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TECHNICAL SPECIFICATION

Primary optics for concentrator photovoltaic systems

colour inside

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

PRIMARY OPTICS FOR CONCENTRATOR PHOTOVOLTAIC SYSTEMS

FOREWORD

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

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

IEC TS 62989, which is a technical specification, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
82/1281/DTS	82/1376/RVDTS

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

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

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

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- withdrawn,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

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

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PRIMARY OPTICS FOR CONCENTRATOR PHOTOVOLTAIC SYSTEMS

1 Scope

This document encompasses key characteristics of primary optical elements (lenses and mirrors) and lens or mirror parquets for concentrator photovoltaics including: optical performance, mechanical geometry, mechanical strength, materials, and surface morphology. The document identifies the essential characteristics, the corresponding quantities of interest, and provides a method for measurement of each quantity.

This document allows lens and mirror manufacturers, concentrator module manufacturers, test laboratories and other interested parties to define lens/mirror qualities and inspect lenses and mirrors. There are no pass/fail criteria associated with the document.

This document defines the test conditions rather than to specify the precise setup of a measurement apparatus. For example, this enables laboratories to acquire reliable and comparable measurement results irrespective of the existing large variety of experimental setups for focal spot characterization. High priority is given to comparable and reproducible measurements of the irradiance distribution in the focal plane and of the optical efficiency. This requires trade-offs that reduce the similarities to outdoor conditions. Furthermore, it is intended not to refer to properties of specific solar cells as this document is dedicated to concentrator optics.

The terms for lenses are applicable for mirrors, unless otherwise specified.

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 60050-845, *International Electrotechnical Vocabulary. Lighting*

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

IEC 62108:2007, *Concentrator photovoltaic (CPV) modules and assemblies – Design qualification and type approval*

IEC 62788-1-4, *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*

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

ISO 489:1999, *Plastics – Determination of refractive index*

ISO 10110-1:2006, *Optics and photonics – Preparation of drawings for optical elements and systems – Part 1: General*

ISO 10110-7, *Optics and photonics – Preparation of drawings for optical elements and systems – Part 7: Surface imperfection tolerances*

ISO 10110-8:2010, *Optics and photonics – Preparation of drawings for optical elements and systems – Part 8: Surface texture; roughness and waviness*

ISO 10110-19:2015, *Optics and photonics – Preparation of drawings for optical elements and systems – Part 19: General description of surfaces and components*

ISO 10303-21, *Industrial automation systems and integration – Product data representation and exchange – Part 21: Implementation methods: Clear text encoding of the exchange structure*

ISO 11664-1 (CIE S 014-1/E:2006), *Colorimetry – Part 1: CIE standard colorimetric observers*

ISO 11664-2 (CIE S 014-2/E:2006), *Colorimetry – Part 2: CIE standard illuminants*

ISO 11664-4 (CIE S 014-4/E:2007), *Colorimetry – Part 4: CIE 1976 L*a*b* Colour space*

ISO 14782, *Plastics – Determination of haze for transparent materials*

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

3.1
entrance aperture
entrance aperture of the primary concentrator optics lies in a plane perpendicular to the direction of irradiation and is defined as the smallest plane area bound by a simple, usually convex, geometric shape that covers all optically concentrating parts of the concentrator

Note 1 to entry: An optically inactive part in the entrance aperture (e.g. draft facets of Fresnel lenses, secondary mirrors of Cassegrain optics, wires and solar cells in the entrance aperture, mounting structures, rounded aperture corners) may not be subtracted from the area of the entrance aperture if it is not part of an adjacent entrance aperture and is smaller than 10 % of the total entrance aperture.

3.2
target area
plane area of simple geometric shape (e.g. square, rectangle, circle) that is located in proximity of the focal spot of the primary concentrator optics

Note 1 to entry: The target area is centred on the barycentre (centre of mass) of the focal spot. The target area shall have a maximum radius at least 2 times the intercept radius.

Note 2 to entry: In a measurement setup, the target area may be part of a larger detector if it is ensured that the radiant flux impinging on the target area can be discriminated from the radiant flux impinging on the parts of the detector lying outside the target area.

3.3
intercept radius
radius of a circular area that results in 95 % of the radiant flux incident on the entire target area

Note 1 to entry: Intercept radius is expressed in millimetres.

3.4
optical efficiency
ratio of radiant flux (Watts) on the target area within the intercept radius to the radiant flux on the entrance aperture of the primary optics, expressed as percentage value

3.5
encircled energy
accumulated radiometric power in a circle on the target as a function of the radius of the target area

Note 1 to entry: Encircled energy in shown in the encircled energy graph. The graph identifies the accumulated power as a function of the radius of the target area. The intercept radius and the optical efficiency can directly be read from the graph. The value for the encircled energy required to calculate the optical efficiency is 95 % of the maximum (see Figure 1).

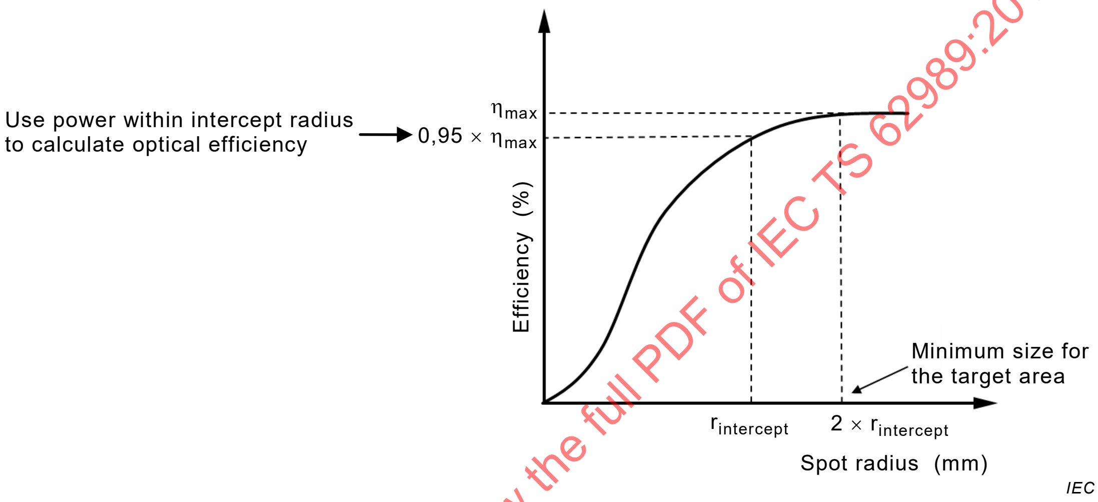

Figure 1 – Example of efficiency versus spot size – Encircled energy level of 95 %

