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INTERNATIONAL STANDARD

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**Measurement procedures for materials used in photovoltaic modules –
Part 7-3: Accelerated stress tests – Methods of abrasion of PV module external Surfaces**

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IEC 62788-7-3 edition 1.1 contains the first edition (2022-02) [documents 82/1987/FDIS and 82/2009/RVD] and its amendment 1 (2024-07) [documents 82/2259/FDIS and 82/2277/RVD].

In this Redline version, a vertical line in the margin shows where the technical content is modified by amendment 1. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

IEC 62788-7-3 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems. It is an International Standard.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 62788 series, published under the general title *Measurement procedures for materials used in photovoltaic modules*, can be found on the IEC website.

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

- reconfirmed,
- withdrawn, or
- revised.

IMPORTANT – The *'colour inside'* logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

There is a need for abrasion test methods in the PV industry, particularly for the front and back surfaces of PV modules. This document defines a set of test methods to be used for evaluating the abrasion of materials and coatings in photovoltaic modules or other solar devices. Linear and rotary machine abrasion methods are specified that can be used to address durability to abrasion with respect to the cleaning of solar devices. Linear abrasion is intended to emulate traditional manual methods of cleaning, where the cleaning equipment typically acts perpendicular to the surface, giving a scratching motion. Rotary abrasion is intended to emulate popular robotic methods of cleaning, where the cleaning element often may act along the surface in a swiping motion. Relative to DIN 53778-2 and ASTM D2486, application specific modifications for the machine abrasion tests include the longer bristle length, use of abrasive (test dust) of the size encountered in PV, the use of dry or wet abrasive as may be encountered during cleaning modules, and the number of test cycles relative to the maintenance of PV systems. A falling sand method is specified that can be used to address durability to abrasion with respect to damage from ordinary use in the application environment, i.e., typically meteorological events. Relative to DIN 52348, modifications include the quantity of test sand, which is intended for examination of PV surfaces and coatings. A forced sand impingement method is specified that can be used to address durability to abrasion from severe weather events and/or the most challenging locations of use. Relative to IEC 60068-2-68, modifications include the composition of test sand that may be compared to the PV application and the falling sand test in this document as well as the specified carrier velocities based on the PV application. The methods in this document can be used to aid performance analysis and/or for the purpose of material design/selection. Comparing the linear brush, rotary brush, falling sand, and forced impingement methods, different rates of abrasion and/or damage morphology can occur between the different test methods – they are not expected to produce the same result.

Formal working reference materials are identified in this document. The purpose of the working reference is to verify the apparatus is installed and working correctly. The characteristic(s) of interest can be verified on a regular basis (monthly, weekly, etc.). The characteristic(s) of interest and their values (with acceptance limits for precision) will be given in a referencing document or future version of this document, based on the results of an interlaboratory precision study.

MEASUREMENT PROCEDURES FOR MATERIALS USED IN PHOTOVOLTAIC MODULES –

Part 7-3: Accelerated stress tests – Methods of abrasion of PV module external surfaces

1 Scope

This part of IEC 62788 defines the test methods that can be used for evaluating the abrasion of materials and coatings in photovoltaic modules or other solar devices. This document may be applied to components on the incident surface (including coatings, frontsheet, and glass) as well as the back surface (including backsheets or back glass). This document is intended to address abrasion of PV module surfaces and any coatings present using representative specimens (e.g. which can be centimetres in size); the methods and apparatus used here can also be used on PV module specimens (e.g. meters in size). A suite of tests and their methods are identified in this document, including falling sand, forced sand impingement, and machine (brush) abrasion. Materials and coatings can have different intended design purposes and design lifetimes and therefore no specific pass/fail criteria are defined in this document. The results of the testing can, however, be used to identify relative durability of coatings for various outdoor environments and cleaning practices. The methods can be used for the purpose of relative comparison, e.g. for the purpose of material or coating selection. The quantitative correlation between artificial abrasion and field erosion (which will depend on factors including climate or location of use as well as application, e.g., use of a tracker, rack-mount, roof-mount, building integrated, or vehicle integrated PV) can be established for each specific material or coating, which is beyond the scope of this document.

The correlation between the rates of degradation from the different test methods (linear brush, rotary brush, falling sand, and forced impingement) is beyond the scope of this document and may be covered in referencing documents. The correlation between the rates of degradation for unaged and aged specimens is also beyond the scope of this document and may be covered in referencing documents.

The methods related to the characterization of abraded specimens (which might include optical transmittance, optical reflectance, surface roughness, and surface energy) are not defined in this document; characterization methods from other standards (including optical transmittance, optical reflectance, electrical performance, surface roughness, and surface energy) can be applied to specimens abraded using the methods defined in this document. Methods for examining the contamination of specimens, including artificial soiling, are not examined in this document. Additional specimen conditioning can be applied prior to the methods in this document. The abrasion tests in this document can be referenced and/or applied in conjunction with an accelerated test or test sequence in other standards.

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.

IEC 60068-2-68, *Environmental testing – Part 2-68: Tests – Test L: Dust and sand*

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

ISO 291, *Plastics – Standard atmospheres for conditioning and testing*

ISO 12103-1, *Road vehicles – Test contaminants for filter evaluation – Part 1: Arizona test dust*

ASTM D2486, *Standard test methods for scrub resistance of wall paints*

DIN 52348:1985-02, *Testing of glass and plastics; abrasion test; sand trickling method*

DIN 53778-2:1983-08, *Emulsion paints for interior use; evaluation of cleanability and of wash and scrub resistance of coatings*

MIL-STD-810G, *Environmental engineering considerations and laboratory tests*

VDI 3956, *Evaluation of the soiling properties of surfaces – Test method for the dust soiling behaviour of solar energy systems*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 and the following 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
artificial abrasion
wear resulting from the cleaning of a PV device, including manual or robotic cleaning

3.2
natural erosion
wear resulting from the ordinary terrestrial use of a PV device

Note 1 to entry: Sources of erosion may include particulate impingement, particulate transport (from wind or water), or autonomous scraping (from snow or ice by gravity).

4 Artificial linear machine abrasion test (SAT01)

4.1 Principle

The machine abrasion methods are specified that can be used to address durability to abrasion with respect to the cleaning of solar devices. Linear abrasion is intended to emulate traditional manual methods of cleaning, where the cleaning equipment typically acts perpendicular to the surface, giving a scratching motion. The test is typically applied to the irradiance incident surface of a PV module. Because either dry or wet cleaning may be used to clean a PV module, both dry and wet (slurry) abrasives may be used in this test. The test may simulate the cleaning of fixed, tracked, or vehicle integrated PV.

4.2 Apparatus

4.2.1 Artificial linear machine abrasion apparatus

A linear abrasion apparatus fulfilling the requirements of ASTM D2486 or DIN 53778-2 shall be used. Essential components of the apparatus include: a linear abrasion mechanism, a brush, an abrasive dispenser (slurry or dry abrasive), and an enclosure (if applicable). An enclosure is recommended for the apparatus to prevent spilling or spraying of abrasive (dry or wet slurry abrasives) or the possibility of silicosis (with ventilation, for dry abrasive). Additional equipment and containers for the management of waste abrasive and its disposal after the test is advised.

The abrasion mechanism shall provide a brush stroke length of at least 14,5 cm. The brush may operate at either a constant or varied velocity through each stroke. The brush velocity of 30 ± 3 $cm \cdot s^{-1}$ shall be used for the through the central 7,5 cm test region on the specimen during machine abrasion testing. Other test rates may be used for the purposes of research and development.

NOTE For example, the brush velocity of 30 $cm \cdot s^{-1}$, when used with a stroke length of 25,4 cm corresponds to a test rate of 37± 1 cycles per minute.

Specimens shall be rigidly mounted relative to the apparatus using mechanical springs or clamps, tape or other means.

To ensure repeatability of results (i.e., avoid temperature-related effects related to the abrasion process or abrasive) the apparatus shall be maintained, in a laboratory maintained at (23 ± 2) °C, (50 ± 10) % RH, as specified per Class 2 in ISO 291.

The dispenser for dry dust shall be separated from the specimen surface by at least 10 cm to provide clearance for the motion of the brush (in both linear and rotary configurations) and also aid dispensing to the designated test area of the specimen.

The dispenser for wet slurry shall be separated from the specimen surface by at least 5 cm to aid dispensing to the designated test area of the specimen.

