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TECHNICAL REPORT

colour inside

Derisking photovoltaic modules – Sequential and combined accelerated stress testing

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DERISKING PHOTOVOLTAIC MODULES – SEQUENTIAL AND COMBINED ACCELERATED STRESS TESTING

FOREWORD

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IEC TR 63279, which is a Technical Report, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

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

Enquiry draft	Report on voting
82/1657/DTR	82/1692B/RVDTR

Full information on the voting for the approval of this technical report 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

- reconfirmed,
- withdrawn,
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DERISKING PHOTOVOLTAIC MODULES – SEQUENTIAL AND COMBINED ACCELERATED STRESS TESTING

1 Scope

This document reviews research into sequential and combined accelerated stress tests that have been devised to determine the potential for degradation modes in PV modules that occur in the field that single-factor and steady-state tests do not show. This document is intended to provide data and theory-based motivation and help visualize the next steps for improved accelerated stress tests that will derisk PV module materials and designs. Any incremental savings as a result of increased reliability and reduced risk translates into lower levelized cost of electricity for PV. Lower costs will result in faster adoption of PV and the associated benefits of renewable energy.

2 Normative references

The following documents are referred 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.

IEC 60721-2-1, *Classification of environmental conditions – Part 2-1: Environmental conditions appearing in nature – Temperature and humidity*

IEC 61215-1:2016, *Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1: Test requirements*

IEC 61215-2:2016, *Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures*

IEC 61730-2:2016, *Photovoltaic (PV) module safety qualification – Part 2: Requirements for testing*

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

IEC TS 62782:2016, *Photovoltaic (PV) modules – Cyclic (dynamic) mechanical load testing*

IEC 62788 (all parts), *Measurement procedures for materials used in photovoltaic modules*

IEC TS 62804-1, *Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 1: Crystalline silicon*

IEC TS 62804-1-1, *Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 1-1: Crystalline silicon – Delamination*

ASTM D7869-17 *Standard Practice for Xenon Arc Exposure Test with Enhanced Light and Water Exposure for Transportation Coatings*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 apply.

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

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

4 Framework for sequential and combined stress testing

A number of researchers, companies and testing laboratories have explored aspects of sequential and combined stress testing to fill outstanding needs. Such needs include testing beyond IEC 61215-2, which for the most part does not purport to examine for end-of-life wear-out and failure mechanisms. In other cases, stresses are sequenced and combined to elicit failure modes that have been seen in the field that existing IEC tests may not evaluate.

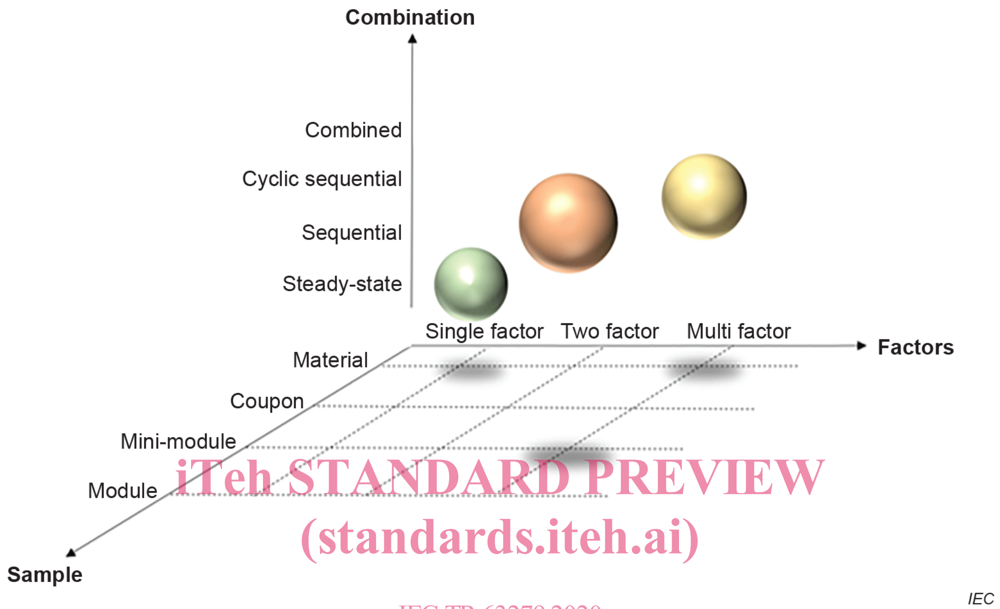
A framework for organization is proposed that implements stress factors of the natural environment, sequences and combinations of applying them, and sample types that may be employed for evaluation. To illustrate this, Figure 1 is introduced, which gives a three-dimensional plot with the axes of sample, factor, and combination, that together indicate the comprehensiveness of test methods to represent the effects of the natural environment on the sample in accelerated testing.

