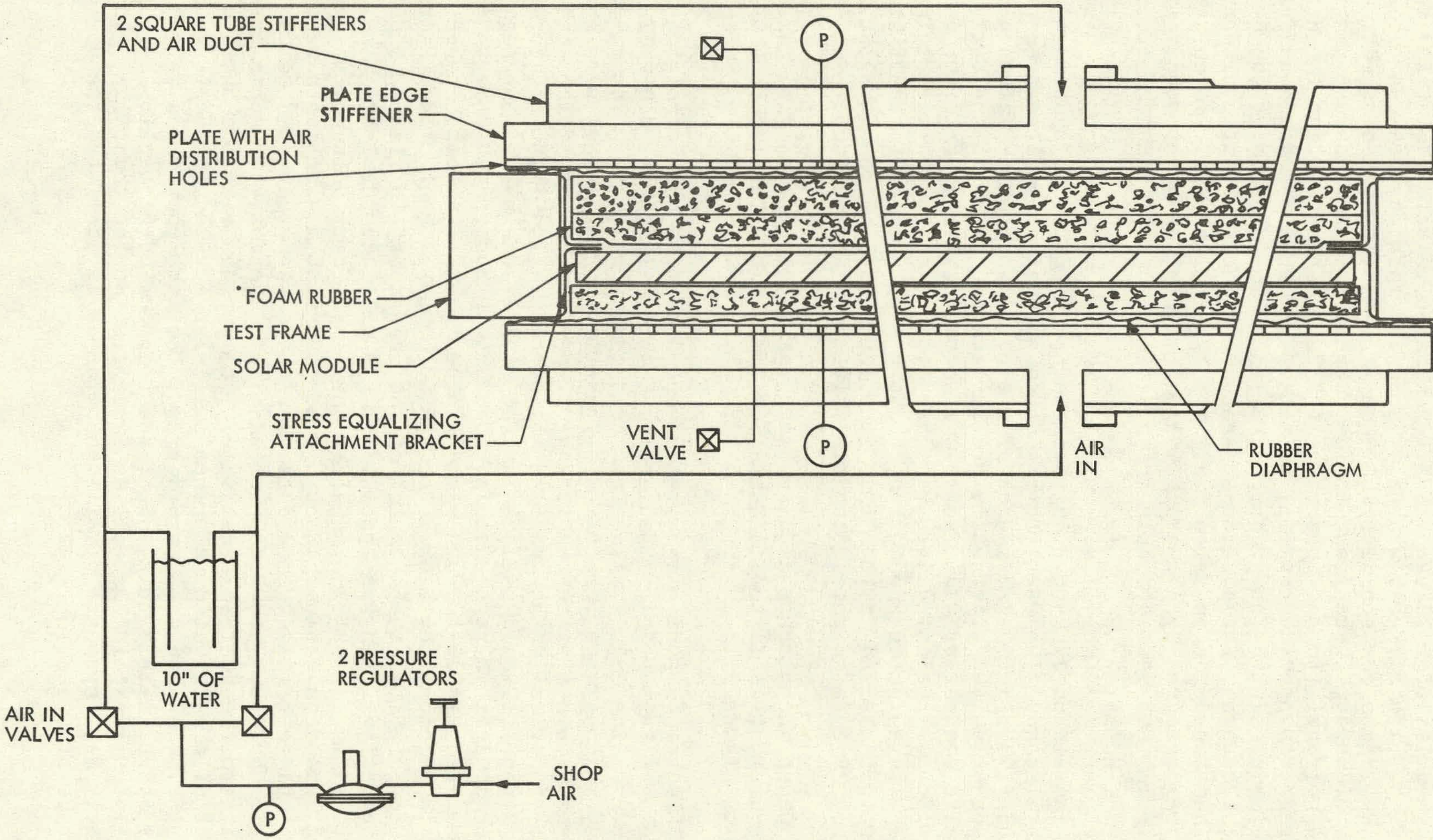


Figure 8. Schematic of Mechanical Integrity Fixture

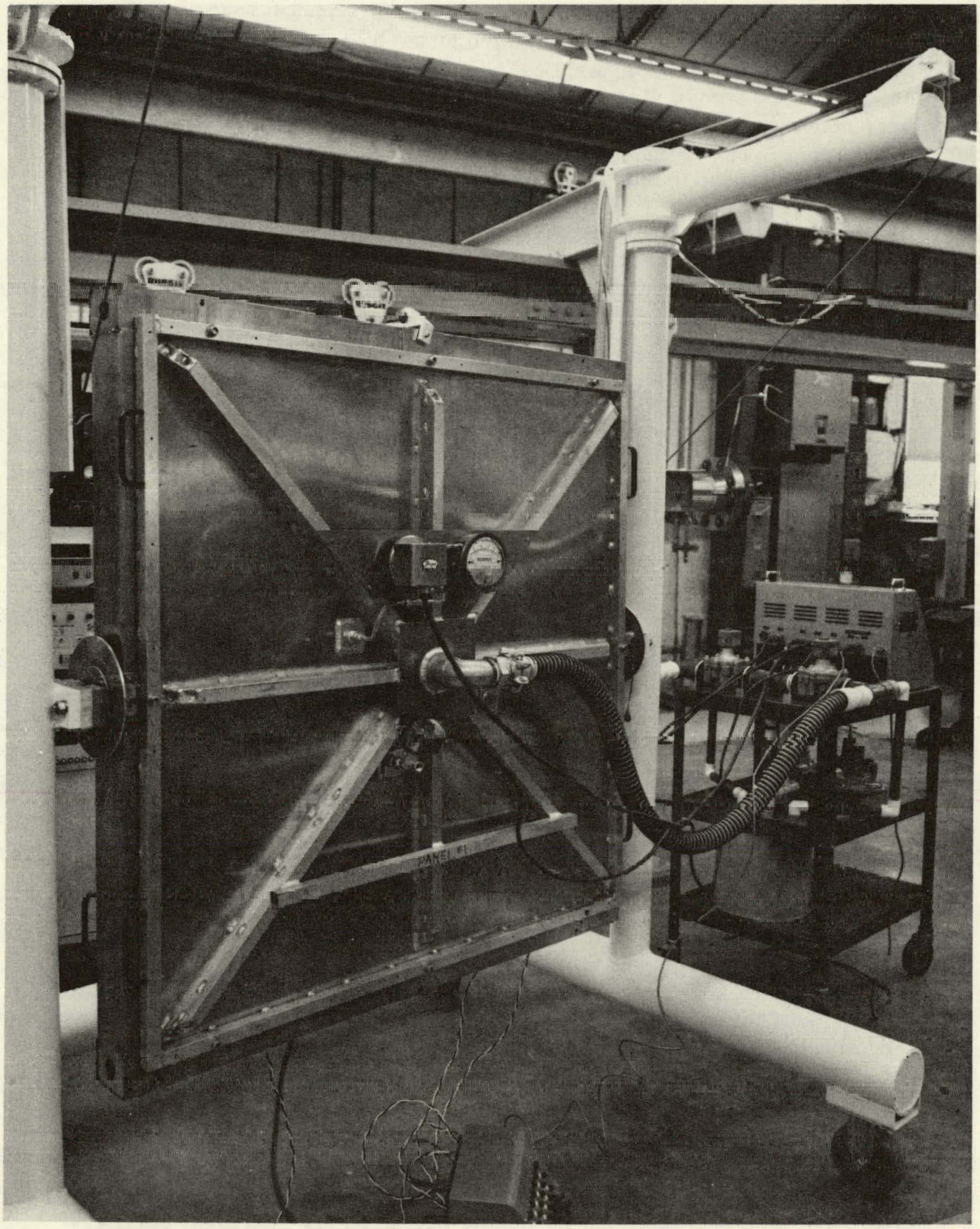


Figure 9. Mechanical Integrity Fixture With Pneumatic Stand

The computer could correct the data for temperature as well. The temperature coefficient measurement described in Section III B2 above provided values for correction of voltage (negative correction), current (positive), and series resistance (negative). Plotted and printed data for each module were generally provided at 28°C and 60°C from measurements at ambient temperatures of about 21-25°C. Precise determination of the temperature coefficients required measurements at two different temperatures. A temperature controlled box (hotbox) with a glass window was fabricated to hold the 1.17m long modules. The voltage-current characteristic curve was taken at 28°C and at 60°C and the coefficients determined per Doc. 5-342-1B, Section II A2. After the coefficients were known, electrical tests could be made at ambient temperatures and performance at 60°C accurately predicted.

C. Results and Discussion

Qualification-type tests (Table 4) were run on the initial set of prototype modules. In addition, temperature coefficients were measured on a quantity from ten to twenty of these (Table 3). Later, sample modules were taken at the end of each kilowatt of modules produced. Most of the latter were given qual-type tests. Also, one in every three were checked for temperature coefficients. A few modules were rechecked for a change in temperature coefficients after completing qual tests. Prototype and 1 kW sample results are presented below (See also Table 1 for initial performance and characteristics).

1. Qualification Test Results for Prototype Modules.