4.2.2 Brush

The brush block shall be (~~35~~38 ± 1) mm × (~~85~~89 ± 1) mm in area and (13 ± 1) mm in thickness.

The brush bristles shall consist of polyamide 612, poly(hexamethylene dodecanediamide) with a 50:50 molar ratio of monomer types, (0,23 ± 0,03) mm in diameter that extend (38 ± 2) mm from the brush block. Brushes with bristles shorter than 35 mm in length shall be replaced. The bristle profile shall be round, with no taper or other change in geometry along their length. The lateral repeat space of 6,4 mm shall be used for the bristle tuft rows across the width of the brush and 12,7 mm shall be used for the bristle tuft columns along the length of the brush~~, with a~~. For the staggered bristles, an offset space of ~~4~~ 3,2 mm between adjacent rows and lateral offset space of 6,4 mm between adjacent bristle columns. The bristle tufts shall be staggered in a 5-4-5-4-... pattern along the brush, with total of 59 tufts. The bristle count shall be (158 ± 6) $tips \cdot tuft^{-1}$. See Figure 1.

~~A 325 g external weight shall be used with the brush, as in ASTM D2486. The nominal brush weight of 125 g includes the dry weight of brush block and bristles. The nominal brush net weight (including 5 g attachment bolt) shall be 455 ± 10 g, including the dry weight of brush block, bristles, external weight, fasteners, and holder. The nominal contact force of 4,46 N shall result from the self-weight of the components; no spring or other external force shall be used.~~

Dimensions in millimetres

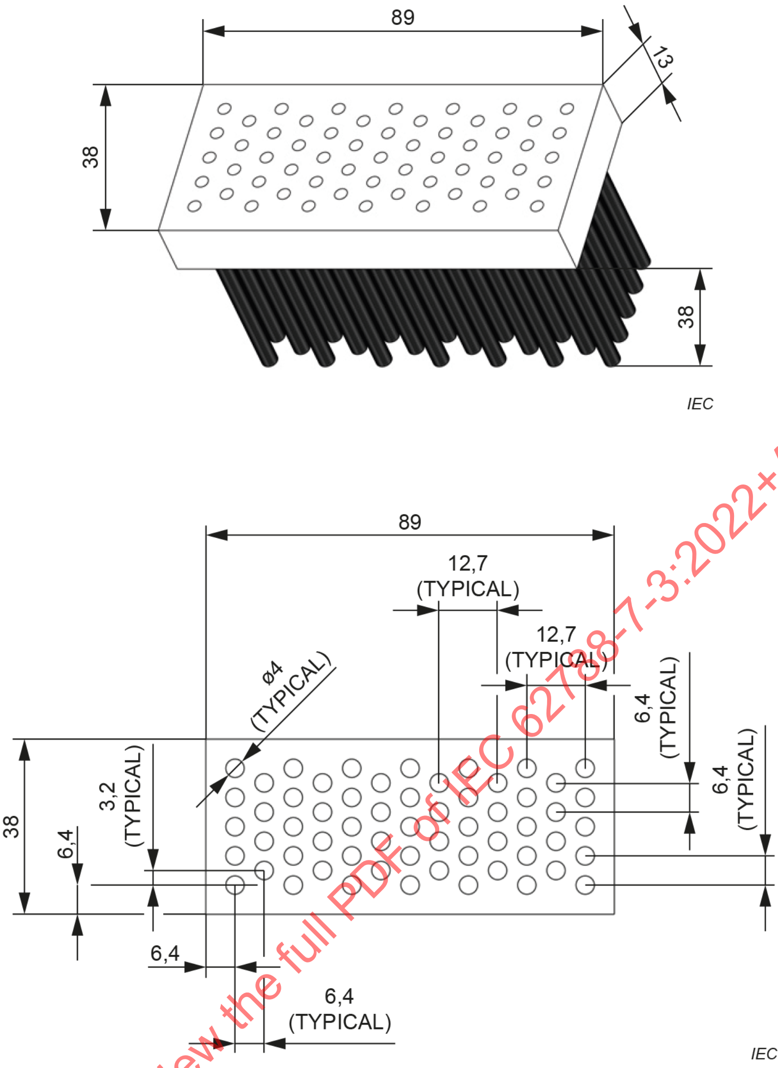

Figure 1 – Schematics showing the arrangement of bristle tufts on the linear brush

4.2.3 Abrasive medium (dry)

The dry abrasive medium shall consist of A3 (medium) AZ test dust, as specified in ISO 12103-1. The nominal abrasive concentration of (0,7) mg·cm^{-2}·cycle^{-1} shall be used during the test. To ensure repeatability, the test dust shall not be reused after testing. Other abrasive materials or quantities of abrasive may be used for the purposes of research and development.

NOTE The abrasive concentration of (20 ± 5) mg·cycle^{-1} when applied to the nominal area of the linear brush (29,75) cm^{-2} provides the nominal abrasive concentration of (0,7) mg·cm^{-2}·cycle^{-1}.

Dry abrasive shall be maintained at (23 ± 2) °C and (50 ± 10) % RH for at least 24 h, as specified per Class 2 in ISO 291, prior to use in the linear abrasion test.

For the dry abrasive test, the brush bristles shall be maintained at (23 ± 2) °C and (50 ± 10) % RH for at least 24 h, as specified per Class 2 in ISO 291, prior to use in the linear abrasion test.

Other dry abrasives may be used for the purposes of research and development. Dry abrasive may be used in conjunction with an artificial soiling method for the purposes of research and development. Alternative abrasives include the "Middle East" (ME) test dust as specified in VDI 3956, and "quartz free" AZ test dust (similar to ISO 12103-1, but using corundum instead of silica to avoid safety issues related to respiration). Both particle size and particle composition can affect the rate of abrasion. The aforementioned alternative abrasives have not been widely studied relative to ISO 12103-1 AZ test dust.

4.2.4 Abrasive medium (wet slurry)

The wet abrasive medium shall consist of A3 (medium) AZ test dust, as specified in ISO 12103-1. The abrasive concentration of (5,0 ± 0,2) g·l^{-1} in deionized water shall be used during the test. The slurry shall be flowed at the rate of (5,0 ± 0,2) l·h^{-1} during the test. To ensure repeatability, the test dust shall not be reused after testing. Other abrasive materials or quantities of abrasive may be used for the purposes of research and development.

NOTE The abrasive concentration of (5,0 ± 0,2) g·l^{-1} when flowed at the rate of (5,0 ± 0,2) l·h^{-1} to the nominal area of the linear brush (29,75) cm^{-2} provides the nominal abrasive concentration of (0,4) mg·cm^{-2}·cycle^{-1} for the nominal brush travel distance (25,4 cm) and operating speed (30 ± 3 cm·s^{-1}).

Deionized water at (23 ± 2) °C shall be used during the test to avoid temperature-related effects related to the abrasion process or abrasive.

For the wet slurry abrasive test, the brush bristles shall be conditioned using water for 24 h before the start of the test. Methods of brush conditioning include soaking the bristles in a container of water, completely immersing the brush in a container of water, and/or the use of water flow (where the water or brush may be adjusted to provide regular conditioning). Brushes that are in frequent use may be stored in water.

A stirring apparatus shall be used with the slurry to improve the uniformity of concentration of dust in the slurry as well as to facilitate uniform concentration through the duration of testing. In addition to the stirring/mixing of the slurry, the apparatus and its plumbing should produce good uniformity of deposition slurry on the sample.

Other wet slurry abrasives may be used for the purposes of research and development.

4.3 Test specimens

4.3.1 Materials and geometry

Specimens may consist of representative coupons. The specimens shall be composed of a base material (or substrate), where a coating (if applicable) may be present on the test surface. Representative coupons shall be at least (7,5 ± 0,2) cm × (7,5 ± 0,2) cm in size. Module specimens or glass specimens (for tempered glass, where cutting is impossible) may also be used, if they may be accommodated in the apparatus. In the case of modules, the specimens shall contain at least three test regions 7,5 cm × 7,5 cm in length and width, separated at least 37,5 cm. In the case of unaged specimens, or specimens with no previous test-history, the test region(s) shall be representative of that used in the PV application, being free from visible damage, delamination, or other defects. In the case of weathered specimens or specimens with a previous test-history, the specimen shall be used in its received condition. In the case of polymeric material specimens such as backsheets or frontsheets, both principal directions should be tested, including the machine extrusion direction and the traverse direction.