3.6
parquet efficiency
arithmetic mean of the optical efficiencies of all optics in the parquet, all measured at the same entrance aperture to target area distance

3.7
geometric concentration
ratio of the circle defined by the intercept radius to the size of the entrance aperture (dimensionless)

3.8
local concentration
ratio of the irradiance (watts per square metre) at a point on the target area to the average irradiance of the entrance aperture (dimensionless)

3.9
focal distance
distance between the entrance aperture (most exterior surface of the primary optics) and target area that minimizes the intercept radius

3.10
solar-weighted transmittance of photon irradiance
proportion of the solar spectral photon irradiance optically transmitted (or reflected) through the specimen, throughout the range of the terrestrial solar spectrum (280 nm to 2 500 nm)

Note 1 to entry: Additional analysis, including representative solar weighted transmittance which may not include wavelengths as low as 280 nm or as great as 2 500 nm may also be reported.

3.11
UV cut-off wavelength
λ_{cUV}
wavelength of light below which the sample is considered optically absorbing and above which the material is considered transmitting (or reflecting)

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.

3.12
yellowness index
YI
calculated value identifying the yellowness of the test specimen perceived by a human observer, as defined in ISO 17223

4 Primary optics for concentrator photovoltaic systems

All primary optics datasheets complying with this document shall provide, as part of their product marking and documentation, the information specified below. See later clauses of this document for further explanation of individual specifications. In addition to the information indicated by the examples, it is required to include a technical drawing of the primary optics and the indicated graphs. Some of the specifications are optional; however, if a manufacturer of primary optics chooses to include optional information, it should be reported and measured using the definitions provided in this document (see Tables 1 to 6).

Table 1 – Characteristics: product identification

Clause	Characteristics	Parameter
4	Product identification	
4	Manufacturer	
4	Model number	
4	Type of primary optics	

Table 2 – Characteristics: optics

Clause	Characteristics	Symbol and unit of measure
5	**OPTICS**	
5.1	**Source definitions**	
Table 7	Angular size (termed collimation half-angle of source)	θ, deg
5.1	Source spectrum	–, $W/(m^2nm)$
5.2	**Optical material properties**	
5.2.1	Spectral transmittance of lens material, calculation of yellowness index, calculation of UV-cutoff wavelength	α,τ(λ, T,h, incidence angle), UV-cut-off, 1-nm increment (as ISO)
5.2.2	Spectral hemispherical reflectance of mirrors	ρ(λ)
5.2.3	Dispersion	V_D
5.2.4	Refractive index	n(λ,T,h), –
5.3	**Focusing characteristics (see Table 7 for description of Methods A-C)**	
5.3	Focal length	$F(T_{nom})$, df/dT
5.3	Lens/mirror efficiency	η, %
5.3	Parquet efficiency	η, %
5.3	Focal spot size and uniformity	95 % in intercept radius
5.3	Deformation caused by differential thermal expansion; irradiance distribution	-, (T), I(λ,T,h), shape, materials, bonding technique; measured as efficiency Δη/K
	Optional Compliance to other standards and specifications, including design qualification and type approval CPV module (IEC 62108)	
	Optional Coatings: mechanical and functional properties	
	Optional Soiling	

Table 3 – Characteristics: mechanics

Clause	Characteristics	Parameter
6	Mechanics	
6.1	Minimum radius	
6.2	Surface hardness (static)	
6.3	Impact resistance (dynamic)	-, f(T)
Optional	Recommendations for transport/shipping, storage, installation, operations, maintenance/cleaning, polishing, recycling/disposal	

Table 4 – Characteristics: materials

Clause	Characteristics	Parameter
7	Materials	
7	Type and manufacturing process	
7	Material type	
7	Manufacturing process	
7	Chemistry	
7	Mass, grain size	mol
7	Chemical composition	
7	Permeability	
7	Absorptivity	%
7	Thermal expansion	10^{-6} m/(m K)
7	Moisture expansion	10^{-6} m/(m %)
7	Durability	
7	UV-absorbants (optional)	
7	Yellowness index	CIE
7	Accelerators	
7	Non-voluntary compliance RoHS, WEEE, OH&S, among others	

Table 5 – Characteristics: geometry

Clause	Characteristics	Parameter
8	Geometry	
8.1	General	
8.2	Definitions	
8.3	Fresnel lenses and Fresnel mirrors	
8.4	Global dimensions ISO 10110-1:2006, ISO 10110-8:2010 and ISO 10110-19:2015	mm
8.4	Lens dimensions	mm
8.4	Number of lenses	n, -
8.4	Flatness	mm/m
8.4	Prism geometry	
8.4	Facet and step size	mm
8.4	Facet shape	
8.4	Tip and groove radii	µm
8.4	Draft angle	°
8.4	Surface morphology	
8.4	Roughness (RMS)	R_q, nm
8.4	Surface energy (ASTM D7490 [1] [1])	°
8.5	Data exchange	

Table 6 – Characteristics: visual appearance

Clause	Characteristics	Parameter
9	VISUAL APPEARANCE	
9.1	Imperfections, blemishes (ISO 10110-7)	
	Scratches	n, 1/m^2
	Bubbles	n, 1/m^2
	Edge chips	
9.2	Clarity and color	
9.2.1	Haze (and schlieren; scorch)	
9.2.2	Colour, ISO 11664-4:2008	-

1 Numbers in square brackets refer to the Bibliography.

5 Optics

5.1 Source spectrum

A reference solar spectral irradiance distribution is specified for comparing the relative performance of optical components or understanding their impact on photovoltaic devices. The spectrum may be used for the purpose of analysis of the throughput of optical flux. The spectrum is also defined as the benchmark for solar simulators and outdoor test conditions used for the verification of performance, see IEC 60904-3.

The spectral photon irradiance [$E_{p\lambda}$, $m^{-2} \cdot s^{-1} \cdot nm^{-1}$, Formula (1)] accounts for the number of incident photons rather than the raw energy. Photon irradiance is examined because one photon can produce at most one electron-hole pair in a PV cell. Parameters in the formula include: λ, the wavelength {m}; E_{λ}, the spectral irradiance {$W \cdot m^{-2} \cdot m^{-1}$}; h, Planck's constant {$6,626 \times 10^{-34}$ $W \cdot s^2$}; and c, the speed of light in a vacuum {$2,998 \times 10^8$ $m \cdot s^{-1}$}.

$$E_{p\lambda}[\lambda] = \frac{\lambda}{hc} E_{\lambda}[\lambda] \quad (1)$$

5.2 Optical material properties

5.2.1 Spectral transmittance of lens material

5.2.1.1 General

The measurement of the total luminous transmittance is specified for verification of the optical performance of component materials used in the primary optical element (POE). The standardized measurements here quantify the expected performance of the POE relative to the component(s) that follow the POE in a CPV module. Subsequent calculation of solar-weighted transmittance allows for comparison between different POE components and/or materials.

