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"Module Design and Testing"

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These are preliminary lecture notes, intended only for distribution to participants.

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MODULE DESIGN AND TESTING

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1. DEFINITION

A module is the basic building block of a photovoltaic generator. It is defined as the smallest complete environmentally protected assembly of interconnected solar cells.

2. CONSTRUCTION

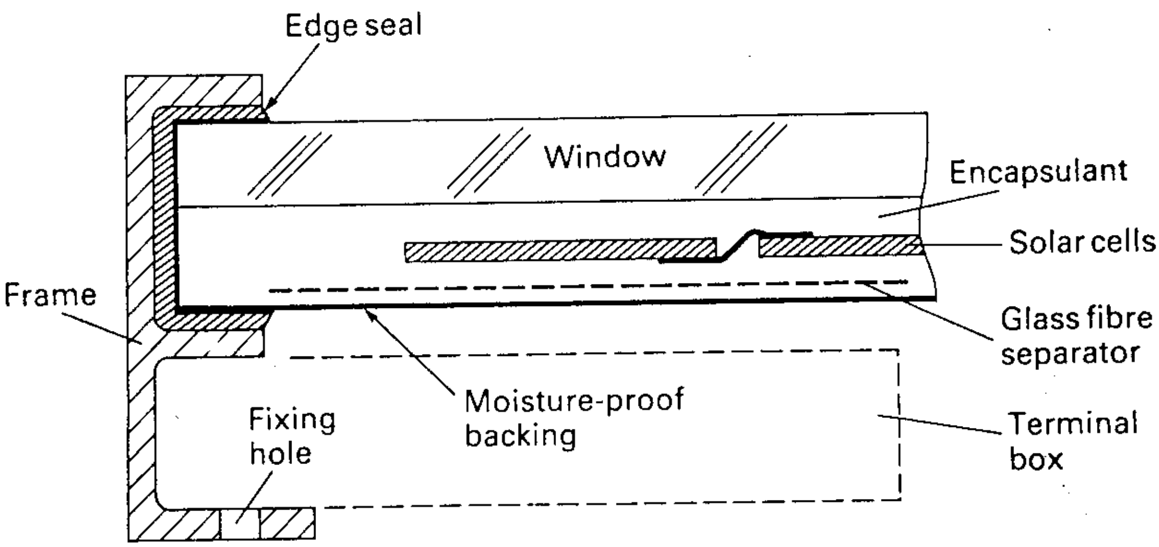

Fig.1 MODULE CONSTRUCTION

Fig.1 shows the principal features of a modern module. The cells are encapsulated between a transparent window and a moisture-proof backing to insulate them electrically and protect them from the weather and accidental damage. Fixing holes or clamps are provided for mounting the module on a supporting structure and a terminal box or pigtail leads for connecting it to other modules or components or the load.

3. DESIGN REQUIREMENTS

1) The module must be capable of reliable, low maintenance operation for many years in the environment for which it is intended. The current target is 30 years.

2) Window and encapsulant materials must be highly transparent to radiation in the response range of the solar cells. The transparency must not be unduly affected by prolonged weathering and exposure to sunlight.

3) The window must have good impact resistance against hailstones and accidental knocks. The surface must be abrasion-resistant, non-staining, hard, smooth and flat, to promote self-cleaning

by wind, rain or spray. It should be free of projections which might provide lodgement for water or dust.

4) The module should be designed to run as coolly as possible.

5) The encapsulation system must resist the permeation or ingress of gases, vapours and liquids. The materials in the assembly must be compatible and the bonds between them capable of withstanding the thermal cycling that will be experienced in the field.

6) Series-connected cells should be well matched (± 2%) in terms of the current output at the maximum power point, as the cell with the lowest current will limit the module output. If two or more strings are connected in parallel, they should be voltage-matched.

7) Intercell connections should be duplicated for reliability.

8) The module must be well insulated against the highest voltages it is likely to experience.

9) It must be mechanically strong enough to protect the fragile cells. It must be capable of accommodating slight imperfections or distortions in the support structure, withstand wind-induced vibrations and take the loads imposed by high winds, snow and ice.