Table 6 presents the data on the principal types of degradation observed. The symbols used indicate the test exposure which caused the degradation observed. The sizes of the symbols provide an assessment of the frequency and severity of the problem.

Cell cracking was a minor problem for prototype modules. Only WB and Z-type modules were affected. Ordinarily, temperature cycling would be expected to cause most cell cracking. However, Z-type had cell cracking from each of the three tests. It was attributed to expansion of trapped air under the cells. Delamination also resulted from the trapped air.

Minor corrosion of the metal frame was observed after humidity test of WA prototypes. Electrical degradation was only a minor problem, with V (glass cover), W and Z affected.

The square symbols (environment independent) indicate erratic power output and was observed even with WA and Z control modules. The photon degradation effect described in References 6 and 7 may explain some of the observed instability. The other WB and Z module electrical degradations were probably due to the cell cracks in those same modules.

Table 6. Block II Prototypes Qualification Test Results

SUPPLIERS	CELL CRACKS	CORROSION	ELECTRICAL DEGRADATION	ELECTRICAL ISOLATION	DELAMINATION
V STANDARD					● ○
V GLASS COVER			⦶		● ○ ⦶
WA		○	□	○	
WB	●		●		
Y					
Z	● ○ ⦶		○ □		● ○

● TEMPERATURE CYCLING
○ HUMIDITY
⦶ CYCLIC PRESSURE LOADING
□ ENVIRONMENT INDEPENDENT

The electrical isolation problem in a WA module was believed to be due to a bus bar that was located too close to the metal frame.

Delamination of the silicone rubber encapsulant was a significant problem with both types of V modules and with Z modules. Both temperature and humidity tests produced delamination. Since temperature cycling occurred first, it may have contributed to the subsequent delamination under humidity exposure.