In the case where reflectance is being measured, it may be measured and analysed similar to the transmittance.

This measurement method can also be used to monitor the performance of POE materials after weathering, to help assess their durability. 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 POE or CPV module manufacturers to support comparing the durability of different materials.

5.2.1.2 Principle

The total spectral transmittance of representative specimens should 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 optical measurements.

NOTE The method does not attempt to account for variations in transmittance with the angle of incidence, which can vary with time of day, sky conditions, geometry of the module, and the concentration of optical flux.

5.2.1.3 Apparatus

The test instrument should consist of a spectrophotometer equipped with a double beam. A single beam spectrophotometer may be used if the port reflectance can be properly accounted for, as in IEC 62788-1-4. Details regarding the construction and configurations of the test instrument can be found in ISO 13468-2 [2] or ASTM E424-71 [3]. 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 direct spectrum as in IEC 60904-3. The minimum measurement increment of 1 nm shall be used in measurements.

5.2.1.4 Test specimens

5.2.1.4.1 Specimen size and geometry

Specimens shall consist of placard or discs composed of the POE material(s). The radius of curvature for the specimens should be sufficiently large that the width of the transmitted (or reflected) beam remains smaller than the aperture of the integrating sphere.

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. A spot size of 1 cm x 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, however, be adequate to allow the specimen to fit inside the test instrument.

The nominal thickness of the specimens shall be equal to the thickness intended for use in CPV modules. When a laminate or composite material is used, the thickness of each of the component layers shall be the same as intended for use in a CPV POE.

Specimens should be prepared 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 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.

Both surfaces of the specimens shall not be faceted or intentionally textured.

5.2.1.4.2 Number of specimens

A minimum of 3 replicates shall be used for the determination of the transmittance 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.

5.2.1.4.3 Conditioning of specimens

Specimens used for the purpose of datasheet reporting shall be maintained at (23 ± 2) °C, (50 ± 10) % relative humidity for at least 24 h, or until the mass has stabilized to ± 10 % (which can take on the order of 300 h for PMMA, if not force-dried), as recommended in ISO 291 Class 2, prior to optical measurement.

5.2.1.5 Measurement procedure

5.2.1.5.1 Specimen preparation

Prior to measurement, specimens should be free of dust, grease, or other contaminants. The specimens and instrument should be in thermal equilibrium prior to measurement.

5.2.1.5.2 Instrument calibration (baseline measurements)

Allow the instrument lamp to adequately equilibrate after it has been lighted, observing the typical warm-up period, for example 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 specimen present. The 100 % reflectance baseline measurement should be performed using a calibrated standard similar to the reflector specimens, for example silvered glass for silvered glass reflectors or Spectralon for general purposes. 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.

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

5.2.1.5.4 Reference measurements

Perform the transmittance measurements on a witness specimen at the beginning of each measurement session to assure 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 or laboratory working witness specimen.

5.2.1.6 Calculation and expression of results

5.2.1.6.1 Post-processing of data

The measurements obtained from three separate specimens shall be averaged at each wavelength increment. The range (difference of the maximum and minimum) shall also be determined at each wavelength increment. In this manner, the transmittance shall be reported at each wavelength measured.

5.2.1.6.2 Calculation of weighted transmittance

The solar-weighted transmittance may be calculated with Formula (2):

$$\tau_{\text{sw}} = \frac{\int \tau[\lambda] E_{\text{p}\lambda}[\lambda] d\lambda}{\int E_{\text{p}\lambda}[\lambda] d\lambda} \tag{2}$$

where

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

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

λ is the wavelength of light (nm);

$E_{\text{p}\lambda}$ is the reference spectral photon irradiance ($\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{nm}^{-1}$, as given in IEC 60904-3).

The solar-weighted transmittance should be calculated for the wavelength range of at least 280 nm to 2 500 nm. The solar-weighted transmittance (as well as YI) obtained from the spectrophotometer measurements (1 nm interval) shall be calculated using a discretized sum. For IEC 60904-3, the denominator of the solar-weighted transmittance equals 4,155 128 570 735 31 × 10^{23} ($\text{m}^{-2}\cdot\text{s}^{-1}$). Other weighted transmitted values may be additionally calculated [similar to Formula (1)] from the tabulated transmittance data for other wavelength ranges.

5.2.1.6.3 Calculation of the yellowness index

YI may then be calculated according to the following procedure. First, calculate the tristimulus values using the Formulas (3) to (5):

$$X = k\int \tau[\lambda]S_{D65}[\lambda]\bar{x}[\lambda]d\lambda \tag{3}$$

$$Y = k\int \tau[\lambda]S_{D65}[\lambda]\bar{y}[\lambda]d\lambda \tag{4}$$

$$Z = k\int \tau[\lambda]S_{D65}[\lambda]\bar{z}[\lambda]d\lambda \tag{5}$$

where

X, Y, and Z represent the three tristimulus coefficients (unitless);

k is the normalizing factor (unitless);

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

λ is the wavelength of light (nm);

S_{D65} is the relative spectral power of the illuminant (unitless, as in ISO 11664-2);

$\bar{x}$, $\bar{y}$, and $\bar{z}$ are the relative colour-matching functions of the observer (unitless, as in ISO 11664-1).

The CIE Standard D65 Illuminant (which represents the midday outdoor sun in northern latitudes) shall be used in calculations as defined in ISO 11664-2. The CIE 1964 XYZ colour space (which represents a human observer with a 10° field of view) shall be used in calculations as defined in ISO 11664-1.

The normalizing factor should be determined from Formula (6):

$$k = \int S_{D65}[\lambda]\bar{y}[\lambda]d\lambda \tag{6}$$

For ISO 11664-1 and ISO 11664-2 (in 1 nm increments), k = 8,606 × 10^{-3}. The normalizing factor is applied to all tristimulus coefficients, but is calculated specifically for the $\bar{y}$ colour-matching function.

