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TECHNICAL REPORT

PRACTICAL METHODS FOR THE MEASUREMENT OF REFLECTANCE AND TRANSMITTANCE

CIE 130 - 1998

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This guide is dedicated to the memory of the late Professor Jürgen Krochmann.

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PRACTICAL METHODS FOR THE MEASUREMENT OF REFLECTANCE AND TRANSMITTANCE

SUMMARY

The characteristics of materials related to their reflection and transmission properties are defined in accordance with the International Lighting Vocabulary and other relevant CIE publications.

The parameters affecting these characteristics and the principles of measurement involved, which are the same whether the measurement is made in terms of spectral or weighted (e.g. luminous) characteristics, are specified.

Methods, using an integrating sphere, are recommended for the measurement of

- reflectance for directional ρ , $\rho(\varepsilon)$ and hemispherical ρ_{diff} incidence of radiation,
- diffuse reflectance ρ_d ,
- transmittance for directional τ , $\tau(\varepsilon)$ and hemispherical τ_{diff} incidence of radiation,
- diffuse transmittance τ_d .

Specific methods are also recommended for the measurement of

- regular reflectance ρ_r ,
- regular transmittance τ_r ,
- radiance/luminance factor β (radiance/luminance coefficient q).

The absorptance α can either be measured directly or calculated from the measured values of reflectance and transmittance. Both procedures are described.

The principal measurement errors are examined and, where possible, methods for their elimination indicated.

MÉTHODES PRATIQUES DE MESURE DES FACTEURS DE RÉFLEXION ET DE TRANSMISSION

RÉSUMÉ

Les caractéristiques des matériaux qui se réfèrent à leurs propriétés de réflexion et de transmission des rayonnements optiques sont définies en conformité avec le Vocabulaire International de l'Eclairage et autres publications de la CIE sur le même sujet.

Les paramètres pouvant affecter les caractéristiques susdites et les principes de mesure sont spécifiés, ces principes étant les mêmes qu'il s'agisse de mesures de caractéristiques spectrales ou intégrales (lumineuses par exemple).

Des méthodes de mesure faisant usage d'une sphère intégratrice sont recommandées pour les déterminations

- du facteur de réflexion sous incidence directionnelle ρ , $\rho(\varepsilon)$ et hémisphériques ρ_{diff} ,
- du facteur de réflexion diffuse ρ_d ,
- du facteur de transmission sous incidence directionnelle τ , $\tau(\varepsilon)$ et hémisphériques τ_{diff} ,
- du facteur de transmission diffuse τ_d .

Des méthodes de mesure particulières sont recommandées pour les déterminations

- du facteur de réflexion régulière ρ_r ,
- du facteur de transmission régulière τ_r ,
- du facteur de luminance β (ou du coefficient de luminance q), ces grandeurs pouvant être énergétiques ou lumineuses.

Le facteur d'absorption α peut être mesuré directement ou calculé à partir des mesures des facteurs de réflexion et de transmission. Les deux procédures sont décrites.

Les erreurs de mesure les plus importantes et, dans la mesure du possible, des méthodes pour les éliminer, sont indiquées.

PRAKTISCHE METHODEN FÜR REFLEXIONS- UND TRANSMISSIONSMESSUNGEN

ZUSAMMENFASSUNG

Die Eigenschaften von Materialien in bezug auf ihre Reflexion und Transmission werden in Übereinstimmung mit dem Internationalen Wörterbuch der Lichttechnik und den entsprechenden CIE Publikationen definiert.

Es werden die Parameter, die diese Eigenschaften und Meßverfahren beeinflussen, angegeben, wobei die Verfahren zur Messung der spektralen und integralen (z.B. lichttechnischen) Eigenschaften gleich sind.

Meßmethoden, die eine Ulbricht-Kugel benutzen, werden empfohlen für

- Reflexionsgrad bei gerichtetem, ρ , $\rho(\varepsilon)$ und diffusem ρ_{diff} Strahlungseinfall,
- Grad der gestreuten Reflexion ρ_d ,
- Transmissionsgrad bei gerichtetem τ , $\tau(\varepsilon)$ und diffusem τ_{diff} Strahlungseinfall,
- Grad der diffusen Transmission τ_d .

Spezielle Meßmethoden werden empfohlen für

- Grad der gerichteten Reflexion ρ_r ,
- Grad der gerichteten Transmission τ_r ,
- Strahldichte/Leuchtdichtefaktor β (Strahldichte/Leuchtdichtekoeffizient q).

Der Absorptionsgrad α kann entweder direkt gemessen werden oder aus den gemessenen Reflexions- und Transmissionsgraden errechnet werden. Beide Verfahren werden beschrieben.

Es werden auch die häufigsten Meßfehler und, so weit wie möglich, Methoden zu ihrer Beseitigung angeführt.

1. SCOPE

The CIE has published four Technical Reports which are basic documents for this Publication:

- International Lighting Vocabulary [1];
- Radiometric and Photometric Characteristics of Materials and their Measurement [2];
- Absolute Methods for Reflection Measurements [3];
- A Review of Publications on Properties and Reflection Values of Material Reflection Standards [4].