Some coatings can have limitations regarding the specimen size that can be used to fabricate a representative sample. For example the glass might need to be tempered as part of the manufacturing process, where a 50 cm × 50 cm minimum glass size is required. In such cases, a larger coupon size or a module specimen can be used.

Commercial abrasion test equipment fulfilling the requirements of the test apparatus may be used to test region(s) within a module, if the test apparatus is located and fixtured relative to the test surface of the module. A custom apparatus with equivalent characteristics to a commercial tester may be used for large coupon or module specimens.

4.3.2 Number of replicate specimens

In the case of representative coupons, at least three replicates shall be used. If the apparatus has adequate space or number of brushes, the replicates may be tested together, simultaneously. The use of glass blanks (where the size may be smaller than 7,5 cm) at the sides of the test specimens is recommended to avoid a discontinuous loading of the brush along its path during testing, i.e., the surfaces in PV modules are typically longer than 7,5 cm.

In the case of a PV module at least three replicate modules or three separate regions on the same module shall be used. Test regions on the same PV module shall be separated at least 37,5 cm. The test areas may be marked prior to testing to aid subsequent examination.

In the case of unaged specimens, or specimens with no previous test-history, the specimen may be cleaned prior to testing. A mild detergent (e.g., a non-perfumed liquid soap as recommended by the manufacturer) may be used with deionized water as a cleaning solvent. A fresh cloth wipe may be used to facilitate cleaning. After cleaning, specimens may be dried in the ambient or dried using a jet of clean dry air.

There are no specimen conditioning requirements for this test. Specimens subject to the slurry test do not need to be soaked in water prior to testing.

4.3.3 Reference material

~~B 270 “Superwite” crown glass (Schott AG) should be used as a default reference material in other abrasion-related standards. “Borofloat” glass (Schott AG) may be used as a reference material, as in the case of a silica thin film or monolithic silica substrate or superstrate. “Acrylite 0Z023” poly(methyl methacrylate) (Evonik Industries AG) may be used as a reference material, as in the case of a polymer substrate or superstrate. Addition coupons of a reference material should be tested alongside the test specimens in the abrasion test.~~

~~NOTE The reference materials are given for the convenience of users of this document and do not constitute an endorsement by IEC of these products.~~

~~An informal working reference specimen may be used for the purposes of process- and manufacturing-control or research and development. In the case of coupon specimens, a substrate with no coating may be used as an informal working reference specimen. In the case of module specimens, a module or mini-module with no coating may be used as an informal working reference. The details of use of an informal working reference, including: the frequency of use; the characteristic(s) of interest; and acceptance limits may be specified by the user.~~

A reference material, which may be used to compare universally relative to the apparatus manufacturer or between laboratories, shall be used to verify proper operation of the abrasion tester, including the abrasive, abrasion apparatus, and the brush. The reference material shall be used before specimens are tested, including after instrument installation or setup and between test sessions. A reference material similar to the test specimen(s) is recommended and should be used through the same measurement session. See Table 1.

Table 1 – Examples of suitable reference materials

Use	Description	Material	Manufacturer
Default reference material, glass substrate or superstrate	Super-white modified soda-lime glass (DIN 52348)	B 270 "Superwite"	Schott AG
Hard thin film, monolithic silica substrate or superstrate	Technical glass	Borofloat 33	Schott AG
Polymer substrate or superstrate	UV durable, solar grade bulk poly(methyl methacrylate)	Acrylite 0Z023	Röhm AG

Working reference materials, with similar characteristics as the suitable reference materials, may be used for internal purposes. Additional coupons of a suitable reference or working reference material should be tested alongside the test specimens (as blanks at the ends) during the abrasion test.

4.4 Test procedure

4.4.1 Setting up the apparatus and specimen

The apparatus shall be cleaned of residual abrasive, remaining from previous testing (if applicable).

The abrasive and apparatus (brush) shall be conditioned as designated prior to testing.

- Attach the specimen to the apparatus.
- Activate the abrasive dispenser.
- Activate the abrasion mechanism.

4.4.2 Performing the abrasion test

The following methods are given to standardize the test procedure, e.g., to facilitate comparison between laboratories or materials. The durability of the specimen(s) to abrasion may, however, be known from previous experience or anticipated based on the prescribed cleaning. Therefore additional methods may be used for the abrasion test. Additional readpoints (more than 5) may also be used with the test.

Method (A): For coatings anticipated to have a low cleaning severity (infrequent cleaning), a 20 cycle increment should be used between readpoints, with readpoints up to 100 cycles.

Method (B): For coatings anticipated to have a moderate cleaning severity (intermediate cleaning), a 100 cycle increment should be used between readpoints, with readpoints up to 500 cycles.

Method (C): For coatings anticipated to have a high cleaning severity (frequent cleaning), a 2 000 cycle increment should be used between readpoints, with readpoints up to 10 000 cycles.

A stroke in the forward and then reverse direction shall be considered complete cycle.

If the coating is observed to be destroyed (during characterization, according to characterization method(s) specified outside of this document), the test may be terminated with no additional readpoints.

NOTE Some examples of the durability of materials to linear abrasion (including roughened surfaces, chemically functionalized surfaces, porous silica coatings – including coatings deposited using a so-gel or other means, thin polymer film, and hard dielectric coatings) can be found in Annex A.

4.5 Specimen preparation for examination after testing

The specimen shall be cleaned to remove residual test sand using a deionized water rinse or deionized water spray. No detergent should be used if the surface energy is to be characterized, e.g., using liquid contact angle or liquid roll-off angle measurements. A cleaning solvent (rinse or spray) may be used before or intermediate-to deionized water for cleaning. A clean dry air spray or nitrogen spray shall then be used to dry the sample. Additional drying methods may be specified in other referencing standards, e.g., use of elevated temperature, an applied irradiance, or a desiccator chamber after abrasion and before specimen characterization.

For some characterization methods it is preferred to avoid contact cleaning of the specimens, because inadvertent abrasion damage may affect the results. For some characterization methods, however, contact cleaning (e.g. with a lens tissue) may be required to remove particulate matter from the specimen surface (e.g. to obtain valid spectral transmittance measurements). The use of noncontact or contact cleaning may be specified in the referencing document.

Perform specimen characterizations as specified elsewhere, i.e., in standards referencing IEC 62788-7-3.

5 Artificial rotary machine abrasion test (SAT02)

5.1 General

The machine abrasion methods are specified that can be used to address durability to abrasion with respect to the cleaning of solar devices. Rotary abrasion is intended to emulate popular robotic methods of cleaning, where the cleaning element often may act along the surface in a swiping motion. The test is typically applied to the irradiance incident surface of a PV module. Because either dry or wet cleaning may be used to clean a PV module, both dry and wet (slurry) abrasives may be used in this test. The test may simulate the cleaning of fixed or vehicle integrated PV. Cleaning of fixed PV may be performed with rotation, combined with a linear direction of motion. Cleaning of vehicle integrated PV may used equipment from the automotive industry.

5.2 Apparatus

5.2.1 Artificial rotary machine abrasion apparatus

There is no existing commercial test equipment for the rotary abrasion test fulfilling the specifications identified below, therefore custom equipment may be used. Essential components of the apparatus include: a linear actuation mechanism, a rotary abrasion mechanism, a brush, an abrasive dispenser (slurry or dry abrasive), and an enclosure (if applicable). An enclosure is recommended for the apparatus to prevent spilling or spraying of abrasive (dry or wet slurry abrasives) or the possibility of silicosis (with ventilation, for dry abrasive). Additional equipment and containers for the management of waste abrasive and its disposal after the test is advised.

The linear actuation mechanism shall provide a brush stroke length of at least 14,5 cm. The brush may operate at either a constant or varied velocity through each stroke. The brush velocity of 30 ± 3 $cm \cdot s^{-1}$ shall be used for the through the central 7,5 cm test region on the specimen during machine abrasion testing. Other test rates may be used for the purposes of research and development.

NOTE 1 For example, the brush velocity of 30 $cm \cdot s^{-1}$, when used with a stroke length of 25,4 cm corresponds to a test rate of 37± 1 cycles per minute.

The rotary brush mechanism shall provide a constant brush rotation rate of (120 ± 5) rpm. Other rotation rates may be used for the purposes of research and development.

Specimens shall be rigidly mounted relative to the apparatus using mechanical springs or clamps, tape or other means.