YI may then be calculated from Formula (7):

$$YI = 100\frac{C_x X - C_z Z}{Y} \tag{7}$$

The yellowness index is calculated using the tristimulus coefficients as well as the coefficients, C_x = 1,301 3 (unitless) and C_z = 1,149 8 (unitless).

NOTE Additional details related to the YI can be found in ISO 17223.

5.2.1.6.4 Calculation of the UV cut-off wavelength

The UV cut-off wavelength, λ_{cUV}, shall be determined as the longest measured wavelength (to the nearest 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.

5.2.1.7 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 material type, specimen thickness (and its range of variation), the specimen size (length and width or diameter);

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

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 test instrument and the use (and make and model) of an 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 preconditioning 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 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 used) 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.

5.2.2 Spectral hemispherical reflectance of mirrors

For additional considerations related to the measurement of the spectral hemispherical reflectance of mirrors, refer to the document prepared and updated by the SolarPACES organization [4].

5.2.3 Dispersion: Abbe number of CPV primary lens materials

5.2.3.1 Definitions

The Abbe number ν is a common characterization of dispersion, i.e. the change of the refractive index n with wavelength λ. Alternatively, ν_D, ν_d or ν_e can be determined, where each Abbe number is calculated from a different set of three refractive indices:

$$\nu_D = (n_D - 1) / (n_F - n_C)$$

$$\nu_d = (n_d - 1) / (n_F - n_C)$$

$$\nu_e = (n_e - 1) / (n_{F'} - n_{C'})$$

where

n_D is the refractive index at 589,3 nm (mid point of the sodium spectral emission line doublet that has lines at 589,0 and 589,6 nm);

n_F is the refractive index at 486,1 nm (spectral emission line of hydrogen);

n_C is the refractive index at 656,3 nm (spectral emission line of hydrogen);

n_d is the refractive index at 587,6 nm (spectral emission line of helium);

n_F is the refractive index at 480,0 nm (spectral emission line of cadmium);

n_C is the refractive index at 643,8 nm (spectral emission line of cadmium).

5.2.3.2 Setup of experiment

ISO 489 does not explicitly describe the measurement of n at wavelengths other than at 589 nm. Use an Abbe refractometer as described in the instructions on "Refractive index n_D of CPV primary lens materials", which requires an Abbe refractometer accurate to 0,001 equipped with a temperature-controlling device for the specimens and prisms, set up in an environment maintained at (23 ± 2) °C and (50 ± 5) % relative humidity. The instrument shall provide monochromatic or nearly monochromatic illumination of the specimen with a spectral distribution centered at one of the wavelengths shown above.

This may be accomplished, for example, by filtering a white light source with individual bandpass interference filters or with a tunable filter, or by the use of spectral lamps.

5.2.3.3 Procedure

Follow the procedure in the instructions on "Refractive index n_D of CPV primary lens materials". Determine the three refractive indices necessary for the particular Abbe number chosen, following any further applicable directions provided by the instrument manufacturer, at (23 ± 0,5) °C for a set of 5 specimens. Calculate the Abbe number for each specimen.

In addition, the Abbe number may be determined at (50 ± 0,5) °C specimen temperature for a second set of 5 specimens.

5.2.3.4 Presentation of results

Express average Abbe number ν_D, ν_d or ν_e at 23 °C without any decimal places.

5.2.4 Refractive index n_D of CPV primary lens materials

5.2.4.1 Definitions

The refractive index n of a material describes how fast light travels through that material. $n = c/v$, where c is the speed of light in vacuum and v is the speed of light in the material. In general n depends on the wavelength λ, and the temperature T and moisture state of the material.

5.2.4.2 Parameters and units

This procedure describes the refractive index at 589 nm only.

5.2.4.3 Setup of experiment

Use ISO 489 method A, which requires an Abbe refractometer accurate to 0,001 equipped with a temperature-controlling device for the specimens and prisms, set up in an environment maintained at (23 ± 2) °C and (50 ± 5) % relative humidity.

5.2.4.4 Procedure

Follow ISO 489:1999 method A / transmission or reflection mode procedure (6.1.1 and 6.1.4). Recommended specimen size for sheet specimens is 8 mm × 20 mm with a thickness of 3 mm to 5 mm. Prepare 2 sets of 5 specimens each. A contacting liquid with a higher refractive index than the specimen is used to establish close contact between the specimen and the prism (3.1.3).

Rectangular prism-shaped specimens may be cut from lenses. Measure refractive index on flat surface facing the Sun or, if necessary, on Fresnel structure surface after removal of the Fresnel structure. Any other adequate preparation technique may be employed that renders specimens with a flat surface to be coupled to the fixed half of the refractometer prisms. In the case of silicone-on-glass lenses, it may be practical to prepare separate glass and silicone specimens from their respective raw materials.

Standard conditioning of specimens shall be done for at least 88 h at (23 ± 2) °C and at (50 ± 5) % relative humidity before the measurement.

Carry out the measurement at (23 ± 0,5) °C for the first set of 5 specimens.

Carry out the measurement at (50 ± 0,5) °C for the second set of 5 specimens.

Assuming linear behaviour, the temperature-dependence of the index of refraction may be calculated between the two temperatures. In addition, the measurement may be carried out at more than two temperatures. If the refractive index is known to be sensitive to humidity, the lens supplier may decide to prepare a third set of 5 specimens that are conditioned by submersing them in water at 23 °C at least until constant weight is reached. Perform measurements of refractive index immediately after removing specimens from the water and drying them with a non-abrasive optic cleaning tissue.

5.2.4.5 Presentation of results

Express average refractive index values n_D^{23} (23 °C) and n_D^{50} (50 °C) to three decimal places.

5.3 Focusing characteristics: Focal length, lens efficiency, focal spot size and uniformity

5.3.1 Preliminaries

A round robin study was conducted to allow for the assessment of the accuracy and suitability of available Methods to measure the focusing characteristics focal length, lens efficiency, focal spot size and uniformity of Fresnel lenses. Sets of Fresnel lenses in the materials PMMA and silicone-on-glass were industrially produced with a tool designed for neither SOG nor PMMA, sent to laboratories, and measured according to the method available there. The results were compared and found to be within acceptable tolerance brackets. Any of the methods developed by the laboratories may be followed. Table 7 lists the methods and results.

Wavelength ranges mentioned in this subclause are related to the instruments that have been used in these methods.

