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TECHNICAL SPECIFICATION

Nanotechnology – Reliability assessment –
Part 2-1: Nano-enabled photovoltaic devices – Stability test

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FOREWORD

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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical Specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC 62876-2-1, which is a Technical Specification, has been prepared by IEC technical committee113: Nanotechnology for electrotechnical products and systems.

The text of this Technical Specification is based on the following documents:

Enquiry draft	Report on voting
113/334/DTS	113/421/RVDTS

Full information on the voting for the approval of this Technical Specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- transformed into an International Standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

Nano-enabled photovoltaics (NePV) is a novel format of photovoltaic technology that can be manufactured in large-area, flexible, thin sheets through solution processing or vapour deposition. Many of the materials involved are nanomaterials and organic semiconductors. They improve the conversion of sunlight into free electrons and support the extraction of the electrons out of the device. Furthermore, nanomaterials are used as boundary layers and act as protective coatings to increase the stability of the PV device. NePV has the potential to provide low-cost renewable energy due to relatively inexpensive, high-throughput manufacturing and low material costs, as a result of the use of low-cost flexible polymeric substrates and packaging films [1]. In addition, NePV is expected to enable new products due to its light weight, flexibility, ability to adapt and tune colour appearance and good efficiency at low light levels, which is conducive to indoor use. Due to these properties NePV is attracting more attention from a variety of groups with a view to improving the efficiency and stability, which has resulted in significant efficiency gains through achievements in materials engineering and process optimization. Concerning stability, however, improvements have not been evident and have not been demonstrated, since standardized testing methods do not exist. In order to commercialize NePV, its stability must be addressed and means for properly comparing stability need to be developed.

Within the scope of this document, NePV refers to photovoltaic devices made from nano-sized material entities, involving a combination of organic and inorganic components and hard and soft matter, sometimes including liquid electrolytes, which are combined using low-cost preparation methods mainly by low-temperature solution processing. The developments of these types of solar cells are primarily through four main directions: organic polymers or small molecules (OPV), dye sensitized solar cells (DSSC), organic/inorganic hybrid solar cells and quantum dot based solar cells. The procedures outlined in this document were designed for NePV, but may be extended to serve as a guideline for early stability assessment for new materials or processes for other photovoltaic technologies as well.

Stability assessment standards define the conditions for a set of stress tests, which address isolated stress factors that can lead to failure in a service environment, in order to allow developers to test under repeatable conditions and to quantitatively compare the stability of photovoltaic devices subjected to these conditions. Several such stability assessment protocols have been proposed by the International Summit on OPV Stability (ISOS) of the OPV community [2,3]. The test conditions defined in this document are based on the ISOS protocol by selecting and modifying the conditions so that they are applicable to a range of NePV devices. True reliability prediction and quantification, however, requires significantly more extensive testing and is not within the scope of this document.

The objectives of this document are to specify the requirements for a general stability assessment standard (SAS) for NePV intended to be used in but not limited to outdoor environments; give direction to developers and engineers developing NePV devices, to guide test laboratories on testing, and to allow for a quantitative stability comparison between different technologies. It is not intended that the requirements specified in this document are to be used for device-type approval or certification. This document simply provides a set of tests for stability assessment and establishes the minimum reporting requirements in order to guide the community through a process of technology improvement by achieving comparable measurements and allowing improvement in device stability to be measured in a qualified and comparable methodology. More specific test conditions for specific devices and/or for specific applications should be developed separately in the future.

The general procedure for the recommended stability testing procedure is to measure device performances before and at certain intervals after applying well defined stresses to NePV devices, in order to track the performance changes due to the applied stresses. Not all recommended tests or stress conditions need to be performed at all stages of development. In the early stages of development a subset of tests which are relatively easy to implement, e.g. dry-heat, damp-heat and light exposure, should be performed first to achieve a first information about the general stability of the tested system. As development of a particular technology progresses and the technology matures, it is recommended to add more sophisticated tests as deemed necessary. Retesting at later stages for regular process control and materials monitoring should also be considered to identify problems. The tests single out certain stress factors that are expected to frequently occur during outdoor exposure. In this document each of the tests is intended to be performed on a new set of devices in order to determine the most detrimental stress factors and aid in an optional failure mode analysis. Sequential tests in various conditions may be performed, but the results are expected to be difficult to interpret. To include the effect of multiple and varied stresses, a laboratory weathering test was adapted and included.

NePV will incorporate many polymeric materials such as binders for nano-materials, substrates, adhesives and packaging materials, which may have a strong interaction with the NePV photovoltaic active layers of the devices under test, and may therefore affect the stability of the device as a whole. To address this, the stability tests in this document are closely related to those used in artificial weathering for polymers. The stability tests outlined in this document could be a component of an exhaustive failure analysis in order to identify the causes of performance losses, which can be the result of many different issues. The procedures described in this document are focused but not limited to nano-enabled PV devices. The document outlines minimal equipment and procedural practices. Stability should always be regarded as a system property. As layers or materials in the system are changed (including in the packaging), retesting will be necessary to ensure that stability is not affected in a detrimental manner.

This document makes no specific recommendation about the materials and device structures to be tested, and can be applied to a wide variety of systems. A generic picture of a device under test is shown in Figure 1.

