Low-Cost Solar Array Project

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Photovoltaic Module Design, Qualification and Testing Specification

March 24, 1978

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the Department of Energy by agreement with the National Aeronautics and Space Administration.

The JPL Low-cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

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PREFACE

This specification was prepared by the Engineering Area of the Low-Cost Solar Array Project. Inquiries related to details of the document or requests for additional information should be directed to Dr. R. G. Ross, Jr., Engineering Area Manager or Mr. J. C. Arnett, Cognizant Module Design Engineer.

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SECTION I

INTRODUCTION

A. SCOPE

This specification establishes minimum design, qualification and acceptance requirements for terrestrial solar cell modules suitable for incorporation in photovoltaic array applications in the 20kW to 500kW range, such as defined by Department of Energy PRDA EM-D-04-0038. Both mandatory and recommended requirement levels for selected performance criteria have been specified for modules within these arrays. As applicable, the manufacturer/contractor shall be responsible for generation and selection of appropriate design or test levels within the scope of these criteria. Specification of any additional requirements as necessary to satisfy the particular array or system application shall be the responsibility of the manufacturer/contractor. Environmental requirements imposed by this specification are considered to be the minimum level acceptable to DOE.

B. APPLICABLE DOCUMENTS

The following documentation is applicable to the extent specified:

(1) Military: MIL-STD-810 C, Environmental Test Methods, March 10, 1975.

(2) Energy Research and Development Administration: ERDA/NASA/1022-77/16 "Terrestrial Photovoltaic Measurement Procedures" June 1977, Lewis Research Center, Cleveland, Ohio, 44135.

(3) Jet Propulsion Laboratory: LSSA Project Document 5101-21, Revision A, "Rejection Criteria for LSSA Modules", dated August 22, 1977.

SECTION II

DESIGN CRITERIA

Solar cell modules meeting the requirements of this document will be mounted or grouped into an array structure compatible with system design constraints for photovoltaic applications ranging from 20 kW to 500 kW. The module designs shall satisfy the following general design criteria.

A. PERFORMANCE MEASUREMENT CRITERIA

The following standard performance measurement criteria shall be utilized:

(1) Power Output - The power output of individual modules shall be determined per Paragraph IV.A as the product of the module Nominal Operating Voltage (V_{NO}) and the module current measured at V_{NO} under Standard Operating Conditions (SOC), defined as an irradiance level of 100 mW/cm^2 and cell temperature equal to the Nominal Operating Cell Temperature (NOCT).

(2) Nominal Operating Voltage - The nominal operating voltage (V_{NO}) is the reference voltage level at which the modules are designed to provide maximum power output at standard operating conditions (100 mW/cm^2, NOCT). The V_{NO} level shall be selected by the module manufacturer/system designer as a convenient fraction of the system working voltage. For purposes of standardization, a convenient fraction or multiple of 15 volts is suggested.

(3) Nominal Operating Cell Temperature - The Nominal Operating Cell Temperature is the module cell temperature under operating conditions in the Nominal Thermal Environment (NTE) which is defined as:

Insolation = 80 mW/cm^2

Air Temperature = 20 $^{\circ}C$

Wind Average Velocity = 1 m/s

Mounting = Tilted, Open Back, Open Circuit

The NOCT measurement procedure is described in Paragraph IV.B.

B. ELECTRICAL DESIGN REQUIREMENTS

The electrical design of the module shall meet the following requirements:

(1) Electrical Voltage Isolation - All module circuitry, including output terminations, shall be insulated from external surfaces. The manufacturer/contractor shall establish the voltage isolation requirement on the basis of the maximum open circuit voltage of the complete system at an ambient temperature of -20°C, with 100 mW/cm^2 irradiance. The design level shall be set at twice this system voltage plus 1000 V_{DC}.

(2) Electrical Grounding and Safety - In order to minimize electrical hazard to personnel, all modules shall be provided with an external grounding terminal or stud serving as a common grounding point for all exposed external conductive surfaces not part of the module circuitry. A grounding stud is not required for modules designed for systems with operating voltage levels less than 50 volts or for modules without exposed conductive surfaces, unless removal of covers or mounting hardware will expose such surfaces.

(3) Cell String Circuit Reliability/Redundancy - Circuit redundancy features shall be incorporated where cost effective to enhance the reliability and manufacturing yield of completed modules. Design features may include, but are not limited to the following:

(a) Redundant interconnections between solar cells, including redundant cell attachment points.

(b) Series/parallel interconnection of cells within the module.

(c) Integral by-pass diodes within each module.

The decision to incorporate redundancy features shall be based on the expected percent improvement in lifetime/yield and replacement cost as contrasted with the percent increase in module cost/watt. Series/parallel circuit arrangements, when used, shall be designed so that "hot-spot" cell heating does not lead to further module degradation under worst-case-single-cell-failure conditions defined as follows:

(a) The module output is short circuited.

(b) A single representative solar cell is open circuited to represent a single cell failure.

(c) The incident irradiance is 100 mW/cm^2, AM1.5.

(d) The thermal boundary conditions are adjusted so that the equilibrium solar cell temperature outside of the hot-spot region is equal to NOCT + 20°C.

C. MECHANICAL DESIGN REQUIREMENTS

The mechanical design of the module shall meet the following requirements:

(1) Module Geometry - To meet the array/system requirements for mounting, each module shall meet the envelope, mechanical and interface requirements specified by an Interface Control Drawing to be prepared by the manufacturer/contractor, providing as a minimum the following information:

(a) Maximum envelope dimensions and tolerances;

(b) Location of output terminations;

(c) Mounting hole or attachment provisions, dimensions and tolerance;

(d) Illuminated (active) surface dimensions and shadowing or view angle constraints for low-level concentrators;

(e) Nominal electrical performance;

To allow for convenient handling and testing of modules from various suppliers, the maximum module dimensions shall not exceed 48 inches by 96 inches. Suggested standard dimensions and hole locations are provided in Figure 2-1. In this figure the module width may be any dimension up to the 96-inch maximum.

(2) Interchangeability - All modules from a given manufacturer shall be physically and functionally interchangeable. Tolerances on all external module dimensions shall be maintained at a level consistent with module interchangeability. Surfaces, mounting holes and any attachment hardware associated with the attachment interfaces shall be maintained within tolerance specified in the Interface Control Drawing.

