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Standard Practice for Obtaining Bispectral Photometric Data for Evaluation of Fluorescent Color[1]

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INTRODUCTION

The fundamental procedure for evaluating the color of a fluorescent specimen is to obtain bispectral photometric data for specified irradiating and viewing geometries, and from these data to compute tristimulus values based on a CIE (International Commission on Illumination) standard observer and a CIE standard illuminant. The considerations involved and the procedures used to obtain precise bispectral photometric data are contained in this practice. Values and procedures for computing CIE tristimulus values from bispectral photometric data are contained in Practice E2152. General considerations regarding the selection of appropriate irradiating and viewing geometries are contained in Guide E179; further specific considerations applicable to fluorescent specimens are contained in this practice.

1. Scope

1.1 This practice addresses the instrumental measurement requirements, calibration procedures, and material standards needed for obtaining precise bispectral photometric data for computing the colors of fluorescent specimens.

1.2 This practice lists the parameters that must be specified when bispectral photometric measurements are required in specific methods, practices, or specifications.

1.3 This practice applies specifically to bispectrometers, which produce photometrically quantitative bispectral data as output, useful for the characterization of appearance, as opposed to spectrofluorimeters, which produce instrument-dependent bispectral photometric data as output, useful for the purpose of chemical analysis.

1.4 The scope of this practice is limited to the discussion of object-color measurement under reflection geometries; it does not include provisions for the analogous characterization of specimens under transmission geometries.

1.5 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E179 Guide for Selection of Geometric Conditions for Measurement of Reflection and Transmission Properties of Materials

E284 Terminology of Appearance

E925 Practice for Monitoring the Calibration of Ultraviolet-Visible Spectrophotometers whose Spectral Bandwidth does not Exceed 2 nm

E958 Practice for Measuring Practical Spectral Bandwidth of Ultraviolet-Visible Spectrophotometers

E1164 Practice for Obtaining Spectrometric Data for Object-Color Evaluation

E1341 Practice for Obtaining Spectroradiometric Data from Radiant Sources for Colorimetry

E2152 Practice for Computing the Colors of Fluorescent Objects from Bispectral Photometric Data

2.2 *NPL Publications:*

NPL Report MOM 12 Problems of spectrofluorimetric standards for reflection and colorimetric use[3]

[1] This practice is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.05 on Fluorescence.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from National Physical Laboratory, Queens Road, Teddington, Middlesex, United Kingdom TW11 0LW, http://www.npl.co.uk/.

2.3 *CIE Publications:*

CIE No. 38 Radiometric and Photometric Characteristics of Materials and Their Measurement[4]

CIE No.15.2 Colorimetry, 2nd Edition[4]

CIE Report of TC-2.25: Calibration Methods and Photoluminescent Standards for Total Radiance Factor Measurement[4]

2.4 *NIST Publications:*

NBS No. 260-66 Didymium Glass Filters for Calibrating the Wavelength Scale of Spectrophotometers[5]

3. Terminology

3.1 *Definitions*—The definitions contained in Terminology E284 are applicable to this practice.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *bispectral fluorescence radiance factor, $b_{F_\lambda}(\mu)$, n*—the ratio of the spectral radiance at wavelength λ due to fluorescence from a point on the specimen when irradiated at wavelength μ to the total radiance of the perfectly reflecting diffuser similarly irradiated and viewed (see NPL Report MOM 12).

3.2.2 *bispectral radiance factor, $b_\lambda(\mu)$, n*—the ratio of the spectral radiance (radiance per unit waveband) at wavelength λ from a point on a specimen when irradiated at wavelength μ to the total (integrated spectral) radiance of the perfectly reflecting diffuser similarly irradiated and viewed.

$$b_\lambda(\mu) \equiv L_\lambda(\mu)/L(\mu)_d \quad (1)$$

3.2.3 *bispectral reflection radiance factor, $b_{R\lambda}(\mu)$, n*—the ratio of the spectral radiance at wavelength λ due to reflection from a point on the specimen when irradiated at wavelength μ to the total radiance of the perfectly reflecting diffuser similarly irradiated and viewed.

