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TECHNICAL SPECIFICATION

Nanomanufacturing – Key control characteristics –
Part 7-2: Nano-enabled photovoltaics – Device evaluation method for indoor light

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FOREWORD

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IEC TS 62607-7-2 has been prepared by IEC technical committee 113: Nanotechnology for electrotechnical products and systems. It is a Technical Specification.

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

Draft	Report on voting
113/710/DTS	113/737/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification 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/publications.

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- withdrawn,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

INTRODUCTION

Commercialization of nano-enabled solar cells, such as organic solar cells, is being promoted by utilizing their advantages over conventional solar cells, such as light weight, flexibility, colour, transparency, and coating processability. Energy harvesting applications that generate power using indoor light have been recognized as important applications for nano solar cells in conjunction with recent advances in the Internet of Things. In general, nano solar cells have a large band gap and are suitable for power generation under indoor lighting whose spectra are localized in the visible light region. In addition, since the low illuminance characteristics can be improved by devising the configuration, it is expected to be suitable for energy harvesting using indoor light.

The IEC 60904 series specifies evaluation methods for sunlight. In IEC 60904, the most important factors in evaluating a solar cell are the selection of a light source and the method of adjusting its irradiance for measurement. By changing the light source from sunlight to indoor light, an evaluation method under indoor light can be obtained. The clause structure of this document corresponds to that of IEC 60904. While light sources are limited to sunlight in the outdoor environment, various light sources are used indoors, such as fluorescent lamps and LED lamps in addition to sunlight. The indoor brightness is expressed by illuminance in lux (lx), which takes into account the sensitivity of the human eye. Strictly speaking, since the spectral characteristics of the eyes are different from those of solar cells, there is not always a correlation between the illuminance and the power generation of solar cells. For example, a crystalline Si solar cell could generate power using only near-infrared light which is invisible to human eyes, i.e. zero lux. However, high-efficiency lighting other than incandescent lamps has a spectrum concentrated in the visible light region, thus expressing the efficiency of an indoor solar cell based on the spectrum of sunlight is not appropriate.

In this document, such uncertainties due to the use of illuminance instead or irradiance are eliminated by setting a reference spectrum for indoor light sources. The reference indoor light spectra are representatives of the spectrum of light sources used for indoor lighting, are defined only between 380 nm and 780 nm, and have no component outside of this wavelength range. Therefore, this document provides a method to evaluate solar cells with illuminance. Since the illuminance is obtained by the overlap integral of the spectral irradiance of the light source and the luminosity, there could be an infinite number of spectral irradiances that give the same illuminance. A large error could arise due to light in the wavelength region with low luminosity. In an extreme case, invisible light has a finite output even at zero illuminance. In this document, however, the output by zero lux illuminance is supposed to be zero, that is, the output is not guaranteed.

The target of this document is to define the output of a solar cell in a bright (finite illuminance) indoor environment. The output with light other than the reference spectrum is out of this target. If it is necessary to include such cases, they will be treated as individual cases. In that case, one would extend the reference spectrum and build an evaluation technique that uses irradiance instead of illuminance. Special illumination conditions can be used by using a user-defined reference spectrum. In this case, however, illuminance can be meaningless if the illumination contains a significant amount of invisible light.

Illumination includes not only the light that the eyes of humans are sensitive to, but also the infrared energy contained in incandescent lighting and sunlight that enters from outdoors. But because incandescent lighting is used less and less due to its poor energy efficiency, this document defines measurement methods with two standard indoor light sources specified by CIE: FL10 and LED-B4, corresponding to the fluorescent lamp and the white LED lamp, respectively, the correlated colour temperatures (CCT) of which are approximately 5 000 K. Other light sources such as sunlight or incandescent lamps are not appropriate because they contain much invisible infrared light and illuminance is not a good measure for performance evaluation of photovoltaic devices, because they contain a significant amount of invisible light.

This document, along with FL10 and LED-B4, establishes methods for evaluating photovoltaic cells under indoor conditions. This document assumes that an arbitrary photovoltaic cell will be measured under indoor lighting. For requirements not listed in this document, refer to the relevant normative references.