10) The module should be easy to mount, interconnect and replace. Mountings, terminals and connectors should be non-corrosive.

11) Production costs must be kept as low as possible.

As yet, there is no consensus on the optimum size of a module, although nowadays most are in the 30W to 50W range. Small modules are cheaper to replace and have advantages in automated manufacture and testing but large ones (100 - 200W) yield higher module efficiency because there is less wasted space, they need simpler support structures and require less on-site labour during installation. Pre-assembled panels of small modules may prove to be an attractive compromise.

4. A MODERN MODULE

Fig.2 shows an example of a modern module which has been designed to meet these requirements. It consists of 35 series-connected monocrystalline silicon cells and measures 982mm x 436mm x 38.5mm. Its rated power is 45Wp at 16.5V, a voltage suitable for charging a 12V battery.

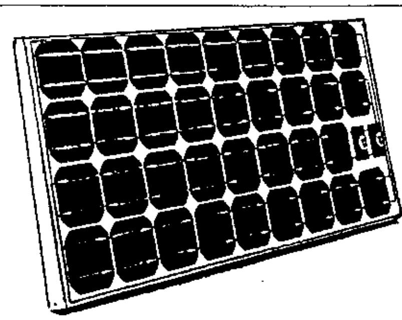

Fig.2 CRYSTALLINE SILICON MODULE

Its main features are :-

Window : Toughened high-transmission glass

Encapsulant: UV-resistant ethylene vinyl acetate (EVA)

Backing : Tedlar/aluminium foil laminate

Frame : Extruded aluminium alloy, anodised

Electrical connections : Screw terminals in rear-mounted box.

The conversion efficiency of this module is 10.5%. This is lower than the cell efficiency, because of the unproductive areas between and around the cells. Modern commercial crystalline silicon modules lie in the range 10% to 13% but 17% has been achieved in recent pilot production.

5. MANUFACTURE

Modules of the type shown in Fig.2 are made in the following way :-

1) The required number of current-matched cells is selected.

2) Interconnections are soldered to the back contacts of the cells, ("cell tabbing").

3) The cells are located in a positioning jig to ensure accurate spacing and the interconnects from the back contact of one cell are soldered to the front contact of the next.

4) Bus ribbons are soldered to the end cells of the string for connection to the output terminals.

5) The connected cell circuit is visually inspected and its electrical performance checked under a simulator.

6) The prepared glass window is washed, rinsed in de-ionised water and dried.

7) The EVA, which comes in the form of soft pliable sheets, is cut to size.

8) The plastic-coated foil backing and a piece of open-weave fibreglass cloth are cut to size.

9) The components of the assembly are laid up in the following order from the bottom :- Backing, fibreglass cloth, EVA, cell circuit, EVA, window.

10) The assembly is subjected sequentially to vacuum (1 mbar), heat (200°C), and pressure (1 atmosphere) in a laminator. This extracts the air, softens the EVA and forces it between the cells and through the fibreglass to form a strong bond. The whole process takes under 10 minutes and is automatically controlled.

11) The assembly is placed in an oven to complete the curing of the EVA.

12) The edges of the laminated assembly are trimmed, sealed with adhesive tape and fitted with a rubber gasket.

13) The frame is fitted around the assembly and the terminal box is installed and connected to the positive and negative ribbons.

14) The completed module is visually inspected and subjected to performance and insulation tests.

All the equipment necessary for a module production line, comprising cell tabber, circuit assembly station, glass preparation station, module lay-up station, laminator, curing oven, final assembly station and test apparatus, is obtainable from specialist suppliers.

6. PERFORMANCE MEASUREMENT

The photovoltaic performance of a module is measured by exposing it at a known temperature to simulated or natural sunlight and tracing its current-voltage (I-V) characteristic, while at the same time measuring the irradiance. The irradiance is monitored, not with a pyranometer, but with a specially calibrated reference cell or module. This automatically relates the measurement to a reference solar spectral irradiance distribution.

For rating purposes, the I-V characteristic is transposed to Standard Test Conditions (STC), which are :-

Irradiance	:	$1000 W/m^2$, with the reference spectral irradiance distribution.
Cell junction temperature	:	$25 \pm 2^\circ C$.