The reflection and transmission properties of materials in the wavelength range of optical radiation, particularly light, are important in many fields. This report deals mainly with the wavelength range $200\text{ nm} < \lambda < 3\,000\text{ nm}$. These properties are characterized by reflectance and transmittance with their regular and diffuse components, and radiance/luminance factor.

Different methods are described in the literature for the measurement of these characteristics and the results may differ according to the method used. It is, therefore, necessary to standardize one or more methods for the measurement of each defined quantity, designed to keep systematic errors as small as possible. This is the only way to ensure that the results of measurements, obtained with different instruments are comparable.

This CIE Technical Report sets out to define recommended methods for measuring the most important characteristics of reflection and transmission in industrial laboratories and to describe both the measurement geometry and the radiometric/photometric specification of the equipment used for irradiation and detection.

Absolute measurements of diffuse reflectance and measurements of the gonioradiometric/goniophotometric properties of materials are outside the scope of this publication. They are the subject of the work of other CIE Technical Committees.

Measurements on retroreflecting materials are also not treated here [5] and only a few brief notes, for guidance, are given on luminescent materials [2].

2. DEFINITIONS

The definitions relating to materials which are given in this Technical Report apply to optical radiation and particularly to visible radiation. The characteristics used for the description of these properties are generally expressed in terms of radiant, luminous or spectral quantities, but can also relate to other spectral weighting functions (see 3.1.2).

The definitions given here are taken from the International Lighting Vocabulary [1]. Where additional explanatory notes not in the ILV have been added, these are indicated by an asterisk *.

2.1 Processes

2.1.1 REFLECTION

Process by which radiation is returned by a surface or a medium, without change of frequency of its monochromatic components.

Note 1: Part of the radiation falling on a medium is reflected at the surface of the medium (surface reflection); another part may be scattered back from the interior of the medium (volume reflection).

Note 2: The frequency is unchanged only if there is no Doppler effect due to the motion of the materials from which the radiation is returned.

2.1.2 TRANSMISSION

Passage of radiation through a medium without change of frequency of its monochromatic components.

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2.1.3 ABSORPTION

Process by which radiant energy is converted to a different form of energy by interaction with matter.

2.1.4 REGULAR REFLECTION; SPECULAR REFLECTION (REGULAR TRANSMISSION; DIRECT TRANSMISSION)

Reflection (transmission) in accordance with the laws of geometrical optics, without diffusion.

2.1.5 DIFFUSE REFLECTION (DIFFUSE TRANSMISSION)

Diffusion by reflection (transmission) in which, on the macroscopic scale, there is no regular reflection (transmission).

2.1.6 MIXED REFLECTION (MIXED TRANSMISSION)

Partly regular and partly diffuse reflection (transmission).

2.1.7 ISOTROPIC DIFFUSE REFLECTION (ISOTROPIC DIFFUSE TRANSMISSION)

Diffuse reflection (transmission) in which the spatial distribution of the reflected (transmitted) radiation is such that the radiance or luminance is the same in all directions in the hemisphere into which the radiation is reflected (transmitted).

2.1.8 PERFECT REFLECTING DIFFUSER (PERFECT TRANSMITTING DIFFUSER)

Ideal isotropic diffuser with a reflectance (transmittance) equal to 1.

2.1.9 TRANSLUCENT MEDIUM

Medium which transmits visible radiation largely by diffuse transmission, so that objects are not seen distinctly through it.

2.2 Characteristics**2.2.1 REFLECTANCE (ρ) (TRANSMITTANCE (τ))**

(for incident radiation of given spectral composition, polarization and geometrical distribution).

Ratio of the reflected (transmitted) radiant or luminous flux to the incident flux in the given conditions.

unit: 1

Note: See Note 1 to 2.2.3.

2.2.2 REGULAR REFLECTANCE (ρ_r) (REGULAR TRANSMITTANCE (τ_r))

Ratio of the regularly reflected (transmitted) part of the (whole) reflected (transmitted) flux, to the incident flux.

unit: 1

Note: See Notes 1 and 2 to 2.2.3.

2.2.3 DIFFUSE REFLECTANCE (ρ_d) (DIFFUSE TRANSMITTANCE (τ_d))

Ratio of the diffusely reflected (transmitted) part of the (whole) reflected (transmitted) flux, to the incident flux.

unit: 1

Note 1: $\rho = \rho_r + \rho_d$ ($\tau = \tau_r + \tau_d$).

Note 2: The results of the measurements of ρ_r and ρ_d (τ_r and τ_d), depend on the instruments and the measuring techniques used.

2.2.4 RADIANCE FACTOR/LUMINANCE FACTOR (β)

(at a surface element of a non-self-radiating medium, in a given direction, under specified conditions of irradiation/illumination).