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 7-2: Nano-enabled photovoltaics – Device evaluation method for indoor light

1 Scope

This Technical Specification specifies the efficiency testing of photovoltaic cells (excluding multi-junction cells) under indoor light. Although it is primarily intended for nano-enabled photovoltaic cells (organic thin-film, dye-sensitized solar cells (DSC), and Perovskite solar cells), it can also be applied to other types of photovoltaic cells, such as Si, CIGS, GaAs cells, and so on.

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.

JIS C 1609-1, *Illuminance meters – Part 1: General measuring instruments*

DIN 5032-7, *Photometry – Part 7: Classification of illuminance meters and luminance meters*

ISO/CIE 19476, *Characterization of the performance of illuminance meters and luminance meters*

3 Terms and definitions

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

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

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

3.1
response time
time required for current to respond after a change is made to the applied voltage

Note 1 to entry: Response time is represented by τ in the formula $I(t) = I(0) + \Delta I\left(1 - \exp\left(-\frac{t}{\tau}\right)\right)$ for expressing change in current over time.

3.2
indoor primary reference photovoltaic cell
photovoltaic cell calibrated from a radiometer, standard detector, or standard indoor light that is traceable to SI units

3.3
indoor standard relative spectral responsivity
measure to define indoor spectral coincidence without relying on the device under test itself

3.4
indoor reference photovoltaic cell
photovoltaic cell used to adjust the intensity of the indoor light source

3.5
indoor spectral coincidence
measure of spectral matching between standard indoor light and the illumination source used for a measurement

Note 1 to entry: It is expressed as a ratio of short-circuit currents calculated from the spectral responsivity of the photovoltaic cell.

3.6
indoor secondary reference photovoltaic cell
photovoltaic cell calibrated from the indoor primary reference photovoltaic cell

3.7
indoor working reference photovoltaic cell
photovoltaic cell calibrated from the indoor secondary reference photovoltaic cell

3.8
standard indoor light
light source with a defined spectral distribution that is used when evaluating photovoltaic cells under indoor light

Note 1 to entry: It covers a variety of indoor light sources, and two types of standard indoor light are adopted in this document.

3.9
standard indoor illuminance
illuminance values used when evaluating photovoltaic cells under indoor light

Note 1 to entry: The standard indoor illuminance values are 50 lx, 200 lx and 1 000 lx.

3.10
fluorescent lamp
light source that operates by electrically exciting mercury vapour and then converting the luminescence generated into visible light using a phosphor

3.11
dye-sensitized solar cell
photovoltaic cell created by coating metal-oxide particles (such as titanium oxide or zinc oxide) with a molecular dye then immersing them in an ionically conductive electrolyte

3.12
illuminance
intensity of a light that illuminates a surface, as perceived by the human eye

Note 1 to entry: Illuminance is expressed in units of lux (lx).

3.13
correlated colour temperature
temperature of the black-body radiator whose CIE (u, v), or (u′, 2/3 v′), colour coordinate is closest to that of a light source

Note 1 to entry: See Ohno, Y., "Practical Use and Calculation of CCT and Duv", Leukos, 10:1, 47-55. (2013).

3.14
measurement delay time
interval of time between the changing of the applied voltage and the start of the current measurement when measuring an I-V curve by varying an externally applied voltage

3.15
white LED lamp
light source that produces white light by using a fluorescent substance to convert the wavelength of light generated by violet or ultraviolet LEDs

3.16
luminosity function
numerical representation of the relative sensitivity of the human eye to the different wavelengths of visible light

3.17
perovskite solar cell
photovoltaic cell containing a semiconductor with a perovskite structure composed of monovalent cations, divalent metal ions, and halogen ions

3.18
organic photovoltaic cell
photovoltaic cell containing an organic semiconductor or dye in the layers where light absorption and charge separation take place

3.19
maximum power point tracking
technique for finding the operating point (I-V or load characteristic) at which a device generates the maximum amount of electric energy under given photo-irradiation conditions

Note 1 to entry: It is typically used for adjusting a photovoltaic cell's optimal operating point under changing conditions such as weather and solar altitude angle, but it can also be utilized to determine the conversion efficiency of a cell when assessing its I-V curve is not feasible.