To ensure repeatability of results (i.e., avoid temperature-related effects related to the abrasion process or abrasive) the apparatus shall be maintained, in a laboratory maintained at (23 ± 2) °C, (50 ± 10) % RH, as specified per Class 2 in ISO 291.

The same dispensing apparatus may be used for dry dust in the rotary machine abrasion test as used in the linear machine abrasion test. A representative mass·area^{-1}·cycle^{-1} concentration is given for dry dust in 4.2.3.

The same dispensing apparatus may be used for wet slurry in the rotary machine abrasion test as used in the linear machine abrasion test. A representative mass·area^{-1}·cycle^{-1} concentration is given for slurry in 4.2.4.

NOTE 2 The rate of rotation for the brush is chosen to give a rate that is representative for some cleaning equipment used in the PV industry. The tangential velocity of the brush tips during use will vary with the rate of rotation of the brush.

The dispenser for dry dust shall be separated from the specimen surface by at least 10 cm to provide clearance for the motion of the brush (in both linear and rotary configurations) and to aid dispensing to the designated test area of the specimen.

The dispenser for wet slurry shall be separated from the specimen surface by at least 5 cm to aid dispensing to the designated test area of the specimen.

The dispenser for wet slurry shall be located relative to the brush so that the tangential velocity from the rotation of the brush and the translational velocity of the brush are maximized (most additive) during abrasion testing. If the brush is observed to rotate in a clockwise direction during its operation, then the dispenser shall be located to the left of the brush. If the brush is observed to rotate in a counter-clockwise direction during its operation, then the dispenser shall be located to the right of the brush.

5.2.2 Brush

The brush block shall be a round cylinder (24 ± 1) mm in diameter and at least (48 ± 1) mm in length.

The brush bristles shall consist of polyamide 612, poly(hexamethylene dodecanediamide) with a 50:50 molar ratio of monomer types, (0,23 ± 0,03) mm in diameter that extend (38 ± 2) mm from the brush block. Brushes with bristles shorter than 35 mm in length shall be replaced. The bristle profile shall be round, with no taper or other change in geometry along their length. As shown in ~~Figure 1~~ Figure 2, the lateral space of 12 mm shall be used for the bristle tuft columns along the axial length of the brush, with a lateral offset space of 6 mm between adjacent bristle columns and circumferential offset space of ~4 mm between rows (to give 18 total rows). The bristle tufts shall be staggered in a 4-3-4-3-... pattern along the brush to give a total of 63 tufts. The bristle count shall be (158 ± 6) tips·tuft-1, which may be mounted in a (2,5 ± 0,1) mm diameter via.

Dimensions in millimetres

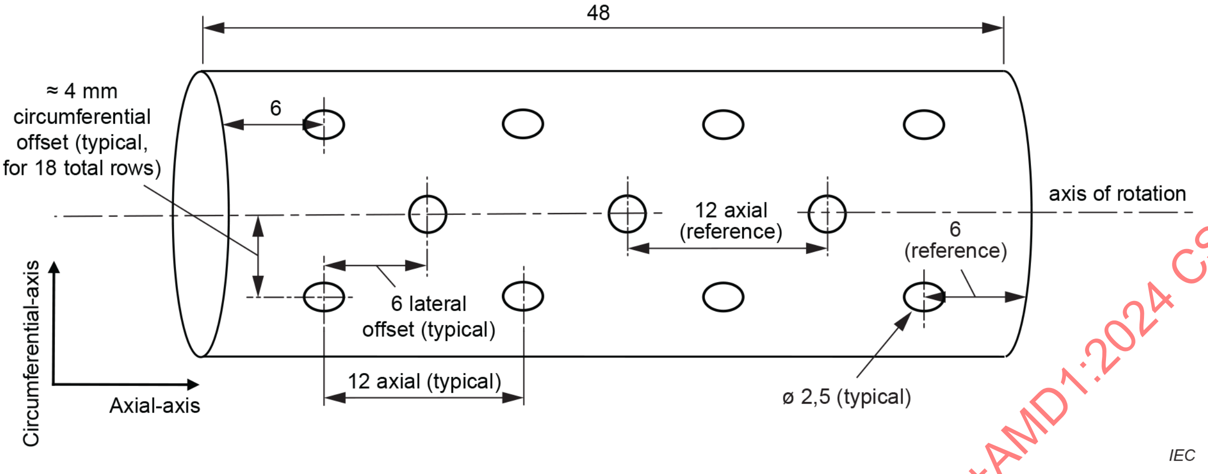

Figure ~~1~~ 2 – Schematic showing the arrangement of bristle tufts on the rotary brush

The nominal brush location in the machine abrasion apparatus shall provide a separation of 45 mm between the surface of the specimen and the center of the axis of rotation of the brush. The separation distance does not need to be adjusted through the useful life of the rotary brush.

NOTE For the rotary brush, the separation distance establishes the contact force during testing.

5.2.3 Abrasive medium (dry)

The dry abrasive medium shall fulfil the requirements of 4.2.3.

5.2.4 Abrasive medium (wet/slurry)

The wet abrasive medium shall fulfil the requirements of 4.2.4.

5.3 Test specimens

Specimens shall fulfil the requirements of 4.3 and the corresponding 4.3.1, 4.3.2, and 4.3.3.

5.4 Test procedure

Using the rotary abrasion apparatus, perform the test according to 4.4.

5.5 Specimen preparation for examination after testing

Prior to examination, perform specimen preparation according to 4.5.

6 Falling sand test (SAT03)

6.1 Principle

The falling sand method can be used to address durability to abrasion with respect to damage from ordinary use in the application environment, i.e., typically meteorological events. The sand drop test is intended to simulate natural erosion from blown sand or dust, i.e., wear resulting from typical meteorological conditions. The test may be applied to irradiance incident surfaces or materials on the back of a PV module.

6.2 Apparatus

6.2.1 Falling sand apparatus

A falling sand apparatus fulfilling the requirements of DIN 52348 shall be used. Essential components of the apparatus include: the diameter of orifice, guide tube inner diameter, number and location of mesh sieves within the guide tube, fall length, and specimen inclination angle.

Diameter of orifice: 3,5 mm

Guide tube inner diameter: 120 mm

Number of mesh sieves: 2

Fall length 1,65 m (Impact velocity: 5,7 m/s)

Specimen angle: 45°.

A rotating specimen fixture (e.g., with 250 rpm as in DIN 52348) may be used in order to obtain a uniformly abraded test area within specimens. To ensure repeatability of results (i.e. avoid clumping of the abrasive and ensure reproducibility of surface erosion) the fixture shall be maintained, with the test being performed, in a laboratory maintained at (23 ± 2) °C, (50 ± 10) % RH, as specified per Class 2 in ISO 291.

An enclosure is recommended for the apparatus to prevent spilling or spraying of abrasive or the possibility of silicosis.

The default specimen mounting angle (for standardization of testing) is 45°. For experiments or research examining the effect of mounting angle (for PV on a fixed tilt rack), or the abrasion of PV on trackers, or for PV module products intended to be used at a specified angle of incidence, the specimen angle for the falling sand test may be varied from the nominal angle of 45°.

6.2.2 Abrasive medium

The abrasive medium shall consist of DIN 52348 silica sand (grain size from 0,5 mm to 0,7 mm). The total quantities of sand shall be used, with a read point performed after each test: 1,5 kg, 3,0 kg, 6,0 kg, 9,0 kg, and 12,0 kg. The sand may be used in successive incremental or separate amounts to achieve the cumulative quantities. To ensure repeatability, the sand shall not be reused after testing. Other abrasive materials or quantities of abrasive may be used for the purposes of research and development.

NOTE 1 The nominal grain size from 0,5 mm to 0,7 mm corresponds to the ISO 3310-1 mesh scale of 30 to 22, and the ASTM E11 mesh scale of 35 to 25.

The abrasive shall be maintained at (23 ± 2) °C and (50 ± 10) % RH for at least 24 h, as specified per Class 2 in ISO 291, prior to use in the falling sand test.

NOTE 2 While the mass is used to determine the quantity of sand, the aforementioned quantities of sand correspond to the approximate volume of 0,6 l, 1,1 l, 2,3 l, 3,4 l, and 4,5 l of sand.

6.3 Test specimens

6.3.1 General

Specimens shall fulfil the requirements of 4.3 and the corresponding 4.3.1, 4.3.2, and 4.3.3.