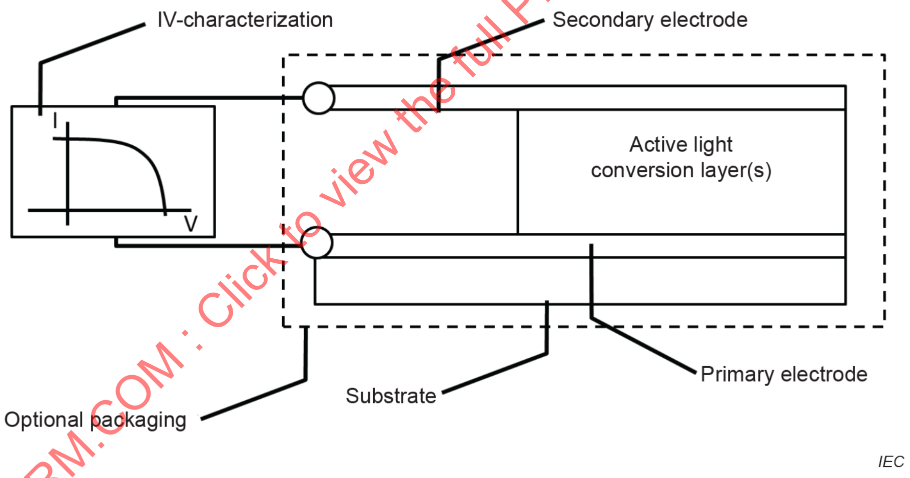

Figure 1 – Generic representation of a device under test during IV-characterization

This document is meant to be a general document that can be applied to all NePV devices. As such, it is not intended to be used as a standard for assembled photovoltaic modules. The stress tests are specific and explicitly defined to establish consistency of test procedures and reporting of reliability information.

NANOTECHNOLOGY – RELIABILITY ASSESSMENT –

Part 2-1: Nano-enabled photovoltaic devices – Stability test

1 Scope

This part of IEC 62876, which is a Technical Specification, establishes a general stability testing programme to verify the stability of the performance of nanomaterials and nano-enabled photovoltaic devices (NePV) devices. These devices are used as subassemblies for the fabrication of photovoltaic modules through a combination with other components. This testing programme defines standardized degradation conditions, methodologies and data assessment for technologies. The results of these tests define a stability under standardized degradation conditions for quantitative evaluation of the stability of a new technology. The procedures outlined in this document were designed for NePV, but can be extended to serve as a guideline for other photovoltaic technologies as well.

NOTE 1 The tests in this document are selected with outdoor use in mind, and as such represent isolated stress factors that devices will be exposed to in outdoor environments. For indoor environments, the stresses faced by the devices in operation are significantly less severe, and not all tests will be applicable. Despite this, the suggested tests provide a means of tracking stability improvements and can provide valuable data during device development.

NOTE 2 The performance of devices will be evaluated before and after the application of the stress tests. The efficiency characterization methods for NePV have not been fully established at present. In the text, notes are therefore added regarding the efficiency characterization. The notes particularly address issues to be discussed in the future for applications such as indoor use, or devices with a slow response or uncommon spectral responses such as tandem cells.

NOTE 3 The scope does not include photovoltaic modules, i.e. the final product. It is only intended to test the technology.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 4892-1, *Plastics – Methods of exposure to laboratory light sources – Part 1: General guidance*

ISO 4892-2:2013, *Plastics – Methods of exposure to laboratory light sources – Part 2: Xenon-arc lamps*

ISO 9370, *Plastics – Instrumental determination of radiant exposure in weathering tests – General guidance and basic test method*

ISO 877-1, *Plastics – Methods of exposure to solar radiation – Part 1: General guidance*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

IEC 60904-1, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*

IEC 60904-9, *Photovoltaic devices – Part 9: Solar simulator performance requirements*

IEC 60068-2-2, *Environmental testing – Part 2-2: Tests – Test B: Dry heat*

IEC 60068-2-78, *Environmental testing – Part 2-78: Tests – Test Cab: Damp heat, steady state*

3 Terms, definitions and abbreviated terms

NOTE A comprehensive nanotechnology vocabulary is under joint development in IEC TC 113 and ISO/TC 229. The vocabulary is being published as different parts of the 80004 Technical Specification. This document is harmonized with the terms and definitions of the 80004 Technical Specification at the time of publication and will be kept harmonized during the maintenance of the document. Definitions not yet specified are taken from scientific literature.

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
nano enabled photovoltaic device
NePV
photovoltaic device in which the conversion of light into electrical energy is enabled or significantly enhanced by nanotechnology

Note 1 to entry Nano-enabled photovoltaics refers to photovoltaic devices and semi-finished products in which one or more of the active light conversion materials are based on a nano-material or semiconductor. NePV includes bulk-heterojunction photovoltaic devices made from organic polymers or small molecules, as well as dye-sensitized solar cells and hybrid solar cells made from both organic and inorganic materials. NePV includes photovoltaic devices made from inorganic nanoparticles as well.

3.1.2
device under test
DUT
representative device used in testing

Note 1 to entry Nano-enabled photovoltaic devices consist of multiple functional layers which are mechanically and electrically connected or are applied (e.g by printing) on a flexible or rigid substrate. For test purposes, samples are recommended to have dimensions that are representative of the technology and allow for a conclusion that a technology can be produced on a larger scale. For this purpose, a suitable minimum aperture area of the NePV devices used in the stability assessment is large enough to test area effects and minimize edge effects (a recommended device area is approx.1 cm^2 or larger in accordance with the standards for efficiency certification of PV-devices). This document is intended to guide and facilitate the development of new technologies, and NePV devices subjected to these tests are intended to be unpackaged or packaged semi-finished devices that are not finished products for the end user.

3.1.3
IV-characterization
measurement of the current-voltage characteristic

Note 1 to entry:

a) Artificial irradiation light sources other than terrestrial solar light are generally used for characterization.

b) For irradiation light sources other than specified in IEC 60904, the total light intensity can be properly determined from the absolute device spectral response and irradiation light spectrum. It is recommended that the irradiation light spectrum and absolute device spectral response is documented in the test report. [1]

c) Due to the nature of NePV as defined in 3.1.1, specifically designed algorithms for IV-characterization may be applied, e.g. [2]. It is recommended that the algorithms are documented in detail in the test report.

