भारतीय मानक

Indian Standard

IS 16792 (Part 1/Sec 4) : 2023
IEC 62788-1-4 : 2016+AMD1 : 2020

फोटोवोल्टिक मॉड्यूल में प्रयुक्त सामग्री के लिए मापन प्रक्रिया

भाग 1 एनकैप्सुलेंट्स

अनुभाग 4 ऑप्टिकल ट्रांसमिशन का मापन और सौर-भारित फोटॉन ट्रांसमिशन की गणना, पीलापन सूचकांक, और यूवी कट-ऑफ तरंगदैर्ध्य

(पहला पुनरीक्षण)

Measurement Procedures for Materials Used in Photovoltaic Modules

Part 1 Encapsulants

Section 4 Measurement of Optical Transmittance and Calculation of the Solar-Weighted Photon Transmittance, Yellowness Index, and UV Cut-Off Wavelength

(First Revision)

ICS 27.160

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NATIONAL FOREWORD

This Indian Standard (Part 1/Sec 4) (First Revision) which is identical with IEC 62788-1-4 : 2016 + Amd 1 : 2020 'Measurement procedures for materials used in photovoltaic modules — Part 1-4: Encapsulants — Measurement of optical transmittance and calculation of the solar-weighted photon transmittance, yellowness index, and UV cut-off wavelength' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Solar Photovoltaic Energy Systems Sectional Committee and approval of the Electrotechnical Division Council.

This standard was first published in 2019. This first revision has been undertaken to take into consideration the developments that have taken place subsequently and also to align with the latest version of IEC 62788-1-4 : 2016 + Amd 1 : 2020.

The text of IEC Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain terminologies and conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards, which are to be substituted in their respective places, are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60904-3 Photovoltaic devices — Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data	IS 12762 (Part 3) : 2020 — Photovoltaic devices: Part 3 Measurement principles for terrestrial photovoltaic PV solar devices with reference spectral irradiance data (*third revision*)	Identical with IEC 60904-3 : 2019

The technical committee has reviewed the provisions of the following international standards referred in this adopted standard and decided that they are acceptable for use in conjunction with this standard:

International Standard	*Title*
ISO 291 : 2008	Plastics — Standard atmospheres for conditioning and testing
ISO 11664-1 : 2007	Colorimetry — Part 1: CIE standard colorimetric observers
ISO 11664-2 : 2007	Colorimetry — Part 2: CIE standard illuminants
ISO 13468-2 : 1999	Plastics — Determination of the total luminous transmittance of transparent materials — Part 2: Double-beam instrument
ISO 17223 : 2014	Plastics — Determination of yellowness index and change in yellowness index
ASTM E424-71 : 2007	Standard test methods for solar energy transmittance and reflectance (Terrestrial) of sheet material

Only the English language text has been retained while adopting it in this Indian Standard, and as such, the page numbers given here are not the same as in the IEC Publication.

For the purpose of deciding whether a particular requirement of this standard is complied with the final value, observed or calculated expressing the result of a test or analysis shall be rounded off in accordance with IS 2 : 2022 'Rules for rounding of numerical values (*second revision*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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MEASUREMENT PROCEDURES FOR MATERIALS USED IN PHOTOVOLTAIC MODULES

PART 1 ENCAPSULANTS

SECTION 4 MEASUREMENT OF OPTICAL TRANSMITTANCE AND CALCULATION OF THE SOLAR-WEIGHTED PHOTON TRANSMITTANCE, YELLOWNESS INDEX, AND UV CUT-OFF WAVELENGTH

(First Revision)

1 Scope

This part of IEC 62788 provides a method for measurement of the optical transmittance of encapsulation materials used in photovoltaic (PV) modules. The standardized measurements in this procedure quantify the expected transmittance of the encapsulation to the PV cell. Subsequent calculation of solar-weighted transmittance allows for comparison between different materials. The results for unweathered material may be used in an encapsulation manufacturer's datasheets, in manufacturer's material or process development, in manufacturing quality control (material acceptance), or applied in the analysis of module performance.

This measurement method can also be used to monitor the performance of encapsulation materials after weathering, to help assess their durability. The standardized measurements are intended to examine an interior region within a PV module, e.g., without the effects of oxygen diffusion at the periphery of the cells. Subsequent calculation of yellowness index allows for quantification of durability and consideration of appearance. The change in transmittance, yellowness index, and ultraviolet (UV) cut-off wavelength may be used by encapsulation or module manufacturers to compare the durability of different materials.