Delamination in V modules was attributed to two causes. Analysis showed that the primer used was not sticking to the aluminum substrate, presumably due to inadequate surface preparation. Interlayer delamination of the RTV 615 was due to a second pour after partial curing of the first pour.

2. Qual-type Tests of Production Samples (kW modules)

Results of tests of production samples in Table 7 show widely different results when compared to prototypes (Table 6). Cell cracks occurred in some modules of all types. Early V modules showed cracks in nearly every module with an average of five cracks in each. Electrical degradation occurred frequently from the cell cracking. Delamination of V and Z modules was less in the production samples.

a. V-type Modules

An investigation of the cracking problem with early V modules showed that the expansion/contraction of the thicker layer of encapsulant in the stiffening ribs below the cells produced the cracking stresses. The supplier developed several new designs (Table 8) and fabricated samples which were then tested at JPL. The aluminum sheet under the cells was chosen and used for the final 13% of the modules delivered. This sheet stopped most of the cell cracking as well as the electrical degradation that had been caused by the cracks.

b. W Modules

Minor cell cracking and electrical degradation were observed. The electrical degradation was in the same module that developed a cracked cell during humidity testing.

c. Y Modules

A moderate number of small cracks appeared after temperature and mechanical integrity tests. Another module showed marginal electrical degradation after mechanical integrity testing.

Table 7. Block II Production Samples (kW) Qualification-Type Tests

SUPPLIERS	CELL CRACKS	DELAMINATION	ELECTRICAL DEGRADATION
V (EARLY)	⬤ ○ ⦶	⬤	⬤ ⦶
V (LATER)	●	○	
W	○		○ ⦶
Y	● ⦶		⦶
Z	● ⦶	⬤ ○	●

⬤ TEMPERATURE CYCLING
○ HUMIDITY
⦶ CYCLIC PRESSURE LOADING

Table 8. Attempts to Reduce V Module Cell Cracking by Redesigns

Type	Effect on Cell Cracking	Other Effects
Glass covers of 40, 60 & 70 mil thicknesses	Greatly reduced	Reduced power, increased delamination
Filled grooves first with a compound with a better thermal expansion coefficient match.	Reduced	Special filler turned yellow
Installed a 20 mil thick aluminum sheet over bottom of pan, vented the grooves (no encapsulant in the grooves).	Greatly reduced	None

d. Z Modules

Moderate cell cracking was observed, primarily from temperature cycling. The minor electrical degradation was not cell crack connected. Moderate delamination occurred as well as splits in the encapsulant.

3. Comparison of Block I and Block II Modules

A comparison of Block I (Table 9) and Block II results shows a great improvement in the later modules in spite of the greater test severity (rigid frames and the added test, cyclic pressure loading).

Delamination has been greatly reduced in Block II. Humidity exposure has resulted in very few discrepancies on these later modules. Electrical degradation didn't occur as frequently and individual power loss percentages were lower. Problems with interconnects have virtually been eliminated. However, cell cracking was as prevalent for Block II as it was for Block I, even if early V type Block II modules are disregarded.

Table 9. Block I Qualification Test Results

SUPPLIERS	CELL CRACKS	ELECTRICAL DEGRADATION	DELAMINATION	DAMAGED INTERCONNECTS
V	● ○	○	● ○	
W	●	● ○	●	●
X	●	● ○	●	
Y (EARLY)	●	● ○	●	
Y (LATER)*				
Z	● ○	●	● ○	●

○ TEMPERATURE CYCLING
○ HUMIDITY CYCLING
*PALLADIUM ADDED TO CONTACTS

V. EXPLORATORY TESTING

A number of supplemental tests were run on sample modules to characterize performance and evaluate techniques of environmental testing. Tests in these environments were not a requirement under the contract.

A. Procedures and Equipment

The procedures and test equipment used were essentially the same as described in Ref. 8, Section IV. Pertinent excerpts from this report are presented in Appendix B; a summary of tests run on Block II modules is given in Table 10. Fungus testing was not done on Block II modules. Exploratory tests were run on only 3 or 4 modules of each type.

B. Results and Discussion

Table 11 summarizes the results of exploratory testing and further details are given below.

1. The humidity-freezing test appeared to be the most severe environment with delamination produced in three out of four cases. V modules showed some discoloration, as well.

2. Salt fog produced loss of electrical isolation to ground in the three W modules tested. This was traced to salt water entry at the point where electrical leads came out of the laminate. After dryout, isolation was recovered. Y module corrosion was due to a steel pin anchoring the plated brass bus strip in the terminal box. Z module corrosion came from steel inserts used with brass terminal screws.

3. Heat-rain produced minor electrical degradation in one each of V and Z modules, and a minor cell crack in a W module.

4. Wind-driven rain produced no observable degradation on any module.

5. Humidity-heat caused one cracked cell in a V module and minor electrical degradation in a Z module.

Table 10. Exploratory Environmental Tests

Tests	Test Levels and Test Equipment
1. Heat-rain	Modules allowed to reach maximum temperature on a clear warm day; hard rain simulated with deionized water spray until modules reach equilibrium (about 8 min.). 5 cycles. Specially designed water spray equipment.
2. Wind-driven rain	Spray of deionized water at 18 m/s and 2mm average droplet size; modules slowly rotated in heavy spray for 15 minutes. Specially designed equipment.
3. Humidity-freezing	MIL-STD-202E, Meth. 106D (no vibration). 2 cycles, 23 to 65°C at 95% RH in 16 hr; then, -13°C for 3 hours. 10 cycles. Standard temperature-humidity test chamber.
4. Humidity-heat	Modules are water-saturated in a chamber for 6 hr at 70°C, 95% relative humidity; then removed and irradiated at full simulated sun to stable temperature. 10 cycles. Standard temperature-humidity chamber and 3400 K lamp bank.
5. Salt fog	MIL-STD-810C, Meth. 509.1. Salt spray, 35°C, 95% R.H. for 48 hr. Salt fog chamber.