Ratio of the radiance/luminance of the surface element in the given direction to that of a perfect reflecting or transmitting diffuser identically irradiated/illuminated.

unit: 1

Note 1: For photoluminescent media, the radiance/luminance factor is the sum of two portions, the reflected radiance/luminance factor β_s and the luminescent radiance/luminance factor β_l : $\beta = \beta_s + \beta_l$.

Note 2:* The radiance/luminance factor can be applied only with reference to diffused radiation.

2.2.5 RADIANCE/LUMINANCE COEFFICIENT (q)

(at a surface element of a medium, in a given direction, under specified conditions of irradiation/illumination).

Quotient of the radiance/luminance of the surface element in the given direction by the irradiance/illuminance on the medium.

unit: sr^{-1}

Note 1:* The radiance/luminance coefficient can be applied only with reference to diffused radiation.

Note 2:* Radiance/luminance factor and radiance/luminance coefficient are related to each other by $\beta = \pi \cdot \Omega_0 \cdot q$, where $\Omega_0 = 1 \text{ sr}$.

2.2.6 ABSORPTANCE (α)

Ratio of the absorbed radiant or luminous flux to the incident flux under specified conditions.

unit: 1

3. PARAMETERS AFFECTING THE CHARACTERISTICS

The characteristics defined in 2.2 above do not depend solely on the properties of the material itself, but are influenced by a number of other parameters [2].

3.1 Spectral parameters

3.1.1 SPECTRAL COMPOSITION OF THE INCIDENT RADIATION

The spectral power distribution of the incident radiation $S(\lambda)$ should be specified, for example, by naming a particular CIE illuminant [6], by the distribution or colour temperature of the source or, for monochromatic radiation, by its wavelength and bandwidth (half-width).

Note: For the measurement of luminescent materials, the sample should be irradiated with the illuminant for which the characteristic is to be determined or a complete evaluation made with a spectrofluorimeter.

CIE Standard Illuminants are tabulated values of relative spectral power distributions which are not always realisable in a practical form. Where spectral values of reflectance or transmittance have been measured, the integral values may be calculated by numerical integration using the tabulated values for the spectral power distributions.

It is recommended [6] [7], that Standard Illuminant A be realised by Source A, a tungsten lamp operating at a correlated colour temperature of 2 856 K. Illuminant C is realised by Source A combined with liquid filters as described in reference [6] and is used to represent the visible part of the daylight spectrum. Standard Illuminant D65 characterizes daylight, including the ultraviolet component but there is, at present, no recommended laboratory

realisation. Other illuminants are occasionally used for the characterization of materials, e.g. D55 and D75 for special phases of daylight [6] and global radiation for different conditions [8].

The symbol for the illuminant can be added as a subscript to the symbol for the quantity, e.g. $\tau_{v,A}$ for the luminous transmittance under Standard Illuminant A.

3.1.2 INTEGRAL CHARACTERISTICS

If the wavelength dependence of a spectral characteristic of a sample is known, a given integral characteristic a for a given spectral power distribution $S(\lambda)$ of the incident radiation may be defined as

$$a = \frac{\int_0^{\infty} S(\lambda) \cdot a(\lambda) \cdot w(\lambda) d\lambda}{\int_0^{\infty} S(\lambda) \cdot w(\lambda) d\lambda} \quad (1)$$

where $a(\lambda)$ is the relevant spectral characteristic of the sample,
 $S(\lambda)$ the relative spectral power distribution of the incident radiation, usually specified and
 $w(\lambda)$ the relative spectral weighting function to be considered, e.g. $V(\lambda)$ for luminous characteristics, unity for radiant characteristics and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ for trichromatic characteristics.

The value of a may either be measured directly, provided that the source has the prescribed spectral distribution and a detector whose spectral responsivity corresponds to the relevant spectral weighting function (see 4.2.2) is available, or it may be computed if all the spectral quantities $a(\lambda)$ are known (see 4.2.1).

If there is any risk of ambiguity, then a photometric characteristic should be preceded by the adjective "luminous" and its symbol should have the subscript "v", e.g. luminous reflectance ρ_v , while a radiant characteristic should be preceded by the adjective "radiant", and its symbol given the subscript "e", e.g. radiant reflectance ρ_e . Where radiant characteristics are to be determined within a certain wavelength range, the range should be specified by a prefix to the term and a subscript to the symbol, e.g. the radiant reflectance within the ultraviolet range: UV radiant reflectance ρ_{UV} .

For each spectral characteristic there exists a corresponding luminous or radiant characteristic as well as several other characteristics.

3.2 Geometric conditions

There are, in principle, nine different geometric measuring conditions for reflection measurements [3] (see table 1), where the incident beam and the observed beam can be either directional (nearly parallel), conic (confined within a more or less extended solid angle), or hemispherical. The hemispherical measurements can be made using an integrating sphere. The same range of conditions applies to transmission measurements.