3.2.4 *bispectrometer, n*—an optical instrument equipped with a source of irradiation, two monochromators, and a detection system, such that a specimen can be measured at independently-controlled irradiation and viewing wavelengths. The bispectrometer is designed to allow for calibration to provide quantitative determination of the bispectral radiation-transfer properties of the specimen. **(6)**

NOTE 1—Typically, a reference detection system monitors the radiation incident on the specimen. This reference detection system serves to compensate for both temporal and spectral variations in the flux incident upon the specimen, by normalization of readings from the instrument's emission detection system.

3.2.5 *diagonal elements, n*—elements of a bispectral matrix for which irradiation and viewing wavelengths are equal.

3.2.6 *diagonal fluorescence, n*—the contribution of fluorescence to diagonal values of a bispectral radiance factor matrix, due to the finite range of actual irradiation and viewing wavelengths when nominal irradiation and viewing wavelengths are equal *($\mu = \lambda$)*.

3.2.7 *discrete bispectral radiance factor, $B(\mu,\lambda)$, n*—the matrix defined for specified irradiation and viewing bandpass functions, and viewing-wavelength sampling interval *($\Delta\lambda$)* as follows:

$$B(\mu,\lambda) \equiv \bar{b}_\lambda(\mu)\cdot\Delta\lambda \quad (2)$$

where:

$\bar{b}_\lambda(\mu)$ = the average bispectral radiance factor of the specimen, as weighted by the specified irradiation and viewing bandpass functions.

3.2.8 *Donaldson radiance factor, $D(\mu,\lambda)$, n*—a special case of the discrete bispectral radiance factor, for which the specified irradiation and viewing bandpass functions are perfectly rectangular, with bandwidth equal to irradiation and viewing-wavelength sampling interval.

NOTE 2—The Donaldson radiance factor is approximately equal to the ratio of the specimen radiance within the rectangular waveband of width Δλ centered at λ to the radiance of the perfect reflecting diffuser when each is irradiated over the rectangular waveband of width Δλ centered at μ.

3.2.9 *fluorescence, n*—this standard uses the term "fluorescence" as a general term, including both true fluorescence (with a luminescent decay time of less than 10^{-8} s) and phosphorescence with a delay time short enough to be indistinguishable from fluorescence for the purpose of colorimetry.

3.2.10 *near-diagonal element, n*—off-diagonal elements of an uncorrected bispectral matrix whose values include a significant reflection component, due to reflection overspill. For instruments with irradiation and viewing bandpass functions which approximate the recommended trapezoidal or triangular shape, this should be limited to within two to three bands of the diagonal.

3.2.11 *off-diagonal element, n*—any element of a bispectral matrix for which irradiation and viewing wavelengths are not equal.

3.2.12 *reflection overspill, n*—the contribution of reflection to off-diagonal values of the discrete bispectral radiance factor matrix, due to the partial overlap of irradiation and viewing wavebands when nominal irradiation and viewing wavelengths are not equal *($\mu \neq \lambda$)*.

3.2.13 *spectral efficiency factor, $b(\mu)$, n*—the ratio of the total (integrated spectral) radiance from a point on a specimen when irradiated at wavelength μ to the total radiance of the perfectly reflecting diffuser identically irradiated and viewed.

$$b(\mu) \equiv L(\mu)/L(\mu)_d \quad (3)$$

4. Summary of Practice

4.1 Procedures are given for selecting the types and operating parameters of bispectrometers used to provide data for the calculation of CIE tristimulus values and other colorimetric values to quantify the colors of objects. The important steps in the calibration of such instruments, and the material standards required for these steps, are described. Guidelines are given for the selection of specimens to obtain the highest measurement precision. Parameters are identified which must be specified when bispectral photometric measurements are required in specific test methods or other documents.

[4] Available from U.S. National Committee of the CIE (International Commission on Illumination), C/o Thomas M. Lemons, TLA-Lighting Consultants, Inc., 7 Pond St., Salem, MA 01970, http://www.cie-usnc.org.

[5] Available from National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070, http://www.nist.gov.

4.2 In this practice, the measuring instrument, a bispectrometer, is equipped with two separate monochromators. The first, the irradiation monochromator, irradiates the specimen with monochromatic light. The second, the viewing monochromator, analyzes the radiation leaving the specimen. A two-dimensional array of bispectral photometric values is obtained by setting the irradiation monochromator at a series of fixed wavelengths *(μ)* in the excitation band of the specimen, and for each *μ*, using the viewing monochromator to record readings for each wavelength *(λ)* in the specimen's emission range. The resulting array, once properly corrected, is known as the Donaldson matrix (**2**), and the value of each element *(μ,λ)* of this array is the Donaldson radiance factor *(D(μ,λ))*.