(3) Optical Surface Soiling - The illuminated optical surface(s) of the module shall be smooth, and generally free of projections which could promote entrapment of dust and other debris. Particular attention shall be given to selection of materials for the optical surface(s) which will minimize the accumulation of nonremovable contaminants, particulate matter and stains, and will promote self-cleaning by natural processes such as wind and rain.

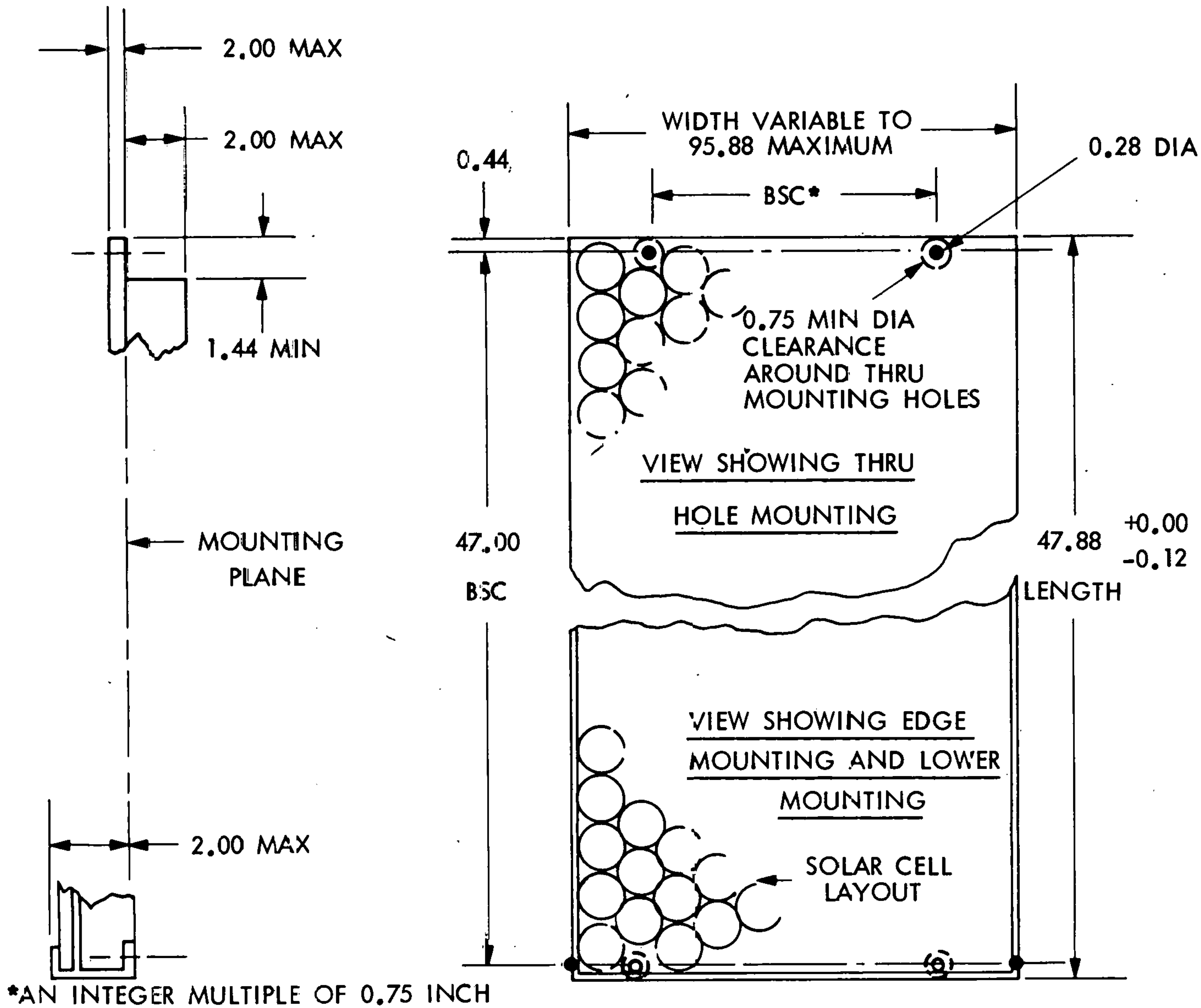

Figure 2-1. Suggested Module Standard Dimensions (all dimensions in inches)

(4) Module Labeling and Identification - Each module shall be identified in a permanent and legible manner with suitable labels or markings specifying the manufacturer's module model number (or drawing) and revision, sequential serial number, year and week of manufacture, and maximum system operating voltage for which the module is designed. Additional information may include the Nominal Operating Voltage and power of the module. The identification shall be installed at a position which is visible from the front (illuminated) side of each module, when installed in the array. The polarity of each electrical termination shall be marked in a permanent and legible manner in a position which is visible when accessing the electrical terminations in a completed array.

D. ENVIRONMENTAL DESIGN REQUIREMENTS

Environments to be considered in assessing possible degradation of module electrical performance and physical properties include: solar exposure (particularly UV); thermal conditions, including freezing and thawing; effects of wind, rain, snow, ice, hail, salt mist, and atmospheric oxidants; dust and debris accumulation, especially nonremovable stains or contamination; and, dynamic loading effects of wind, snow, and hail. As a minimum the module design shall be capable of withstanding exposure to the following environmental test environments:

(1) Thermal cycling from $-40^{\circ}C$ to $+ 90^{\circ}C$ per Test Procedure V.A.

(2) Humidity per Test Procedure V.B.

(3) Mechanical cyclic loading per procedure V.C. The test load level shall be determined by the manufacturer/contractor on the basis of the anticipated application site maximum wind gust velocity. A test level of ± 50 pounds per square foot is common practice.

(4) Twisted mounting surface of 1/4 inch per foot per Test Procedure V.D.

(5) Hail impact testing per Test Procedure V.E. The maximum size hailstones which the module shall withstand shall be determined by the manufacturer/contractor on the basis of an assessment of the hail risk at the intended application site.

The manufacturer/contractor shall establish additional environmental requirements dictated by special environmental conditions at the intended application site.

SECTION III

QUALIFICATION AND ACCEPTANCE REQUIREMENTS

A. PERFORMANCE CHARACTERIZATION REQUIREMENTS

The tests included in this section will be performed to characterize the module performance and to provide a high level of confidence that production modules will function within the specified performance requirements. The characterization testing will be performed in the sequence shown in the flow diagram in Figure 3-1.