Table 11. Exploratory Testing of Block II Modules Operations Area

SUPPLIER	HUMIDITY-FREEZING	SALT FOG	HEAT-RAIN	WIND-DRIVEN RAIN	HUMIDITY HEAT
V	DISCOLORATION, DELAMINATION	PASS	ELECTRICAL DEGRADATION	PASS	CRACKED CELL
W	PASS	ELECTRICAL ISOLATION	CELL CRACKED	PASS	PASS
Y	DELAMINATION	TERMINAL CORROSION	PASS	PASS	PASS
Z	MINOR DELAMINATION	TERMINAL CORROSION	ELECT. DEGRAD, SPLIT ENCAP.	PASS	ELECTRICAL DEGRADATION

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Block II modules performed better than Block I modules on all counts except for cell cracking. This improvement is especially significant since the testing was more severe due to addition of rigid frames and the mechanical integrity test to the Block II procedures. The frequency of discovery of cell cracks may be due in part to better inspection methods and the more numerous and larger areas of cells on Block II modules. However, cell cracking is a serious problem.

2. Production sample testing is necessary even though qualification tests on prototypes show no module defects. Cell cracking and electrical degradation in V (standard) and Y modules occurred in production modules and not in prototypes. Apparently, the shift to high production may introduce processing and quality control problems not present in prototype runs.

3. The values of the various tests in revealing module weaknesses are, in order, temperature cycling, humidity, and mechanical integrity. However, humidity-freezing, an exploratory test, showed high value in the discovery of delamination. Except for the hard rain test, all of the exploratory tests were useful. None of the modules had any difficulties with the warped frame (twist) test.

4. There is good agreement between environmental chamber test results and field test results based on early data from field test. However, further comparison and study is needed.

B. RECOMMENDATIONS

1. Production sample testing should be continued in addition to prototype qualification until there is assurance that production quality control is effective.

2. JPL should endeavor to reduce its response time to module design or quality problems to minimize time required for corrective action at the manufacturer.

3. An integrated study is needed to correlate environmental chamber, field test, and application area results. A comparison of the frequency and severity of real time degradation of Block I and Block II modules vs. test chamber results will show up inadequacies in the latter. Then, adjustments and improvements in chamber test procedures can be made. This should be an on-going study because of the relatively short duration of the field test and application area experience at the present time.

4. Concurrently with this study (3, above), determine the effect of various changes in the exploratory test series including the following:

a. Combine the temperature cycling and humidity-freezing tests to measure the effect on delamination.

b. Increase limits and/or cycles on salt fog, heat-rain, and humidity-heat (delete wind-driven rain).

c. In addition to a longer duration salt fog test, incorporate dissimilar metal mounting and electric power generation, if feasible.

5. The Quality Assurance group should be a part of the study (3, above) with the objective of improving the correlation of the inspeotion acceptance criteria with long time reliability and the elimination of non-relevant criteria.

REFERENCES

1. Program Research and Development Announcement (PRDA), Solar Photovoltaic Flat Panel Applications Experiments, Department of Energy, Albuquerque Operations Office, PRDA EM-78-D-04-0038.

2. JPL Internal Report 5101-62, Photovoltaic Solar Panel Resistance to Simulated Hail, D. Moore, A. Wilson, Oct. 15, 1978.

3. JPL Internal Report 5101-84, Bias-Humidity Testing of Solar Cell Modules, A. Hoffman, E. Miller, Oct. 15, 1978.

4. Block II specification, Document 5-342-1B, "Silicon Solar Cell Module Performance, Environmental Test and Inspection Requirements," December 20, 1976 Revision.

5. JPL Internal Report 5101-76 (DOE/JPL-1012-78/9), Thermal and Other Tests of Photovoltaic Modules Performed in Natural Sunlight, J.W. Stultz, July 31, 1978.

6. Weizer, V., Brandhorst, H., Broder, J., Hart, R., and Lamneck, J., "Photon Degradation Effects in Terrestrial Solar Cells," pp. 1327-1332, Thirteenth IEEE Photovoltaic Specialists Conference, 1978.

7. Cheng, L., Turner, G., Downing, R., Wang, E., and Seaman, C., "Mechanisms of Photon-Induced Changes in Silicon Solar Cell Parameters," pp. 1333-1341, Thirteenth IEEE Photovoltaic Specialists Conference, 1978.

8. JPL Internal Report 5101-27, Summary of Block I (46 KW) Module Testing, May 2, 1977.

APPENDIX A

JET PROPULSION LABORATORY INTEROFFICE MEMO #341-77-D-108

March 8, 1977

TO: L. Dumas

FROM: G. Downing, R. Mueller

SUBJECT: Measurement Procedure and Results for Determining Solar Cell Module Temperature Coefficients for Current, Voltage and Bulk Series Resistance

Modules under test are mounted inside an insulated aluminum box having a transparent Plexiglass II UVA front door. The box is located at the normal test distance from the LAPSS illumination source and the test module is mounted to the rear surface of the box with four standoffs to center it inside the box. The test module is equidistant to the transparent front door which has a measured transmission loss of 8%. Heated air is circulated throughout the box interior to provide uniform heating of the test module at required temperatures up to 65°C.