6.3.2 Number of replicate specimens

In the case of representative coupons, at least three replicates shall be used.

In the case of a PV module at least three replicate modules or three separate regions on the same module shall be used. Test regions on the same PV module shall be separated by at least 37,5 cm. The test areas may be marked prior to testing to aid subsequent examination.

In the case of unaged specimens, or specimens with no previous test-history, the specimen may be cleaned prior to testing. A mild detergent (e.g., a non-perfumed liquid soap as recommended by the manufacturer) may be used with deionized water as a cleaning solvent. A fresh cloth wipe may be used to facilitate cleaning. After cleaning, specimens may be dried in the ambient or dried using a jet of clean dry air.

There are no specimen conditioning requirements for this test. Specimens subject to the slurry test do not need to be soaked in water prior to testing.

6.4 Test procedure

The specimen(s), abrasive, and apparatus shall be conditioned as designated prior to testing.

- Attach the specimen to the apparatus target.
- Align the target relative to the guide tube in the falling sand fixture (if applicable).
- Activate rotation of the apparatus target (if applicable).
- Pour abrasive into the hopper of the falling sand fixture to initiate the test.
- Remove the specimen from the test fixture.

The specimen shall be cleaned to remove residual test sand using a deionized water rinse or deionized water spray. No detergent should be used if the surface energy is to be characterized, e.g., using liquid contact angle or liquid roll-off angle measurements. A cleaning solvent (rinse or spray) may be used before or intermediate-to deionized water for cleaning. A clean dry air spray or nitrogen spray shall then be used to dry the sample. Additional drying methods may be specified in other referencing standards, e.g., a desiccator chamber for surface energy measurements.

For some characterization methods it is preferred to avoid contact cleaning of the specimens, because inadvertent abrasion damage may affect the results. For some characterization methods, however, contact cleaning (e.g. with a lens tissue) may be required to remove particulate matter from the specimen surface (e.g. to obtain valid spectral transmittance measurements). The use of noncontact or contact cleaning may be specified in the referencing document.

Perform specimen characterizations as specified elsewhere, i.e., in standards referencing IEC 62788-7-3.

6.5 Specimen preparation for examination after testing

Prior to examination, perform specimen preparation according to 4.5.

7 Forced sand impingement test (SAT04)

7.1 Principle

The forced sand impingement method can be used to address durability to abrasion from severe weather events and/or the most challenging locations of use. For fixed PV, the forced sand impingement test is intended to simulate natural erosion from blown sand or dust during infrequent, high energy storms. For vehicle integrated PV, the forced sand impingement test may simulate natural erosion from blown sand or dust during vehicle use. The test may be applied to irradiance incident surfaces or materials on the back of a PV module.

7.2 Apparatus

7.2.1 Forced sand impingement apparatus

A forced sand apparatus fulfilling the requirements of IEC 60068-2-68 or MIL-STD-810G shall be used. Essential components of the apparatus include: a test chamber (including temperature and humidity control), an air stream of controlled velocity, and an abrasive injection system. To ensure repeatability of results (i.e. avoid clumping of the abrasive and ensure reproducibility of surface erosion) the chamber shall be maintained, with the test being performed at (63 ± 2) °C, (25 ± 10) % RH. Specimen mounting may be used including: Configuration A (the target fixture and specimen is maintained at (90 ± 2)° to the air flow direction), or Configuration B (the specimen is maintained at (45 ± 2)° to the air flow direction).

A rotating specimen/target fixture is not required, but may be used to improve the uniformity of abrasion from the test. Factors including gravity and a boundary layer (including rebounding sand at the specimen surface) may reduce the uniformity of abrasion.

The air flow velocity may be used including: Method A (the velocity of (18 ± 2) $m{\cdot}s^{-1}$), Method B (the velocity of (30 ± 2) $m{\cdot}s^{-1}$), or other velocities according to national, regional, or local codes in specific PV applications.

The default specimen mounting angle (for standardization of testing) is 90° (perpendicular to the air flow). For experiments or research examining the effect of mounting angle (for PV on a fixed tilt rack), or the abrasion of PV on trackers, or for PV module products intended to be used at a specified angle of incidence, the specimen angle for the falling sand test may be varied from the nominal angle of 90°.

7.2.2 Abrasive medium

The abrasive medium shall consist of DIN 52348 silica sand (grain size from 0,5 mm to 0,7 mm). The abrasive concentration of 2,2 $g{\cdot}m^{-2}$ shall be used in the air stream during the test. To ensure repeatability, the sand shall not be reused after testing. Other abrasive materials or quantities of abrasive may be used for the purposes of research and development.

NOTE The nominal grain size from 0,5 mm to 0,7 mm corresponds to the ISO 3310-1 mesh scale of 30 to 22, and the ASTM E11 mesh scale of 35 to 25.

The abrasive shall be baked at (80 ± 2) °C (with the relative humidity uncontrolled) for at least 2 h prior to use in the forced sand test.

7.3 Test specimens

Specimens shall fulfil the requirements of 4.3 and the corresponding 4.3.1, 4.3.2, and 4.3.3.

7.4 Procedure

The specimen(s), abrasive, and apparatus shall be conditioned as designated prior to testing.

- Attach the specimen to the apparatus target.
- Align the target relative to the air flow (if applicable).
- Activate rotation of the apparatus target (if applicable).
- Activate the air flow, with the controlled concentration of abrasive present for 2 h.
- Remove the specimen from the test fixture.

The specimen shall be cleaned to remove residual test sand using a deionized water rinse or deionized water spray. No detergent should be used if the surface energy is to be characterized, e.g., using liquid contact angle or liquid roll-off angle measurements. A cleaning solvent (rinse or spray) may be used before or intermediate-to deionized water for cleaning. A clean dry air spray or nitrogen spray shall then be used to dry the sample. Additional drying methods may be specified in other referencing standards, e.g., a desiccator chamber for surface energy measurements.

For some characterization methods it is preferred to avoid contact cleaning of the specimens, because inadvertent abrasion damage may affect the results. For some characterization methods, however, contact cleaning (e.g. with a lens tissue) may be required to remove particulate matter from the specimen surface (e.g. to obtain valid spectral transmittance measurements). The use of noncontact or contact cleaning may be specified in the referencing document.

Perform specimen characterizations as specified elsewhere, i.e., in standards referencing IEC 62788-7-3.

7.5 Specimen preparation for examination after testing

Prior to examination, perform specimen preparation according to 4.5.

8 Test report

A test report shall be prepared containing the following minimum 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 and of each page;

d) name and address of client;

e) description and identification of the item tested, including the specimen size;

f) characterization and condition of the test item, including sample orientation (if applicable);

g) date of receipt of test item and date(s) of test;

h) identification of the apparatus equipment, test (falling sand, forced sand impingement, linear abrasion, or rotary abrasion), method (if applicable) and abrasive used;

i) the severity of exposure (including the mass of sand, test duration, or number of test cycles);

j) the specimen history (e.g., before or after testing in a sequence, if applicable);

k) reference to sampling procedure, where relevant;

l) any deviations from, additions to, or exclusions from, the test method and any other information relevant to a specific test, such as environmental conditions; and the procedure(s) and condition(s) used for weathering and any preconditioning conducted prior to measurements;

m) measurements, examinations and derived results supported by tables, graphs, sketches and photographs as appropriate;

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 report shall not be reproduced except in full, without the written approval of the laboratory.

Annex A
(informative)

References describing the durability of materials to linear abrasion

Jaione Bengoechea, María Jesús Rodríguez, Eugenia Zugasti, Ana Rosa Lagunas, "Susceptibility of CPV optical materials to abrasion", *AIP Conference Proceedings 2149,* 2019, 070002; https://doi.org/10.1063/1.5124201

K. Lange, M.A. Bahattab, S.H. Alqahtani, M. Mirza, W. Glaubitt, V. Naumann, C. Hagendorf, K.K. Ilse, "Combined Soiling and Abrasion Testing of Anti-Soiling Coatings", *IEEE J PV*, 10 (1), 2020, 243-249, doi: 10.1109/JPHOTOV.2019.2945192

Jimmy M. Newkirk, Illya Nayshevsky, Archana Sinha, Adam Law, QianFeng Xu, Bobby To, Paul F. Ndione, Laura T. Schelhas, John M. Walls, Alan M. Lyons, David C. Miller, "Artificial Linear Brush Abrasion of Coatings for Photovoltaic Module First Surfaces", *Solar Energy Materials and Solar Cells*, 219, 2021, 110757. DOI: https://doi.org/10.1016/j.solmat.2020.110757"

Bibliography

ISO 3310-1, *Test sieves – Technical requirements and testing – Part 1: Test sieves of metal wire cloth*

ASTM C778, *Standard specification for standard sand*

ASTM E11, *Standard specification for woven wire test sieve cloth and test sieves*

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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MEASUREMENT PROCEDURES FOR MATERIALS USED IN PHOTOVOLTAIC MODULES –

Part 7-3: Accelerated stress tests – Methods of abrasion of PV module external surfaces

FOREWORD

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9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.