3.1.4
conditioned efficiency
light conversion efficiency measured for a device after the conditioning procedure has been applied

Note 1 to entry: A conditioning may need to be applied to devices prior to IV-characterization in order to achieve reproducible efficiency measurements. The conditioning procedure outlined in this document is recommended to be followed to ensure that the device does not change its efficiency during the measurement.

3.1.5
initial conditioned efficiency
efficiency measured for a device after the conditioning procedure has been applied prior to exposure to stress testing

3.1.6
t_{80}
time until the conditioned efficiency has reached 80 % of the initial conditioned efficiency

Note 1 to entry t_{80} refers to the stability criterion that is used to define the end of testing. It is the time that the DUT is subjected to the accelerated ageing conditions in the stress test until its stabilized efficiency has reached 80 % of the initial stabilized efficiency. Recommended duration for the accelerated stress tests is until either t_{80} or a satisfactory exposure level representative for use conditions has been reached.

3.1.7
maximum power point
MPP
point in the IV-characteristic of a photovoltaic device where the product of current and voltage, the output power, achieves its maximum value

[SOURCE: IEC TS 61836:2007, 3.4.42 c), modified.]

3.1.8
visual inspection
procedure to detect any visual defects in the specimen

3.1.9
resistive temperature detector
RTD
temperature measurement device that utilizes the temperature based change in resistance in order to measure temperature

EXAMPLE Commercially available PT100 detectors.

3.2 Abbreviated terms

t_{80}	time to reach 80 % of the initial stabilized efficiency
DUT	device under test
MPP	maximum power point
RTD	resistive temperature detector
SAS	stability assessment standard
NePV	nano-enabled photovoltaics

4 General requirements

4.1 Device

The specific NePV device to which this document relates is typically an individual cell or a subassembly which will be used by a module assembler to fabricate the end product to be sold to the end user. For the purpose of this stability assessment procedure the product does not need to be clearly defined. The purpose of this document is to assess the stability of the technology. The test samples shall be selected randomly from a larger population of samples such that the DUTs are representative for the ensemble of test devices. The physical size of the samples shall be such that the DUTs are large enough to be susceptible to relevant degradation mechanisms.

Regarding the scope of this document, it is assumed that the device is a subassembly.

4.2 Tests

4.2.1 General

All the tests in this document fall into the class of accelerated stability tests. These tests are designed to expose the DUTs to specific well-defined and reproducible stress factors that accelerate critical failure mechanisms. Being able to quantify the response of the devices to the stresses at an early development stage allows for efficient development cycles to improve the stability of the devices under laboratory conditions.

In a later service environment a technology will face different stresses based on the final application that is chosen. To evaluate the stability, a suitable selection of relevant stress factors is important in order to reflect realistic conditions. These stress factors are not so harsh that they will disqualify a technology too early, but are harsh enough to identify weaknesses in a technology and to provide a means to quantify improvement in a development process. An overview of typical stress factors that photovoltaic devices are exposed to is shown in Figure 2.

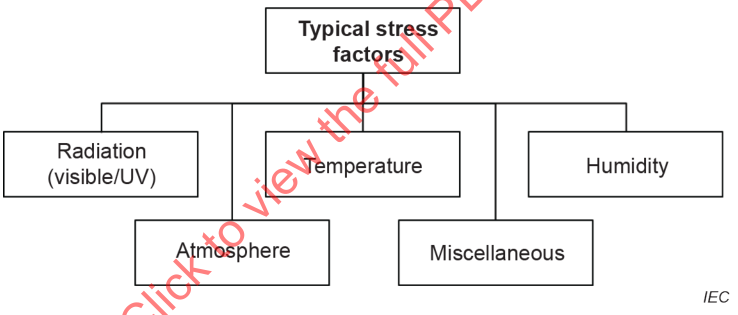

Figure 2 – Overview of stresses that photovoltaic devices are exposed to in service environments

General stability testing is performed by repeated measurements of the performance of DUTs before and after exposure to a stress or a combination of stresses for a period of time. A typical procedure is shown in Figure 3. After initial characterization the device is submitted to the stress environment for a regular time interval. After the exposure interval the device is conditioned for measurement, characterized and then re-exposed. This document provides certain combinations of suggested stresses so that appropriate stress conditions may be selected. In addition it defines the procedures and equipment requirements that are necessary to perform reliable and reproducible stability measurements.

In selecting the appropriate type and severity of stress, knowledge about the most frequent failure modes and failure mechanisms for nano-enabled PV devices is required. For guidance, Annex A lists the most important failure modes for this PV device type. In Annex B the most common failure mechanisms for PV devices are compiled.

Annex C provides guidance for choosing an appropriate temperature for the application of the selected stress factors.

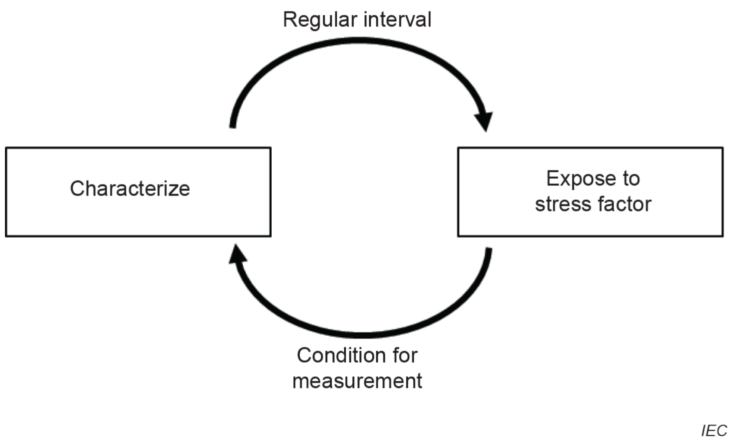

Figure 3 – General stability test procedure

The stress tests that are recommended are combinations of a limited number of well-defined stresses. Table 1 gives an overview of recommended values for the typical stresses which are encountered in many testing protocols.