First the sample comprehensiveness axis of Figure 1 is discussed. As a new material is explored, the material itself is studied to achieve a basic understanding of its intrinsic degradation mechanisms and durability. Thus, material and coupon tests as they are performed now according to IEC 62788 series material tests will be valuable. However, failures often occur at the interfaces between materials, and the performance of one component of the module often depends on the behaviour of another component or material in the assembly. Therefore, to represent the material interactions, boundary conditions in actual use, and stresses experienced, it is necessary to examine mini-modules, and most comprehensively, full-size modules with all their components.

Next the factors comprehensiveness axis is discussed. This is the number of stress factors of the natural environment applied in testing of the sample. Moving from single stress factor tests to multi-factor tests increases confidence of capturing the factors relevant to both known and unknown degradation modes. Using one factor alone may be useful to evaluate an acceleration factor or an activation energy associated with that stress for a specific degradation mode or mechanism that is already understood to depend principally on that stress factor independently of others.

Finally, the combination comprehensiveness axis is discussed. It represents the manner of integration of the stress factors on the sample. We seek to sequence and combine the stress factors in a manner that represents how they appear together in nature to increase the probability of accelerating only the real degradation modes in the module as they would manifest in nature. As stress factors are considered, individually or in combination, it is necessary to understand whether stress levels applied are maintained within the levels of the natural environment, or if they are exceeded. If exceeded, acceleration of the test may be increased, but there is significantly increased potential of incurring degradation modes that are artifacts—modes not necessarily representative of those that would be seen in the natural environment.

Tables are given in this document for various experimental results in the framework of Figure 1 condensed into two dimensions. These serve to explain how the sequential and combined accelerated stress tests, with consideration of sample type, factors, and their combination, have served to produce particular failures or degradation modes. In these condensed twodimensional plots, the various column-listed stress factors may be an individual stress factor such as mechanical load, or an existing IEC 61215 stress test, such as damp heat or thermal cycling, which in itself contains factors of temperature cycling and current through the cell circuit. Annexes in which the failure modes are collected for reference are as follows: Annex A : Overview of degradation modes and causal stress factors, Annex B: Failure modes plotted on a failure tree diagram for selected clauses in this document, and Annex C : Summary table of sequential and combined testing: samples, factors, combination, and stress test results of the samples studied. The templates in these Annexes may be useful for classifying other failure or degradation modes as they become understood in the future.



Points shown are possibilities for testing within this space.

Figure 1 – Framework for sequential and combined stress testing, showing three axes of comprehensiveness: testing samples, the number of stress factors of the natural environment, and their sequence or combination of application

5 Sequential and cyclic sequential test methods

5.1 Extended damp heat and addition of ultraviolet light

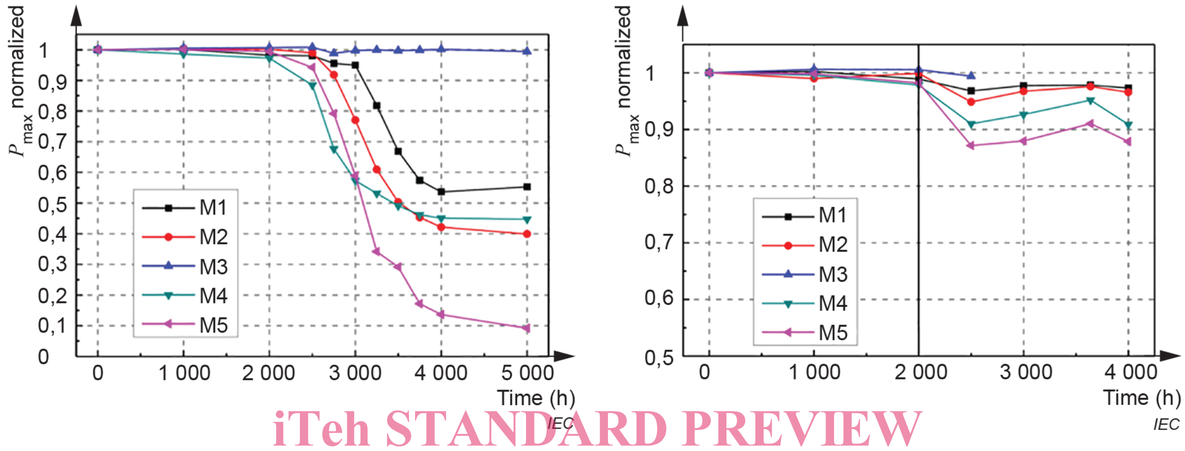
Extended damp-heat (DH) testing has frequently been used to attempt to differentiate durability of PV modules. An example of this is shown in Figure 2a). Five modules undergo five iterations of 1 000 h duration DH tests at 85 °C and 85 % relative humidity (RH). Four module types exhibit great degradation after 2 000 h that is due to fill factor (FF) loss from metallization to silicon contact-resistance increase. The degradation comes at test conditions with temperature in combination with humidity significantly exceeding those found for modules in PV field installations, and the degradation mechanisms observed with extended DH tests have frequently been inconsistent with those seen in fielded PV modules [1][1]. Reviews of agglomerated field-degradation data for crystalline silicon cell modules have shown degradation primarily by short-circuit current (I_{sc}) loss followed by FF loss and the least degradation exhibited by open-circuit voltage (V_{oc}) [2].