The reference standard cell provided by LeRC is mounted outside the box well within the ±1% uniformly illuminated test plane and is not subjected to heating. It normally operates at a temperature of 22 ± 1°C. The LAPSS illumination source is adjusted to an illumination level 8% higher than normal to insure a 100 mW/cm^2 intensity inside the box. The normal calibration value for the reference standard cell is also increased by 8% so that the LAPSS computer will apply only a minor correction to the module IV characteristics for an intensity of 100 mW/cm^2 inside the box rather than outside the box.

Prior to a series of runs being made on a particular module design, one of the modules is instrumented with a number of thermocouples on the solar cells and substrate. In addition, many thermocouples are positioned in the air around the test module in the box. A temperature profile is made where the time period required to attain equilibrium between the module and air temperature is determined. In addition, overall temperature uniformity is found. These time periods are noted for all the required test temperatures and the remaining modules are instrumented with one to three thermocouples on the rear surfaces of several solar cells. These are used to measure module temperature after the predetermined time period for heating. Module IV characteristics are measured at required temperature (i.e. 28°C and 60°C) and temperature coefficients are determined from the resulting data.

The change in IV characteristics of a module at two different temperatures is found by comparing the IV curves as shown in Figure A-1. Eleven voltage-current coordinates are determined from the tabular printout provided with the curves. The locations are shown in Figure A-1. The following formulae are used to find various module parameters leading up to the determination of the temperature coefficients for current, voltage and bulk series resistance.

1. Shunt Resistance for curves 1 and 3 (R_{SH_1}, R_{SH_3}) =

$$\frac{V_2-V_1}{I_1-I_2}$$

2. Short Circuit current for curve 1 (Isc_1) =

$$I_1 + \frac{V_1}{R_{SH_1}}$$

3. Shunt Resistance for curve 2 (R_{SH_2}) =

$$\frac{V_4-V_3}{I_3-I_4}$$

4. Short Circuit current for curve 2 (Isc_2) =

$$I_3 + \frac{V_3}{R_{SH_2}}$$

5. Bulk Series Resistance for curves 1 and 3 (R_{S_1}, R_{S_3}) =

$$\frac{V_6-V_5}{I_5-I_6}$$

6. Open circuit voltage for curve 1 (Voc_1) =

$$V_6 + I_6 R_{S_1}$$

7. Bulk Series Resistance for curve 2 (R_{S_2}) =

$$\frac{V_8 - V_7}{I_7 - I_8}$$

8. Open Circuit Voltage for curve 2 and 3 (Voc_2, Voc_3) =

$$V_8 + I_8 R_{S_2}$$

9. Short Circuit Current for curve 3 (Isc_3) =

$$Isc_2 + \frac{Isc_2 (R_{S_2} - R_{S_1})}{R_{SH_3}}$$

10. Displacement voltage from curve 1 to curve 3, removing the influence of any change in bulk series resistance. (V_{DT}) =

$$Voc_3 + \left[\left(1 + \frac{R_{S_3}}{R_{SH_3}} + \left(\frac{R_{S_3}}{R_{SH_3}}\right)^2\right)\left(R_{S_3}\ (Isc_1 - Isc_3) + \frac{R_{S_3}}{R_{SH_3}}\ (Voc_3 - Voc_1)\right)\right]$$

11. Displacement current from curve 1 to curve 3, removing the influence of any change in bulk series resistance. (I_{DT}) =

$$Isc_3 + \left[\left(\frac{Voc_1 - Voc_3}{R_{SH_3}}\right)\left(1 + \frac{R_{S_3}}{R_{SH_3}} + \left(\frac{R_{S_3}}{R_{SH_3}}\right)^2\right) + \left(\frac{Isc_3 - Isc_1}{R_{SH_3}}\right)\left(R_{S_3} + \frac{R_{S_3}^{\,2}}{R_{SH_3}}\right)\right]$$

12. Displacement voltage, near maximum power, from curve 3 to curve 2 to determine the influence of any change in bulk series resistance (V_{DST}) =

$$V_{11} - \left(\frac{V_{11} - V_{10}}{I_{10} - I_{11}}\right)(I_9 + I_{DT} - Isc_1 - I_{11})$$

13. Change in bulk series resistance (R_{DST}) =

$$\frac{(V_9 + V_{DT} - Voc_1 - V_{DST})}{(I_9 + I_{DT} - Isc_1)}$$

14. Coefficient for change in bulk series resistance near maximum power in 1/10's of milliohms per ^oC temperature change. (R_{DS}) =

$$\frac{1 \times 10^4 R_{DST}}{T_H - T_L}$$

15. Coefficient for the displacement of voltage for the entire IV curve in v/cell per ^oC temperature change. (V_{DS}) =

$$\frac{1 \times 10^6 (V_{DT} - Voc_1)}{N_{SC}(T_H - T_L)}$$

16. Coefficient for the displacement of current for the entire IV curve in A/cm^2 cell area per ^oC temperature change. (I_{DS}) =

$$\frac{1 \times 10^6 (I_{DT} - Isc_1)}{1 \times 10^{-2} A_c Npc (T_H - T_L)}$$

Using this technique, temperature coefficients have been experimentally determined for the four vendor's 130 kW prototype modules as shown in Tables A-1 through A-4. These numbers are used then to generate axis translation constants for the vendor's use as described in the procurement spec.