Table 1 – Summary of the stresses utilized in this document

Stress	Typical values				
Temperature (T)	Ambient	45 °C	65 °C	85 °C	Thermal cycle −40 °C to 85 °C
Humidity (H)	Ambient	0 % RH	50 % RH	85 % RH	
Light (L)	No(dark)	Outdoor	Solar simulator (AM1.5, 1 000 W/m^2)	Lamp	UV
Misc. (M)	Atmospheric effects	Mechanical (pressure, shear)			

Any combination is possible. For acceleration of degradation, however, appropriate combinations should be chosen, which reflect the expected service environment in which the technology is likely to be used later. In addition, it is desirable to have a measurable degradation effect, i.e. the degradation should not be too small which might be the case if too small a measurement area has been chosen for evaluation. For example, test conditions which cause more than 20 % degradation of the performance in the evaluation period are considered to be appropriate.

For photovoltaic devices a number of suggested tests have evolved. An overview of the suggested tests for standard stability testing is shown in Figure 4, in the order of increasing complexity.

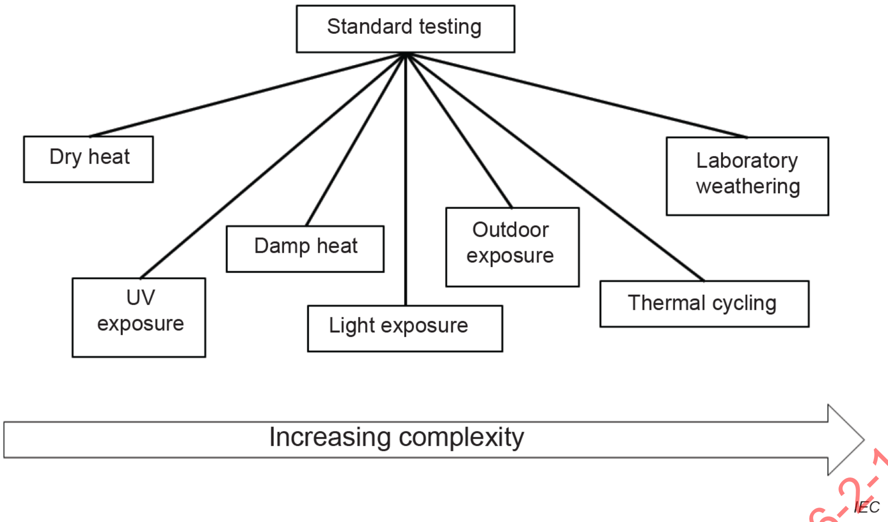

Figure 4 – Overview of the stability assessment tests that are recommended for standard testing in order to assess the stability of NePV

4.2.2 Quantity of specimens

All stability testing shall be performed on statistically relevant sample groups. While the sample groups should generally be chosen as large as possible, a minimum group size is defined to be of five samples for each of the tests performed in the case of small samples. For larger devices (> 25 cm^2) testing may also be performed on smaller groups.

4.2.3 Sequence

The tests are not intended to be performed in sequence. DUTs can only be subjected to one particular test, so that several of the stress tests can be performed in parallel to expedite the testing. To fully assess stability it is recommended that groups of DUTs are subjected to each of the tests. At the initial stages, testing should be performed with the less complex tests. Once acceptable stability levels are achieved, the more complex tests should be performed on new groups of DUTs. Acceptable stability levels are not defined in this document and should be determined by the manufacturer.

4.2.4 Equipment specifications

In order for the testing to be acceptable all tests shall be performed in qualified and calibrated equipment that allows for the monitoring of the environmental conditions.

Detailed specifications are listed in the relevant subclauses or should be taken from the referenced standards.

4.2.5 Test methods

All the test methods recommended in this document, with the exception of outdoor exposure, fall into the class of “accelerated degradation tests”. These tests expose the DUTs to a selected but tightly controlled set of stress parameters in highly specialized testing equipment, in order to perform quantitative stability testing. Since in an outdoor service environment a device is always exposed to a combination of a multitude of these stresses, it is generally recommended to perform additional outdoor weathering of the devices in order to observe whether the failure mechanisms in the outdoor environment are similar to the ones observed in laboratory stability testing, and thus to validate the laboratory tests. An overview of all the recommended tests with the main control parameters is shown in Table 1.

In order to assess the stability of NePV devices it is necessary to perform a number of accelerated degradation and environmental tests. Table 2 gives an overview of the recommended tests within the scope of this document.

Table 2 – Summary overview of the relevant test methods and main control parameters.

Parameter	Test ID and description						
	ST1 **Dry heat**	**ST2** **UV exposure**	**ST3** **Damp heat**	**ST4** **Light exposure**	**ST5** **Outdoor exposure**	**ST6** **Laboratory weathering**	**ST7** **Thermal cycling**
Light	None	UV	None	Daylight, (600 to 1 000) W/m^2	Ambient	Daylight, (600 to 1 000) W/m^2	None
Temperature	45 °C 65 °C [a] 85 °C	65 °C	45 °C 65 °C 85 °C [a]	65 °C	Ambient	38 °C	−40 °C to +85 °C
Humidity	Ambient	Ambient	85 % RH	Ambient	Ambient	50 % RH/ water spray	Ambient
Environment	Oven	UV chamber	Climate chamber	Light soak chamber	Outdoor	Weathering instrument	Climate chamber
Load	None	None	None	Passive or Active, MPP	Passive or Active, MPP	Passive or Active, MPP	None

[a] Underline indicates the preferred temperature for that test.

4.3 Measurements

4.3.1 General

In order to obtain representative and comparable data, all measurements should be performed with qualified and calibrated data acquisition equipment. For specifics, refer to IEC 60904 (all parts).