Excessive humidity may lead to unrealistically high levels of acetic acid formation, leading in turn to unrealistically high FF losses through grid finger to silicon contact corrosion and other mechanisms. Therefore, excessively long DH stress tests that produce very high acetic acid

[1] Numbers in square brackets refer to the Bibliography.

levels are believed to have limited use in evaluating the durability of conventional crystalline silicon PV modules installed in the field.

If, after 2 000 h of DH testing, modules were transferred for ultraviolet (UV) exposure in a DH environment with an 85 °C target module temperature, then the power losses were more modest as shown in Figure 2b) and reported to be primarily associated with I_{sc} degradation [1], which is representative of what is observed in the field. Including UV radiation is necessary to represent this stress factor of the natural environment. A summary of the sample type used, stress factors, and their sequence and combination, along with resulting degradation modes seen for the modules in the study, is given in Table 1.



a) b)

a) Module M1 with thermoplastic and modules M2–M5 with ethylene vinyl acetate encapsulant through 1 000 h of 85 °C and 85 % relative humidity damp heat cycles;

b) Modules through 2 000 h of the damp heat exposure in (a) followed by placement under UV radiation and damp heat [1].

Figure 2 – Fraction power loss of modules though stress testing

Table 1 – Extended damp heat and ultraviolet light

Sequential/ combined	**Stress factor A**	**Stress factor B**	**Combined stress effect(s)**
	DH	**UV+DH**	
Material			
Coupon			
Mini-Module			
Module	85 °C/85 % RH 2 000 h	200 W/m^2 UV-A, 85 °C module temperature, 2 000 h	Degradation of I_{sc} and FF in better proportion to field, toward field-relevant levels of humidity after UV exposure.
Sequential / Combined: A → B			

5.2 Sequential/combined testing with damp-heat, thermal cycling and ultraviolet light

A sequential test is shown in Figure 3a) developed for the application of additional stress factors with more balanced levels considering the relative levels seen in outdoor exposure and to produce degradation modes in reasonable proportion to those seen in the field. In addition to DH and DH with UV sequences, temperature cycling is included, which adds thermomechanical stresses. Table 2 summarizes the stress factors applied, the levels, and the results of the combined stress effects.

Because of acetic acid formation, attention has been given to humidity levels when alternating between DH in the dark, which drives humidity into the module, and DH with UV radiation, which drives moisture out of the module, as illumination does in PV modules installed in the field [1]. On the backsheet side of the cell, humidity levels reach correspondence with chamber equilibrium; on the front side of the cell, simulations show humidity levels stabilizing around 30 % lower in the alternating sequence than in the continuous DH case, reducing unrealistically high formation of acetic acid that can affect the metallization-silicon contact of some solar cells. The UV can also degrade the cell-front passivation, reducing I_{sc} and V_{oc} [3], and it can cause transmission loss in the encapsulant, contributing to degrading I_{sc} [4], which is observed in the results in Figure 3b) to d).

Appropriate humidity levels and durations for accelerated tests in DH depend on whether moisture-barrier components are required and on the degradation kinetics of the particular solar cells [5]. Based on simulations, it has been proposed that testing for more than 3 000 h in 85 °C and 85 % RH is necessary to duplicate the moisture-ingress distance experienced by an edge seal after 25 years of exposure in the Miami, Florida (USA) use environment [6]. This level, however, causes hydrolysis of polyethylene terephthalate (PET) layers in backsheets used in many crystalline silicon cell-based modules. Extensive degradation by hydrolysis of PET has not been seen in fielded PV modules, so extended DH testing (in this case, 85 °C, 85 % RH, and 3 000 h) is considered too extreme a level for testing failure modes that could be linked to PET degradation [7].