(1) Determination of Nominal Operating Cell Temperature

For purposes of providing a measurement of module performance that is representative of the anticipated terrestrial application, all module performance measurements are referenced to the Nominal Operating Cell Temperature (NOCT). NOCT is defined as the average cell temperature in the module under operating conditions in the Nominal Thermal Environment (NTE). The Nominal Thermal Environment is characterized by 80 mW/cm^2 insolation, ambient air temperature of 20°C, average wind velocity of 1.0 m/s, with the module mounted in an open back condition (i.e., not insulated on back side), and electrical output terminations open-circuited. Actual cell temperatures shall be taken at conditions approximating NTE in order to obtain the solar cell NOCT. The NOCT shall be used for all measurements of module performance at Standard Operating Conditions (SOC). The approved techniques for performing the NOCT characterization test are included in Section IV.B.

(2) Initial Electrical Measurement

A minimum of five (5) prototype modules will be used to determine baseline electrical performance.

Measurements will be conducted at the NOCT determined per paragraph III.A.1 and at the nominal operating voltage (V_{NO}) specified by the manufacturer/contractor for the intended application. In addition to obtaining a baseline I-V characteristic curve for each module, the average output power (P_{avg}) at nominal operating voltage shall be calculated from measurements of all prototype samples. Any sample producing less than 90% of this average power shall be replaced by an acceptable module prior to subjecting these modules to the design qualification tests (III.B). The output power determined for each module shall be the calculation base for determining extent of performance degradation during environmental qualification testing.

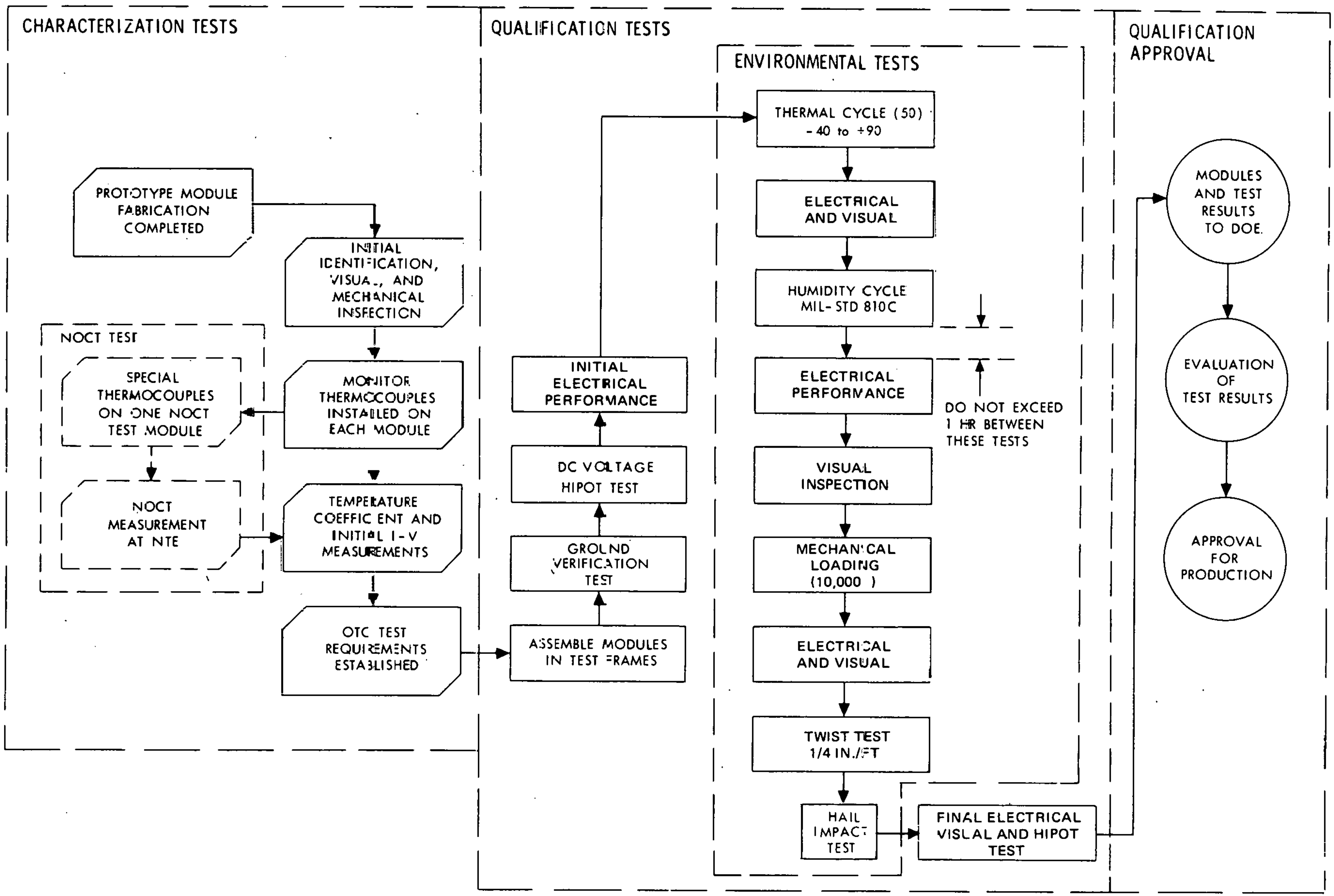

Figure 3-1. Characterization and Qualification Test Flow Plan

B. DESIGN QUALIFICATION TEST REQUIREMENTS

This section specifies the minimum tests that shall be performed by the contractor/manufacturer in order to verify that the modules will satisfy the design requirements of this specification. DOE may, at its option, in addition to the characterization tests described in III.A, perform any or all of these tests on submitted prototype modules prior to approval of the module design for production. Modules shall be mounted on rigid structural frame simulating the selected mounting interface and configuration for all design qualification testing. As a minimum, the following qualification tests shall be performed in the order listed. For clarification, the test sequence is shown in the flow chart (Figure 3-1).

(1) Ground Continuity Test

Each module having exposed external conductive surfaces (i.e. frame or structural members) shall be tested using a suitable continuity tester to verify that electrical continuity exists between all such surfaces and the module grounding point. The maximum resistance to ground shall be 50 milliohms.

(2) Electrical Isolation Test

Each module shall be subjected to a DC voltage withstanding (Hi-Pot) test to assure the capability of the encapsulation system to provide adequate electrical isolation of internal circuitry. The test level shall equal the design level established by the manufacturer per paragraph II.B.1. Leakage current during the test shall not exceed 50 micro amps and there shall be no evidence of arcs, or flashover indicating insulation failure. Modules for which the maximum system voltage does not exceed 50 V_{DC} are exempt from this requirement.