4.3 While recognizing the CIE recommendation (in CIE Publication 15.2) of numerical integration at 1 nm intervals as the basic definition, this practice is limited in scope to measurements and calculations using spectral intervals greater than or equal to 5 nm.

5. Significance and Use

5.1 The bispectral or two-monochromator method is the definitive method for the determination of the general (illuminant-independent) radiation-transfer properties of fluorescent specimens (**2**). The Donaldson radiance factor is an instrument- and illuminant-independent photometric property of the specimen, and can be used to calculate its color for any desired illuminant and observer. The advantage of this method is that it provides a comprehensive characterization of the specimen's radiation-transfer properties, without the inaccuracies associated with source simulation and various methods of approximation.

5.2 This practice provides a procedure for selecting the operating parameters of bispectrometers used for providing data of the desired precision. It also provides for instrument calibration by means of material standards, and for selection of suitable specimens for obtaining precision in the measurements.

6. Requirements for Bispectral Photometry

6.1 When describing the measurement of specimens by the bispectral method, the following must be specified:

6.1.1 The photometric quantity determined, such as Donaldson radiance factor or spectral efficiency factor.

6.1.2 The geometry of irradiation and viewing, including the following:

6.1.2.1 For bi-directional geometry, whether annular, circumferential, or uniplanar measurement conditions are to be used, and the number and angular distribution of any multiple beams.

6.1.2.2 For hemispherical geometry, whether total or diffuse measurement conditions (specular component of reflectance included or excluded) are to be used.

6.1.3 The spectral parameters for both irradiation and viewing, including wavelength range, wavelength measurement interval, and spectral bandpass.

6.1.4 Identification of the material standards used for instrument calibration.

6.1.5 Special requirements determined by the nature of the specimen, such as measurement orientation for anisotropic specimens.

7. Apparatus

7.1 *Bispectrometer*—The basic instrumental requirement is a bispectrometer designed for measurement of Donaldson radiance factor using one or more of the standard irradiation and viewing geometries described in Section 8.

7.2 *Irradiator*—The irradiator, which consists of the radiation source, a dispersive element and related optical components, shall irradiate the specimen with monochromatic radiation of known wavelength bandpass and measurement interval.

7.2.1 The radiation source must be stable with time and have adequate energy output over the wavelength range used for specimen irradiation.

7.2.2 The dispersive element, which provides energy in narrow wavelength bands across the UV and visible spectral range, may be a prism, a grating, or one of various forms of interference filters or wedges. The element should conform to the following requirements:

7.2.2.1 When highest measurement accuracy is required, the wavelength range should extend from 300-830 nm; otherwise the range from 300 to 780 nm should suffice. For specimens confirmed to be non-fluorescent or those exhibiting only visible-activated fluorescence (negligible excitation below 380 nm), the wavelength range from 380 to 780 can be used. Each user must decide whether the loss of accuracy in the measurements is negligibly small for the purpose for which data are obtained.

7.2.2.2 The wavelength interval should be 5 or 10 nm. Use of wider wavelength intervals, such as 20 nm, may result in reduced accuracy. Each user must decide whether the loss of accuracy in the measurements is negligibly small for the purpose for which data are obtained.

7.2.2.3 The irradiation wavelength interval should equal the viewing wavelength interval.

7.2.2.4 The spectral bandpass (full-width at half maximum power in the band of wavelengths transmitted by the dispersive element) should, for best results, be equal to the wavelength interval. The spectral bandpass function should be symmetrical, and approximately triangular or trapezoidal.

7.2.3 The irradiator should uniformly irradiate the sample.

7.3 *Receiver*—The receiver consists of the detector, a dispersive element and related optical components.

7.3.1 The detector must be a suitable photodetector such as a photoelectric device or silicon photodiode. The detector must be stable with time and have adequate responsivity over the wavelength range used.