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 60904-3, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*

ISO 291:2008, *Plastics – Standard atmospheres for conditioning and testing*

ISO 11664-1:2007, *Colorimetry – Part 1: CIE standard colorimetric observers*

ISO 11664-2:2007, *Colorimetry – Part 2: CIE standard illuminants*

ISO 13468-2:1999, *Plastics – Determination of the total luminous transmittance of transparent materials – Part 2: Double-beam instrument*

ISO 17223:2014, *Plastics – Determination of yellowness index and change in yellowness index*

ASTM E424-71:2007, *Standard test methods for solar energy transmittance and reflectance (Terrestrial) of sheet material*

3 Terms and definitions

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

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

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

NOTE In cases where definitions already exist, refer to IEC TS 61836. Calculations related to these definitions are given in Clause 8.

3.1
solar-weighted transmittance of photon irradiance
proportion of the solar spectral photon irradiance ($E_{p\lambda}$, $m^{-2} \cdot s^{-1} \cdot nm^{-1}$) optically transmitted through the specimen, throughout the range of the terrestrial solar spectrum (280 nm to 2 500 nm) (see Table 1)

Note 1 to entry: The photon irradiance ($E_{p\lambda}$, $m^{-2} \cdot s^{-1} \cdot nm^{-1}$) accounts for the wavelength-specific energy of the optical flux and should not be confused with spectral irradiance (E_{λ}, $W \cdot m^{-2} \cdot nm^{-1}$).

3.2
representative solar-weighted transmittance of photon irradiance
proportion of the solar spectral photon irradiance ($E_{p\lambda}$, $m^{-2} \cdot s^{-1} \cdot nm^{-1}$) optically transmitted through the specimen, throughout the range of the terrestrial solar spectrum (300 nm to 1 250 nm) (see Table 1)

Note 1 to entry: In the case of a PV device, the representative solar-weighted transmittance of photon irradiance is defined throughout the range of the spectrum utilized by a representative PV device (which may not include wavelengths as low as 280 nm or as great as 2 500 nm).

3.3
UV cut-off wavelength
λ_{cUV}
wavelength of light below which the encapsulation is considered optically absorbing and above which the encapsulation is considered transmitting

Note 1 to entry: In this procedure, the absolute transmittance of 10 % (corresponding to the optical absorbance of 1) is considered as the threshold of the UV cut-off wavelength. As described further in [9][1], the UV cut-off wavelength may also be used to quantify the effects of weathering.

3.4
weathering
process of subjecting specimens to environmental conditions that could include ultra-violet radiation, temperature, humidity, and ozone

Note 1 to entry: Weathering may occur in artificial or natural environments. Weathering could occur at the nominal (field) or an accelerated rate.

3.5
yellowness index
YI
calculated value identifying the yellowness of the test specimen perceived by a human observer (see ASTM E313-10)

Note 1 to entry: YI may be used to quantify the effects of weathering.

1 Numbers in square brackets refer to the Bibliography.

4 Principle

The total spectral transmittance of laminated specimens, containing encapsulation material, shall be measured using a spectrophotometer equipped with an integrating sphere. Solar-weighted transmittance, yellowness index, and UV cut-off wavelength will be subsequently calculated from the transmittance measurements.

The transmittance measured using this procedure may be used in a more advanced optical analysis to improve the accuracy of PV performance analysis or distinguish between different encapsulation materials, as described in Annex A. The transmittance measured using this procedure may be used to estimate module performance (current yield) if the quantum efficiency of the PV cell is known, as described in Annex B. The method does not attempt to account for variations in transmittance with the angle of incidence, which may vary with time of day, sky conditions, and geometry of the module, especially if optical concentration is used.

5 Apparatus

The test instrument shall consist of a double beam spectrophotometer equipped with an integrating sphere. A single beam spectrophotometer may be used if the port reflectance can be properly accounted for, as in Annex A and [2]. Details regarding the construction and configurations of the test instrument may be found in ISO 13468-2 or ASTM E424-71. A measurement range of at least 280 nm to 2 500 nm is required for calculation of the solar-weighted transmittance using the AM1.5 global spectrum as in IEC 60904-3. A wavelength increment no larger than 1 nm is preferred for the measurement, however increments up to 5 nm are permitted with linear interpolation to 1 nm.

An integrating sphere of at least 100 mm in diameter with a port area of < 5 %, as in [11], is recommended to reduce the error in the measurement. The port area as in [9] should not exceed 13 %.

6 Test specimens

6.1 Nominal (and unweathered) transmittance to the cell

Specimens shall be constructed using a laminate structure of glass/encapsulation, as described in Annex A and [12].