(3) Environmental Testing

Each module shall be subjected to the following environmental exposures, plus any additional special environmental tests which the manufacturer/contractor may require for the intended application. These tests shall be conducted in the order indicated:

(a) Ground Continuity Test.

(b) Electrical Isolation Tests per Procedure V.F.

(c) Thermal Cycling Test per Procedure V.A.

(d) Humidity Cycling Test per Procedure V.B.

(e) Mechanical Cycling Test per Procedure V.C.

(f) Twisted Mounting Surface Test per Procedure V.D.

(g) Hail Impact Test per Procedure V.E.

(h) Electrical Isolation Tests per Procedure V.F.

(i) Final Electrical Performance Test per Section IV.A.

(4) Qualification Pass/Fail Criteria

The output power degradation of each tested module determined after completion of all qualification tests, shall not exceed 5% of the initial electrical performance determined per section III.A.2. The module shall pass the electrical isolation test (Procedure V.F.) when retested at completion of qualification tests. The allowable level of observable cracks or other mechanical degradation (such as delamination of coatings) shall be determined by the manufacturer/contractor. Acceptable performance under the qualification testing requirements is a prerequisite for DOE approval of the module design.

C. MODULE ACCEPTANCE REQUIREMENTS

The contractor shall prepare a "Production Module Acceptance Testing Plan". This document is subject to review and approval by the DOE contract monitoring organization. This document shall indicate how the manufacturer/ contractor intends to screen production modules for verifying production workmanship and for characterizing beginning of life conditions. The testing plan shall include, but not be limited to sampling approach and rationale, and the following minimum test requirements: electrical performance, electrical isolation, and mechanical and visual inspection.

(1) Electrical Performance

Each module shall be measured to determine its current-voltage characteristics (I-V curve). Measurements shall be made in accordance with paragraph IV.A. No module shall be accepted for delivery which produces less than 90% of the Nominal Average Power under Standard Operating Conditions. The Nominal Average Power is defined as the average power at SOC and Nominal Operating Voltage (V_{NO}) of 25 randomly selected modules of the first 200 modules produced.

(2) Electrical Isolation

Each module shall be subjected to a DC Hi-Pot test to assure adequate electrical isolation for safety of operating personnel at system operating voltages.

(3) Mechanical and Visual Inspection

Modules shall be mechanically and visually inspected, on the basis of criteria to be established by the manufacturer, for acceptable/rejectable defects in workmanship and quality. One source of such criteria is JPL LSSA Document 5101-21, Revision A, dated August 22, 1977, entitled "Rejection Criteria for JPL LSSA Modules".

SECTION IV

PERFORMANCE MEASUREMENT PROCEDURES

A. ELECTRICAL PERFORMANCE

Electrical performance measurements shall be referenced to Standard Operating Conditions (SOC) defined as 100 mW/cm^2 AM1.5 irradiance, Nominal Operating Cell Temperature. All procedures, equipment and standards related to measurements shall conform to the latest revision of date of the contract of NASA TM 73702, Terrestrial Photovoltaic Measurement Procedures, dated June 1977. Manufacturer's conformance to this procedure is subject to acceptance by DOE. The reference cell, which shall be supplied by DOE, shall be the only irradiance reference used. Secondary standards or transfer modules shall not be used.

To provide for efficient module testing, module performance may be based on module output at either SOC conditions or at Optional Test Conditions (OTC) defined as 100 mW/cm^2 irradiance, and a cell temperature other than NOCT. When measurements are made at OTC the power output (P) at NOCT cell temperature shall be determined as follows:

$$P = V_{NO} (I_{OTC} + \Delta I) \qquad (1)$$

where

V_{NO} = Module nominal operating voltage at NOCT

I_{OTC} = Module current measured at OTC and at a voltage equal to $(V_{NO} + \Delta V)$ volts.

ΔI = Current temperature correction

= $I @ (NOCT, V') - I @ (OTC, V = V' + \Delta V)$

ΔV = Voltage temperature correction

= $V @ (OTC, I = I' - \Delta I) - V @ (NOCT, I')$

V' = Voltage $\simeq 0.6\ V_{oc}$ @ NOCT

I' = Current $\simeq 0.9\ I_{sc}$ @ NOCT

V_{oc} = Open circuit voltage

I_{sc} = Short circuit current

Determination of the temperature correction factors, ΔI and ΔV, in the above equation shall be based on actual measurements of a minimum of five prototype modules at both Optional Test Conditions and NOCT $\pm$ 2° cell temperature. The current-voltage (I-V) characteristics of each module shall be measured at both conditions. The corresponding I-V curves for the two temperatures may then be overlayed to determine the correction factors. A simultaneous translation of the curves along both current and voltage axes may be made until an accurate match of the curves is accomplished at two points near the maximum power point. The OTC curve should match the NOCT curve at a point where the NOCT current is approximately 90% of I_{sc} (I'), and at a second point where the NOCT voltage is approximately 60% of V_{oc} (V'). The current and voltage shift required to produce the curve match shall be determined for the exact cell temperature difference between tests. The change per degree C for each factor is then calculated and multiplied by the difference between NOCT and the temperature used for OTC. The resulting ΔI and ΔV shall be averaged for the modules tested to establish temperature correction factors to be used when testing modules at other than SOC. Alternate temperature correction procedures such as that provided by computer controlled Large-Area Pulsed Solar Simulator (Xenon source) may be used if approved by DOE.

B. NOMINAL OPERATING CELL TEMPERATURE

1. Purpose

The purpose of this test is to acquire sufficient data to allow an accurate determination of the nominal operating temperatures of the solar cells of a terrestrial solar array module.

By definition, the Nominal Operating Cell Temperature (NOCT) is the module cell temperature under operating conditions in the Nominal Thermal Environment (NTE) which is defined as:

Insolation = 80 mW/cm^2

Air Temperature = 20°C

Wind Average Velocity = 1 m/s

Mounting = Tilted, Open Back, Open Circuit

The NOCT test procedure is based on gathering actual measured cell temperature data via thermocouples attached directly to the cells of interest, for a range of environmental conditions similar to the NTE. The data are then presented in a way that allows accurate and repeatable interpolation of the NOCT temperature.