The rated power is defined as the power output at STC when the module is loaded to a voltage at or near the maximum power point (the "rated voltage"). This can be read off from the trasposed characteristic. It is commonly expressed in terms of "peak" watts (Wp).

The International Electrotechnical Commission (IEC) has published the following international standards in a series covering PV performance measurement. Copies are available from IEC headquarters in Geneva or from national standards institutions.

IEC 904-3 (1989)	Measurement principles for terrestrial photovoltaic (PV) solar devices, with reference spectral irradiance data.
IEC 904-1 (1987)	Measurement of photovoltaic current-voltage characteristics.
IEC 891 (1987)	Procedures for temperature and irradiance corrections to measured I-V characteristics of crystalline silicon photovoltaic devices.
IEC 904-2 (1989)	Requirements for reference solar cells.

The reference spectral irradiance distribution specified in IEC 904-3 corresponds to a total irradiance (sun + sky) of $1000 W/m^2$ at AM1.5 on a plane surface tilted at 37° to the horizontal, with 0.2 ground albedo, under specified values of atmospheric water vapour, ozone content and turbidity coefficient.

Standards covering the measurement of relative spectral response, solar simulator requirements and the computation of spectral mismatch error are ready for printing.

7. NOMINAL OPERATING CELL TEMPERATURE (NOCT)

NOCT is defined as the equilibrium mean solar cell junction temperature in an open-rack mounted module in the following Standard Reference Environment :-

Module orientation	:	At normal incidence to the direct solar beam at solar noon.
Total irradiance	:	$800 W/m^2$

Ambient temp.	:	20°C
Wind speed	:	1 m/s
Electrical load	:	Nil (open circuit)

NOCT gives system designers a guide to the thermal design of competing modules and will enable them to choose the one that is likely to run the coollest. The NOCT of most modern modules of the type described above is about 45°C.

8. HOT-SPOT EFFECT

In the early days of photovoltaics, modules sometimes failed through what is known as the "hot-spot effect". This phenomenon can be provoked by partial shadowing or soiling, cracked or mismatched cells or interconnect failures. In extreme cases, it can lead to the melting of solder joints and damage to the encapsulant.

To understand the hot-spot effect, consider a series string of s cells, as in Fig.3 (a). If one of the cells, Y, is shadowed, soiled or damaged so as to reduce the current it can generate to a value below that being generated by the others, it will be forced into reverse bias. This is because all the cells must carry the same current and cell Y can do this only under negative voltage.

In this condition, power is dissipated in cell Y and the amount is equal to the product of the string current and the reverse voltage developed across cell Y. Maximum power will be dissipated in the short-circuit condition, when the reverse voltage across Y is equal to the voltage across the other (s-1) cells in the string. This condition is illustrated for two typea of cell in Figs.3 (b) and (c). The power dissipated in cell Y is shown by the hatched rectangle constructed at the intersection of the reverse I-V characteristic of Y with the mirror image of the forward I-V characteristic of the (s-1) cells. In the case of a cell with high shunt resistance (Fig.3 (b)),the condition of maximum dissipation occurs when it is partially shadowed, to the extent that its reverse characteristic intersects the image of the (s-1) characteristic at its maximum power point. In contrast, with a cell of low shunt resistance (Fig.3 (c)), the condition of maximum dissipation occurs when it is fully shadowed. Note that, in both cases, the I-V characteristic of the complete string is distorted. This provides important clues in fault detection.

In cases where the cell string extends along several modules in series, the reverse voltage developed across cell Y can amount to hundreds of volts. To prevent this happening, it is now common practice to connect a by-pass diode across each module or, in some cases, across sections of large modules, as indicated by the broken line in Fig.3 (a). These diodes are usually housed in the terminal box.