The solar-weighted transmittance and representative solar-weighted transmittance, as calculated in Clause 8, may be used for the purpose of reporting on an encapsulation manufacturer's datasheet.

The specimens shall contain an examination region free from visible flaws including: scratches, pits, sink marks, bubbles, or other imperfections. The examination region shall be at least 50 % larger in diameter than the measurement area of the test instrument.

NOTE 1 A spot size of 1 cm × 1 cm is common in many commercial spectrophotometer instruments. Use of specimens at least 2 to 3 times this size will improve uniformity (resulting from fabrication) and handling (during measurement).

The size (length and width) should be adequate to allow the specimen to fit inside the test instrument.

The nominal thickness of the encapsulant specimens shall be equal to the thickness intended for use in PV modules.

Specimens should be cured (if applicable) according to the manufacturer's specification and using a process as similar as possible to the method used in the intended manufacturing process.

The thickness of the encapsulation portion of the test specimen shall be measured after its preparation. The thickness shall be taken as the average of three measurements obtained at different locations on the test region of the specimen.

Glass plates shall be parallel with minimal edge pinch or edge flare. I.e. the encapsulation thickness at any of the corners shall not be more than 10 % different than that in the centre of the sample. In a typical bag laminator this will require the use of a frame around the samples during lamination, but any other means of accomplishing this specification is acceptable.

The back surface of the specimens (the exposed encapsulation intended to face to the integrating sphere) shall not be intentionally textured.

For additional resolution to more accurately distinguish between materials, subsequent studies may utilize a thicker encapsulation layer that may be analysed to determine the optical attenuation coefficient as described in Annex A.

If the encapsulation material is intended to be used with superstrates other than glass, the same procedure may be used in a subsequent study. Specimens using polymeric superstrates may be prone to optical polarization occurring within the instrument. As in [9] and [12], a depolarizer should be used with the instrument to minimize the effects of polarization.

NOTE 2 The effect of haze in specimens prone to optical haze can be mitigated through the use of a diffusing film, as described in [13].

6.2 Weathering studies

A glass/encapsulation/glass laminate specimen geometry is recommended.

The size (length and width) should be adequate to allow the specimen to fit inside the test instrument.

The minimum size of 7,5 cm × 7,5 cm is recommended for weathering specimens based on previous examinations of poly (ethylene-co-vinyl acetate).

Large specimens are preferred in weathering studies, because a test region may be distinguished, where the diffusion of oxygen or moisture is limited.

Other geometries may be used with this procedure to evaluate the effects of weathering. For example, a permeable polymeric backsheet facilitates the examination of moisture ingress. Some PV modules make use of an edge seal to reduce moisture permeation.

Separate “blank” pieces of superstrate or substrate may be weathered with the test specimens to quantify the degradation of those components.

The specimens shall contain an examination region free from visible flaws including: scratches, pits, sink marks, bubbles or other imperfections. The examination region shall be at least 50 % larger in diameter than the measurement area of the test instrument.

The nominal thickness of the encapsulant specimens shall be as intended for use in the PV module. Specimens should be cured (if applicable) according to the manufacturer’s specification and as similar as possible to the method used in the intended manufacturing procedure.

The thickness of the encapsulation in the laminate may be controlled by inserting a removable material around the specimen perimeter.

6.3 Glass for superstrates/substrates

Measurements of the nominal (unweathered) transmittance to the cell for the purpose of encapsulation manufacturer's datasheets shall be performed using (3 ± 0,2) mm thick silica glass. The glass shall have smooth, defect-free surfaces that are sufficiently flat and parallel such that the diffuse component of transmitted light is less than 1 % between 280 nm and 2 500 nm.

The solar-weighted transmittance of photon irradiance of silica glass, which may be used to verify that the composition of the glass is appropriate, is approximately (93 ± 1) % between 280 nm and 2 500 nm, because the reduction in transmittance comes from reflections at the surfaces. The UV cut-off wavelength for silica should be less than 225 nm. As in [1] and [12], the transmittance of the glass should be greater than 90 % at 280 nm.

The glass shall not be coated or contain antireflective layers. The glass shall not be intentionally textured.

Subsequent examination beyond that intended for the encapsulation material datasheet (including performance and weathering), such as for the purpose of quality control for production monitoring, may be performed according to this procedure using other superstrate and/or substrate materials that can incorporate other optical features, e.g., antireflective coatings, surface texture, and untempered soda-lime PV glass.