2. Determination of NOCT

The temperature of the solar cell (T_{cell}) is primarily a function of the air temperature (T_{air}), the average wind velocity ($\bar{V}$), and the total solar insolation (L) impinging on the active side of the solar array module. The approach for determining NOCT is based on the fact that the temperature difference ($T_{cell}-T_{air}$) is largely independent of air temperature and is essentially linearly proportional to the insolation level. Analyses indicate that the linear assumption is quite good for insolation levels greater than about 40 mW/cm^2. The procedure calls for plotting (T_{cell}-T_{air}) against the insolation level for a period when wind conditions are favorable. The NOCT value is then determined by adding T_{air} = 20°C to the value of (T_{cell}-T_{air}) interpolated for the NTE insolation level of 80 mW/cm^2, i.e., NOCT = $(T_{cell}-T_{air})|_{NTE}$ + 20°C.

The plot of (T_{cell}-T_{air}) vs L shall be determined by conducting a minimum of two field tests in which the module being characterized is tested under terrestrial environmental conditions approximating the NTE in accordance with the testing guidelines which follow. Each test shall consist of acquiring a semicontinous record of (T_{cell}-T_{air}) over a one- or two-day period, together with other measurements as required to characterize the terrestrial environment during the testing period. Acceptable data shall consist of measurements made when the average wind velocity is 1 m/s ± 0.75 m/s and with gusts less than 4 m/s for a period of 5 minutes prior to and up to the time of measurement. Local air temperature during the test period shall be 20°C ± 15°C. Using only acceptable data as so defined, a plot shall be constructed from a set of measurements made either prior to solar noon or after solar noon which defines the relationship between (T_{cell}-T_{air}) and the insolation level (L) for L ≥ 40 mW/cm^2.*

When (T_{cell}-T_{air}) is plotted as a function of L for average wind velocities less than 1.75 m/s, results similar to those shown in Figure 4-1 are obtained. For the data shown, the local air temperature was 15.6°C ± 4.5°C and the wind speed varied from zero to less than 4 m/s with an average of 1 m/s. Using the plot of (T_{cell}-T_{air}) vs L, the value of (T_{cell}-T_{air}) at NTE is determined by interpolating the average value of (T_{cell}-T_{air}) for L = 80 mW/cm^2. Using the data in Figure 4-1 as an example, (T_{cell}-T_{air}) at NTE is determined to be 20.2°C. The preliminary value of NOCT is thus 20.2°C + 20°C = 40.2°C.

3. Air Temperature and Wind Correction

A correction factor to the preliminary NOCT for average air temperature and wind velocity is determined from Figure 4-2. This value is added to the preliminary NOCT and corrects the data to 20°C and 1 m/s. $\overline{T}_{air}$ and $\overline{V}$ are the average temperature and wind velocity for the test period.

For the test data shown in Figure 4-1, $\overline{V}$ is 1 m/s and $\overline{T}_{air}$ is 15.6°C. From Figure 4-2, the correction factor is 0°C. The NOCT is therefore 40.2°C.

*The two sets of measurements can be combined into a single set provided the average air temperature of the two sets does not differ by more than approximately 5°C. If the average air temperature is significantly different, the resulting effect appears as an increase in the scatter of the plotted data. As a result the data will be more difficult to fit and a less accurate result is possible.

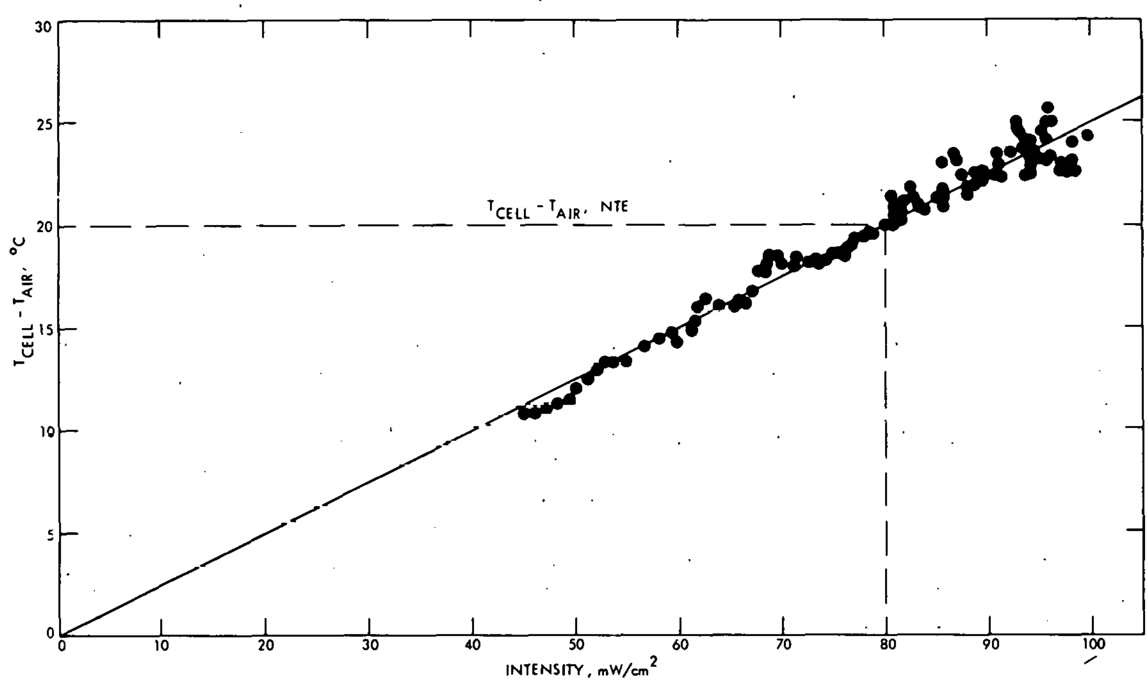

Figure 4-1 Typical Cell Temperature Data

4. Test Geometry

a. Tilt Angle. The plane of the module shall be positioned so that it is normal to the sun ($\pm 5^{\circ}$) at solar noon.

b. Height. The bottom edge of the module shall be 2 feet or more above the local horizontal plane or ground level.

c. Panel Configuration. The module shall be located in the interior of a 1.2 m x 1.2 m (4 ft x 4 ft) panel. Black aluminum panels or other modules of the same design shall be used to fill in any remaining open area of the panel structure. The back of the panel shall be exposed.

d. Surrounding Area. There shall be no obstructions to prevent full irradiance of the module beginning a minimum of 4 hours before solar noon and up to 4 hours after solar noon. The ground surrounding the module shall not have a high solar reflectance and shall be flat and/or sloping away from the test fixture. Grass and various types of ground covers, blacktop, and dirt are recommended for the local