4.3.2 Conditioning

To stabilize the electrical characteristics of NePV devices undergoing testing, a conditioning by means of natural sunlight or simulated solar irradiation may be necessary prior to IV-characterization. Conditioning shall be performed with a class BCB solar simulator or better, in accordance with IEC 60904-9, or natural sunlight. Conditioning requires a suitable reference device, with integrator, for monitoring the irradiation, which means mounting the devices co-planar with the reference device and monitoring the temperature of the device(s) to an accuracy of ±2 °C.

For conditioning the following procedure should be applied.

a) Attach the monitoring equipment to the devices and mount them, as recommended by the manufacturer, with the reference device in the test plane of the simulator.

b) When using a solar simulator, use the reference device to set the irradiance between 800 W/m^2 and 1 000 W/m^2. Record the irradiance.

c) During the simulator exposure, the device temperatures shall stay in the range 25 °C ± 2 °C.

d) Record the IV-characteristic repeatedly in 10 min intervals. The devices are considered conditioned when in a 10 min interval less than 2 % relative difference in efficiency between two successive IV-characterizations is achieved, while the devices are kept under AM1.5 illumination in the solar simulator at constant temperature. This procedure should also be followed for the initial measurement prior to stability testing.

e) Report the irradiation dose and exposure time required for the conditioning procedure as well as any further conditioning applied to the devices.

If multijunction NePV devices are conditioned, each pn junction shall meet the described stability requirement. Thus, the IV-characteristics shall be measured with different appropriate spectra.

4.3.3 Visual inspection

Carefully inspect each specimen under an illumination of not less than 1 000 lux for the following defect conditions:

- cracked, bent, misaligned or torn external surfaces;
- faulty interconnections or joints;
- voids in, and visible corrosion of any of the thin film layers of the active circuit;
- visible corrosion of output connections, interconnections and busbars;
- failure of adhesive bonds;
- bubbles or delaminations forming a continuous path between a cell and the edge of the module;
- tacky surfaces of plastic materials;
- any other conditions which may affect performance.

Make note of and/or photograph the nature and position of any cracks, bubbles or delamination, etc., which may worsen and adversely affect the module performance in subsequent tests.

4.3.4 Data collection

Data acquisition during stability testing shall fulfil the following minimum requirements.

a) Minimum rate of data acquisition

Initial interval of one measurement per day for the first five days; thereafter devices should be measured weekly.

b) Temperature measurement

Use a PT100 (or similar) or thermocouple affixed to the back of at least one representative device/module in illuminated tests or calibrate the temperature of a representative device/module against a BST. For other tests monitor chamber temperature.

c) IV curves

Measure following IEC 60904-1. Due to the nature of NePV as defined in 3.1.1, specifically designed algorithms to trace the IV curve may have to be applied. The algorithms should be documented in detail in the test report.

d) MPP

Obtain the maximum power point directly from the IV curve by multiplication of current I and voltage U for each measurement point and identification of the maximum of the product power $P = U \times I$.

4.3.5 Pass/fail criteria

The purpose of the testing is to quantify the stability of nano-enabled photovoltaic devices subject to controlled stability tests. For this purpose no pass/fail criteria are defined within this document. The result of the testing is a quantified stability criterion defined as t_{80}, the time it takes in a particular test for the device to reach 80 % of the initial stabilized (conditioned) efficiency.

5 Test methods

5.1 ST1 – Dry heat

5.1.1 Purpose

To determine the ability of the DUT to withstand thermal stress.

5.1.2 Temperature/humidity

The test shall be carried out in accordance with IEC 60068-2-2. Typical temperatures used in this test are 45 °C, 65 °C and 85 °C to test for degradation mechanisms. Testing at 85 °C is recommended. Termination of the test is either t_{80} or user defined.

5.1.3 Data logging

Periodic with an initial interval of one measurement per day for the first five days, with no more than six hours interruption of stress exposure per measurement. Thereafter devices should be measured weekly with no more than six hours interruption of stress exposure. The total exposure time in stress test shall be recorded in hours. IV-characterization under calibrated solar simulation is necessary. Devices shall be stored under open circuit condition. Allow cells to equilibrate to standard conditions before efficiency measurements.

5.1.4 Output

Conditioned efficiency or maximum power output should be extracted from IV-measurements and plotted over time. Then the burn-in range, the initial conditioned efficiency, the time to t_{80}, and the decay rate of the performance should be extracted from the plot and reported. Visually inspect the device and record any changes.

5.1.5 Required equipment

a) Calibrated AM1.5 solar simulator according to IEC 60904-9 for the indoor IV measurements. For IV-measurement, refer also to the note in 3.1.3.

b) Furnace with a temperature stability of ± 2 °C, Temperature logger in accordance with IEC 60068-2-2.

5.2 ST2 – UV exposure

5.2.1 Purpose

Device stability test under ultra-violet (UV) radiation to identify the materials/parts of the device that are susceptible to UV degradation.

5.2.2 Radiation source

A UV source capable of producing UV irradiation with an irradiance uniformity of ± 5 % over the test plane of the device(s) with no appreciable irradiance at wavelengths below 285 nm and above 400 nm. The test chamber should be equipped with instrumentation capable of measuring the irradiation of the UV radiation produced by the UV source at the test plane of the device(s), within the wavelength ranges of 285 nm to 400 nm with an uncertainty of ± 15 %. Devices shall be subjected to UV irradiation in the wavelength range between 285 nm and 400 nm, from 5 % to 7 % within the wavelength band from 285 nm to 320 nm, 30 % to 40 % from 320 nm to 340 nm, while maintaining the device temperature within the prescribed range. In the proposed device test plane the UV-radiation intensity shall not exceed 250 W/m^2 (i.e. about five times the natural sunlight level) at wavelengths between 285 nm and 400 nm and it shall be uniform to ± 15 % over the test plane.