The coefficients shown in the tables are all consistent with the nominal coefficients as found in the literature and in use for many years. A recent discrepancy, however, did arise when Vendor Y reported their current coefficient as 3.1 ma/^oC for their 130 kW module which is 2.5 times higher than the 1.22 ma/^oC measured at JPL for identical modules. Since their measurement was made under tungsten illumination rather than solar or solar simulated illumination, and further, since qualitatively an increase in the current coefficient would be expected under tungsten illumination, the JPL measurements were extended to include tungsten and solar illumination. Under tungsten illumination a current coefficient of 3.05 ma/^oC was obtained confirming their measurement. Under solar illumination a value of 1.25 ma/^oC was obtained confirming the use of xenon as a solar simulation source. This difference could produce an error in P_{max} @ 60°C of about 4 to 5% which is significant. It is recommended, therefore, that the value obtained in xenon be used.

RGD:RLM:sjt

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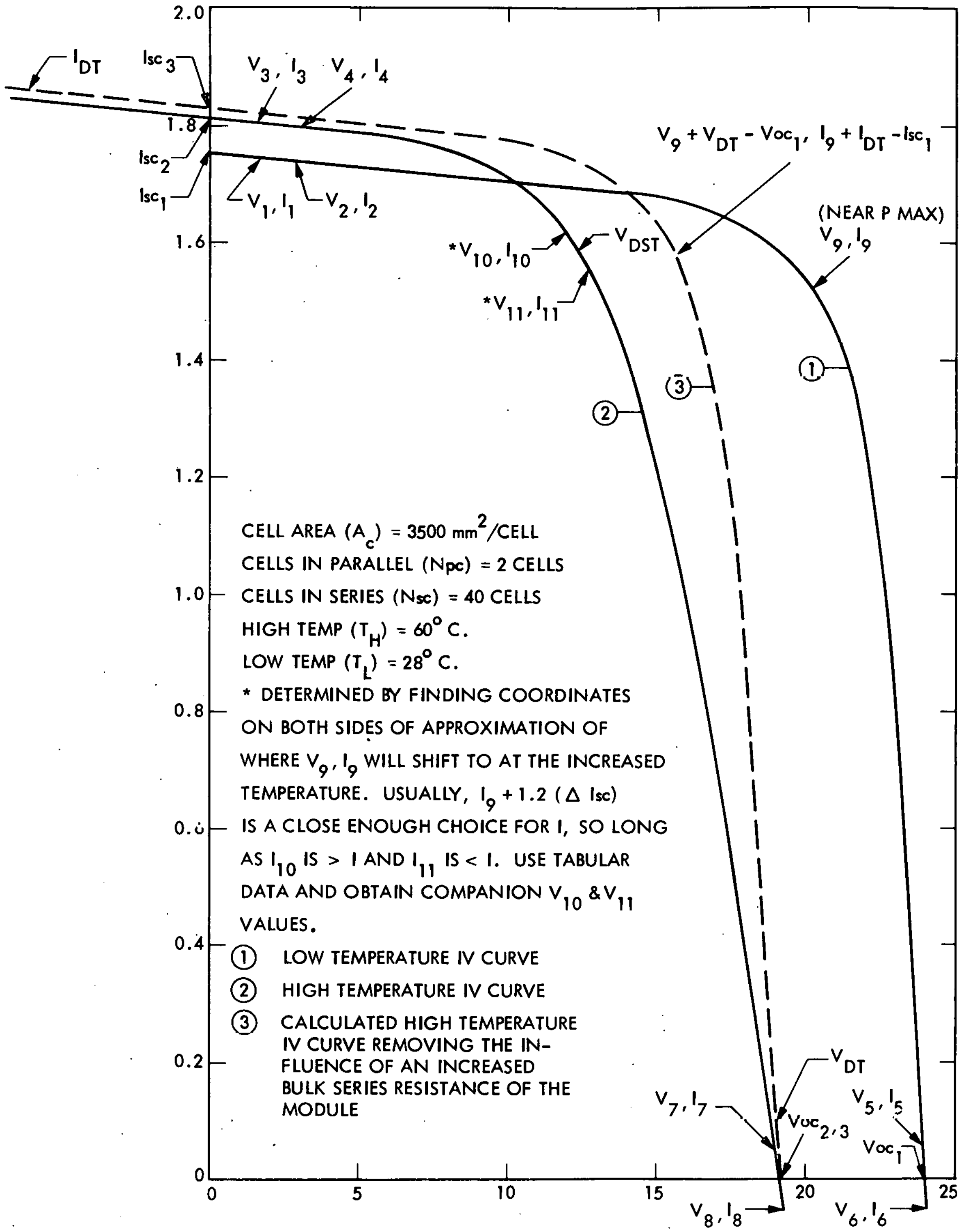