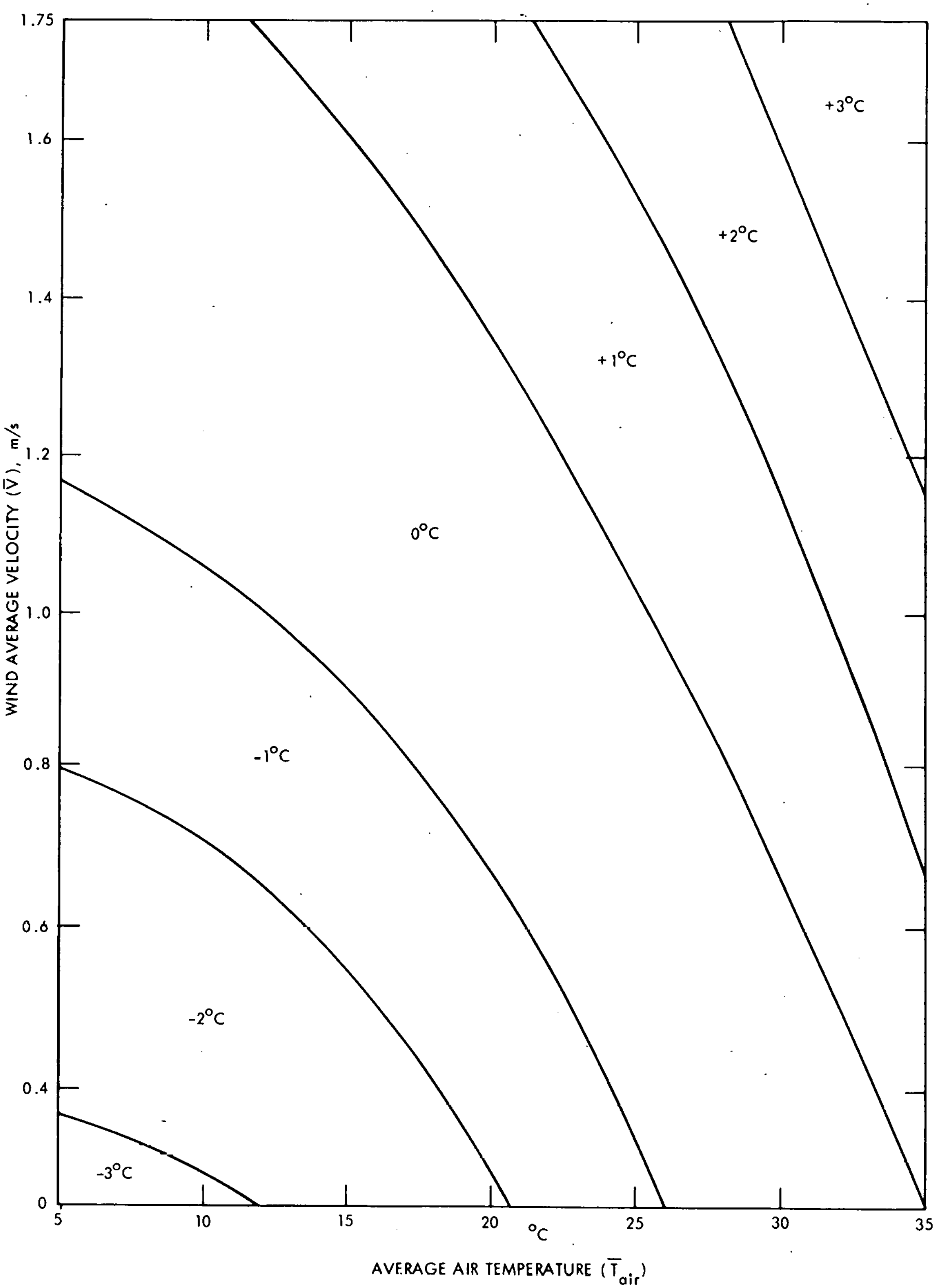

Figure 4-2 NOCT Correction Factor

surrounding area. Buildings having a large solar reflective finish shall not be present in the immediate vicinity. Good engineering judgment shall be exercised to ensure that the module, both front and back sides, is receiving a minimum of reflected solar energy from the surrounding area.

e. Wind Direction. The wind shall not be predominantly from due east or due west; flow parallel to the plane of the array is not acceptable and can result in a lower-than-typical operating cell temperature.

f. Module Electrical Load. Data shall be obtained for a module open-circuit condition corresponding to zero electrical power output.

5. Test Equipment

a. Pyranometer. The total solar irradiance on the active side of the module shall be measured by a pyranometer mounted on the plane of the module and within .3 m (1 foot) of the array. The pyranometer used shall have a traceable annual calibration to a recognized standard instrument and shall be either (1) a temperature-compensated unit which has less than $\pm$ 1% deviation in sensitivity over the range $-20^{o}C$ to $+40^{o}C$, or (2) a unit which incorporates a temperature sensor and has a sensitivity-temperature correction supplied with its calibration.

b. Wind Measurement. Both the wind direction and wind speed shall be measured at the approximate height of the module and as near to the module as feasible.

c. Air Temperature. The local air temperature shall be measured at the approximate height of the module. The measurement shall be made in the shadow of the module and shall be accurate to $\pm$ $1^{o}C$. (Note: An average local air temperature is desired. This is obtained satisfactorily by increasing the thermal mass of the thermocouple by imbedding the thermocouple in a solder sphere or approximately 1/4-inch diameter.) The measurement must be appropriately shielded and vented.

d. Cell Temperature. The temperature of at least two representative interior solar cells shall be measured to $\pm$ $1^{o}C$. Thermocouples shall be 36 gauge, and shall be soft-soldered directly to the back of the cells.

e. Substrate Surface Temperature. The exterior temperature of the rear of the solar module shall be measured to $\pm$ $1^{o}C$ beneath a representative cell and when practical beneath a representative space between cells. Thermocouples shall be 26 gauge, and shall be bonded down with 57-C epoxy or the equivalent.

6. Data Recording

All data shall be printed out approximately every 2 minutes. In addition, solar intensity, wind speed, wind direction, and air temperature shall be continuously recorded.

7. Cleaning

The active side of the solar cell module and the pyranometer bulb shall be cleaned before the start of each test. Dirt shall not be allowed to build up. Cleaning with a mild soap solution followed by a rinse with distilled water has proven to be effective.

8. Equipment Calibration

A calibration check shall be made of all the equipment prior to the start of the test.