Table 7 – Methods and results of the round robin for the focal characteristics of Fresnel lenses

Laboratory method	Focal spot size			Focal spot distance			Lens efficiency				Method					
	SOG	PMMA		SOG	PMMA		SOG	PMMA	Accuracy	Reproducibility (same day series/ different days with recalibration)	Temperature	Instrument type	Wavelength	Source type	Collimation half-angle of source	Date
	Radius mm			mm			%				°C		nm		°	
A	1,53	1,07		104,5	83,0		83,2	81,2			25	Spectroradiometer + diapraghm	300 to 1 600	Xenon lamp	0,458	
B	1,18	0,96	± 2,6 %	105,9	86,1	± 0,2	82,9	83,6	± 2 %	± 0,2 % /	27,5	CCD camera + solar cell	400 to 730	Xenon flash	0,270	
B	1,27	0,98	± 2,6 %	106,5	86,4	± 0,2	81,4	82,6	± 2 %	± 0,2 % /	25	CCD camera + solar cell	730 to 1 040	Xenon flash	0,270	
C	0,93	0,53	± 2,5 %	103,3	84,1	± 0,2	82,1	81,4	± 2 %	± 0,2 % / ± 1,0 %	26,8	CCD camera	622	LED		
C	0,74	0,55	± 2,5 %	106,4	84,0	± 0,3	82,5	81,4			49,1	CCD camera	622	LED		

5.3.2 Method A

5.3.2.1 General

This second method characterizes the light distribution, spatial and spectrally, at the focal spot using a collimated Xe lamp, a spectroradiometer and several apertures attached to its head. This method provides the intercept radius and the optical efficiency (as described before) together with the spatial distribution of the spectral irradiance at the focal spot.

5.3.2.2 Apparatus

5.3.2.2.1 General

The complete setup is composed of a light source, the sample holder, apertures, and the detector. The components shall be fixed in a manner that ensures their proper alignment, mechanical stability and repeatability.

5.3.2.2.2 Light source

The light source is a collimated Xe lamp. The spectral and power distribution of the Xe light on the entrance aperture shall be uniform.

5.3.2.2.3 Sample holder

The sample holder allows the CPV primary optical component under study to be positioned perpendicularly towards the incident light beam. To this end, it provides the required translational and tilt movements. The sample holder is attached to a breadboard where the detector head and other required components are also fixed. In this way, the mechanical stability and repeatability of the measurements is facilitated.

5.3.2.2.4 Apertures

For the determination of the intercept radius, a diaphragm with a variable aperture diameter ranging from 1 mm to 11 mm is used. On the other hand, and with the purpose of studying the spatial distribution of the light at the focal spot, the light irradiance is mapped using a pinhole of a fixed aperture size. Since CPV primary optical components might have very different focal spot sizes, the pinhole size would need to be adapted for each component under study.

5.3.2.2.5 Detector

The detector is a calibrated spectroradiometer, consisting of a head (also known as optical probe), and the spectroradiometer. The head, which should ensure a good cosine correction (such as an integrating sphere) is responsible for coupling the light into the spectroradiometer. This head is connected to the spectroradiometer by means of a bifurcated fibre. The detector, whose spectral range goes from 300 nm to 1 600 nm, may be composed of two CCD arrays, for example one based on Si, for the spectral range from 200 nm to 850 nm, and another one for the 800 nm to 1 650 nm spectral range made of InGaAs. All the measurements are carried out using this detector.

5.3.2.3 Test specimens

Specimens used for the purpose of datasheet reporting shall be maintained at (23 ± 2) °C, (50 ± 5) % relative humidity for at least 24 h, as recommended in ISO 291, prior to optical measurement.

5.3.2.4 Measurement procedure

5.3.2.4.1 Specimen preparation

Prior to measurement, specimens should be free of dust, grease, or other contaminants. The specimens and instrument should be in thermal equilibrium prior to measurement.

The temperature of the test specimen shall be homogeneous over the entrance aperture within ± 2 K. The temperature of the test specimen shall not vary by more than 2 K during the data acquisition time of a measurement. The temperature shall be measured with a precision of ± 1 K and shall not deviate more than 1 K from the temperature of the test specimen.

5.3.2.4.2 Determination of the focal distance and the intercept radius

a) The sample to be measured shall be placed in the holder, and positioned perpendicularly to the incident light. The distance between the sample and the detector head should be close to the expected focal distance. The detector head and aperture (attached to it) should also be aligned perpendicularly to the incident light.

b) The diaphragm aperture size shall be chosen to be smaller than the total spot size. With the diaphragm aperture attached to the detector head, the detector head is moved in x, y, and z directions until the radiant flux (spectral flux integrated from 300 nm to 1 600 nm) is maximized. The position for which the radiant flux is maximized is designated to be the focal point, and the distance from this point to the sample is the focal distance.

c) Once being located at this focal point, the diaphragm shall be opened and the spectral flux from 300 nm to 1 600 nm shall be measured for different diaphragm aperture sizes. Previously, a spectrum in dark condition (i.e. with the source deactivated) shall have been measured, and then automatically subtracted from the measured data. For each aperture size, the radiant flux, obtained as the spectral flux integrated from 300 nm to 1 600 nm, shall be calculated, and from the representation of this radiant flux versus the diaphragm aperture radius, the intercept radius shall be determined.

5.3.2.4.3 Determination of the optical efficiency

The spectral flux from 300 nm to 1 600 nm is measured on the entrance aperture of the CPV primary optics using the detector head free of apertures. From the integration of these data, the radiant flux is obtained. Then, the optical efficiency is calculated as the ratio of the radiant flux within the intercept radius to the radiant flux on the entrance aperture of the primary optics, expressed as a percentage value.

5.3.2.4.4 Determination of the irradiance maps

With the purpose of studying the spatial distribution of the spectral irradiance at the focal spot, the light is mapped using a pinhole with a defined aperture. This pinhole is moved a distance (which depends on the focal spot size and the pinhole aperture size) with a determined step in x and y directions. Since CPV primary optics might have very different focusing characteristics, both pinhole aperture size and step would need to be adapted for each component under study. For each position, the spectral irradiance from 300 nm to 1 600 nm is detected. The spatial distribution of the irradiance integrated for different spectral ranges that correspond to the absorption regions of the materials that form a multi-junction solar cell can be calculated and plotted.

5.3.3 Method B

5.3.3.1 Apparatus

5.3.3.1.1 General

The test instrument shall include a light source, a sample holder, and a detector unit.

5.3.3.1.2 Light source

A collimated beam solar simulator shall be used to illuminate the optics aperture. The solar simulator should be classified as class A for the category spatial non-uniformity described in IEC 60904-9-1 [5].

The collimation angle as defined in IEC 60904-9-1 should be (4,65 ± 0,05) mrad. The collimation angle is defined as the angular radius, with respect to a vector normal to the test plane, containing 90 % of all incoming light flux.