The process of solarization, where a redox reaction of trace impurities affects the UV cut-off wavelength and corresponding range of transmittance, can occur if glass other than silica is used [14]. It is therefore advised for weathering studies to UV condition substrate and superstrate materials, other than silica, prior to lamination.

NOTE Silica glass is more durable than soda-lime glass and will better resist glass corrosion in accelerated tests.

6.4 Number of specimens

A minimum of 3 replicates shall be used for the determination of the transmittance to the cell or in weathering studies. Optical characteristics, including transmittance, YI, and the UV cut-off wavelength shall be subsequently calculated using the average of the three separate specimens, with the range of the measurements indicated to identify their variability.

6.5 Conditioning of specimens

Specimens used for the purpose of datasheet reporting shall be maintained at (23 ± 2) °C, (50 ± 10) % RH for at least 24 h, as specified per Class 2 in ISO 291, prior to optical measurement.

The use of elevated temperature and humidity conditions in a weathering study may result in a supersaturated moisture condition within specimens, affecting their optical transmittance when they are returned to the laboratory ambient condition. In such cases, specimen conditioning, including a controlled environmental chamber, may be applied to prevent spurious effects, e.g., optical haze or moisture related absorptance. Specimen-condition effects may be verified using periodic measurements. Refer to the weathering test procedure for any specific details related to specimen conditioning and storage intermittent to weathering.

7 Measurement procedure

7.1 General

Transmittance measurements shall be performed in accordance with the procedure in ISO 13468-2.

7.2 Specimen preparation

Prior to measurement, specimens should be free of dust, grease or other contaminants. Specimens may be wiped with a solution of deionized water and mild soap for cleaning prior to measurement using a cleanroom wipe or lint free cloth. The specimens and instrument should be in thermal equilibrium prior to measurement.

7.3 Instrument calibration (baseline measurements)

Allow the instrument lamp to adequately equilibrate after it has been lighted, observing the typical warm-up period, e.g., 15 min or as recommended by the instrument manufacturer. Perform the correction scan(s) to compensate for the instrument baseline signal.

The 100 % transmittance baseline measurement should be performed in air, with no superstrate, specimen, or substrate material present. The 0 % transmittance baseline measurement should also be performed, if possible.

Periodic measurement of the baseline is recommended to minimize instrument drift and ensure the measured values are accurate. The instrument drift occurring over an extended measurement session may be instrument specific.

It is recommended to maintain the instrument drift below 0,05 % to minimize the uncertainty of measurement (Clause 9). The instrument drift should be considered in the instrument bias when the uncertainty of measurements is determined.

7.4 Specimen measurements

Perform the transmittance measurements for the test specimens over the wavelength range of at least 280 nm to 2 500 nm using a 1 nm increment.

Linear interpolation to a 1 nm increment may be used when only a coarser measurement increment (maximum of 5 nm) is available. The error associated with a coarser increment may be more influential at shorter wavelengths (where YI and the UV cut-off wavelength are determined) than at longer wavelengths (where only the solar-weighted transmittance is affected). When applied, the use of linear interpolation should be noted in the test report.

Discontinuities associated with changes in the optical components (including detector, light source, and/or monochromator) may occur during the measurement. Such discontinuities can be minimized via the instrument settings.

It may be useful to extend the range of measurement in weathering durability studies to provide insight into the results. For example, by measuring UV wavelengths as low as 200 nm, the integrity of UV absorbers and stabilizers can be confirmed from the UV cut-off wavelength.

The spectral bandwidth of the measurement should be less than or equal to the increment of the measurement, i.e., 1 nm or 5 nm.

7.5 Witness measurements

Perform the transmittance measurements on a witness specimen at the beginning of each measurement session to ensure proper operation of the instrument and minimize the measurement error. Perform the transmittance measurements of any witness specimens using the same procedure applied to the test specimen(s). The witness specimens may include a traceable standard specimen, laboratory working witness specimen, or the silica superstrate/substrate material.

7.5.1 Witness specimen(s)

The witness specimens may include a traceable standard specimen, laboratory working witness specimen, or the silica superstrate/substrate material. Witness specimen(s) for control measurements may also include a non-weathered glass working witness specimen of the same construction used in module representative test specimen(s) or reference (glass or polymeric superstrate) specimen(s). When not being used for control measurements, a working witness specimen shall be stored in the dark at 23 °C and 50 % humidity as specified per Class 2 in ISO 291.

7.5.2 Procedure for the witness specimen prior to the test specimen(s)

After instrument equilibration and baselining, perform the transmittance measurements on a witness specimen at the beginning of each measurement session to ensure proper operation of the instrument and minimize the measurement error. Perform the transmittance measurements of the witness specimen using the same procedure that will be applied to the test specimen(s).