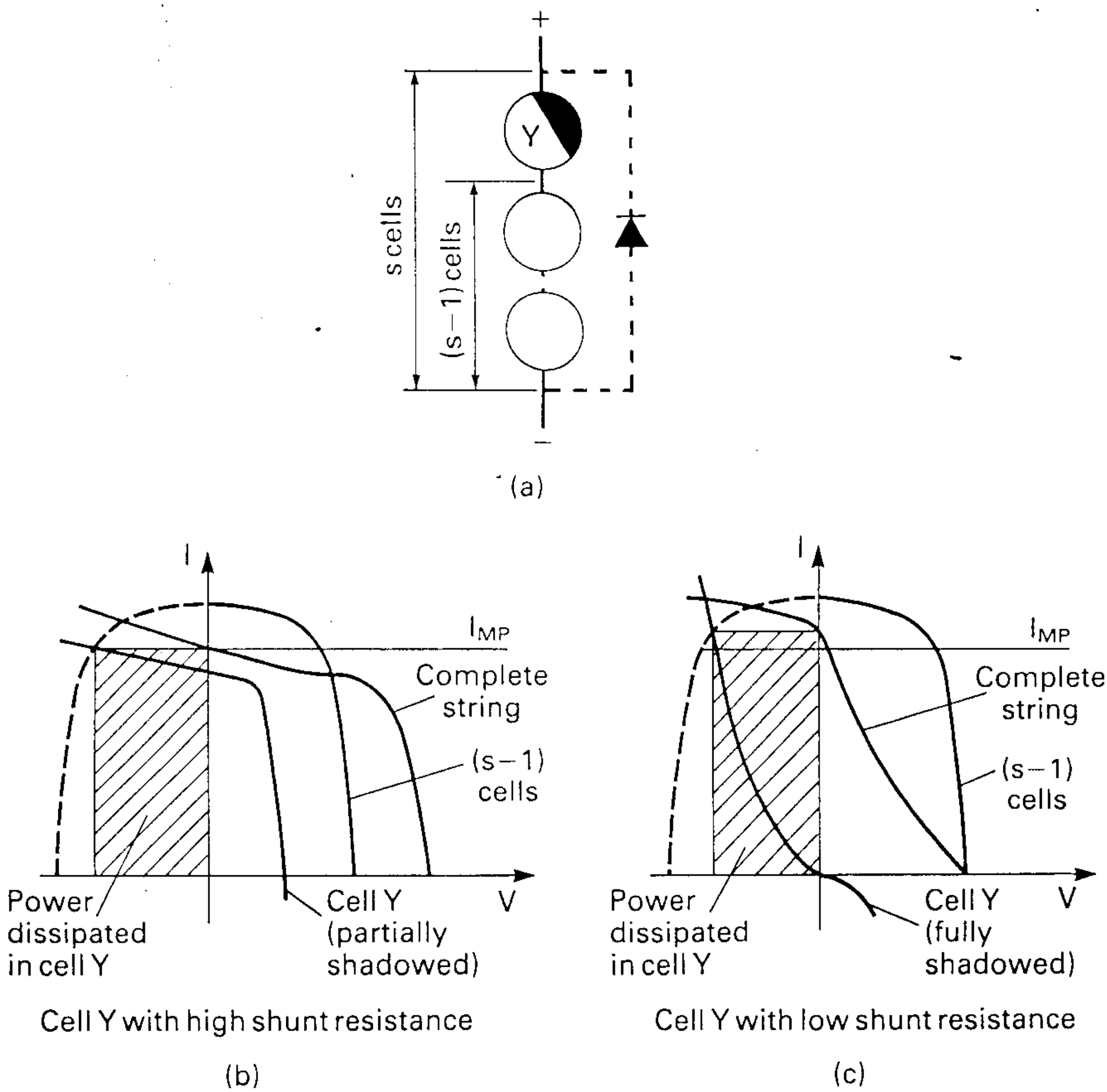

Fig.3 HOT-SPOT EFFECT

9. DESIGN QUALIFICATION

Modules intended for the PV power market should be subjected before series production to design qualification or type approval tests. This is to ensure, within reasonable constraints of cost and time, that the design meets all the specified electrical, mechanical and thermal requirements and will give many years of trouble-free service in its working environment.

The IEC has recently published an international standard for the design qualification of crystalline silicon modules (IEC 1215). For the past two years, the CEC Joint Research Centre (JRC), Ispra, Italy has been using a specification (No. 503) based on the IEC standard in their module qualification tests, which they carry out on a commercial basis.

Fig.4 shows the test sequences from Specification 503.