7.3.2 The dispersive element, which provides energy in narrow wavelength bands across the visible spectral range, may be a prism, a grating, or one of various forms of interference filters or wedges. The element should conform to the following requirements:

7.3.2.1 The receiver's dispersive element may either be coupled with a slit, in order to function as part of a scanning

monochromator, or coupled directly to a detection array, in order to function as a spectrograph (polychromator) (**3**).

7.3.2.2 When highest measurement accuracy is required, the wavelength range should extend from 360 to 830 nm; otherwise the range from 380 to 780 nm should suffice. Each user must decide whether the loss of accuracy in the measurements is negligibly small for the purpose for which data are obtained.

7.3.2.3 The wavelength interval should be 5 or 10 nm. Use of wider wavelength intervals, such as 20 nm, may result in reduced accuracy. Each user must decide whether the loss of accuracy in the measurements is negligibly small for the purpose for which data are obtained.

7.3.2.4 The viewing wavelength interval should equal the irradiation wavelength interval.

7.3.2.5 The spectral bandpass (full-width at half maximum power in the band of wavelengths transmitted by the dispersive element) should, for best results, be equal to the wavelength interval. The spectral bandpass function should be symmetrical, and approximately triangular or trapezoidal.

7.3.3 The receiver should uniformly view the sample.

8. Irradiating and Viewing Conditions

8.1 *Types and Tolerances*—Unless special considerations requiring other tolerances are applicable, the instrument shall conform to the same geometric requirements defined for spectrophotometers in Practice E1164. Types described in Practice E1164 include the following:

8.1.1 45°/Normal (45/0) and Normal/45° (0/45) Geometries.

8.1.2 Total/Normal (t/0) or Diffuse/Normal (d/0) and Normal/Total (0/t) or Normal/Diffuse (0/d) Geometries.

8.2 *Selection of Irradiating and Viewing Conditions*—The guidelines provided by Practice E1164 shall generally apply to the selection of appropriate geometric conditions of irradiation and viewing with a bispectrometer. Additional considerations pertaining specifically to fluorescent specimens include the following:

8.2.1 In absence of specific geometrical requirements, a bi-directional instrument geometry (such as 45/0 or 0/45) is normally preferred. For certain applications, however, the use of an integrating-sphere instrument geometry may be desirable; for example, in order to produce more repeatable measurement of specimens with a structured surface, for historical consistency, or for compatibility with other measurements.

8.2.2 Use of integrating-sphere instrument geometries (t/0, d/0, 0/t, 0/d) with fluorescent specimens will introduce certain systematic errors into the measurement of Donaldson radiance factor (**9**). It is the responsibility of the user to assess the significance of such errors for the purpose for which data are obtained.

NOTE 3—When users choose the use of integrating sphere instrument geometries, they can reduce the systematic errors due to such instrument geometries by:

(*1*) Using a sphere coating which is as spectrally-neutral as possible.
(*2*) Using the specular component excluded mode.
(*3*) Using the smallest possible sample port area.
(*4*) Increasing the exit and entrance port fractional areas.
(*5*) Lowering the reflectance of the coating to a reflectance factor of 80 % or less (**10**).

NOTE 4—Options 4 and 5 will decrease the absolute efficiency of the sphere.

9. Calibration and Material Standards

9.1 Calibration and its verification are essential steps in ensuring that accurate results are obtained by bispectral photometric measurement. Calibration and verification may require the use of material standards not supplied by the instrument manufacturer. The instrument user must assume the responsibility for obtaining and maintaining the necessary material standards.

9.2 *Photometric Scale:*

9.2.1 *General Requirements for Photometric Calibration*—Specific procedures for photometric calibration of a bispectrometer are described in Annex A1. General requirements for such calibration are as follows:

9.2.2 *Full-Scale Calibration*—For accurate bispectral measurement, it is necessary to calibrate the bispectrometer so that:

9.2.2.1 *Absolute Photometric Calibration*—For diagonal elements of the Donaldson radiance factor matrix, the values of the perfect reflecting diffuser are assigned the numerical value 1.00 (100 %). For off-diagonal elements, (where irradiation and viewing wavelengths are unequal), the perfect reflecting diffuser is assigned the numerical value 0 (See 9.2.3).

9.2.2.2 *Relative Spectral Photometric Calibration*—The relative spectral selectivity of the instrument, due to the relative spectral power distribution of the source of irradiation or the relative spectral responsivity of the instrument's detection system, or both, is compensated by means of correction factors applied to off-diagonal elements of the bispectral matrix of instrument readings.