The measured value of a characteristic depends on the measuring geometry which should be specified:

- incident angles (ε_1 and φ_1) and viewing angles (ε_2 and φ_2) (see figure 1),
- aperture angle of the incident and the observed beam (angles $2\sigma_1$ and $2\sigma_2$), (see figure 2).

The aperture angle of the incident and observed beam should both be specified if they are larger than the prescribed values.

Figures 1 and 2 are based on the implicit hypothesis of a uniform cross section of the beams and uniform responsivity across the acceptance area of the detector. However, in practical instruments different angular distributions and responsivities may occur.

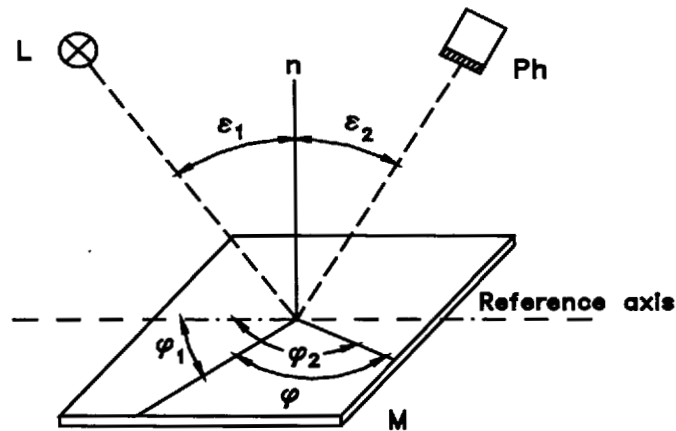


Fig. 1. Angle notation for radiometric/photometric properties.

L	source of radiation,
Ph	detector,
M	sample,
n	axis normal to the sample,
ε_1	angle of incidence,
ε_2	angle of view,
φ_1 and φ_2	azimuth angles.

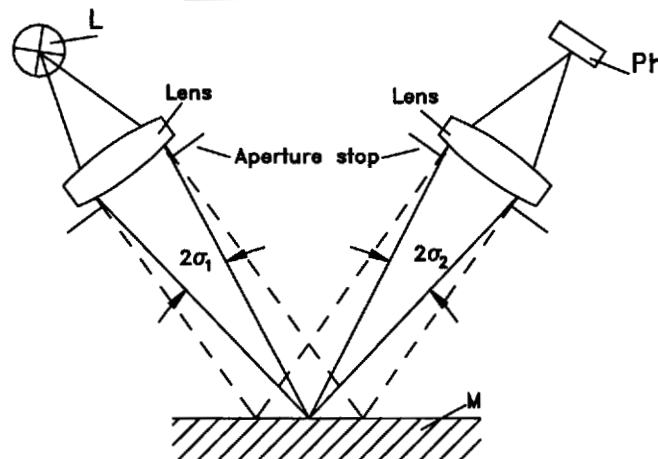


Fig. 2. Aperture angles (exaggerated for clarification) illustrated for the case of regular reflectance.

L	source,
Ph	detector,
M	sample,
$2\sigma_1$	aperture angle of the incident beam,
$2\sigma_2$	aperture angle of the viewing beam.

Note: For simplicity, the angles $2\sigma_1$ and $2\sigma_2$ refer to the beams subtended by the source and the detector at the centre of the measured area.

For hemispherical irradiation the index "dif" is used, e.g. reflectance for diffuse incidence of radiation: ρ_{dif} .

Note: In the case of the radiance/luminance factor β the index "d" is used instead of "dif".

If a characteristic is determined for a particular angle of view, this angle should be characterized by the angle ε_2 between the optical axis of the observed beam and the normal to the surface, and the azimuth angle φ , (the angle between the plane of incidence and the plane of view, $\varphi = \varphi_2 - \varphi_1$). If ε_1 and ε_2 are coplanar ($\varphi = 0^\circ$ or 180°) they may be given as a subscript; for example, the luminance factor for $\varepsilon_1 = 45^\circ$ and $\varepsilon_2 = 0^\circ$ is expressed as $\beta_{45/0}$.

If the surface of the material has a structure with directional features, the angular orientation of these features with respect to the plane of incidence or the plane of view must be specified.

The geometric conditions should be stated for each characteristic and recommended measuring method.

Table 1. Geometric conditions for reflection measurements.

Measuring geometry	Characteristic	Symbol
hemispherical/hemispherical	reflectance	ρ_{dif}
hemispherical/conic	reflectance factor	R_{dif}
hemispherical/directional	radiance factor	β_{dif}
conic/hemispherical	reflectance	ρ_{c}
conic/conic	reflectance factor	R_{c}
conic/directional	radiance factor	β_{c}
directional/hemispherical	reflectance	ρ_{g}
directional/conic	reflectance factor	R_{g}
directional/directional	radiance factor	β_{g}

Index "dif" hemispherical irradiation ($2\sigma_1 = 180^\circ$, figure 2).

Index "c" conic irradiation described by the extent, shape and orientation of the solid angle (angles ε_1 and $2\sigma_1$).

Index "g" directional irradiation described by the extent, shape and orientation of the solid angle (angles ε_1 and $2\sigma_1$).