5.2.3 Temperature/humidity

Equipment to control the temperature of the device while it is irradiated by UV radiation. The equipment should be capable of maintaining the device at a constant temperature of 65 °C ± 5 °C. The temperature of the device(s) shall be measured to an accuracy of ± 2 °C. The temperature sensors shall be attached to the front or back surface of the device, near the middle. Measurement of the temperature of a reference device instead of all individual DUTs is acceptable. Humidity is not controlled.

5.2.4 Data logging

Periodic with an initial interval of one measurement per day for the first five days, with no more than six hours interruption of stress exposure per measurement. Thereafter devices should be measured weekly with no more than six hours interruption of stress exposure. The total exposure time in stress test shall be recorded in hours. IV-characterization under calibrated solar simulation is necessary. Devices shall be stored under open circuit condition. Cells should be allowed to equilibrate to standard conditions before efficiency measurement.

5.2.5 Output

Conditioned efficiency or maximum power output shall be extracted from IV-measurements and plotted over time. Then the burn-in range, the initial conditioned efficiency, the time and irradiation dose to t_{80}, and the decay rate of the performance shall be extracted from the plot and reported. The results of the visual inspection of the device, in particular any changes, shall be recorded.

The test may be terminated when 15 kWh/m^2 total light exposure has been reached. In this case, the final performance should be reported.

5.2.6 Required equipment

a) Calibrated AM1.5 solar simulator according to IEC 60904-9 for the indoor IV measurements. For IV-measurement refer also to the note in 3.1.3.

b) UV-chamber capable of satisfying the requirements in 5.2.2 and 5.2.3.

5.3 ST3 – Damp heat

5.3.1 Purpose

To determine the ability of the DUT to withstand the effects of long-term penetration of humidity at elevated temperature.

5.3.2 Procedure

The test shall be carried out in accordance with IEC 60068-2-78 with the provisions given in 5.3.3 to 5.3.6.

5.3.3 Temperature/humidity

Three typical combinations (45 °C/85 % RH, 65 °C/85 % RH, 85 °C/85 % RH). Choose condition according to stability of device to allow for reasonable experimental length and data density.

5.3.4 Data logging

Periodic with an initial interval of one measurement per day for the first five days, with no more than six hours interruption of stress exposure per measurement. Thereafter devices should be measured weekly with no more than six hours interruption of stress exposure. Total exposure time in stress test shall be recorded in hours. IV-characterization under calibrated solar simulation is necessary. Devices are stored under open circuit condition. Allow cells to equilibrate to standard conditions before efficiency measurement.

5.3.5 Output

Conditioned efficiency or maximum power output should be extracted from the IV-measurements and plotted over time. Then the burn-in range, the initial conditioned efficiency, the time to t_{80}, and the decay rate of the performance should be extracted from the plot and reported. The results of the visual inspection of the device, in particular any changes, shall be recorded.

5.3.6 Required equipment

a) Calibrated AM1.5 solar simulator according to IEC 60904-9 for the indoor IV measurements. For IV-measurement refer also to the note in 3.1.3.

b) Climate-chamber in accordance with IEC 60068-2-78.

5.4 ST4 – Light exposure

5.4.1 Purpose

To determine the ability of the DUT to withstand long-term exposure to spectral radiation with a spectral distribution similar to the radiation of the sun.

5.4.2 Light source

Xenon, sulfur lamp or LED light with (600 to 1 000) W/m^2 or alternatively a class “CCC” solar simulation light source (i.e. the most relaxed specification regarding spectral match, spatial and temporal uniformity) in accordance with IEC 60904-9. It is preferable to use constant/uniform irradiation. The intensity of every lamp can diminish over the course of experiments and may have significant spatial variations in the intensity, so the irradiation and spectrum should be monitored across devices and recorded over the course of experiments. The spatial variation of a system across a device or module should be estimated and reported, but can be assumed to remain relatively constant over the course of an experiment.

Light intensity should be monitored over time and should not vary by more than ±10 %. Intensity monitoring between 300 nm and 400 nm is sufficient for xenon or sulfur lamps, for LEDs the full applicable wavelength range.

5.4.3 Devices and load condition

Devices should be set perpendicular to the beam of the lamp with an adjustable distance. The devices should be connected to either an active or a passive load. In the case of a passive load the resistive load should be chosen such that the device is at MPP at T_0. In case of an active load the resistance of the load should be kept at values to operate the device at MPP. The interval of MPP tracking can be in the range 1 s to 1 day.

5.4.4 Temperature

A PT100 (RTD) or thermocouple temperature sensor should be attached to the back side of a device to monitor the temperature. The offset between the real temperature and the detected temperature is not significant in this context. Use of black panel temperature or black standard temperature to monitor temperature is sufficient. The device temperature should be calibrated in that case. The device's temperature may be controlled by a cooling stage.

5.4.5 Humidity at ambient conditions

Ambient conditions are to be controlled to be within 30 % to 60 % RH at a room temperature of 16 °C to 30 °C.

5.4.6 Data logging

Periodic with an initial interval of one measurement per day for the first five days, with no more than six hours interruption of stress exposure per measurement. Thereafter devices should be measured weekly with no more than six hours interruption of stress exposure. The total exposure time in stress test shall be recorded in hours. The IV-characterization under calibrated solar simulation is required. Devices shall be stored under open circuit condition. Cells shall be allowed to equilibrate to standard conditions before the efficiency measurement.

5.4.7 Output

Conditioned efficiency or maximum power output should be extracted from IV-measurements and plotted over time. Then the burn-in range, the initial conditioned efficiency, the time and irradiation dose to t_{80}, and the decay rate of the performance should be extracted from the plot and reported. The results of the visual inspection of the device, in particular any changes, shall be recorded.

5.4.8 Required equipment

a) Calibrated AM1.5 solar simulator according to IEC 60904-9 for the indoor IV measurements. For IV-measurement refer also to the note in 3.1.3.

b) Calibrated lamp with intensity logger, temperature logger. Standard equipment that combines these functions is recommended. Provisions of ISO 4892-1 and ISO 4892-2 should be observed.