The verification wavelengths for the working reference shall be ± 50 nm from the instrument transitions for the source, detector, and gratings. Because of the limitations of measurement, including noise from scattering at short wavelengths, the verification wavelengths shall not extend below 225 nm. In the case of many commercial instruments where the source, detector, and grating transitions occur at 350 nm, 800 nm, and 800 nm, respectively, the verification wavelengths should include the ranges 250 nm to 300 nm, 400 nm to 750 nm and 850 nm to 2500 nm (in the case of standard measurements) or 225 nm to 300 nm, 400 nm to 750 nm and 850 nm to 2 500 nm (in the case of measurements of weathered specimens).

The transmittance at each of the verification wavelengths should be within 0,25 % of the known transmittance (or laboratory running average) for the witness specimen. If the transmittance at each verification wavelength is not within 0,25 % of the known transmittance, the instrument baseline shall be performed again (including as many as three times) and the witness specimen shall be remeasured. If the transmittance at each wavelength continues to be greater than 0,25 % of the known transmittance, the instrument should be maintenanced or repaired.

7.5.3 Measurement of the test specimen(s)

After the witness specimen has been verified, the test specimen(s) shall be measured.

7.5.4 Procedure for the witness specimen after the test specimen(s)

After the test specimen(s) have been measured, perform the transmittance measurements on a witness specimen at the end of each measurement session to ensure proper operation of the instrument through the measurement session. Perform the transmittance measurements of the witness specimen using the same procedure that will be applied to the test specimen(s). The transmittance at each of the verification wavelengths should be within 0,25 % of the known transmittance (or laboratory running average) for the witness specimen. If the transmittance at each verification wavelength is not within 0,25 % of the known transmittance, the measured data for the test specimen(s) shall be considered invalid and the test specimen(s) shall be measured again in a subsequent session.

8 Calculation and expression of results

8.1 Post-processing of data

The measurements obtained from three separate specimens shall be averaged at each wavelength increment. The variability shall be reported for each characteristic (weighted transmittance, yellowness index, and UV cut-off wavelength) as the range (difference of the maximum and minimum measurements) for the three specimens.

8.2 Calculation of weighted transmittance

The solar-weighted transmittance may be calculated from formula (1):

$$\tau_{sw} = \frac{\int \tau[\lambda] E_{p\lambda}[\lambda] d\lambda}{\int E_{p\lambda}[\lambda] d\lambda} \quad (1)$$

Where

τ_{sw} refers to the solar-weighted transmittance (%);

τ is the measured transmittance of the specimen (%);

λ is the wavelength of light (nm); and

$E_{p\lambda}$ is the reference global spectral photon irradiance (as given in IEC 60904-3).

The details for the calculation of the various solar-weighted transmittance parameters are identified in Table 1. The parameters include: the "solar-weighted" transmittance, which may be applied generally, based on a broad solar spectrum; and the "representative solar-weighted" transmittance, which may be applied for most commercially available single junction terrestrial PV cells (including silicon, cadmium telluride, copper indium gallium selenide, and gallium arsenide) based on their useable wavelength range. The solar-weighted transmittance (as well as *YI*) obtained from the spectrophotometer measurements (1 nm interval) shall be calculated using a discretized sum, by means of the modified trapezoidal integration technique, as in IEC 60904-3. The denominator for formula (1) is specified in Table 1 for the purpose of verification, based on IEC 60904-3.

Table 1 – Details of the solar weight transmittance parameters

Parameter	Symbol	Lower bound wavelength nm	Upper bound wavelength nm	$\int E_{p\lambda}[\lambda] d\lambda$ $m^{-2} \cdot s^{-1}$
"solar-weighted" transmittance	τ_{sw}	280	2 500	$4,15502132187479 \times 10^{21}$
"representative solar-weighted" transmittance	τ_{rsw}	300	1 250	$3,03000915425 \times 10^{21}$
NOTE The solar-weighted spectral transmittance may be more specifically applied to estimate module performance, i.e., current yield, if the quantum efficiency of the PV cell is known, as described in Annex B.				

8.3 Calculation of the Yellowness Index (*YI*)

YI shall be calculated according to the procedure in ISO 17223. The three tristimulus coefficients shall be determined using the CIE Standard D65 Illuminant spectrum (as in ISO 11664-2), and the CIE 1964 XYZ colour space (for a human observer with a 10° field of view, as in ISO 11664-1). *YI* shall be calculated for a wavelength increment, e.g., 1 nm, consistent with the measured transmittance data.