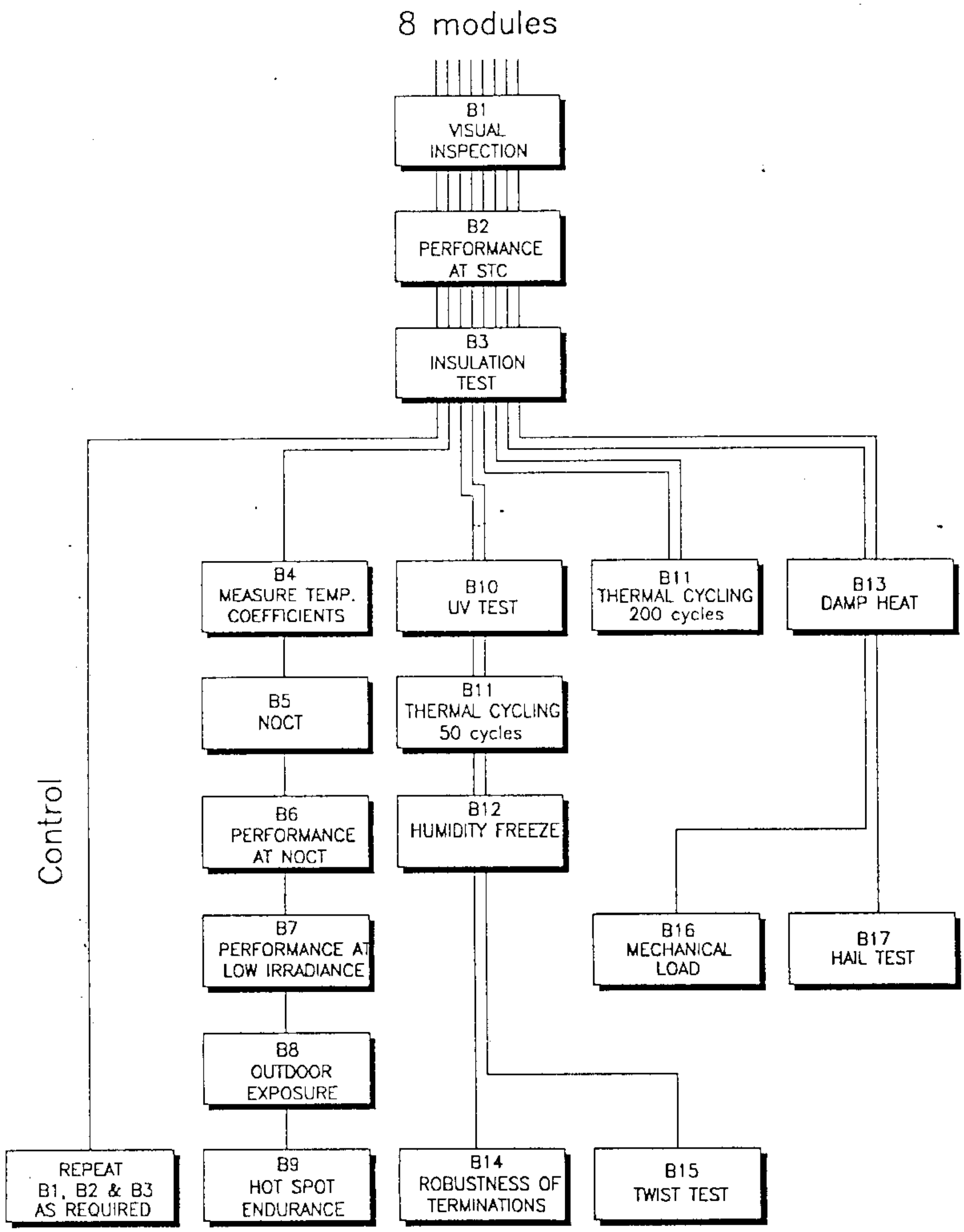

Fig.4 DESIGN QUALIFICATION TESTS

Eight representative test samples are subjected to Visual Inspection, Performance at STC and Insulation Tests. One is then set aside as a control while the others are divided into groups for the various test sequences. After each environmental test, the three initial tests are repeated, to detect any degradation. They are also repeated on the control module, when the tests on the other modules have been completed, in order to check the repeatability of the measurements. Brief descriptions of the tests follow.