5.5 ST5 – Outdoor exposure

5.5.1 Purpose

To determine the ability of the DUT to withstand long-term exposure to outdoor conditions and to reveal any synergistic degradation effects which may not be detected by laboratory tests. All outdoor exposures shall be performed in accordance with ISO 877-1.

5.5.2 Locations

Latitude/longitude, elevation, start date, and duration of exposure shall be recorded and reported. The DUT shall be mounted facing true south on the northern hemisphere and facing true north on the southern hemisphere and match local latitude. It is desirable to perform testing in various benchmark locations (e.g. arid, subtropical, coastal, high altitude, pollution) under conditions conforming to general open-air climates, as defined in IEC 60721-2-1 [4]. Devices shall be protected from any shadow sources, except for clouds.

5.5.3 Solar irradiance

A pyranometer with an uncertainty of less than ±50 W/m^2 or a calibrated reference cell shall be used to monitor the irradiance at the point of exposure of the specimens, with an in-plane orientation. Other spectrally sensitive irradiance sensors are not necessary.

5.5.4 Devices

Devices should be mounted co-planar with the irradiation measurement device.

5.5.5 Temperature

A PT100 (RTD) or thermocouple temperature sensor should be attached to the back side of a reference device to monitor the temperature. The offset between the real temperature and the detected temperature is regarded as irrelevant for this testing.

5.5.6 Load condition

A resistive load shall be connected to the device. The resistive load shall be selected such that the device will operate at MPP at T_0. Alternatively, an active load may be connected to the device. In the case of an active load the device should be operated at MPP.

5.5.7 Humidity/wind

Local humidity and wind conditions (direction and speeds) shall be recorded and reported.

5.5.8 Data logging

Devices shall be exposed outdoors and brought inside for characterization under standardized conditions periodically. Recommended intervals for this are weekly or monthly. As an alternative, radiation doses may be defined as intervals for characterization.

5.5.9 Output

Conditioned efficiency or maximum power output should be extracted from IV-measurements and plotted over time. Then the burn-in range, the initial conditioned efficiency, the time and irradiation dose to t_{80}, and the decay rate of the performance should be extracted from the plot and reported. The results of the visual inspection of the device, in particular any changes, shall be recorded.

5.5.10 Required equipment

a) Calibrated AM1.5 solar simulator according to IEC 60904-9 for the indoor IV measurements. For IV-measurement refer also to the note in 3.1.3.

b) Pyranometer or calibrated reference cell, temperature logger and equipment in accordance with ISO 877-1.

5.6 ST6 – Laboratory weathering

5.6.1 Purpose

To determine the effect of solar radiation simulated by a laboratory light source, heat and moisture acting simultaneously on the DUT, in order to induce chemical and physical changes as they occur during natural ageing processes, in an accelerated way. General guidance and specific instructions on how to perform an accelerated weathering test using an appropriately filtered xenon-arc light source are provided in ISO 4892-1 and ISO 4892-2.

5.6.2 Temperature/humidity/light

The following test parameters shall be used in accordance with ISO 4892-2.

Spectral power distribution: Spectral irradiance of xenon-arc or carbon-arc lamps with daylight filters according to ISO 4892-2:2013, Table 1 (method A).

The exposure parameters should be chosen according to ISO 4892-2:2013, Table 3, cycle 1. An overview of this test cycle is represented in Table 3.

Table 3 – Exposure parameters according to ISO 4892-2:2013, Table 3, cycle 1

Exposure period	Irradiance		Black standard temperature °C	Chamber temperature °C	Relative humidity %
	Broadband [(300 to 400) nm] W/m^2	Narrowband [340 nm] W/(m^2 nm)			
102 min dry	60 ± 2	0,51 ± 2	65 ± 3	38 ± 3	50 ± 10
18 min water spray	60 ± 2	0,51 ± 2	–	–	–

5.6.3 Devices

Devices shall be mounted co-planar with the irradiation measurement device.

5.6.4 Load condition

The devices shall be placed under light with a passive load. The resistive load should be chosen such that the device is at MPP at T_0. Alternatively testing may be performed at open circuit conditions.

5.6.5 Data logging

Periodic with an initial interval of one measurement per day for the first five days, with no more than six hours interruption of stress exposure per measurement. Thereafter devices should be measured weekly with no more than six hours interruption of stress exposure. The total exposure time in stress test shall be recorded in hours and cycles. IV-characterization under calibrated solar simulation is required. Cells shall be allowed to equilibrate to standard conditions before efficiency measurement.

5.6.6 Output

Conditioned efficiency or maximum power output should be extracted from IV-measurements and plotted over time. Then the burn-in range, the initial conditioned efficiency, the time and irradiation dose to t_{80}, and the decay rate of the performance should be extracted from the plot and reported. The results of the visual inspection of the device, in particular any changes, shall be recorded.

5.6.7 Required equipment

a) Calibrated AM1.5 solar simulator according to IEC 60904-9 for the indoor IV measurements. For IV-measurement refer also to the note in 3.1.3.

b) Apparatus in accordance with ISO 4892-2 capable of measuring and controlling irradiance, chamber air temperature, black standard temperature, and relative humidity, as well as providing cyclic water spray. All sensors for measurement of irradiance, temperature, or humidity shall be operated and calibrated according to ISO 4892-1, ISO 4892-2, and ISO 9370.

5.7 ST7 – Thermal cycling

5.7.1 Purpose

To determine the ability of the module to withstand thermal mismatch, fatigue and other stresses caused by repeated changes of temperature.