5.3.3.1.3 Sample holder

The sample holder shall support the sample in a way that ensures that the sample does not move or vibrate during measurement. It shall position the sample in the homogeneous light beam of the light source with its optical axis aligned to the direction of the light beam. The misalignment of the optical axis of the sample to the direction of the light beam shall not exceed 1 mrad. No non-transparent part of the sample holder or any edge of a transparent part may be in front of the entrance aperture (blocking the direct light beam) or closer than 1 mm to the entrance aperture of the sample. No part of the sample holder shall be closer than 1 mm to the light path between the entrance aperture and the detector. Care shall be taken so that no stray light from any parts of the sample holder can reach the entrance aperture of the sample or the detector.

The sample holder may also include equipment to adjust the temperature the sample.

5.3.3.1.4 Detector

This test method requires one or several of the following detectors: translucent Lambertian diffusing surface, digital camera, calibrated solar cell.

5.3.3.1.5 Digital camera and translucent Lambertian diffusing surface

The digital camera (CCD or CMOS) is used to determine the distribution of radiant flux on the target area. The target area shall be a thin translucent Lambertian diffusing surface where the digital camera is imaged. Spectral filters may be added to the digital camera to modify its spectral response. If the digital camera sensor is large enough, the sensor can act as the target area and the primary optics can be directly focused on the sensor. To fulfil this condition, a circle whose radius is twice as large as the intercept radius shall be able to be inscribed in the digital camera sensor.

Regarding adequate use of a digital camera, if the pixel with the highest recorded value is equal to the full-scale value of the CCD device or less than half the full-scale value of the CCD device, neutral density filters should be added or the camera integration time should be adjusted and the measurement shall be repeated.

The pixel with the lowest recorded value shall be less than 0,5 % of the value of the pixel with the highest recorded value. If the level of noise is greater than 0,5 %, then the neutral density filters, camera integration time, or other aspects of the measurement setup up shall be adjusted and the measurement shall be repeated.

5.3.3.1.6 Calibrated solar cell

The calibrated solar cell is used to determine the total irradiance at the aperture entrance of the optics as well as the irradiance at the focal plane.

The calibrated solar cell acts as the target area. A circle whose radius is twice as large as the intercept radius shall be able to be inscribed in the active area of the solar cell.

It is the responsibility of the user to ensure the linearity of the reference cell.

5.3.3.2 Test specimens – Preconditioning of specimens

Specimens used for the purpose of datasheet reporting shall be maintained at (23 ± 2) °C, (50 ± 5) % relative humidity for at least 24 h, as recommended in ISO 291, prior to optical measurement.

5.3.3.3 Measurement procedure

5.3.3.3.1 Specimen preparation

Prior to measurement, specimens should be free of dust, grease, or other contaminants. The specimens and instrument should be in thermal equilibrium prior to measurement.

The temperature of the test specimen shall be homogeneous over the entrance aperture within ± 2 K. The temperature of the test specimen shall not vary by more than 2 K during the data acquisition time of a measurement. The temperature shall be measured with a precision of ± 1 K and shall not deviate more than 1 K from the temperature of the test specimen.

5.3.3.3.2 Determination of the intercept radius and the focal distance

The measurement procedure comprises the following steps:

a) The sample to be measured shall be placed in the holder, the primary optics shall be aligned with the incident light and the optical axis shall be perpendicular to the translucent Lambertian diffusing surface. The distance between the primary optics and the translucent Lambertian diffusing surface shall be close to the expected focal distance.
b) The digital camera shall be focused on the translucent Lambertian diffusing surface. If spectral filters are used to modify the spectral response of the digital camera, they shall be placed between the digital camera and the translucent Lambertian diffusing surface.
c) The irradiance distribution over the translucent Lambertian diffusing surface shall be photographed with the digital camera.
d) The centroid of the photographed irradiance distribution shall be calculated. Using the centroid as origin, the encircled energy graph shall be calculated. The intercept radius, as defined in 3.3, shall be calculated.
e) The distance between the primary optics and the target area shall be modified and steps b), c) and d) shall be repeated. It is recommended to change the distance between the primary optics and the target area in incremental displacements of 0,5 % of the expected focal distance.
f) The focal distance, as defined in 3.9, shall be calculated. The encircled energy and the intercept radius at the focal distance shall be determined.

5.3.3.3.3 Determination of the optical efficiency

The measurement procedure comprises the following steps:

a) The entrance aperture, as defined in 3.1, shall be measured.
b) The sample to be measured shall be placed in the holder, the primary optics shall be aligned with the incident light.
c) The calibrated solar cell shall be placed close to the primary optics entrance aperture to determine the radiant flux on the entrance aperture. The active surface of the calibrated solar cell shall be placed parallel to the entrance aperture. The calibrated solar cell shall be placed into a collimating tube to ensure that only direct irradiance reaches the calibrated solar cell. The short-circuit current of the calibrated solar cell shall be measured, and the calibration value shall be used to calculate the radiant flux on the entrance aperture of the primary optics.
d) The calibrated solar cell shall be placed at the lens focal plane. The calibrated solar cell acts as target area. The calibrated solar cell surface shall be perpendicular to the primary optical axis. The distance between the primary optics and the calibrated solar cell shall be

close to the expected focal distance. The short-circuit current of the calibrated solar cell shall be measured, and the calibration value shall be used to calculate the radiant flux on the target area. The optical efficiency, as defined in 3.4, shall be calculated. If two equivalent calibrated solar cells are available, steps c) and d) can be performed simultaneously placing one of the calibrated solar cells near the entrance aperture of the optics and using the other calibrated solar cell as the target area. Two calibrated solar cells are equivalent when both have the same spectral response.

e) The distance between the primary optics and the target area shall be modified and step d) shall be repeated. The optical efficiency shall be determined as the mean of the optical efficiency values for the positions where the optical efficiency is higher than 98 % of the maximum calculated value. It is recommended to change the distance between the primary optics and the target area in incremental displacements of 0,5 % of the expected focal distance.

5.3.3.4 Calculation and expression of results

5.3.3.4.1 Calculation of the optical efficiency

The optical efficiency may be calculated with Formula (8):

$$\eta_{op} = \frac{P_{out}}{P_{in}} = \frac{G_{out} A_{out}}{G_{in} A_{in}} = \frac{G_{out}}{G_{in} X_{geo}} \tag{8}$$

where

η_{op} refers to the optical efficiency (%);

P_{out} is the radiant flux (W) on the target area within the intercept radius;

P_{in} is the radiant flux (W) over the entrance aperture.