Note: For a perfect diffuser, the value of all nine parameters is 1.

3.3 Thin and thick translucent samples

Different measuring methods and equipment are recommended for testing thin and thick translucent samples.

The decision as to whether a sample should be classified as thick or thin cannot be made solely on the grounds of physical thickness. The critical thickness is much lower for strongly diffusing materials than for samples having a quasi-regular transmittance. A translucent sample should be regarded as thick, and treated accordingly, when special procedures are required to prevent a significant fraction of the reflected or transmitted radiation from escaping detection. A visual inspection, made while irradiating the sample with a collimated beam, may be useful to establish to which family a sample belongs. If there is any doubt, a method suitable for thick samples should be used.

3.4 Other parameters

Certain other parameters also influence the measured value of a specified characteristic.

- State of polarization of the radiation.

Unless a characteristic is determined with unpolarized incident radiation, the state of polarization and the azimuth of the plane of polarization should be specified. The reflected or transmitted radiation is usually partly polarized even if the incident radiation is unpolarized.

- Temperature.

Characteristics are normally given for an ambient temperature of 25°C, if no other temperature is specified.

- State of the surface.

Characteristics are normally given for a clean, dry sample, unless otherwise specified.

4. MEASUREMENT PRINCIPLES

4.1 Absolute and relative methods

Since they are defined as the ratio of two fluxes, reflectance and transmittance are, in themselves, relative characteristics, but, whenever their values are measured directly without the use of another material standard as a reference, the corresponding method is termed "absolute".

Diffuse reflectance measurements are generally carried out with the help of a standard and are accordingly classified as relative methods. Absolute methods do exist [3], but they are normally restricted to standards laboratories, where they are used to make accurate calibrations of standards.

In the case of transmittance, similar considerations apply. Since the flux transmitted through an unknown sample is to be referred to the flux falling on it and this comparison with the incident flux does not, theoretically, require any standard. It is only necessary to leave a free passage for the flux. According to this principle, measurements of transmittance should be absolute ones. However, practical difficulties sometimes lead to the use of calibrated transmittance standards and thus to relative methods.

4.2 Spectral and integral characteristics

4.2.1 SPECTRAL METHOD

With the spectral method, the relevant spectral characteristic $a(\lambda)$ is measured as a function of the wavelength using as narrow a bandwidth as possible.

The integral characteristic can then be calculated from equation 1 using the relative spectral power distribution $S(\lambda)$ of the incident radiation and the relative spectral weighting function, $w(\lambda)$ which are prescribed for that characteristic.

The spectral method must be used when:

- information on the spectral characteristic is required;
- the spectral power distribution of the prescribed illuminant cannot be reproduced;
- a detector with the prescribed relative spectral responsivity is not available.

4.2.2 INTEGRAL METHOD

With the integral method the relevant weighted characteristic is measured directly, using a source having the prescribed spectral power distribution $S(\lambda)$ and a detector with the required

relative spectral weighting function $w(\lambda)$ [9], e.g. for luminous characteristics Standard Illuminant A and the $V(\lambda)$ function.

4.2.3 PHOTOMETER, RADIOMETER, SPECTRORADIOMETER

A photometer is a detector with a relative spectral responsivity corresponding to $V(\lambda)$ for the measurement of photometric quantities. The $\bar{y}(\lambda)$ detector of a colorimeter may also be used to measure luminous reflectance or transmittance.

A radiometer is an instrument with a relative spectral responsivity other than $V(\lambda)$. The term is particularly used to refer to a detector with a constant (wavelength independent) $w(\lambda)$ function (over a limited wavelength range), although instruments for the measurement of other, non-photometric, weighted radiant quantities are also referred to as radiometers;

Spectroradiometers and spectrophotometers are instruments for the measurement of spectral quantities (evaluation of radiation within a narrow wavelength band).

A radiometer/photometer for measuring the characteristics of materials using an integrating sphere is known as a sphere radiometer/photometer [10].

4.3 Spatial evaluation

Characteristics with hemispherical or conical incidence or collection of radiation can be measured using:

- gonioradiometers/goniophotometers;
- integrating sphere radiometers/photometers;
- directional methods.

4.3.1 GONIORADIOMETERS/GONIOPHOTOMETERS

With gonioradiometric/goniophotometric measurements the radiation reflected/transmitted by the sample into different directions is measured in those directions. When necessary, the angular data can then be mathematically integrated, e.g. to yield the reflected luminous flux. Measurements with these instruments are outside the scope of the present report [4].

4.3.2 PRACTICAL METHODS

In industrial laboratories reflectance and transmittance are generally determined with commercial radiometer/photometer systems which perform the measurements either by directional methods or with the help of an integrating sphere (sphere radiometer/photometer) [10]. Such instruments are relatively simple to use and can be correctly operated by less trained personnel. This technical report will recommend the most suitable method for each characteristic.