Figure A-1. Effect of Temperature on Cell Current-Voltage Characteristics

Table A-1. JPL LAPSS Temperature Corrections

Vendor W

Module S/N	R CORR $1 \times 10^{-4}\Omega/^{o}C$	V CORR $\mu V/cell/^{o}C$	I CORR $\mu A/cm^2/^{o}C$
04012	72.1	-2140	8.48
04018	72.1	-2132	10.16
04019	81.1	-1990	8.57
04021	72.1	-2143	12.93
04023	87.7	-2183	12.37
04025	81.1	-2213	10.54
04026	72.1	-2238	8.57
04028	81.1	-2080	13.61
04029	70.2	-2154	10.38
04030	81.1	-2210	9.51
04032	72.1	-2163	10.33
04035	78.9	-2188	11.11
04036	86.9	-2180	-
04003	-	-2138	8.48
04009	-	-2153	8.05
AVG	77.58	-2153.67	10.22
STD DEV	±6.09	±59.67	± 1.78
% STD DEV	±7.85%	± 2.77%	±17.4%

Parameter Settings for JPL LAPSS

Parameter #	Title	Value	Units
1	Cell area	*914	Square Millimeters
2	Cells Parallel	3	Cells
3	Cells Series	40	Cells
6	I Temp Corr	*25	$\mu A/cm^2/^{o}C$
7	V Temp Corr	-2154	$\mu V/cell/^{o}C$
22	R Temp Corr	78	Tenths of Milliohms/^{o}C

*Actual values for parameters 1 and 6 are 2235 and 10.22, respectively. However, the LAPSS computer cannot accept these values because of program constraints. The values have been scaled to provide the same product of the values, which is the only way the values are used by the LAPSS computer.

Table A-2. JPL LAPSS Temperature Corrections

Vendor V

Module S/N	R CORR $1 \times 10^{-4}\Omega/^{o}C$	V CORR $\mu V/cell/^{o}C$	I CORR $\mu A/cm^2/^{o}C$
007	229.67	-2251.90	12.24
006	187.70	-2122.87	11.97
023	210.03	-2172.02	10.58
027	238.39	-2179.87	12.89
001	202.49	-2219.34	12.67
002	224.26	-2190.58	10.11
005	202.39	-2156.10	9.99
011	218.54	-2202.72	9.14
019	255.65	-2170.89	11.65
021	182.31	-2179.31	11.64
015	216.77	-2159.02	14.26
014	203.43	-2258.67	13.85
017	194.53	-2145.30	12.88
022	230.69	-2231.36	11.69
012	162.96	-2218.70	10.04
008	246.35	-2233.10	11.76
026	190.87	-2190.64	14.81
016	181.91	-2148.55	10.42
020	198.87	-2187.26	12.61
004	177.28	-2226.35	10.53
AVG	207.75	-2192.23	11.79
STD DEV	±24.57	±37.30	± 1.53
% STD DEV	±11.8%	± 1.70%	±13.0%

Parameter Settings for JPL LAPSS

Parameter #	Title	Value	Units
1	Cell area	*1104	Square Millimeters
2	Cell Parallel	1	Cells
3	Cells Series	42	Cells
6	I Temp Corr	*25	$\mu A/cm^2/^{o}C$
7	V Temp Corr	-2192	$\mu V/cell/^{o}C$
22	R Temp Corr	208	Tenths of Milliohms/^{o}C

*Actual values for parameters 1 and 6 are 2342 and 11.79, respectively. However, the LAPSS computer cannot accept these values because of program constraints. The values have been scaled to provide the same product of the values, which is the only way the values are used by the LAPSS computer.

Table A-3. JPL LAPSS Temperature Corrections

Vendor Y

Module S/N	R CORR $1 \times 10^{-4} \Omega/^{o}C$	V CORR $\mu V/cell/^{o}C$	I CORR $\mu A/cm^2/^{o}C$
5122	147.28	-2203.69	31.24
5120	69.05	-2187.23	30.40
5124	6.03	-2112.30	25.11
5123	73.04	-2143.20	23.11
5121	75.26	-2146.14	26.06
20105	107.41	-2285.36	31.12
20104	108.09	-2084.42	27.33
20103	76.54	-2148.52	24.93
20102	65.99	-2218.09	22.42
20101	88.41	-2238.96	25.87
AVG	81.71	-2176.79	26.76
STD DEV	±36.48	±61.24	± 3.20
% STD DEV	±44.6%	± 2.81%	±12.0%

Parameter Settings for JPL LAPSS

Parameter #	Title	Value	Units
1	Cell area	*2260	Square Millimeters
2	Cells Parallel	2	Cells
3	Cells Series	42	Cells
6	I Temp Corr	*27	$\mu A/cm^2/^{o}C$
7	V Temp Corr	-2177	$\mu V/cell/^{o}C$
22	R Temp Corr	82	Tenths of Milliohms/°C

*Actual values for parameters 1 and 6 are 2280 and 26.76, respectively. However, the LAPSS computer cannot accept these values because of program constraints. The values have been scaled to provide the same product of the values, which is the only way the values are used by the LAPSS computer.

Table A-4. JPL LAPSS Temperature Corrections

Vendor Z

Module S/N	R CORR $1 \times 10^{-4}\Omega/^{o}C$	V CORR $\mu V/cell/^{o}C$	I CORR $\mu A/cm^2/^{o}C$
016	93.57	-2247.51	-4.65
024	57.20	-2105.88	10.22
013	25.98	-2161.85	6.90
014	25.45	-2129.51	10.28
018	19.55	-2128.92	-6.38
022	56.07	-2080.05	-4.70
021	45.43	-2161.52	6.44
020	48.66	-2139.95	-2.46
012	21.38	-2188.50	6.68
019	40.07	-2021.85	1.07
015	33.35	-2131.28	8.22
025	65.97	-2046.62	4.11
AVG	44.39	-2128.79	2.976
STD DEV	±21.72	±60.94	± 6.13
% STD DEV	±48.9%	± 2.86%	±206%

Parameter Settings for JPL LAPSS

Parameter #	Title	Value	Units
1	Cell area	*917	Square Millimeters
2	Cells Parallel	1	Cells
3	Cells Series	40	Cells
6	I Temp Corr	*25	$\mu A/cm^2/^{o}C$
7	V Temp Corr	-2129	$\mu V/cell/^{o}C$
22	R Temp Corr	44	Tenths of Milliohms/^{o}C

*Actual values for parameters 1 and 6 are 7706 and 2.976, respectively. However, the LAPSS computer cannot accept these values because of program constraints. The values have been scaled to provide the same product of the values, which is the only way the values are used by the LAPSS computer.