The optical efficiency can be expressed in terms of G_{in} the average irradiance at the entrance aperture (W/m^2); G_{out} the output irradiance at the target area (W/m^2), and X_{geo} the geometric concentration. The geometric concentration is defined as the ratio of the entrance aperture A_{in} to the target area A_{out}.

5.3.4 Method C

5.3.4.1 General

This third method characterizes the spatial light distribution at the focal spot using a collimated narrow bandwidth (e.g. red, (622 ± 7) nm) LED and a highly linear scientific CCD camera chip without a camera lens. This method provides the intercept radius and the optical efficiency together with the spatial distribution of the narrow bandwidth LED irradiance at the focal spot. This enables the qualification of concentrator lenses in terms of optical performance and the determination of possible errors of the manufacturing process and their consequences on performance.

5.3.4.2 Apparatus

5.3.4.2.1 General

The complete setup is composed of a light source, the sample holder, apertures, and the detector. The components shall be fixed in a manner that ensures their proper alignment, mechanical stability and repeatability.

The setup is designed to hold lens panels of different sizes. The panels are moved on a sliding carriage along two linear axes between light source and detector unit. The detector unit may be fixed or also moved on (optionally motorized) XYZ precision linear stages.

5.3.4.2.2 Light source

The light source consists of a narrow bandwidth(s) (e.g. red or a multicolour) LED which illuminates a circular aperture. The width of the aperture and the focal length of the successive collimating optics define the angular divergence of the light in test. This divergence should be (4,65 ± 0,05) mrad, which equals the angular divergence of the Sun. Using LEDs allows a narrow bandwidth illumination. An aspheric lens for a single monochromatic LED illumination or an achromat lens for multi LED illumination is illuminated by the aperture and creates the collimated beam as incident light on the lens panel. The spatial irradiation at sample level should not change more than 2 % across the sample's aperture in test. It is recommended to measure this lateral irradiation distribution to post-correct the measured signals in numerical analysis. The time stability of the light source intensity should be better than 0,1 %/h, which directly affects the reproducibility of successive measurements' results.

5.3.4.2.3 Sample holder

The sample holder allows the lens panel's moving on a sliding carriage along two linear axes between light source and detector unit. The sample does not move or vibrate during measurement and it is important that the holder is positioned perpendicularly (±2,5 mrad) towards the incident light beam. The holder should be mat black to minimize stray light.

5.3.4.2.4 Apertures

For the investigation of partial areas of a sample specimen, additional apertures may be applied to limit the illuminated area of the specimen. If apertures define partial areas of the specimen, this should be reported with all subsequent results by specifying the size and position of the aperture.

5.3.4.2.5 Detector unit

The detector is a highly linear and well-specified scientific-grade monochrome CCD camera with a 14-bit dynamic range, without a camera lens and is to be calibrated prior to measurement (in house). The chip has a very low incidence angular dependence (90 % at 30°) and a high resolution. The camera chip is based on Si technology and is appropriate for all light sources between the spectral ranges from 250 nm through 950 nm. Principally, the detector size limits the maximum detectable intercept radius. With the aforementioned precision stages, a stitching of the measurement signal is possible.

5.3.4.3 Measurement procedure

5.3.4.3.1 Specimen preparation

Prior to measurement at room temperature, the specimens should be clean and at the same temperature like the laboratory. For measurements at specimen temperatures deviating from room temperature (e.g. measurement of heated specimen), the desired temperature of the test specimen should be homogeneous ±2 K across the entire entrance aperture measured. The light source and the camera should be in a steady state and in thermal equilibrium.

5.3.4.3.2 Determination of the focal distance and the intercept radius

a) The quantitative analysis of the CCD signal is performed by referencing to a measurement without a sample, which is recorded immediately before the sample measurement.

b) The primary optics to be measured is placed in the holder, positioned and aligned perpendicularly to the incident light source.

c) To avoid large differences in exposure time between sample and reference measurement, the light source is dimmed automatically using neutral density filters during measurement of the sample lenses. The attenuation of the filter in the light source is calibrated externally in a measurement of the light source with and without filter.

d) The resulting CCD signal of a primary optics measurement is analysed with respect to the dimension of the focus and the integral value over a target area is calculated. The target area is a plane area of simple geometric shape (e.g. square, rectangular, round) that is located in proximity of the focal spot of the primary concentrator optics. The target area is centred on the barycentre (centre of mass) of the focal spot.

e) The distance between the primary optics and the target area shall be modified (e.g. manually or automatically) and step d) shall be repeated.

The CCD signal images provide irradiance maps as measured at the target plane. From these irradiance maps, the following quantities are calculated (see step d) above).

The distance between camera CCD surface and lens sample with the lowest intercept radius is the identified focal distance. The focal distances may be measured with reference to the plane besides the lens structure, which is the support plane for samples under measurement. In this case, the focal distance between the entrance aperture (most exterior surface of the primary optics) and target area is equivalent to the identified focal distance that minimizes the intercept radius plus the thickness of specimen (e.g. glass or PMMA). With a report on results, the definition of focal distance (focal length) shall be provided to avoid confusion with different definitions.

For evaluation of optical efficiency, the target area is chosen according to the procedure described above (i.e. circular of radius twice the intercept radius). Then, the irradiance within this area is dervied from the CCD camera signal and referenced to the CCD signal without a sample in the light path.

5.3.4.3.3 Test report

This subclause is applicable for all Methods A to C above. A report of the tests shall be prepared by the test group. 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, type of optics (lens/mirror), the specimen size (length and width or diameter);

f) characterization and condition of the test item, including the method and details of specimen preparation (including cleaning or similar processing, if applicable) and preconditioning;

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

h) identification of test method used, including a brief description of the measurement setup and including the wavelength and spectral width of the light used for measurement as well as the spectral response of the detector;