Visual Inspection

Each module is inspected for faults which might affect performance or reliability.

Performance Tests

The performance at STC, NOCT and low irradiance (200 W/m^2) is measured as laid down in IEC 904-1 and IEC 891.

Insulation Test

A dc voltage applied to the insulation of the module is gradually increased to a maximum of 1000V plus twice the maximum system voltage. It is maintained at this level for 1 minute. Afterwards, the insulation resistance is measured at 500V. It must be no less than 50 megohms.

NOCT Measurement

The test module is mounted on an open rack in the middle of a plane surface of black aluminium plates or other modules of the same design that extends at least 0.6m beyond the module in all directions. The plane is orientated normal to the direct solar beam at solar noon.

On a suitable clear sunny day with little wind, periodic measurements are taken of cell temperature, T_J, ambient temperature T_{AM}, irradiance, wind speed and wind direction. Data taken at irradiances below 400 W/m^2 or when the ambient temperature and wind conditions do not conform closely enough to the Standard Reference Environment are rejected. From a minimum of 10 acceptable data points covering an irradiance range of at least 300 W/m^2, $(T_J - T_{AM})$ is plotted as a function of irradiance and a straight line is drawn through the points. The value of $(T_J - T_{AM})$ at 800 W/m^2 is taken from this graph and 20°C added to give the NOCT. If necessary, small corrections are made for wind speed and ambient temperature. The entire procedure is repeated on another suitable day and an average taken of the two results.

Outdoor Exposure Test

The module is short-circuited and subjected outdoors to irradiation totalling 60 kWh/m^2.

Hot-Spot Endurance Test

The hottest cell in the test module is selected and the shadowed condition in which this cell dissipates maximum power is determined. In this condition, the module is subjected to 5 cycles, each consisting of 1 hour under a Class C simulator at 1000 W/m^2, followed by 30 minutes in the shade.

UV Test

Two modules, held at 60°C, are subjected to a total UV irradiation of 15 kWh/m^2, as measured by a monitor sensitive only to radiation between 280 and 400 nm. This corresponds to 325 hours exposure in IEC 904-3 reference sunlight.

Thermal Cycling Tests

Two modules are subjected to 50 cycles from -40°C to +85°C in a climatic chamber. Circuit continuity and the integrity of the insulation are continuously monitored. Two modules in another group undergo 200 similar cycles.

Humidity Freeze Test

Two modules are subjected to 10 cycles, each consisting of a minimum of 20 hours at $+85^{\circ}C$ and 85% RH, followed by a minimum of 30 minutes at $-40^{\circ}C$, with no humidity control. Circuit continuity and insulation integrity are continuously monitored.

Damp Heat Test

This consists of subjecting the modules to 1000 hours at a temperature of $85^{\circ}C$ and a relative humidity of 85%.

Robustness of Terminations Test

Tensile, bending and torque tests, as described in IEC 68-2-21, are specified for various types of terminations.

Twist Test

One corner of the module is displaced by a specified amount from the plane of the other three corners, while circuit continuity and insulation resistance are monitored.

Mechanical Load Test

A uniform load of 2400 Pa is gradually applied, first to the front surface of the module and then to the back. This corresponds to the pressure from a 130 km/h wind, with a safety factor of 3 for gusts. The load is increased to 5400 Pa for modules required to withstand heavy accumulations of snow and ice. Electrical continuity is monitored during the test.

Hail Test

Ice balls 25 mm in diameter are fired sequentially at the module window, so as to hit 11 prescribed target points at a velocity of 23 m/s. Other sizes of ice ball from 2.5 mm to 75 mm may be specified to suit the expected environment. Each size has a test velocity based on the terminal velocity of the equivalent size of hailstone.

A module design is judged to have passed the qualification tests if each test sample meets all the following criteria :-

1) Degradation of maximum power at STC does not exceed 5% after each test, nor 8% after each test sequence.

2) No sample has exhibited any open circuit or ground fault during the tests.

3) There is no visual evidence of a major defect.

4) The insulation test requirements are met after the tests.