NOTE Additional details related to the *YI* may be found in ASTM E313-10 and ASTM E308-08.

8.4 Calculation of the UV cut-off wavelength

The UV cut-off wavelength, λ_{cUV}, shall be determined as the longest wavelength (linearly interpolated to the nearest tenth of a nm) in the UV range (where $\lambda \leq 400$ nm) where the transmittance equals 10 % or less.

In cases where the UV cut-off wavelength is known to be less than 280 nm, the range of measurement should be extended below 280 nm to quantify its specific value.

9 Uncertainty of measurements

The uncertainty associated with the randomness of measurement may be estimated from:

$$\sigma_{\text{ran}} = \frac{\int \Delta\tau[\lambda] E_{\text{p}\lambda}[\lambda] d\lambda}{\int E_{\text{p}\lambda}[\lambda] d\lambda} = S_{\text{n}} \sqrt{\sum_{i=1}^{n} (\sigma_{\tau}[\lambda])^2} \tag{2}$$

where

σ_{ran} represents the random variation of measurement;

$\Delta\tau$ is the uncertainty of the transmittance measurement;

λ is the wavelength of light;

$E_{\text{p}\lambda}$ is the reference spectral photon irradiance;

S_{n} is the coefficient for Student's t-distribution (3,18245 for 3 specimens at the 95 % confidence interval), and

σ_{τ} is the standard deviation of the transmittance measurements (at each wavelength increment).

The final (reported) uncertainty may be estimated from:

$$\sigma_{\text{tot}} = \sqrt{(\sigma_{\text{inst}})^2 + (\sigma_{\text{ran}})^2} \tag{3}$$

where

σ_{tot} represents the total uncertainty;

σ_{inst} is the instrument bias (accounting for the particular make of the instrument, the instrument settings (including integration time), as well as instrument drift); and

σ_{ran} is the random variation of measurement (the accuracy of the instrument as well as the specimen variability).

σ_{ran} may be evaluated for the test instrument from the average of 10 measurements (multiplied by the corresponding S_{n} value of 2,22814) with no specimen present (nominal transmittance of 100 %). Similarly, σ_{inst} may be evaluated for the test instrument from a series of successive periodic measurements with no specimen present, with the rate of drift being determined from a trendline fit. While σ_{tot} may vary with the lamp age, a single representative evaluation is expected to adequately represent the test instrument used within a particular test laboratory.

Calculate the uncertainty for other test results (such as *YI*) using the same method as for transmittance, *i.e.*, the method of propagation of error. These estimates should also account for the uncertainty associated with instrument bias in addition to random error.

The repeatability and reproducibility of the method, including solar-weighted transmittance, yellowness index, and the UV cut-off wavelength, are described in Annex A and [12].

10 Test report

A report of the tests shall be prepared by the test agency. The report shall contain the detail specification for the specimens. Each certificate or test report shall include at least the following information:

a) a title;

b) name and address of the test laboratory and location where the tests were carried out;

c) unique identification of the certification or report and of each page;

d) name and address of client, where appropriate;

e) description and identification of the item tested, including specimen type, specimen thickness (and its range of variation), the specimen size (length and width), the superstrate/substrate material(s) and their characteristics;

f) characterization and state of the test item, including the method and details of specimen preparation (including curing, lamination, or similar processing if applicable) and conditioning;

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

h) identification of test method used; including the make and model of the spectrophotometer and the integrating sphere;

i) reference to sampling procedure, where relevant;

j) 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 conditioning conducted prior to measurements;

k) measurements, examinations and derived results supported by tables, graphs, sketches and photographs as appropriate including the complete set of the tabulated average transmittance values and the corresponding range of the averaged values; the estimated uncertainty of the transmittance measurement (instrument); the averaged solar-weighted transmittance of photon irradiance and the corresponding range of the averaged values; the averaged representative solar-weighted transmittance of photon irradiance and the corresponding range of the averaged values (as well as the wavelength range considered); the UV cut-off wavelength and its uncertainty; and any failures observed;

l) the yellowness index and its uncertainty (which should be determined after each weathering interval in addition to its original value in the case of weathering experiments);

m) a statement of the estimated uncertainty of the test results (where relevant); the measurement of the witness specimen (if utilized) and its deviation from its witness values. When applicable, the details of the witness specimen (such as its preparation, composition, and thickness) shall be specified;

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

o) where relevant, a statement to the effect that the results relate only to the items tested;

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

Annex A
(informative)

Advanced analysis of transmittance (absorption coefficients)

The measurements described in this procedure may be supplemented to allow for a more rigorous optical analysis. The determination of the optical attenuation coefficient allows the optical transmittance to be generalized and extended to any possible configuration. Such analysis may be used to improve the accuracy of PV performance analysis, account for changes in the module design (such as the thickness of the encapsulation), or to distinguish between different encapsulation materials. Characteristics including transmittance, YI, and the UV cut-off wavelength strongly vary with the specimen thickness; the methods described in this annex may therefore be used to standardize measurements to a representative thickness.