APPENDIX B

EXCERPTS FROM JPL REPORT 5101-27 on EXPLORATORY TESTING

A number of supplemental tests were run on sample modules to characterize performance and evaluate techniques of environmental testing. Tests in these environments were not a requirement under the contract. These environments include the following:

(1) Humidity-freezing

(2) Salt fog

(3) Hard rain

(4) Heat-rain

(5) Humidity-heat

(6) Fungus

(7) Wind loading

(8) High voltage

(9) Thermal response

The facilities used for these tests were similar to those described in Section III (Qualification Testing), with exceptions as noted in the following detailed discussion.

A. HUMIDITY-FREEZING

1. Procedures

This test simulated high humidity followed by freezing. The procedure was based on MIL-STD-202E, Method 106D, except that no vibration test was included. The temperature in the chamber was cycled from ambient to 65°C and 95% relative humidity twice; then the temperature was lowered to -10°C for three hours. The test was repeated for a total of 10 cycles. Modules were installed almost horizontally in the chamber. Droplets of condensed moisture were generally frozen onto the surface of the modules.

2. Equipment and Facilities

The standard 0.9m X 0.9m X 0.9m (3' X 3' X 3') environmental chambers used for qualification testing were suitable for humidity freezing. The other equipment described in Section III was used for this test.

B. SALT FOG

1. Procedures

The salt fog test procedure used was MIL-STD-810C, Test Method 509.1. After suspending the modules vertically in a test chamber, the temperature was raised to 35°C and the humidity to 95%. A concentrated salt solution was sprayed from an atomizing nozzle into the chamber continuously for two days. An electrical performance test was performed within one hour of module removal from the chamber. The electrical test was repeated two days later after dryout.

2. Equipment and Facilities

The salt fog chamber was a large test chamber lined with a non-corrosive plastic-fiberglass composite. An external tank contained concentrated sodium chloride solution, which was drawn from the tank by a pump and ejected continuously into the chamber through an atomizer nozzle. The solution was not recirculated.

C. HARD RAIN

1. Procedures

The hard rain test simulated a 40-mph (18 m/s) wind-driven rain with an average droplet size of 2 mm. No wind was used; water velocity was provided by discharging water under pressure through nozzles. Individual modules were mounted on a motor-driven geared-down shaft parallel to their long axes. Three nozzles mounted at various angles caused water impingement on the modules from the side and ends. Shaft rotation provided exposure of the module to the rain from 360°--front, back, and edges. The water was deionized and provided at a rate of about 20 liters/minute (5 gpm), a much higher rate than terrestrial rainfall. Fifteen minutes of rain exposure were provided. Electrical performance testing was performed in less than one hour after exposure. (Note: Water flow was increased from 20 to 44 l/min and nozzles from 3 to 5 for the 1.2m long Block II modules.)

2. Equipment and Facilities

The hard rain equipment is shown in Figures 6 and 7. The four deionizer tanks shown in Figure 7 provided about 8,000 liters (2,000 gallons) before they had to be exchanged for fresh tanks. This portable water supply stand was used for both hard rain and heat-rain tests. Tap water supply to deionizer tanks was regulated.

3. Test Conditions:

Minutes of exposure	15
Shaft Rotation Rate, rpm	5
Droplet size, avg., mm	2
Drop velocity, avg., m/s	18

D. HEAT-RAIN

The test simulated the effect of a sudden hard rain falling on modules previously heated by a clear-day sun on a warm day.

1. Procedure

The initial heating of the modules could be done outdoors in the sun or indoors under a lamp bank, although all tests reported here were done outside.

When heated outdoors, the test was limited to clear, warm days with low wind. The modules were mounted on a rack which could be tilted and rotated manually for approximately normal incidence to the sun. Thermocouples on the back of each module were connected to a recorder. The modules were allowed to warm in the sun to a stable temperature. The rain was then turned on. The device sprayed the modules with deionized water at a rate of over 2.5 cm (1 inch) per hour. After the modules reached a stable temperature, the water was turned off. The cycle was repeated a total of five times.

2. Equipment and Facilities

Outdoor equipment used for this test is shown in Figure 7 and described in Paragraph C-2. The alternative indoor heater is described in Paragraph E-2.

E. HUMIDITY-HEAT

This test was designed to simulate the effect of a clear, bright sun upon a module following a period of high humidity and/or rain.

1. Procedure

The modules were subjected overnight to high humidity in a chamber at 40.5^{o}C. Chamber temperature was reduced to ambient, and the modules were then quickly put on a rack under an overhead lamp array. The lamps were turned on. Lamp irradiance level was predetermined to achieve maximum module temperature typical in a field installation at full sun on a warm day. Modules were allowed to reach a stable temperature on this rack.