9.2.3 *Zero Calibration or Verification*—When a calibration of the zero point of the photometric scale is required, it may be carried out by any of the methods listed in Practice E1164 (paragraph 9.2.2), or by the following means:

9.2.3.1 A bispectral baseline matrix may be derived from a matrix of readings for a known non-fluorescent specimen by deleting diagonal and near-diagonal values from this matrix, and replacing them with values derived by interpolation across the near-diagonal region. The value of each element of this baseline matrix may then be subtracted from corresponding elements of the matrix of readings obtained for the specimen.

9.2.4 *Linearity Verification*—After the full-scale and zero-scale photometric readings are verified, the linearity of the scale should be verified by measuring one or more calibrated standards having intermediate radiance factor.

9.3 *Wavelength Scale*—This section applies to both the instrument's irradiation and viewing wavelength scales:

9.3.1 *Scale Calibration or Verification*—The wavelength scale should be calibrated or verified, or both, for linearity and offset as follows:

9.3.1.1 For instruments with a spectral bandpass of about 10 nm or less, a line source, or a combination of line sources, such as Mercury or Argon-vapor lamps, should be used, as described in Practice E1341. Alternatively, a rare-earth oxide reflectance standard may be used, following procedures similar to those given in NBS SP-260-66.

9.3.1.2 For instruments with a wider spectral bandpass, the method of linear filters should be used (7).

9.3.2 *Spectral Bandpass Verification*—The approximate spectral bandpass of the instrument should be verified by using a line source, or a combination of line sources, such as Mercury or Argon-vapor lamps, as described in Practice E1341. Alternatively, a rare-earth oxide reflectance standard may be used, following procedures similar to those given in NBS SP-260-66, Practice E925 or Practice E958.

9.4 *Stray Light*—The level of stray light in the instrument should be verified as being adequately low by measuring a suitable specimen or specimens with low radiance factor. A detailed discussion on methods of stray light verification is beyond the scope of this standard; see Practices E1164 and E1341.

NOTE 5—A known non-fluorescent specimen may be used for such verification for off-diagonal elements of the bispectral matrix, in a manner similar to that described in 9.2.3.1.

9.5 *System Verification*—The precision and bias of the entire measurement system, including calculation of CIE tristimulus values, should be determined by periodic measurement of calibrated verification standards, either supplied by the instrument manufacturer or obtained independently. Such standards should include both non-fluorescent color standards, such as the BCRA series ceramic color standards (8), and standards exhibiting fluorescence in the bispectral region of interest.

10. Test Specimens

10.1 Measurement results depend on the quality of the specimens used. Test specimens should be representative of the material being tested, and should also conform to the following geometric and optical requirements set by the nature of the measuring instruments. When the specimens do not have these desired characteristics, departures should be noted.

10.2 Specimens should be uniform in properties over the area measured.

10.3 Opaque specimens should have at least one plane surface; translucent and transparent specimens should have two surfaces that are essentially plane and parallel.

10.4 When specimens are not completely opaque, the following considerations are important:

10.4.1 The measurement results will influenced by the Donaldson radiance factor of the material behind the specimen; this should be a specified backing material.

10.4.2 The measurement results will depend upon the thickness of the specimen.

10.4.3 An indeterminate amount of radiation may escape from the sides of the specimen, affecting the measurement results.

10.5 Measurement data for transparent specimens will depend upon the thickness of the specimen.

10.6 Special considerations, some of which have been noted, apply to the measurement of retroreflective or translucent specimens.

10.7 Specimens should be handled carefully to avoid contamination. Care should be taken not to touch the area to be measured except for application of a suitable cleaning procedure. The condition of the specimens before and after measurement should be noted and reported.

11. Procedure

11.1 *Selection of Measurement Parameters*—To the extent allowed by the measuring instrument(s) available, select the following measurement parameters:

11.1.1 Select the irradiating and viewing geometry; for bi-directional geometries, select whether annular, circumferential, or uniplanar conditions will be used, and for hemispherical geometries, select whether total or diffuse quantities will be measured.

11.1.2 Select the irradiation and viewing wavelength ranges, wavelength measurement interval, and spectral bandpass.

11.1.2.1 *General Requirements for Unscreened Specimens*—For a specimen of unknown excitation and emission properties, the selected irradiation wavelength range should extend at least from 300 to 780 nm, and the selected viewing wavelength range should extend at least from 380 to 780 nm.