4.3.2.1 *Methods using an integrating sphere*

In these methods, the radiation reflected/transmitted by the sample in all directions is collected and spatially integrated by the sphere. Measurements with integrating spheres are treated in chapters 7 and 8.

4.3.2.2 *Directional methods*

Directional methods are based on an irradiation and detection system prealigned in a suitable geometry relative to the sample so as to yield directional reflectance, transmittance, or radiance factor. Measurements with spectroradiometers/spectrophotometers are treated in chapters 9 and 10.

5. MEASURING EQUIPMENT

5.1 Components

An instrument for measuring the characteristics of materials consists of

- equipment for irradiation;
- equipment for detection;
- additional mechanical and/or optical components.

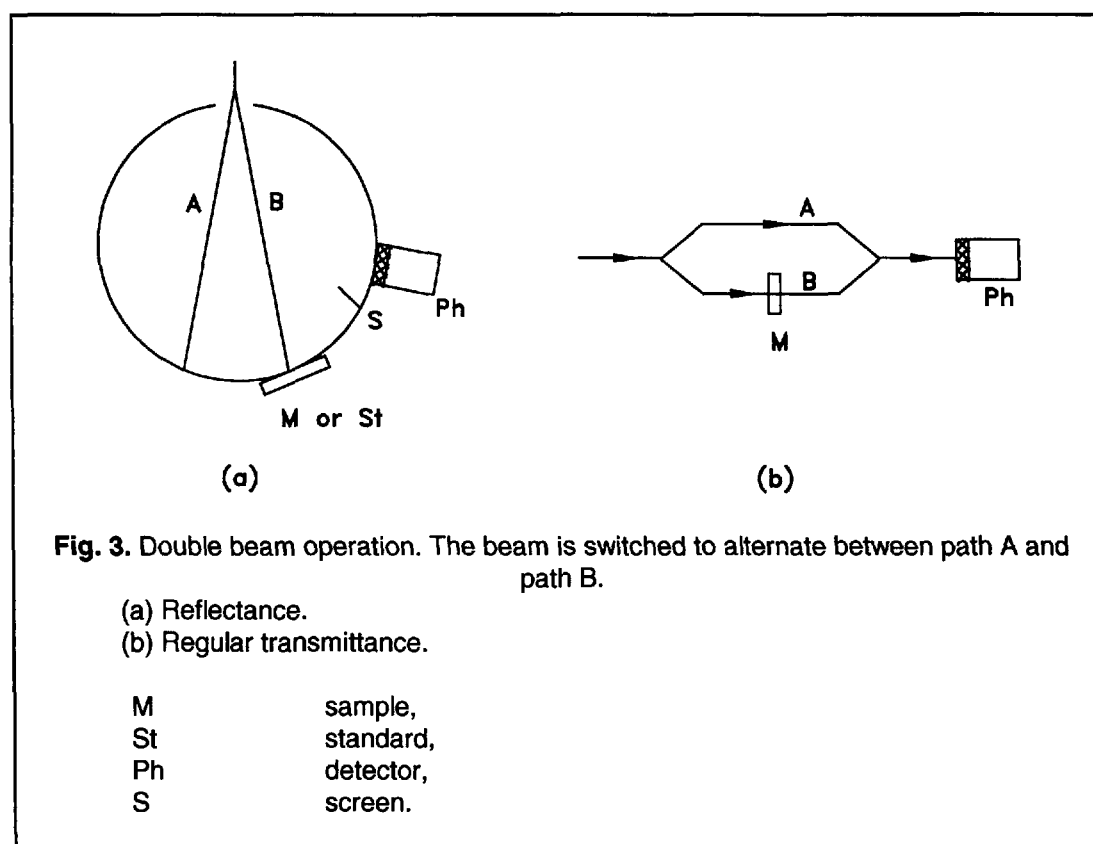
For spectral measurements a monochromator (or narrow band filters for measurements at defined wavelengths) is added to the irradiation or detection equipment.

5.2 Equipment for irradiation

5.2.1 SINGLE AND DOUBLE BEAM

The instrument may be of the single or double beam type. Single beam instruments are simpler but a number of problems can arise with them. The radiant output of the lamp or the responsivity of the detector may change between the sample reading and the reference reading. For instruments incorporating an integrating sphere the average reflectance of the sphere wall may change between the sample reading and the reference reading, if the sample and reference alternatively form part of the sphere wall.

These problems are overcome in double beam, ratio recording instruments where the beam is switched between a path which includes an incidence on the sample and one which does not. The detector signal is thus proportional to the ratio of the fluxes of the sample and reference beams. Examples are shown in figure 3 for both reflectance and regular transmittance. The reference beam by-passes the sample for transmittance measurement and may be incident on a reference surface for reflectance.



Double beam operation is not the only way of solving the above problems, however. Some instruments try to solve them by stabilising the source and the detector and by applying a numerical correction for integrating sphere errors.