IEC 62788-7-3 edition 1.1 contains the first edition (2022-02) [documents 82/1987/FDIS and 82/2009/RVD] and its amendment 1 (2024-07) [documents 82/2259/FDIS and 82/2277/RVD].

This Final version does not show where the technical content is modified by amendment 1. A separate Redline version with all changes highlighted is available in this publication.

IEC 62788-7-3 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems. It is an International Standard.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 62788 series, published under the general title *Measurement procedures for materials used in photovoltaic modules*, can be found on the IEC website.

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

- reconfirmed,
- withdrawn, or
- revised.

IMPORTANT – The *'colour inside'* logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

There is a need for abrasion test methods in the PV industry, particularly for the front and back surfaces of PV modules. This document defines a set of test methods to be used for evaluating the abrasion of materials and coatings in photovoltaic modules or other solar devices. Linear and rotary machine abrasion methods are specified that can be used to address durability to abrasion with respect to the cleaning of solar devices. Linear abrasion is intended to emulate traditional manual methods of cleaning, where the cleaning equipment typically acts perpendicular to the surface, giving a scratching motion. Rotary abrasion is intended to emulate popular robotic methods of cleaning, where the cleaning element often may act along the surface in a swiping motion. Relative to DIN 53778-2 and ASTM D2486, application specific modifications for the machine abrasion tests include the longer bristle length, use of abrasive (test dust) of the size encountered in PV, the use of dry or wet abrasive as may be encountered during cleaning modules, and the number of test cycles relative to the maintenance of PV systems. A falling sand method is specified that can be used to address durability to abrasion with respect to damage from ordinary use in the application environment, i.e., typically meteorological events. Relative to DIN 52348, modifications include the quantity of test sand, which is intended for examination of PV surfaces and coatings. A forced sand impingement method is specified that can be used to address durability to abrasion from severe weather events and/or the most challenging locations of use. Relative to IEC 60068-2-68, modifications include the composition of test sand that may be compared to the PV application and the falling sand test in this document as well as the specified carrier velocities based on the PV application. The methods in this document can be used to aid performance analysis and/or for the purpose of material design/selection. Comparing the linear brush, rotary brush, falling sand, and forced impingement methods, different rates of abrasion and/or damage morphology can occur between the different test methods – they are not expected to produce the same result.

Formal working reference materials are identified in this document. The purpose of the working reference is to verify the apparatus is installed and working correctly. The characteristic(s) of interest can be verified on a regular basis (monthly, weekly, etc.). The characteristic(s) of interest and their values (with acceptance limits for precision) will be given in a referencing document or future version of this document, based on the results of an interlaboratory precision study.

MEASUREMENT PROCEDURES FOR MATERIALS USED IN PHOTOVOLTAIC MODULES –

Part 7-3: Accelerated stress tests – Methods of abrasion of PV module external surfaces

1 Scope

This part of IEC 62788 defines the test methods that can be used for evaluating the abrasion of materials and coatings in photovoltaic modules or other solar devices. This document may be applied to components on the incident surface (including coatings, frontsheet, and glass) as well as the back surface (including backsheets or back glass). This document is intended to address abrasion of PV module surfaces and any coatings present using representative specimens (e.g. which can be centimetres in size); the methods and apparatus used here can also be used on PV module specimens (e.g. meters in size). A suite of tests and their methods are identified in this document, including falling sand, forced sand impingement, and machine (brush) abrasion. Materials and coatings can have different intended design purposes and design lifetimes and therefore no specific pass/fail criteria are defined in this document. The results of the testing can, however, be used to identify relative durability of coatings for various outdoor environments and cleaning practices. The methods can be used for the purpose of relative comparison, e.g. for the purpose of material or coating selection. The quantitative correlation between artificial abrasion and field erosion (which will depend on factors including climate or location of use as well as application, e.g., use of a tracker, rack-mount, roof-mount, building integrated, or vehicle integrated PV) can be established for each specific material or coating, which is beyond the scope of this document.

The correlation between the rates of degradation from the different test methods (linear brush, rotary brush, falling sand, and forced impingement) is beyond the scope of this document and may be covered in referencing documents. The correlation between the rates of degradation for unaged and aged specimens is also beyond the scope of this document and may be covered in referencing documents.

The methods related to the characterization of abraded specimens (which might include optical transmittance, optical reflectance, surface roughness, and surface energy) are not defined in this document; characterization methods from other standards (including optical transmittance, optical reflectance, electrical performance, surface roughness, and surface energy) can be applied to specimens abraded using the methods defined in this document. Methods for examining the contamination of specimens, including artificial soiling, are not examined in this document. Additional specimen conditioning can be applied prior to the methods in this document. The abrasion tests in this document can be referenced and/or applied in conjunction with an accelerated test or test sequence in other standards.

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.

IEC 60068-2-68, *Environmental testing – Part 2-68: Tests – Test L: Dust and sand*

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

ISO 291, *Plastics – Standard atmospheres for conditioning and testing*

ISO 12103-1, *Road vehicles – Test contaminants for filter evaluation – Part 1: Arizona test dust*

ASTM D2486, *Standard test methods for scrub resistance of wall paints*

DIN 52348:1985-02, *Testing of glass and plastics; abrasion test; sand trickling method*

DIN 53778-2:1983-08, *Emulsion paints for interior use; evaluation of cleanability and of wash and scrub resistance of coatings*

MIL-STD-810G, *Environmental engineering considerations and laboratory tests*

VDI 3956, *Evaluation of the soiling properties of surfaces – Test method for the dust soiling behaviour of solar energy systems*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 and the following 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
artificial abrasion
wear resulting from the cleaning of a PV device, including manual or robotic cleaning

3.2
natural erosion
wear resulting from the ordinary terrestrial use of a PV device

Note 1 to entry: Sources of erosion may include particulate impingement, particulate transport (from wind or water), or autonomous scraping (from snow or ice by gravity).

4 Artificial linear machine abrasion test (SAT01)

4.1 Principle

The machine abrasion methods are specified that can be used to address durability to abrasion with respect to the cleaning of solar devices. Linear abrasion is intended to emulate traditional manual methods of cleaning, where the cleaning equipment typically acts perpendicular to the surface, giving a scratching motion. The test is typically applied to the irradiance incident surface of a PV module. Because either dry or wet cleaning may be used to clean a PV module, both dry and wet (slurry) abrasives may be used in this test. The test may simulate the cleaning of fixed, tracked, or vehicle integrated PV.

4.2 Apparatus

4.2.1 Artificial linear machine abrasion apparatus

A linear abrasion apparatus fulfilling the requirements of ASTM D2486 or DIN 53778-2 shall be used. Essential components of the apparatus include: a linear abrasion mechanism, a brush, an abrasive dispenser (slurry or dry abrasive), and an enclosure (if applicable). An enclosure is recommended for the apparatus to prevent spilling or spraying of abrasive (dry or wet slurry abrasives) or the possibility of silicosis (with ventilation, for dry abrasive). Additional equipment and containers for the management of waste abrasive and its disposal after the test is advised.

The abrasion mechanism shall provide a brush stroke length of at least 14,5 cm. The brush may operate at either a constant or varied velocity through each stroke. The brush velocity of 30 ± 3 cm·s^{-1} shall be used for the through the central 7,5 cm test region on the specimen during machine abrasion testing. Other test rates may be used for the purposes of research and development.

NOTE For example, the brush velocity of 30 cm·s^{-1}, when used with a stroke length of 25,4 cm corresponds to a test rate of 37± 1 cycles per minute.

Specimens shall be rigidly mounted relative to the apparatus using mechanical springs or clamps, tape or other means.