3.20
programmable reference cell system for irradiance adjustment by spectral measurement
method for adjusting the intensity of an illumination source through the formula

$$\int S_{\mathrm{abs}}(\lambda) E_{\mathrm{ref}}(\lambda)\,\mathrm{d}\lambda = \int S_{\mathrm{abs}}(\lambda) E_{\mathrm{mes}}(\lambda)\,\mathrm{d}\lambda\,,$$

where $S_{\mathrm{abs}}(\lambda)$ is the absolute spectral responsivity of the DUT, $E_{\mathrm{mes}}(\lambda)$ is the absolute spectral irradiance of the illumination source, and $E_{\mathrm{ref}}(\lambda)$ is the spectral irradiance of the standard light

4 Abbreviated terms

PV:	photovoltaic
DSC:	dye-sensitized solar cell
CIGS:	copper indium gallium selenide
GaAs:	gallium arsenide
c-Si:	crystalline silicon
a-Si:	amorphous silicon
LED:	light emitting diode
DUT:	device under test
CCT:	correlated colour temperature

OPV: organic photovoltaic cell

V_{oc}: open circuit voltage

I_{sc}: short circuit current

FF: fill factor

EQE: external quantum efficiency

PRISM: programmable reference cell system for irradiance adjustment by spectral measurement

MPPT: maximum power point tracking

I-V: current-voltage

SI: système international d'unités (international unit system)

5 Methods for measuring current-voltage characterization

5.1 General

IEC 60904-1 describes procedures for the measurement of current-voltage characteristics (I-V curves) of photovoltaic (PV) devices in natural or simulated sunlight. Efficiency is not directly an I-V parameter, but rather an additional quantity obtained from the maximum-power, the irradiance and the device area. For guidance on area measurement see Annex A.

5.2 Requirements

5.2.1 Device under test (DUT)

Define the area A (m^2) of the DUT used to calculate conversion efficiency. If the DUT is a photovoltaic cell, attach a shadow mask then measure the area of the mask's opening and use that as the area of the DUT. If the DUT is a module, use the area of the entire element (including nonconductive components) as the area of the DUT.

5.2.2 Illumination adjustment

For adjusting illuminance at the DUT described in 5.2.3, one of the three methods a) to c) shall be used.

a) Indoor reference photovoltaic-cell method: A method for adjusting the intensity of an illumination source by matching it to the calibrated value for an indoor reference photovoltaic cell. When performing spectral-mismatch correction, however, adjust the intensity to match the value obtained by dividing the calibrated value by the spectral-mismatch correction factor.

b) PRISM or spectroradiometer method: A method for adjusting the intensity of an illumination source through the formula $\int S_{abs}(\lambda) E_{ref}(\lambda) d\lambda = \int S_{abs}(\lambda) E_{mes}(\lambda) d\lambda$, where $S_{abs}(\lambda)$ is the absolute spectral responsivity of the test photovoltaic cell, $E_{mes}(\lambda)$ is the absolute spectral irradiance of the light source, and $E_{ref}(\lambda)$ is the spectral irradiance of the standard light, using a calibrated spectroradiometer, in accordance with ASTM G138-12 (2020) [1][1], for example.

c) Illuminometer method: A method for adjusting the intensity of an illumination source to match standard indoor illuminance by using an illuminometer calibrated according to JIS C 1609-1, DIN 5032-7, or ISO/CIE 19476. For this method of adjusting illuminance, the class of the light source should be restricted to Class-A or higher defined in 12.1.4.

Measure illuminance in the sample plane as measured by a reference device. If the reference device is an illuminometer, then the measured illuminance is the output of the illuminometer. If

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

the reference device is a reference cell or PRISM then make the measured illuminance [$L_{mes} = L_{ref} \cdot I_{mes}$ / $(M \cdot I_{cal})$] close to L_{ref} within 5 % by adjusting I_{mes}, where L_{ref} is the reference illuminance at which the reference cell is calibrated, I_{cal} is the calibrated short-circuit current of the reference cell at L_{ref}, I_{mes} is the measured short-circuit current, and M is the spectral-mismatch correction factor (if it is not applied, M = 1). If $L_{mes} \neq L_{ref}$ then measured current value shall be corrected by multiplying by L_{eff} / L_{mes}.