5.7.2 Temperature/humidity

The temperature cycle from IEC 61646 shall be used. The DUTs shall be cycled between module temperatures of −40 °C ± 2 °C and +85 °C ± 2 °C, in accordance with the profile in Figure 5. The rate of change of temperature between the low and high extremes shall not exceed 100 °C/h and the module temperature shall remain stable at each extreme for a period of at least 10 min. The cycle time shall not exceed 6 h. Humidity is not controlled. Cycle time and actual conditions shall be reported. Ambient conditions and the actual humidity shall be recorded and reported.

5.7.3 Data logging

Periodic with an initial interval of one measurement after every 10 cycles, with no more than six hours interruption of stress exposure per measurement. Thereafter devices shall be measured every 50 cycles with no more than six hours interruption of stress exposure. Total exposure time in stress test shall be recorded in hours and cycles. IV-characterization under calibrated solar simulation is required. Devices are to be stored under open circuit condition. The DUTs shall be allowed to equilibrate to standard conditions before efficiency measurement.

5.7.4 Output

Conditioned efficiency or maximum power output should be extracted from IV-measurements and plotted over the number of cycles. Then the burn-in range, the initial conditioned efficiency, the time and irradiation dose to t_{80}, and the decay rate of the performance should be extracted from the plot and reported. The results of the visual inspection of the device, in particular any changes, shall be recorded.

5.7.5 Required equipment

a) Calibrated AM1.5 solar simulator according to IEC 60904-9 for the indoor IV measurements. For IV-measurement refer also to the note in 3.1.3.

b) Climate chamber with automatic temperature control, means for circulating the air inside and means to avoid condensation on the device(s) during the test, capable of subjecting one or more devices to the thermal cycle in Figure 5.

c) Means for mounting or supporting the module(s) in the chamber, so as to allow free circulation of the surrounding air. The thermal conduction of the mount or support shall be low, so that, for practical purposes, the device(s) are thermally isolated.

d) Means for measuring and recording the temperature of the device(s) to an accuracy of ±1 °C.

e) Means for monitoring, throughout the test, the continuity of the internal circuit of each device.

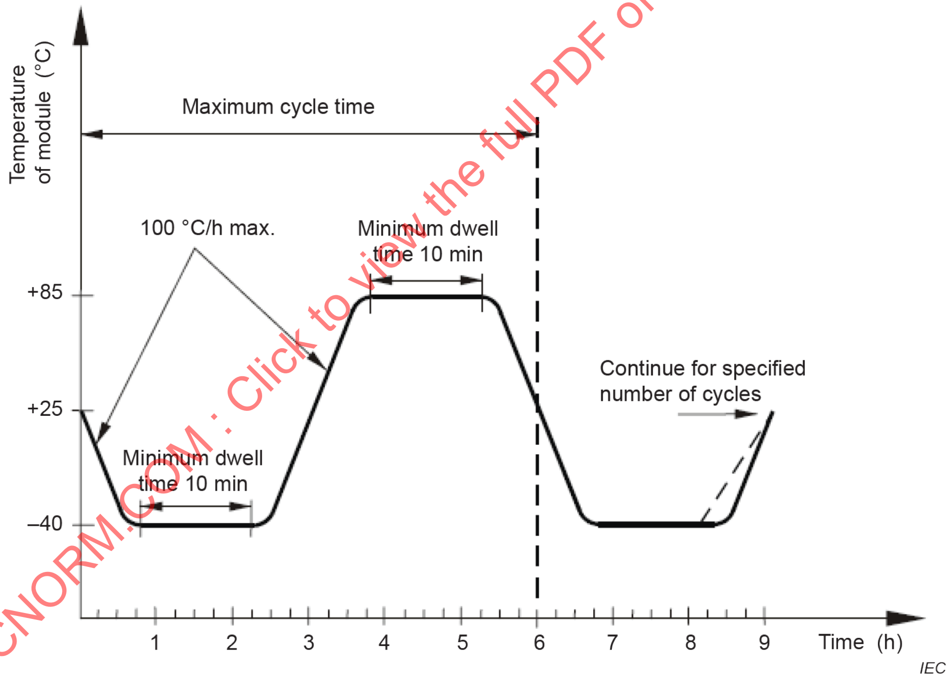

Figure 5 – Plot of the temperature cycle to be used for thermal cycling.

6 Report

Performance characteristics and details of any failures and re-tests shall be prepared by testing laboratories in accordance with ISO/IEC 17025. Each test report shall include at least the following information.

a) A title.

b) Name and address of the test laboratory and location where the tests were carried out.

c) Unique identification of the report on each page.

d) Name and address of the client, where appropriate.

e) Description and identification of the DUTs and technology tested.

f) Characterization and condition of the test item.

g) Date of receipt of test item and date(s) of test, where appropriate.

h) Identification of test method used.

i) Reference to sampling procedure, where relevant.

j) Number of devices in the test and number of devices that failed during testing.

k) Any deviations from, additions to or exclusions from the test method, and any other information relevant to a specific test, such as environmental conditions.

l) Measurements, examinations and derived results supported by tables, graphs, sketches and photographs as appropriate.

m) A statement of the estimated uncertainty of the test results (where relevant).

n) A signature and title, or equivalent identification of the person(s) accepting responsibility for the content of the report, and the date of issue.

o) Where relevant, a statement to the effect that the results relate only to the items tested.

p) A statement that the certificate or report shall not be reproduced except in full, without the written approval of the laboratory.

A copy of this report shall be kept by the laboratory and manufacturer for reference purposes.

Annex A
(informative)

Overview of common failure modes – Failure mode and known failure mechanisms for nano-enabled photovoltaic devices

Failure mode analysis and the relation of observed failure modes to the failure mechanisms is a central part of NePV stability assessment. Special attention is paid to failure mechanisms which are related to the nanoscale structure of the involved materials.

Typical failure modes:

1) loss in short circuit current;
2) loss in open circuit voltage;
3) loss in fill factor;
4) shunting;
5) increase in serial resistance;
6) development of an inflection point at V_{oc} (“second diode”);
7) mechanical failure of the device.