Optical transmittance also depends upon the material layers present within the specimen. A more rigorous analysis, summarized in this annex, may be used to consider loss of transmitted light, including the reflectance at material interfaces.

Hemispherical reflectance and transmittance data may be used to calculate the attenuation coefficient for a minimally absorbing material. The terminology “low absorbing” implies that light reflected from the rear interface is not fully absorbed prior to reaching the front interface. For this method, the specimen is ideally flat, free standing, of uniform known thickness, and minimally scattering, i.e., minimal optical haze. The method is based on work presented in [1]. As described in [2] and [3], the absorptance is first determined using the formula:

$$\alpha_c[\lambda] = 1 - \tau_m[\lambda] - \rho_m[\lambda] \tag{A.1}$$

Nomenclature in the formula includes: α_c, the calculated optical absorptance (normalized intensity); τ_m, the measured optical transmittance (normalized intensity); ρ_m, the measured optical reflectance (normalized intensity); and λ, the wavelength (m). The measured reflectance should be corrected to an absolute scale (using a certified calibrated reflectance specimen) for spectrophotometers that report relative reflectance measurements. The absolute reflectance of the specimen may be determined if its measured relative reflectance is multiplied by the reflectance of a calibrated specimen. The measured transmittance and measured reflectance include the effects of multiple passes of light, occurring as the result of internal reflections, as described in [4].

A subsequent analysis of the measured reflectance and transmittance data may be used to account for the internal reflections, in order to represent a single optical pass through the material. The reflections occurring at the air/sample interface as well as the absorptance for a single pass (occurring normal to the specimen), can be determined from the measured values using the formulas:

$$\rho_i[\lambda] = \frac{-\left(1 + \left(\tau_m[\lambda]\right)^2 + 2\rho_m[\lambda] - \left(\rho_m[\lambda]\right)^2\right) + \sqrt{\left(1 + \left(\tau_m[\lambda]\right)^2 + 2\rho_m[\lambda] - \left(\rho_m[\lambda]\right)^2\right)^2 + 4\left(\rho_m[\lambda] - 2\right)\rho_m[\lambda]}}{2\left(\rho_m[\lambda] - 2\right)} \tag{A.2}$$

$$\alpha_{sp}[\lambda] = \frac{\rho_i[\lambda]\alpha_c[\lambda] - \alpha_c[\lambda]}{\rho_i[\lambda]\alpha_c[\lambda] + \rho_i[\lambda] - 1} \tag{A.3}$$

$$\psi[\lambda] = -\frac{1}{z}\ln\left(1 - \alpha_{sp}[\lambda]\right) \tag{A.4}$$

New nomenclature in the formulas includes: ρ_i, the reflectance at the interfaces (normalized intensity); α_{sp}, the absorptance occurring for a single optic pass through the specimen (normalized intensity); ψ, the attenuation coefficient (typically represented as "α" in Beer's law, m^{-1}); and z, the specimen thickness (m).

After determining the attenuation coefficient, it is possible to predict the transmittance for a specimen of arbitrary thickness using the "single pass transmittance", indicated using the subscript –sp, considered here to represent a laminated silica glass superstrate/encapsulation geometry:

$$\tau_{sp}[\lambda] = [1 - \rho'[\lambda]] e^{-\psi g[\lambda] \cdot zg} e^{-\psi p[\lambda] \cdot zp} \qquad (A.5)$$

$$\rho' = \frac{(n_a - n_g)^2 + (k_a - k_g)^2}{(n_a + n_g)^2 + (k_a + k_g)^2} \qquad (A.6)$$