5.2.2 GEOMETRIC CONDITIONS

In the present document, the hypothesis of an axially symmetric irradiating beam is made. Commercially available instruments such as spectroradiometers normally have a rectangular beam cross section. The recommendations given in this report should be adapted to take account of the actual beam shape.

The equipment should fulfil the following requirements.

- Size of the irradiated/illuminated area of the sample sufficiently large, in comparison to the structure of the sample. If this is not possible, several measurements should be made with the sample in different positions and the results averaged.
- Nearly uniform irradiance on the irradiated area of the sample.
- The ratio of the evaluated area to the irradiated/illuminated area should be appropriate to the type of measurements carried out.
- In the case of oblique irradiation/illumination the size of the irradiated/illuminated area increases with $(\cos \varepsilon)^{-1}$. For large angles care must be taken to satisfy the above requirements.
- Stray radiation outside the irradiated area of the sample should be avoided.
- The angle between the optical axis and any ray of the beam should be $\leq 5^\circ$ unless more stringent conditions are required.
- Aperture angle $2\alpha_1 \leq 10^\circ$ unless more stringent conditions are required (see figure 2).
- Angle ε_1 between normal of the sample and optical axis of the incident beam for the measurement of ρ at "nearly normal incidence" should be $\leq 10^\circ$. For the measurement of τ at normal incidence, $\varepsilon_1 = 0^\circ \pm 2^\circ$. For the measurement of $\rho(\varepsilon)$ or $\tau(\varepsilon)$ at other angles of incidence, these angles should be stated.

Special geometric conditions for the measurement of regular reflection/transmission are considered in chapters 9 and 10.

Special equipment is used for diffuse irradiation for the measurement of reflectance ρ_{diff} (chapter 7), transmittance τ_{diff} (chapter 8) and radiance/luminance factor at diffuse incidence of radiation β_d (chapter 12).

5.2.3 SPECTRAL CONDITIONS

The equipment should fulfill the following conditions.

- For luminous characteristics. The spectral power distribution should correspond to a defined standard illuminant [6] or some other defined illuminant [11] (see 3.1.1). If not otherwise specified, Standard Illuminant A.
- For radiant characteristics. These are generally related to some form of solar radiation. The spectral power distribution of the source representing the solar radiation should be specified [8].
- For spectral characteristics. Monochromatic irradiation and broad-band measurement, or broad-band irradiation and monochromatic measurement. Note that in the case of luminescent materials, these should be irradiated polychromatically with the correct illuminant and measured monochromatically [12] [13].

5.2.4 POLARIZATION

The characteristics of materials for non-normal incidence depend on the state of polarization of the irradiating beam. Directional measurements may be performed with unpolarized incident radiation only if no polarization arises from the source or the deflecting or focusing

optics (when present) and the detector is insensitive to polarization [14]. Otherwise, for conditions of non-normal incidence, two separate measurements should be made with the incident radiation fully linearly polarized in the plane perpendicular to the plane of incidence and in the plane parallel to the plane of incidence, respectively. The value of the characteristic for unpolarized incident radiation may then be computed as the mathematical average of the two results.

In those cases where measurements are required with fully linearly polarized radiation, the angle of the plane of polarization relative to the plane of the incident beam shall be stated.

Note1: The radiation emitted from a lamp is generally partially polarized. A beam entering an integrating sphere is depolarized by the multiple reflections inside the sphere.

Note2: The irradiating beam can be depolarized by the use of an additional tilted thin glass plate inserted in the beam. The degree of depolarization can be checked by rotating a polarizing filter around the optical axis of the irradiating beam and checking the constancy of the reading.

5.2.5 LAMPS

The following types of lamps are employed in the equipment used to irradiate the sample.

- Luminous characteristics:

incandescent lamps (sometimes tungsten-halogen lamps) for Standard Illuminant A.

- Spectral characteristics:

deuterium lamps for $200 \text{ nm} < \lambda < 350 \text{ nm}$;

tungsten-halogen lamps for $350 \text{ nm} < \lambda < 3\,000 \text{ nm}$;

xenon lamps for $250 \text{ nm} < \lambda < 1\,200 \text{ nm}$.

- Radiant characteristics:

xenon lamps, often filtered;

combinations of xenon lamps, metal halide lamps and incandescent lamps [15].

The equipment for irradiation should provide a time-independent irradiation of the sample by power or photo-electronic control of the beam. As the output of a xenon lamp can change randomly with time it is recommended that several measurements be performed at different times and the mean value taken.

5.3 Equipment for detection

5.3.1 IRRADIANCE/ILLUMINANCE AND RADIANCE/LUMINANCE MEASUREMENT

The detector consists of an irradiance/illuminance meter or a radiance/luminance meter [9] [16].

Spatial evaluation takes place in the following way:

- for irradiance/illuminance meters by hemispherical evaluation;
- for radiance/luminance meters by an evaluation within the measuring field which depends on the geometrical conditions of the equipment.

Irradiance/illuminance meters should be provided with a suitable cosine correcting device located in front of the acceptance area of the detector.