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 preconditioning conducted prior to measurements;

k) measurements, examinations and derived results supported by tables, graphs, sketches and photographs as appropriate, and any failures observed;

l) the focal distance, the optical efficiency at focal distance, the intercept radius at focal distance and the maximum local concentration at focal distance of each optics that was measured, including the wavelengths and spectral width of the light used for measurement, the geometry and size of the target area, the geometric concentration, the focal length, and the temperature of the specimen;

m) if the specimen is a parquet of optics, the parquet efficiency and the minimum optical efficiency of all optics in the parquet, including the wavelengths and spectral width of the light used for measurement, the geometry and size of the target area, the geometric concentration, the distance of the target area to the entrance aperture of the specimen, and the temperature of the specimen;

n) for at least one optics of each specimen measurements at three different temperatures (if possible) of the specimen that differ by at least 10 K from each other: focal distance, optical efficiency at focal distance, intercept radius at focal distance, for each temperature including the wavelengths and spectral width of the light used for measurement, the geometry and size of the target area, the geometric concentration, the distance of the target area to the entrance aperture of the specimen, and the temperature of the specimen. Temperature-dependent efficiency values may differ from the optimum value of lens efficiency, focal spot size and uniformity;

o) for at least one optics of each specimen: a two-dimensional plot of the local concentration at focal distance with a spatial resolution of at least 10 % of the target area diameter (if round) or edge length (if square) and supplemental information for this plot including the wavelengths and spectral width of the light used for measurement, the geometry and size of the target area, the geometric concentration, the focal distance, and the temperature of the specimen;

p) a statement of the estimated uncertainty of the test results (where relevant);.

q) 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;

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

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

6 Mechanics

6.1 Minimum radius

The manufacturer should specify the minimum bending radius of the material in accordance with other standards, e.g. IEC 62899-201 [6].

6.2 Surface hardness

The methods to determine surface hardness vary by material, include Rockwell for metals and hard plastics (ISO 2039-1 [7]), Shore for elastomers (ISO 7619-1 [8]); there is a Pencil Hardness Test for plastics (ASTM D3363-05 [9]) related to the test for hardness of coatings ISO 15184 [10]. The Knoop hardness for glass is defined in ISO 9385:1990 [11]. The manufacturer should give a method, value and unit for the hardness of the material of the primary optics.

6.3 Impact resistance (dynamic)

6.3.1 Definitions

The purpose of the hail impact test is to determine whether primary optical elements (lenses, mirrors, lens parquets or mirror parquets) can survive a hailstorm. The test follows 10.9 of IEC 62108:2007 with the exception that the primary optical elements are mounted to frames and not built into modules. The mounting may be of a generic type or mimic a certain module design.

6.3.2 Setup of experiments

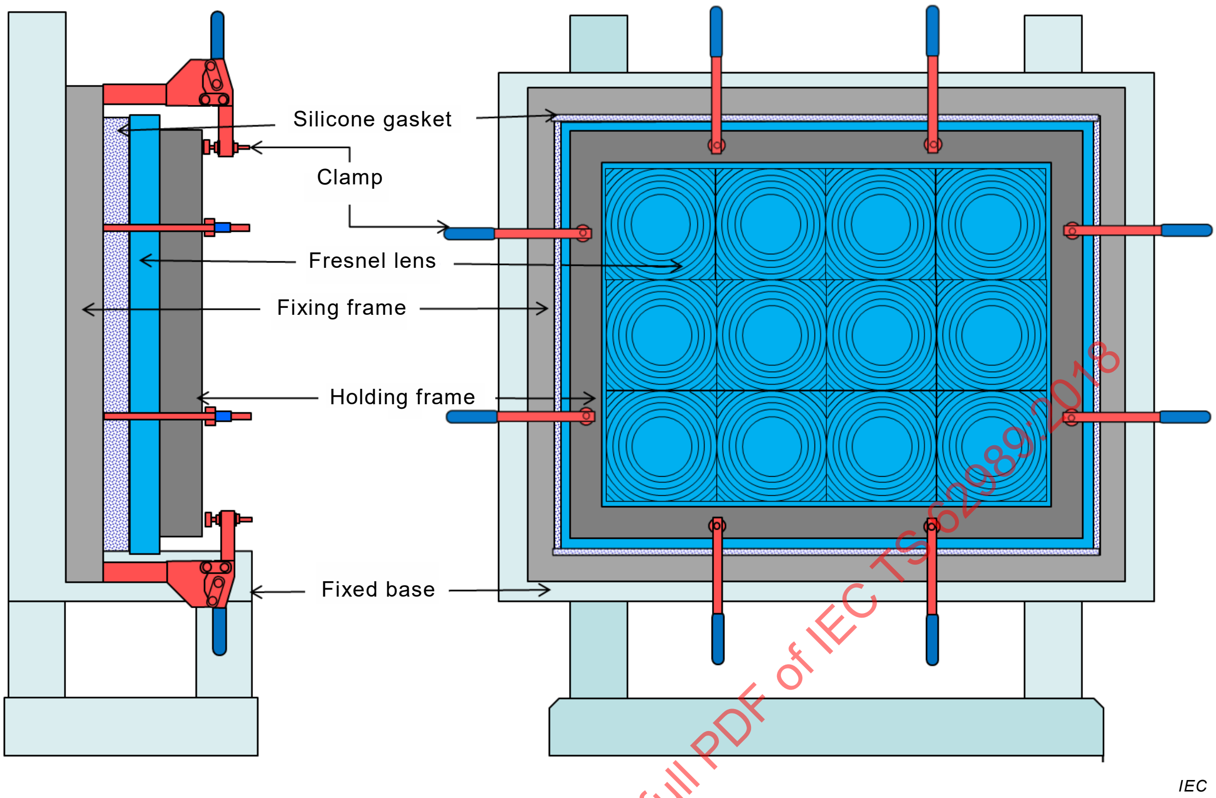

Figure 2 – Example of a primary lens parquet, set up for the hail impact test

Follow 10.9.2 a) to d), 10.9.2 f) and 10.9.2 g) of IEC 62108:2007. As long as the ice ball size and weight requirements in 10.9.2a) and 10.9.2f) of IEC 62108:2007 are satisfied, any other preparation method can be applied. In that case, state the substitute preparation method.

For rectangular optical elements, the following mounting method is recommended. The sample is supported by a rectangular metal fixing frame, faced with a rubber or silicone gasket. The sample is clamped to the fixing frame by a metal holding frame and quick-release toggle clamps along all four edges, set apart by an appropriate distance (Figure 2).

Mounting methods other than that shown in Figure 2 may be used, including using the CPV module or assembly component. It is recommended that the sample does not shift its position during impact with respect to the frames, or other means of mounting. Report the mounting method.

6.3.3 Procedure

Follow 10.9.3 of IEC 62108:2007, except that the test piece consists of the primary optical element mounted as described in Clause 4.

6.3.4 Presentation of results

Follow 10.9.4 of IEC 62108:2007. Add a description of the mounting method used. Add a description of the preparation procedure of the ice balls, if necessary.

7 Materials

The material type of the lens shall be given, revealing the chemical nature without grade or manufacturer, directions for assembly (mechanically, chemically) should be listed, including