To ensure repeatability of results (i.e., avoid temperature-related effects related to the abrasion process or abrasive) the apparatus shall be maintained, in a laboratory maintained at (23 ± 2) °C, (50 ± 10) % RH, as specified per Class 2 in ISO 291.

The dispenser for dry dust shall be separated from the specimen surface by at least 10 cm to provide clearance for the motion of the brush (in both linear and rotary configurations) and also aid dispensing to the designated test area of the specimen.

The dispenser for wet slurry shall be separated from the specimen surface by at least 5 cm to aid dispensing to the designated test area of the specimen.

4.2.2 Brush

The brush block shall be (38 ± 1) mm × (89 ± 1) mm in area and (13 ± 1) mm in thickness.

The brush bristles shall consist of polyamide 612, poly(hexamethylene dodecanediamide) with a 50:50 molar ratio of monomer types, (0,23 ± 0,03) mm in diameter that extend (38 ± 2) mm from the brush block. Brushes with bristles shorter than 35 mm in length shall be replaced. The bristle profile shall be round, with no taper or other change in geometry along their length. The lateral repeat space of 6,4 mm shall be used for the bristle tuft rows across the width of the brush and 12,7 mm shall be used for the bristle tuft columns along the length of the brush. For the staggered bristles, an offset space of 3,2 mm between adjacent rows and lateral offset space of 6,4 mm between adjacent bristle columns. The bristle tufts shall be staggered in a 5-4-5-4-... pattern along the brush, with total of 59 tufts. The bristle count shall be (158 ± 6) tips·tuft^{-1}. See Figure 1.

Dimensions in millimetres

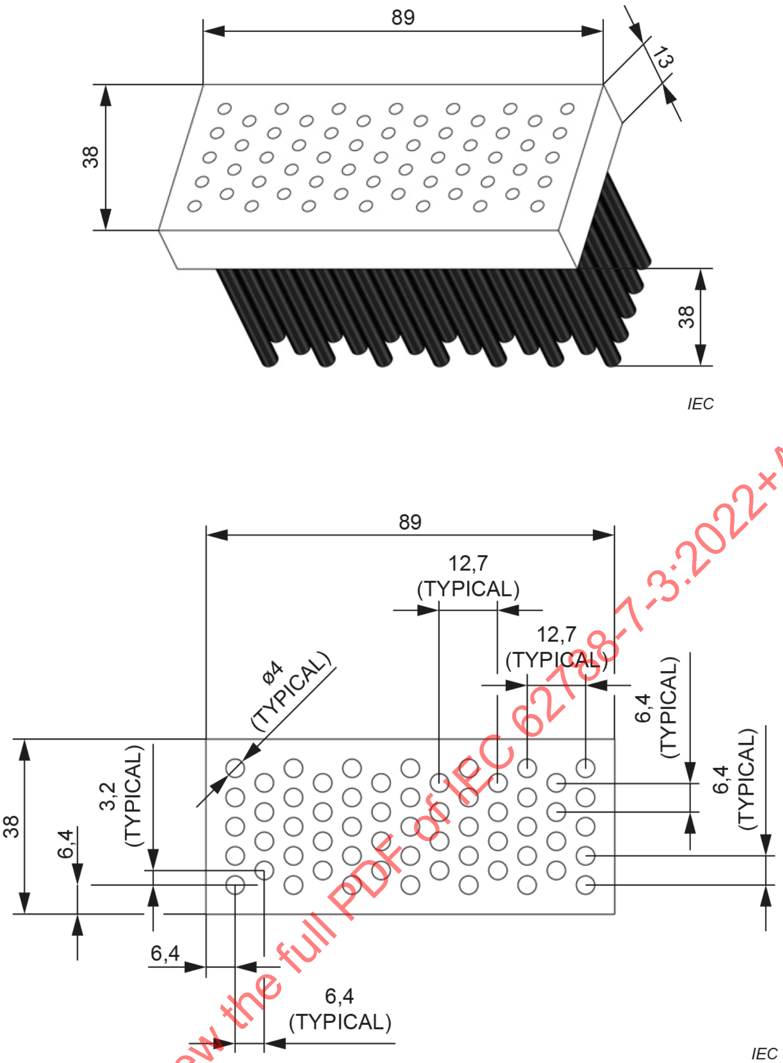

Figure 1 – Schematics showing the arrangement of bristle tufts on the linear brush

4.2.3 Abrasive medium (dry)

The dry abrasive medium shall consist of A3 (medium) AZ test dust, as specified in ISO 12103-1. The nominal abrasive concentration of (0,7) mg·cm^{-2}·cycle^{-1} shall be used during the test. To ensure repeatability, the test dust shall not be reused after testing. Other abrasive materials or quantities of abrasive may be used for the purposes of research and development.

NOTE The abrasive concentration of (20 ± 5) mg·cycle^{-1} when applied to the nominal area of the linear brush (29,75) cm^{-2} provides the nominal abrasive concentration of (0,7) mg·cm^{-2}·cycle^{-1}.

Dry abrasive shall be maintained at (23 ± 2) °C and (50 ± 10) % RH for at least 24 h, as specified per Class 2 in ISO 291, prior to use in the linear abrasion test.

For the dry abrasive test, the brush bristles shall be maintained at (23 ± 2) °C and (50 ± 10) % RH for at least 24 h, as specified per Class 2 in ISO 291, prior to use in the linear abrasion test.

Other dry abrasives may be used for the purposes of research and development. Dry abrasive may be used in conjunction with an artificial soiling method for the purposes of research and development. Alternative abrasives include the “Middle East” (ME) test dust as specified in VDI 3956, and “quartz free” AZ test dust (similar to ISO 12103-1, but using corundum instead of silica to avoid safety issues related to respiration). Both particle size and particle composition can affect the rate of abrasion. The aforementioned alternative abrasives have not been widely studied relative to ISO 12103-1 AZ test dust.

4.2.4 Abrasive medium (wet slurry)

The wet abrasive medium shall consist of A3 (medium) AZ test dust, as specified in ISO 12103-1. The abrasive concentration of (5,0 ± 0,2) $g{\cdot}l^{-1}$ in deionized water shall be used during the test. The slurry shall be flowed at the rate of (5,0 ± 0,2) $l{\cdot}h^{-1}$ during the test. To ensure repeatability, the test dust shall not be reused after testing. Other abrasive materials or quantities of abrasive may be used for the purposes of research and development.

NOTE The abrasive concentration of (5,0 ± 0,2) $g{\cdot}l^{-1}$ when flowed at the rate of (5,0 ± 0,2) $l{\cdot}h^{-1}$ to the nominal area of the linear brush (29,75) cm^{-2} provides the nominal abrasive concentration of (0,4) $mg{\cdot}cm^{-2}{\cdot}cycle^{-1}$ for the nominal brush travel distance (25,4 cm) and operating speed (30 ± 3 $cm{\cdot}s^{-1}$).

Deionized water at (23 ± 2) °C shall be used during the test to avoid temperature-related effects related to the abrasion process or abrasive.

For the wet slurry abrasive test, the brush bristles shall be conditioned using water for 24 h before the start of the test. Methods of brush conditioning include soaking the bristles in a container of water, completely immersing the brush in a container of water, and/or the use of water flow (where the water or brush may be adjusted to provide regular conditioning). Brushes that are in frequent use may be stored in water.

A stirring apparatus shall be used with the slurry to improve the uniformity of concentration of dust in the slurry as well as to facilitate uniform concentration through the duration of testing. In addition to the stirring/mixing of the slurry, the apparatus and its plumbing should produce good uniformity of deposition slurry on the sample.

Other wet slurry abrasives may be used for the purposes of research and development.

4.3 Test specimens

4.3.1 Materials and geometry

Specimens may consist of representative coupons. The specimens shall be composed of a base material (or substrate), where a coating (if applicable) may be present on the test surface. Representative coupons shall be at least (7,5 ± 0,2) cm × (7,5 ± 0,2) cm in size. Module specimens or glass specimens (for tempered glass, where cutting is impossible) may also be used, if they may be accommodated in the apparatus. In the case of modules, the specimens shall contain at least three test regions 7,5 cm × 7,5 cm in length and width, separated at least 37,5 cm. In the case of unaged specimens, or specimens with no previous test-history, the test region(s) shall be representative of that used in the PV application, being free from visible damage, delamination, or other defects. In the case of weathered specimens or specimens with a previous test-history, the specimen shall be used in its received condition. In the case of polymeric material specimens such as backsheets or frontsheets, both principal directions should be tested, including the machine extrusion direction and the traverse direction.