5.3.2 RADIOMETER/PHOTOMETER HEAD

The following properties may affect the quality of a radiometer/photometer head [16]:

- deviation of the relative spectral responsivity from the prescribed relative spectral weighting function;
- change in responsivity as a function of position in the photosensitive area;

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- effects of polarization of the incident radiation.

The following types of detectors may be used for the measurements of the various characteristics:

- for luminous characteristics, $V(\lambda)$ corrected, filtered, silicon photovoltaic cells;
- for radiant characteristics, thermopiles;
- for spectral characteristics, photomultiplier for $200 \text{ nm} < \lambda < 900 \text{ nm}$,
Si-photovoltaic cells for $200 \text{ nm} < \lambda < 1100 \text{ nm}$,
PbS, InGaAs and other solid state detectors, $\lambda > 800 \text{ nm}$.

5.3.3 RADIOMETER/PHOTOMETER

In addition to the items mentioned in 5.3.2, the accuracy of a radiometer/photometer may also be affected by the following:

- linearity error;
- error of the display unit;
- fatigue;
- temperature dependence;
- errors arising from range changes;
- warm-up period;
- influence of supply voltage.

A numerical assessment of the above properties is described in Publication CIE 69 [16].

Additional properties affecting the accuracy of the radiometer/photometer, for which a numerical assessment cannot yet be recommended are:

- ageing effects;
- zero setting drift;
- mechanical durability;
- climatic durability;
- effects of external magnetic fields.

5.3.4 DATA RECORDING

Direct recording of data with a small computer/microprocessor in combination with a printer/plotter is recommended. This is essential for spectral measurements where many data points must be recorded and corrected.

5.4 Monochromator

Instruments designed to measure spectral characteristics generally incorporate a monochromator [17]. This may use a prism or a diffraction grating as the dispersive element. Alternatively a filter monochromator using an interference filter or wedge may be used. Some instruments use double monochromators or additional filters to improve their stray light performance.

For non-luminescent materials, the monochromator may be positioned either in the irradiating optics or in the detecting optics, but, if luminescent samples are to be measured using only one monochromator, then it must be positioned between the sample and the detecting optics. The complete characterisation of luminescent samples requires two monochromators, one in the irradiating optics and the other in the detecting optics [12] [13].

6. INTEGRATING SPHERE

An integrating sphere is a hollow sphere whose internal surface is a diffuse reflector, as non-selective as possible. An integrating sphere equipped with a radiometer/photometer is recommended for the measurement of

- reflectance and transmittance;
- diffuse reflectance and transmittance.

The regular components can then be obtained by subtracting one from the other.

Note 1: The use of a "box photometer" cannot be recommended [10].

Note 2: Integrating spheres are not suitable for measuring luminescent materials.

6.1 Measurement principles

The radiant/luminous flux, incident on and reflected/transmitted by a sample is measured using a radiometer/photometer equipped with an integrating sphere, by comparing it with the same flux incident on and reflected/transmitted by a standard. The indirect irradiance/illuminance or radiance/luminance of the inner wall of the sphere is assumed to be proportional to the flux [19] [20] [21].

6.2 Sphere theory

Sphere theory was first developed for the measurement of the luminous flux of lamps, and later used for the measurement of the radiant/luminous flux reflected/transmitted by materials [19].

According to Ulbricht's theory, the radiant/luminous flux reflected/transmitted by a sample is related to the indirect irradiance/illuminance on the inner surface of the integrating sphere by:

$$\Phi_r (\Phi_t) = E_{\text{ind}} \cdot A \cdot \frac{1 - \rho_k}{\rho_k} \quad (2)$$

where Φ_r (Φ_t) is the reflected (transmitted) flux,
 E_{ind} the indirect irradiance/illuminance on the diffusing window in front of the detector,
 A the area of the sphere surface and
 ρ_k the average reflectance of the whole surface of the sphere.

Note: Equation 2 takes no account of the flat character of the sample (or standard) and of the opal window in front of the detector, and assumes that everything within the sphere behaves as an isotropic diffuser.

The sample is positioned at a sphere port. Direct irradiation of the photosensitive area of the radiometer/photometer head by reflected/transmitted radiation is prevented by a screen. The diffusing window in front of the detector (radiometer/photometer) should be mounted flush with the inner surface of the sphere.

Instead of measuring the irradiance/illuminance at some position in the sphere wall, it is possible to measure the radiance/luminance of the surface of the sphere. In either case, it is essential for correct measurements that the area of the sphere surface over which the measurement is made is completely shielded against direct irradiation from the sample. A larger shielding screen is generally required for the measurement of radiance/luminance than for irradiance/illuminance.

Because of the deviation between a real and a theoretical sphere the reflected/transmitted radiant/luminous flux cannot be calculated directly from equation 2, but must be determined at least for reflectance measurements by an additional measurement with a standard. Ideally the reflectance of a sample is given by

$$\rho_x = \rho_N \cdot \frac{E_{\text{ind},x}}{E_{\text{ind},N}} \quad (3)$$