5.2.3 Measurement procedure

1) If necessary, allow the DUT to stabilize prior to measurement. IEC TR 63228 [2] describes stabilization for emerging PVs.
2) Regulate the temperature of the DUT to 25 °C ± 1 °C.
3) Illuminance at the DUT (L_{mes}) shall be adjusted to the illuminance to the standard indoor illuminance (L_{ref}) – 50 lx, 200 lx, or 1 000 lx – according to 5.2.2.
4) Determine the maximum output power (P_m) by sweeping the bias voltage while illuminating the DUT to perform I-V measurements.
   - Make a correction to the measured current (I) by multiplying by L_{eff} /L_{mes}.
   - When sweeping the bias voltage, set the measurement delay time to a value at least four times greater than the response time of the DUT.
   - If the response time is unknown, set the measurement delay time so that the difference in P_m values for the forward and reverse directions is 2 % or less. For slowly responding elements, adjust the measurement delay time in accordance with the response speed so that P_m variance is 2 % or less. In cases where P_m variance exceeds 2 %, record the P_m values and I-V characteristics for both the forward and reverse directions.
   - Measurement stability: Perform at least five measurements for both the forward and reverse directions, then verify that variation among those P_m values is 2 % or less. Variation among multiple measurement values is given by

$$\left(\frac{P_{m\_max} - P_{m\_min}}{P_{m\_average}}\right) \times 100 ,$$

   where

   P_{m_max} is the maximum P_m value;

   P_{m_min} is the minimum P_m value; and

   $P_{m\_average}$ is the average P_m value.

   - Use $P_{m\_average}$ as the maximum output (P_m).
5) Determine conversion efficiency η as given by

$$\eta = \frac{P_m}{G \cdot A}$$

   where A is the area of the DUT (m^2) and E is the irradiance per unit area (W/m^2) given by

$$G = \int E(\lambda) d\lambda$$

   where $E(\lambda)$ is the spectral irradiance ($W/m^2/nm$) of the illumination source.
6) Irradiance values for standard indoor illuminance are listed in Table 1.

Table 1 – Standard indoor illuminance

Illuminance (lx)	**Standard indoor light FL10** (mW/m²)	**Standard indoor light B4** (mW/m²)	**User light source, u**
1 000	3 076	3 132	$\int E_{u}(\lambda)\mathrm{d}\lambda$ (where $K_{m}\int E_{u}(\lambda)V(\lambda)\mathrm{d}\lambda = 1\,000$)
200	615	626	$\int E_{u}(\lambda)\mathrm{d}\lambda$ (where $K_{m}\int E_{u}(\lambda)V(\lambda)\mathrm{d}\lambda = 200$)
50	154	157	$\int E_{u}(\lambda)\mathrm{d}\lambda$ (where $K_{m}\int E_{u}(\lambda)V(\lambda)\mathrm{d}\lambda = 50$)

7) Recording results.

The information in Table 2 should be recorded.

Table 2 – Result record

Item	Subitem	Details
Test date		
Tested by		
Device under test	Type	
	Dimensions	
P_m		
Electrical characteristics		I_{sc}, V_{oc}, FF, V_{max}, I_{max}
Conversion efficiency		
P_m	[a]	Forward-direction P_m Reverse-direction P_m
Electrical characteristics	[a]	Forward-direction I_{sc}, V_{oc}, FF, V_{max}, I_{max} Reverse-direction I_{sc}, V_{oc}, FF, V_{max}, I_{max}
Conversion efficiency	[a]	Forward-direction η Reverse-direction η
I-V characteristic	[a]	Record on separate sheet
Standard indoor light	Type	
	Illuminance	
	Spectral irradiance [b]	Record on separate sheet
	Irradiance	
	Wavelength range [b]	
Indoor reference PV cell method (if using reference PV cell method)	Type	
	Calibration value	
	Calibration date	
PRISM method (if using PRISM method)	Spectral-response measurement system	
	Type	
	Calibration date	
	Spectroradiometer	
	Type	
	Calibration date	
Illuminometer method (if using illuminometer method)	Type	
	Calibration date	
I-V measurement device	Type	
	Calibration date	

[a] Record this data if P_m varies more than 2,0 % between the forward and reverse directions.

[b] Record this data only if a user-defined light source was used.

5.3 Important additional information

a) If there is considerable distance between the DUT and the I-V measuring device, perform the I-V measurement with the four-point probe method to eliminate the potential distortion of the result by the voltage drop in the cables.

b) Connect the electrodes of the DUT to the electrical characteristics measuring device using a lead wire or specialized jig for measuring electrical characteristics.