Test	Conditions	Duration	
Damp heat	85 °C / 85 % RH	500 h	initial
Temperature cycle	−40 °C / 85 °C	100 cycles	
Damp heat − UV	85 °C module temperature	500 h	
Damp heat	85 °C / 85 % RH	500 h	repeating
Temperature cycle	−40 °C / 85 °C	100 cycles	
Damp heat − UV	85 °C module temperature	500 h	

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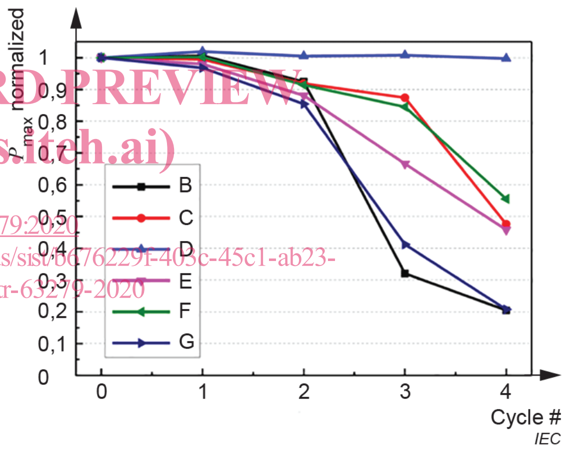
a)



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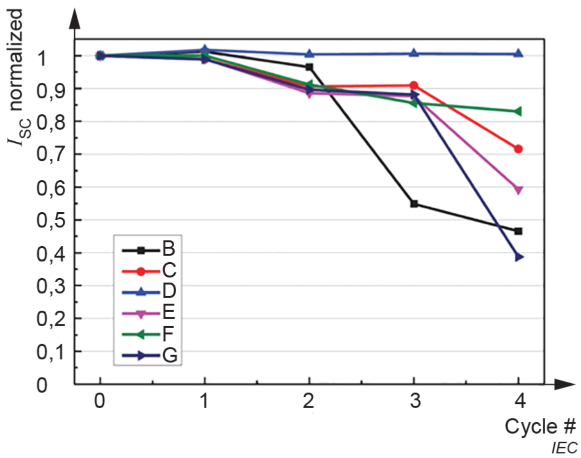

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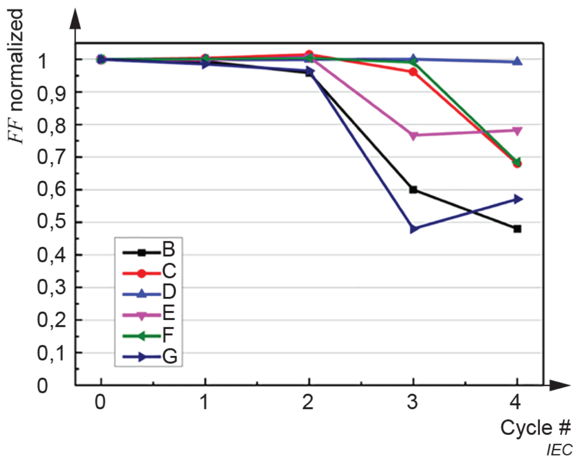

d)

Figure 3 – a) Combined test sequence, and resulting b) normalized power loss, c) short-circuit current (I_{SC}), and d) fill factor (FF) [1]

Table 2 – Sequential/combined testing with damp-heat thermal cycling and ultraviolet radiation

Sequential/ combined	**Stress factor A**	**Stress factor B**	**Stress factor C**	**Combined stress effect(s)**
	DH	**TC**	**DH/UV**	
Material				
Coupon				
Mini-Module				
Module	85 °C/ 85 % RH 1 000 h or 500 h	–40 °C/ 85 °C 100 cycles	200 W/m^2 UV-A, 85 °C module temperature, 500 h	Degradation of I_{sc} and FF in proportion to field, toward field-relevant levels of humidity ingress with use of UV exposure
Sequential/Combined: A → B → C → [A → B → C] × n The stress sequence (A–C) is repeated cyclically; however, stress factor A (DH) time is reduced to 500 h after the first time.				