$$\psi = \frac{4\pi k}{\lambda} \qquad (A.7)$$

New nomenclature in the formulas includes: τ_{sp}, the estimated single pass transmittance (normalized intensity); ρ', the reflectance at the interface between air and glass (normalized intensity); n, the real component of the refractive index (unitless); k, the extinction coefficient (unitless); and π, the mathematical constant, 3,142. The subscript -g represents the glass; -p represents the encapsulation; and -a represents air. The analysis here assumes that the reflections occurring at the glass/encapsulation interface are negligible at all wavelengths. Then for an air/glass system, n_a, the refractive index for air, approximately equals 1 and the k_a, the extinction coefficient for air, approximately equals 0. To estimate ρ', the refractive index for glass (n_g) shall be known. The extinction coefficient for glass, k_g, may be taken from [5] for soda-lime glass or determined from the analysis, i.e., ψ, of a monolithic glass specimen for other types of glass. An iterative solution method, described in [6], may be used to solve for n, k, *and* ψ instead of the closed-form solutions in formulas (A.5) and (A.6). For the purpose of comparing encapsulation materials based solely on their optical performance, excluding the PV module architecture, it is possible to remove reflection from τ_{sp}, giving the "internal absorptance" of the encapsulation, α_i (normalized intensity):

$$\alpha_i[\lambda] = 1 - e^{-\psi p[\lambda] \cdot zp} \qquad (A.8)$$

Annex B
(informative)

Applying the quantum efficiency of a specific cell technology

In practice, a PV module cannot capture all of the radiant energy emitted from the sun. Each cell technology has its own capability for converting optical energy into electrical energy. This capability may also vary according to the manufacturer, and is summarized in the quantum efficiency. Representative external quantum efficiency profiles may be found in [7] and [8]. The quantum efficiency-weighted transmittance may be calculated from the formula:

$$\tau_{\mathrm{QE}} = \frac{\int \tau[\lambda] Q_{\mathrm{ext}}[\lambda] E_{\mathrm{p}\lambda}[\lambda] d\lambda}{\int Q_{\mathrm{ext}}[\lambda] E_{\mathrm{p}\lambda}[\lambda] d\lambda} \qquad \text{(B.1)}$$

where

τ_{QE} refers to the quantum efficiency-weighted transmittance (performance units, specific to a particular cell);

τ is the measured transmittance of the specimen at the incident angle (units of normalized intensity);

λ is the wavelength of light (m);

Q_{ext} is the external quantum efficiency of the cell (electrons·photon^{-1}); and

$E_{\mathrm{p}\lambda}$ is the reference spectral photon irradiance

($E_{\mathrm{p}\lambda}[\lambda] = \frac{\lambda}{hc} E\lambda[\lambda]$ as given in IEC 60904-3, m^{-2}·s^{-1}·nm^{-1}).

τ_{QE} may be used to evaluate application specific transmittance. For example, τ_{QE} may be used to select between encapsulation materials based on their expected performance with a particular PV cell technology. When comparing between encapsulation materials, all other components (including superstrate and substrate) and factors (including thermal management) are assumed to be equal.

In cases where more than one junction is connected within a cell, τ_{QE} shall be evaluated separately for each of the junctions. In such cells, the junctions may be connected in series, where the least illuminated junction, e.g., lowest τ_{QE}, may limit the current produced by the cell. In such cases the transmittance through each junction shall be known. It should be noted that in addition to τ_{QE}, other factors may motivate a current-limited condition, including: the physical thickness of the junction (affecting its capacity to harvest energy), the series resistance of each junction, and the colorcast present, e.g., the atmospheric depth and corresponding transmittance of the atmosphere.

The theoretical maximum current density may be estimated from the formula:

$$J = q \int \tau[\lambda] Q_{\mathrm{ext}}[\lambda] E_{\mathrm{p}\lambda}[\lambda] d\lambda \qquad \text{(B.2)}$$

where

J refers to the short circuit current density (A·m^{-2});

q is the charge of a single electron (1,602 × 10^{-19} C);

h is Planck's constant (6,626 × 10^{-34} W·s^{2});

c is the speed of light in a vacuum ($2{,}998 \times 10^8$ m·s^{-1});

λ is the wavelength of light (m);

τ is the measured transmittance of the specimen (normalized intensity);

Q_{ext} is the external quantum efficiency of the cell (unitless); and

$E_{p\lambda}$, the incident spectral photon irradiance (m^{-2}·s^{-1}·nm^{-1}).

Alternatively the absolute spectral response (S, units of A/W) and E_{λ}, the reference spectral irradiance (as in IEC 60904-3, W·m^{-2}·nm^{-1}) can be used to estimate the theoretical maximum current density:

$$J = \int \tau[\lambda] S[\lambda] E_{\lambda}[\lambda] d\lambda \qquad \text{(B.3)}$$

NOTE The current density may be determined similarly for any known spectral photon irradiance, in addition to that in IEC 60904-3.

The current yield may be affected by additional losses associated with a PV module or system, including: inverter efficiency, temperature related loss, and the area coverage of the module by the cells.

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