SECTION V

TEST PROCEDURES

A. THERMAL CYCLING TEST PROCEDURE

The module shall be subjected to the thermal cycling procedure per Figure 5-1, consisting of 50 cycles with the cell temperature varying between -40°C and +90°C. The temperature shall vary approximately linearly with time at a rate not exceeding 100°C per hour and with a period not greater than 6 hours per cycle (from ambient to -40°C to +90°C to ambient). The module circuitry shall be instrumented and monitored throughout the test to verify that no open circuits or short circuits occur during the exposure.

B. HUMIDITY TEST PROCEDURE

The module shall be subjected to the humidity cycling procedure per Figure 5-2. The module shall be tested in the open circuit condition, but with terminations protected from water condensation. Electrical performance test, per Paragraph IV.A, shall be performed within one hour after removal from the humidity chamber, or within another mutually agreed-upon time period if the testing is subcontracted.

C. MECHANICAL CYCLING TEST PROCEDURE

The module shall be subjected to a cyclic load test in which the module is supported only at the design support points and a uniform load normal to the module surface is cycled 10,000 times in an alternating negative and positive direction. Cycle rate shall not exceed 20 cycles/minute. The module circuitry shall be instrumented to verify that no open circuity or short circuits occur during the test. JPL Document 5101-19 "Cyclic Pressure-Load Developmental Testing of Solar Panels," February 1977, describes techniques suitable to the performance of this test.

D. TWISTED MOUNTING SURFACE TEST PROCEDURE

The module shall be subjected to a twist test by deflection of the substrate to which it is mounted. The deviation from a true flat surface during the test shall be ± ¼ inch per foot measured along either mounting surface as shown in Figure 5-3. The module circuitry shall be instrumented to verify that no open circuits or short circuits occur during the deflection test.

E. HAIL IMPACT TEST PROCEDURE

The module shall be subjected to normal impact loading with the required diameter iceball traveling at terminal velocity for the specified size. Typical hail characteristics are provided in Table 5-1. At least three different points of impact shall be selected to include the test specimen's most sensitive exposed point, and each point will be struck at least 3 times (a minimum of 9 impacts). The most sensitive exposed point on a test specimen must be determined experimentally through destructive testing of a sample panel. Iceballs 1-1/2 times the required diameter shall be fired at candidate sensitive points with increasing velocity until the panel is broken. Several different points on the panel should be broken, and the points broken at the lowest velocities should be used for subsequent testing.

Table 5-1. Typical Hail Characteristics

SIZE in.	WEIGHT* lb.	TERMINAL VELOCITY mph
1/2	0.0021	36
3/4	0.0072	45
1	0.017	52
1-1/4	0.033	58
1-1/2	0.057	63
2	0.136	73
2-1/2	0.266	81
3	0.459	89

*Density of ice taken as 0.9 gm/cm^3

The candidate points selected should include (where applicable) the following:

(1) Corners and edges of the module.

(2) Edges of cells, especially around electrical contracts.

(3) Points of minimum spacing between cells.

(4) Points of support for any superstrate material.

(5) Points of maximum distance from points of support in (4).

Some scatter is expected in hitting a location on a module. Three repeated impacts are required to ensure that a sensitive point has been struck. Error of up to 1/2 inch in the location hit is acceptable. Either pneumatic or spring-actuated guns for projecting the iceballs against the modules are acceptable, however iceball velocity at impact must be controlled to within + 5% of terminal velocity for the required hailstone size. Iceballs shall be generally spherical in shape with a maximum deviation in diameter of $\pm$ 1/8 inch. The iceballs shall be cooled to −10°C $\pm$2° as measured in the compartment where they are stored. The module shall be mounted in a manner representative of that used for actual installation of the module in the array. After each impact, the module shall be inspected for evidence of visible damage. Note that iceballs are the only acceptable hailstone simulation. Dropped steel balls, for example, shall not be used.

F. ELECTRICAL ISOLATION TEST PROCEDURE

The module 'Hi-Pot' test shall be conducted with the output terminations short-circuited. Test leads from a suitable DC voltage power supply shall be connected with the positive lead on the terminals and the negative lead on the module grounding stud.

In the case of modules not required to provide a grounding stud, the mounting structure shall be used as the second test point. Voltage shall be applied at a rate not to exceed 500 V/sec up to the test voltage, and then held at the required test voltage for 1 minute. The module shall be observed during the test for signs of arcing or flashover. Leakage current shall be monitored during the test to verify that leakage current does not exceed 50 microamps.

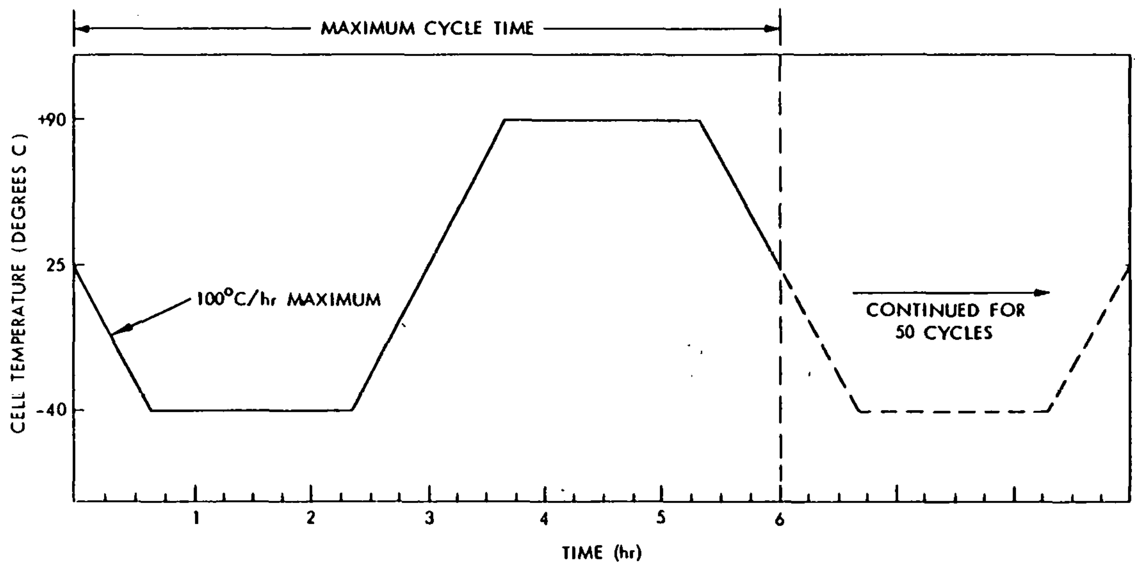

Figure 5-1. Thermal Cycle Test (Shorter cycle time is acceptable if 100°C/hr maximum rate of temperature change is not exceeded. Chamber may be opened at 25 cycles for visual inspection.)