11.1.2.2 *Screening Specimens to Determine Regions of Fluorescence*—When the bispectral region of fluorescence is known for a particular specimen, it is acceptable to limit the collection of fluorescence data (off-diagonal values) to this region.

11.2 *Selection of Computational Variables*—When the instrument incorporates or is interfaced to a computer so that calculation of CIE tristimulus values and derived color coordinates automatically follows measurement, select the variables defining these computations, following Practice E2152.

11.3 Measure the specimen(s), following the instrument manufacturer's instructions.

11.3.1 *Sample Measurement*—With specimen in sample position, instrument collects sample readings $S(\mu,\lambda)$ for all irradiation and viewing wavelengths within the specified ranges.

11.3.2 *Sample Reading*—The bispectrometer sample reading $(S(\mu,\lambda))$ represents the ratio of the signal $(j_m(\mu,\lambda))$ recorded by the instrument detection system for viewing wavelength λ when specimen is irradiated monochromatically at wavelength μ, to the signal $(j_r(\mu))$ simultaneously recorded by the reference detector which monitors the sample irradiation.

12. Calculation

12.1 Instrument-independent properties of fluorescent specimens are derived from bispectrometer readings by means of the calculations outlined below. When the instrument incorporates or is interfaced to a computer, such calculations are typically performed automatically following measurement.

12.2 *Calculation of Bispectral Photometric Quantities*

12.2.1 *Photometric Correction:*

12.2.1.1 *Calculation of Discrete Bispectral Radiance Factors*—Correct bispectrometer readings by application of calibration factors determined as described in Annex A1. The direct result of this calculation is a matrix of discrete bispectral radiance factor values $(B(\mu,\lambda))$.

12.2.1.2 *Estimation of Donaldson Radiance Factors*—Derive an estimate of the specimen's Donaldson radiance factor from its discrete bispectral radiance factor as follows:

12.2.1.3 *Discussion*—To a first approximation, the contributions of reflection to bispectral photometric values are confined to diagonal elements, while those of fluorescence occur primarily in the off-diagonal elements. For any real instrument, however, diagonal and near-diagonal values obtained may represent contributions of both reflection and fluorescence. This is due primarily to two effects, described here as reflection overspill and diagonal fluorescence. If the instrument's spectral bandpass functions are sufficiently well-known, it is possible to correct for these effects. One method of performing such correction is described in Annex A2.

12.2.1.4 *Estimating Reflection Component ($D_R(\mu,\lambda)$)*—Estimate the reflection component of each element of the Donaldson matrix by correcting for reflection overspill, as described in Annex A2.

12.2.1.5 *Estimating Fluorescence Component ($D_F(\mu,\lambda)$)*—Estimate the fluorescence component of each element of the Donaldson matrix by correcting for reflection overspill, as described in Annex A2.

12.2.1.6 *Combining Reflection and Fluorescence Components*—Estimate the total value of each element of the specimen's Donaldson matrix by adding the reflection and fluorescence components, as described in Annex A2.

12.2.2 *Converting Bispectral Photometric Data*—The result of the calculations outlined above is a matrix of Donaldson radiance factor values ($D(\mu,\lambda)$). These values may be reported as such or converted to equivalent terms, as described below:

12.2.2.1 *Bispectral Radiance Factor ($\bar{b}_\lambda(\mu)$)*—When required to report bispectral radiance factor values, derive average values from Donaldson radiance factor values, according to the equation:

$$\bar{b}_\lambda(\mu) = D(\mu,\lambda)/\Delta\lambda \quad (4)$$

where:

$\Delta\lambda$ = the nominal viewing bandwidth (equal to measurement interval).

12.2.2.2 *Reflection and Fluorescence Components ($\bar{b}_{R\lambda}(\mu)$)*—When required to report fluorescence and reflection components separately, derive these from corresponding components of Donaldson radiance factor as described above.