Some coatings can have limitations regarding the specimen size that can be used to fabricate a representative sample. For example the glass might need to be tempered as part of the manufacturing process, where a 50 cm × 50 cm minimum glass size is required. In such cases, a larger coupon size or a module specimen can be used.

Commercial abrasion test equipment fulfilling the requirements of the test apparatus may be used to test region(s) within a module, if the test apparatus is located and fixtured relative to the test surface of the module. A custom apparatus with equivalent characteristics to a commercial tester may be used for large coupon or module specimens.

4.3.2 Number of replicate specimens

In the case of representative coupons, at least three replicates shall be used. If the apparatus has adequate space or number of brushes, the replicates may be tested together, simultaneously. The use of glass blanks (where the size may be smaller than 7,5 cm) at the sides of the test specimens is recommended to avoid a discontinuous loading of the brush along its path during testing, i.e., the surfaces in PV modules are typically longer than 7,5 cm.

In the case of a PV module at least three replicate modules or three separate regions on the same module shall be used. Test regions on the same PV module shall be separated at least 37,5 cm. The test areas may be marked prior to testing to aid subsequent examination.

In the case of unaged specimens, or specimens with no previous test-history, the specimen may be cleaned prior to testing. A mild detergent (e.g., a non-perfumed liquid soap as recommended by the manufacturer) may be used with deionized water as a cleaning solvent. A fresh cloth wipe may be used to facilitate cleaning. After cleaning, specimens may be dried in the ambient or dried using a jet of clean dry air.

There are no specimen conditioning requirements for this test. Specimens subject to the slurry test do not need to be soaked in water prior to testing.

4.3.3 Reference material

A reference material, which may be used to compare universally relative to the apparatus manufacturer or between laboratories, shall be used to verify proper operation of the abrasion tester, including the abrasive, abrasion apparatus, and the brush. The reference material shall be used before specimens are tested, including after instrument installation or setup and between test sessions. A reference material similar to the test specimen(s) is recommended and should be used through the same measurement session. See Table 1.

Table 1 – Examples of suitable reference materials

Use	Description	Material	Manufacturer
Default reference material, glass substrate or superstrate	Super-white modified soda-lime glass (DIN 52348)	B 270 "Superwite"	Schott AG
Hard thin film, monolithic silica substrate or superstrate	Technical glass	Borofloat 33	Schott AG
Polymer substrate or superstrate	UV durable, solar grade bulk poly(methyl methacrylate)	Acrylite 0Z023	Röhm AG

Working reference materials, with similar characteristics as the suitable reference materials, may be used for internal purposes. Additional coupons of a suitable reference or working reference material should be tested alongside the test specimens (as blanks at the ends) during the abrasion test.

4.4 Test procedure

4.4.1 Setting up the apparatus and specimen

The apparatus shall be cleaned of residual abrasive, remaining from previous testing (if applicable).

The abrasive and apparatus (brush) shall be conditioned as designated prior to testing.

- Attach the specimen to the apparatus.
- Activate the abrasive dispenser.
- Activate the abrasion mechanism.

4.4.2 Performing the abrasion test

The following methods are given to standardize the test procedure, e.g., to facilitate comparison between laboratories or materials. The durability of the specimen(s) to abrasion may, however, be known from previous experience or anticipated based on the prescribed cleaning. Therefore additional methods may be used for the abrasion test. Additional readpoints (more than 5) may also be used with the test.

Method (A): For coatings anticipated to have a low cleaning severity (infrequent cleaning), a 20 cycle increment should be used between readpoints, with readpoints up to 100 cycles.

Method (B): For coatings anticipated to have a moderate cleaning severity (intermediate cleaning), a 100 cycle increment should be used between readpoints, with readpoints up to 500 cycles.

Method (C): For coatings anticipated to have a high cleaning severity (frequent cleaning), a 2 000 cycle increment should be used between readpoints, with readpoints up to 10 000 cycles.

A stroke in the forward and then reverse direction shall be considered complete cycle.

If the coating is observed to be destroyed (during characterization, according to characterization method(s) specified outside of this document), the test may be terminated with no additional readpoints.

NOTE Some examples of the durability of materials to linear abrasion (including roughened surfaces, chemically functionalized surfaces, porous silica coatings – including coatings deposited using a so-gel or other means, thin polymer film, and hard dielectric coatings) can be found in Annex A.

4.5 Specimen preparation for examination after testing

The specimen shall be cleaned to remove residual test sand using a deionized water rinse or deionized water spray. No detergent should be used if the surface energy is to be characterized, e.g., using liquid contact angle or liquid roll-off angle measurements. A cleaning solvent (rinse or spray) may be used before or intermediate-to deionized water for cleaning. A clean dry air spray or nitrogen spray shall then be used to dry the sample. Additional drying methods may be specified in other referencing standards, e.g., use of elevated temperature, an applied irradiance, or a desiccator chamber after abrasion and before specimen characterization.

For some characterization methods it is preferred to avoid contact cleaning of the specimens, because inadvertent abrasion damage may affect the results. For some characterization methods, however, contact cleaning (e.g. with a lens tissue) may be required to remove particulate matter from the specimen surface (e.g. to obtain valid spectral transmittance measurements). The use of noncontact or contact cleaning may be specified in the referencing document.

Perform specimen characterizations as specified elsewhere, i.e., in standards referencing IEC 62788-7-3.

5 Artificial rotary machine abrasion test (SAT02)

5.1 General

The machine abrasion methods are specified that can be used to address durability to abrasion with respect to the cleaning of solar devices. Rotary abrasion is intended to emulate popular robotic methods of cleaning, where the cleaning element often may act along the surface in a swiping motion. The test is typically applied to the irradiance incident surface of a PV module. Because either dry or wet cleaning may be used to clean a PV module, both dry and wet (slurry) abrasives may be used in this test. The test may simulate the cleaning of fixed or vehicle integrated PV. Cleaning of fixed PV may be performed with rotation, combined with a linear direction of motion. Cleaning of vehicle integrated PV may used equipment from the automotive industry.

5.2 Apparatus

5.2.1 Artificial rotary machine abrasion apparatus

There is no existing commercial test equipment for the rotary abrasion test fulfilling the specifications identified below, therefore custom equipment may be used. Essential components of the apparatus include: a linear actuation mechanism, a rotary abrasion mechanism, a brush, an abrasive dispenser (slurry or dry abrasive), and an enclosure (if applicable). An enclosure is recommended for the apparatus to prevent spilling or spraying of abrasive (dry or wet slurry abrasives) or the possibility of silicosis (with ventilation, for dry abrasive). Additional equipment and containers for the management of waste abrasive and its disposal after the test is advised.

The linear actuation mechanism shall provide a brush stroke length of at least 14,5 cm. The brush may operate at either a constant or varied velocity through each stroke. The brush velocity of 30 ± 3 $cm \cdot s^{-1}$ shall be used for the through the central 7,5 cm test region on the specimen during machine abrasion testing. Other test rates may be used for the purposes of research and development.

NOTE 1 For example, the brush velocity of 30 $cm \cdot s^{-1}$, when used with a stroke length of 25,4 cm corresponds to a test rate of 37± 1 cycles per minute.

The rotary brush mechanism shall provide a constant brush rotation rate of (120 ± 5) rpm. Other rotation rates may be used for the purposes of research and development.

Specimens shall be rigidly mounted relative to the apparatus using mechanical springs or clamps, tape or other means.

To ensure repeatability of results (i.e., avoid temperature-related effects related to the abrasion process or abrasive) the apparatus shall be maintained, in a laboratory maintained at (23 ± 2) °C, (50 ± 10) % RH, as specified per Class 2 in ISO 291.

The same dispensing apparatus may be used for dry dust in the rotary machine abrasion test as used in the linear machine abrasion test. A representative $mass \cdot area^{-1} \cdot cycle^{-1}$ concentration is given for dry dust in 4.2.3.

The same dispensing apparatus may be used for wet slurry in the rotary machine abrasion test as used in the linear machine abrasion test. A representative $mass \cdot area^{-1} \cdot cycle^{-1}$ concentration is given for slurry in 4.2.4.

NOTE 2 The rate of rotation for the brush is chosen to give a rate that is representative for some cleaning equipment used in the PV industry. The tangential velocity of the brush tips during use will vary with the rate of rotation of the brush.