5.3 Consideration of interaction of UV radiation and damp heat

UV radiation affects acetic acid production in susceptible encapsulants [8]. This can be seen in the results shown in Figure 4 with modules constructed using conventional back-surface-field cells and poly(ethylene-co-vinyl acetate) (EVA) encapsulant tested with differing durations of preconditioning with a Xe-full-spectrum arc lamp [9]. The module type that did not degrade at all in 85 °C and 85 % RH damp heat through 1 500 h showed increasing degradation with increasing preconditioning with Xe-source illumination of 90 W/m^2 in the range of 300 nm to 400 nm and 65 °C chamber temperature at 30 % RH or less. Under such conditions, the resulting sample temperature is 90 °C and module surface RH is ≤ 13 %. If exposed to the Xe arc lamp for 4 000 h beforehand, 42% of the initial power is seen within 1 500 h of the DH exposure. Higher acetic acid concentration was not found after the UV exposures, but acetic acid levels were higher after damp heat according to the extent of preconditioning with light before the DH test; this indicates some other chemical process occurring under light that facilitates the formation of acetic acid with subsequent DH exposure. Preconditioning in heat alone (90 °C) also did not promote subsequent degradation in 1 500 h of damp heat. The root cause of the degradation was assigned to the development of higher series resistance between the grid fingers and the silicon cell from the acetic acid and humidity. A summary of the sample type used, stress factors, and their sequence and combination, along with resulting degradation modes seen for the modules in the study, is given in Table 3.

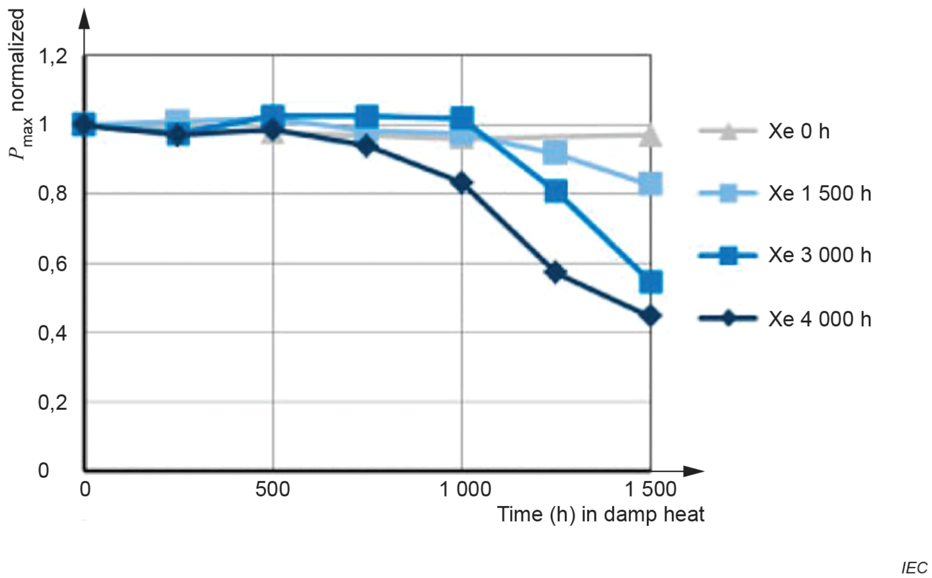

Figure 4 – Power degradation of modules in 85 °C and 85 % relative humidity as a function of extent of preconditioning under Xe light [9]

Table 3 – Ultraviolet light and damp-heat interaction

Sequential/ combined	**Stress factor A**	**Stress factor B**	**Combined stress effect(s)**
	UV	**DH**	
Material			
Coupon			
Mini-module	90 W/m² (300 nm to 400 nm), 90 °C module temperature 1 500 h to 4 000 h	85 °C/ 85 % RH 1 500 h	UV radiation activates appearance of acetic acid in subsequent DH, causing increased contact resistance of grid fingers to silicon
Module			
Sequential: A → B			

5.4 Test-to-failure – A sequential test protocol

The "Terrestrial Photovoltaic Module Accelerated Test-to-Failure (TTF) Protocol" was devised in 2008 and subsequently demonstrated to fill a gap between qualification testing and comprehensive accelerated lifetime testing [10-12]. This protocol shown in Figure 5a) also adds stress sequences in combinations, which manifest in degradation mechanisms not presently examined in standardized qualification testing. The TTF protocol extends the environmental chamber testing until failure modes in the module can be seen to a sufficient magnitude to be studied (e.g. greater than 20 % degradation). The protocol was devised to compare the reliability of different modules on a quantitative basis and to evaluate the performance of new module types to incumbents. A key technical and intellectual exercise not to be overlooked in the analysis of the TTF results is an evaluation of the significance of degradation modes or failures seen. This is in part because the stress levels applied are far greater than found in nature, therefore spurious failures may occur. Field testing and further chamber testing to determine acceleration factors for issues found may need to be performed to evaluate if the degradation modes will be seen in fielded PV modules.

Examples of module power results through the TTF protocol are shown in Figure 5b).