12.3 *Data Reduction*—Bispectral data may be reduced to spectral, tristimulus, or mononumeric values as follows:

12.3.1 *Derivation of Spectral Efficiency Factor, $b(\mu)$*—The spectral efficiency factor as a function of irradiation wavelength may be derived from the specimen's Donaldson radiance factor values by summation over viewing wavelengths:

$$b(\mu) = \sum_{\lambda=380}^{780} D(\mu,\lambda) \quad (5)$$

12.3.2 *Derivation of Spectral Radiance Factor Values*—The spectral radiance factor may be derived from the specimen's Donaldson radiance factor values as described in Practice E2152.

12.3.3 *Derivation of Colorimetric Values*—The stimulus function and related colorimetric values may be derived from the object's Donaldson radiance factor values as described in Practice E2152.

13. Report

13.1 The report of the measurement of bispectral data shall include the following:

13.2 *Specimen Description*—Including the following:

13.2.1 Type and identification,

13.2.2 Date of preparation or manufacture, if required,

13.2.3 Method of cleaning and date, if cleaned,

13.2.4 Orientation of the specimen during measurement, and

13.2.5 Any changes in the specimen during measurement.

13.3 *Date of Measurement.*

13.4 *Instrument Parameters*—All measurement parameters and special requirements stated in Section 6 of this practice.

13.5 *Bispectral Data*—The Donaldson matrix, in the form of tables of irradiation and viewing wavelengths and Donaldson radiance factor values. Alternatively, bispectral data may be reported as the combination of bispectral fluorescence radiance factor ($b_{F\lambda}(\mu)$) and the reflectance component of spectral radiance factor ($\beta_R(\lambda)$; equivalent to spectral reflectance factor for non-fluorescent materials). In absence of any other specific requirement, however, the Donaldson matrix is the recommended format.

13.6 *Spectral Data (optional)*—If required, spectral efficiency factor values in the form of tables of wavelengths and measured quantity.

14. Keywords

14.1 bispectral; bispectrometer; calibration; color; colorimetry; Donaldson matrix; Donaldson radiance factor; fluorescence; instrumental measurement; luminescence; radiance factor; spectrophotometry

ANNEXES

(Mandatory Information)

A1. PHOTOMETRIC CALIBRATION PROCEDURE

A1.1 *Overview*—Four different approaches to photometric calibration of a bispectrometer are theoretically consistent with this practice. These are listed in Appendix X2. Of these four approaches, the default recommendation (approach #3), is presented here. This approach to calibration employs a non-fluorescent, diffuse white reflectance standard, calibrated for spectral reflectance factor ($R(\lambda)$), in combination with a standard detector calibrated for relative spectral responsivity ($K(\lambda)$).

A1.2 *Calibration Procedure:*

A1.2.1 *Sample Measurement*—Place specimen in sample position and collect sample readings $S(\mu,\lambda)$ for all irradiation and viewing wavelengths within range of the two monochromators.

A1.2.2 *Sample Reading*—The bispectrometer sample reading $(S(\mu,\lambda))$ represents the ratio of the signal $(j_m(\mu,\lambda))$ recorded by the instrument detection system for viewing wavelength λ when specimen is irradiated monochromatically at wavelength μ, to the signal $(j_r(\mu))$ simultaneously recorded by the reference detector which monitors the sample irradiation.

A1.2.3 *Reflectance Factor Calibration*—Place reflectance standard in sample position, and collect reflectance calibration readings $S_d(\mu,\lambda)$ for all for all wavelengths λ within range of the viewing monochromator, and all irradiation wavelengths in the near-diagonal region. In other words, for each viewing wavelength λ, collect readings for all irradiation wavelengths μ within Δλ of λ.

A1.2.3.1 *Reflectance Calibration Reading*—The reflectance calibration reading $(S_d(\mu,\lambda))$ is identical to the sample reading, except for the specimen in sample position during measurement.

A1.2.4 *Irradiation Calibration*—Place standard detector in sample position, and collect irradiation calibration readings $S_x(\mu)$ for all wavelengths μ in the spectral range of the irradiation monochromator.

A1.2.4.1 *Irradiation Calibration Reading*—The irradiation calibration reading $(S_x(\mu))$ represents the ratio of the signal $(j_x(\mu))$ recorded by the standard detector mounted in sample position when irradiation monochromator is positioned at wavelength μ, to the signal $(j_r(\mu))$ simultaneously recorded by the reference detector.