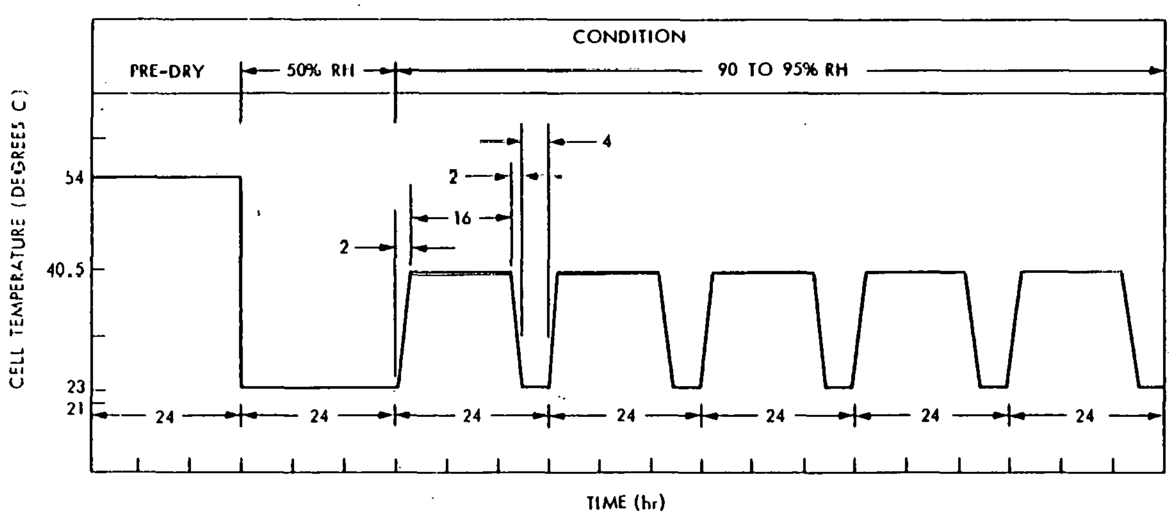

Figure 5-2. Humidity Cycle Test (Suitable procedures for accomplishing this test are described in MIL-STD-810C, Method 507.1, Procedure V.)

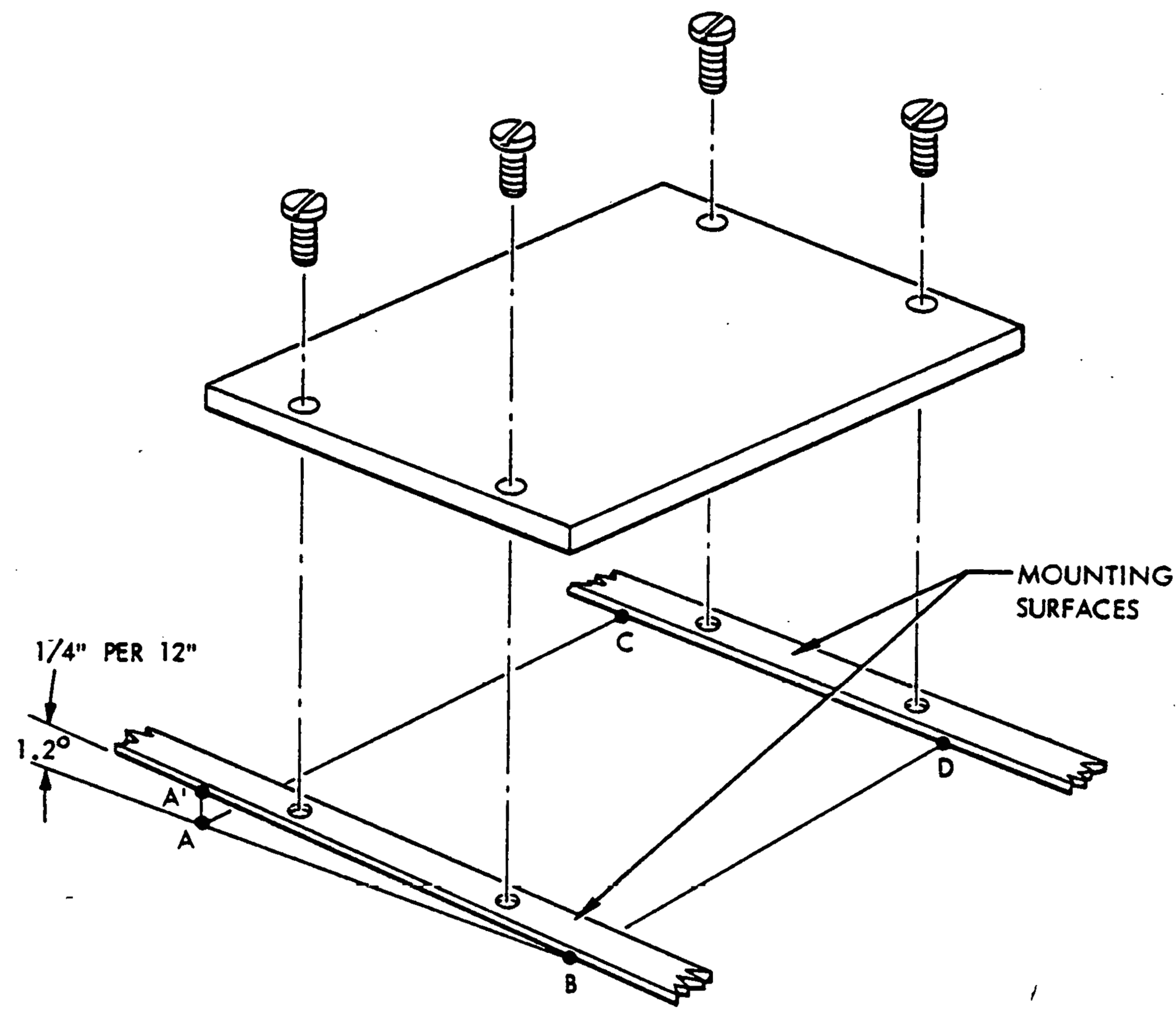

Figure 5-3. Graphical Representation of "Twisted Mounting Surface" Requirement

- Points A, B, C, D are in a Plane
- Point A' is out of Plane the Amount Shown