A1.3 *Basic Measurement Equation*—The discrete bispectral radiance factor of the specimen under test is derived by the following equation:

$$B(\mu,\lambda) \approx \frac{S(\mu,\lambda)}{S'_{d3}(\lambda)} \cdot \frac{S_x(\lambda)}{S_x(\mu)} \cdot R(\lambda) \cdot \frac{K(\mu)}{K(\lambda)} \tag{A1.1}$$

where:

$$S'_{d3}(\lambda) \equiv \sum_{\mu=\lambda-\Delta\lambda}^{\lambda+\Delta\lambda} S_d(\mu,\lambda) \cdot \frac{S_x(\lambda)}{S_x(\mu)} \frac{K(\mu)}{K(\lambda)} \tag{A1.2}$$

A2. CORRECTION FOR REFLECTION OVERSPILL

A2.1 *Discussion*—To a first approximation, the contributions of reflection to bispectral photometric values are confined to diagonal elements, while those of fluorescence occur primarily in the off-diagonal elements. For any real instrument, however, diagonal and near-diagonal values obtained may represent contributions of both reflection and fluorescence. This is due primarily to two effects, described here as reflection overspill and diagonal fluorescence.

A2.1.1 *Reflection Overspill*—In the special case of perfect rectangular bandpass, for which the discrete bispectral radiance factor (B) is simply equal to the Donaldson radiance factor (D), reflection values are confined to the diagonal of the bispectral matrix, and these diagonal values are equal to the spectral reflectance factor of the specimen. For any real measurement, however, irradiation and viewing bandpass functions may overlap significantly, even when these are centered at different wavelengths $(\mu \neq \lambda)$. The effect of reflection may therefore be observed in elements adjacent to the diagonal; reflection values may be said to "spill over" into these elements. In such cases, diagonal values of the discrete bispectral radiance factor matrix are not equal to the specimen's spectral reflectance factor. Nevertheless, if the instrument's bandpass functions satisfy the requirements of Section 7, the sum over all reflection values within a given emission waveband λ approximates the specimen's spectral reflectance factor at λ; similarly, the sum over all reflection values within a given excitation waveband μ approximates the specimen's spectral reflectance factor at μ. Within the constraints of Section 7, the sum of reflection values over any row or column of the B matrix is approximately the same regardless of the instrument's bandpass functions; it is only the distribution of reflection values within each row or column which differs. If this distribution can be described by an overspill distribution function, and diagonal fluorescence can be assumed to be negligible (see A2.1.2), the value of the reflection component of each element of the B matrix can be estimated by normalizing this function to the known diagonal values. If the instrument's excitation and emission bandpass functions are sufficiently well-characterized, such an overspill

distribution function can be derived analytically; otherwise, it must be determined empirically, by analysis of the distribution observed for one or more non-fluorescent specimens. The procedure described in this annex employs the empirical approach.

A2.1.2 *Diagonal Fluorescence*—The finite bandwidths associated with any real measurement make it possible for diagonal elements of the bispectral matrix to have a nonzero fluorescent component. This phenomenon may be described as diagonal fluorescence. For an instrument which conforms to the requirements of Section 7, the magnitude of diagonal fluorescence is much less than of reflection overspill. In this practice, the effect of diagonal fluorescence is assumed to be negligible. Failure to account for diagonal fluorescence may contribute to the systematic error associated with this practice. Each user must decide whether the loss of measurement accuracy is negligible for the purpose for which data are obtained.

A2.2 *General Procedure*—Calculation of colorimetric values for a fluorescent specimen requires an estimate of the specimen's Donaldson radiance factor. The Donaldson radiance factor represents a special case of the discrete bispectral radiance factor, corresponding to ideal bandpass functions which cannot be realized in practice. Nevertheless, an estimate of the Donaldson radiance factor can be derived from discrete bispectral radiance factor data obtained by physical measurements. For an instrument which conforms to the requirements of Section 7, the fluorescent component of the B matrix represents a good approximation to the fluorescent component of the Donaldson matrix. In order to obtain a good approximation to the reflection component of the Donaldson matrix, the reflection component of the B matrix must be corrected to account for reflection overspill. Alternatively, the reflection component of the Donaldson matrix (or reflection radiance factor) of the specimen can be determined by means of a separate experiment (**4**, **5**). In either case, correction for reflection overspill is achieved by first separating reflection and fluorescence components of the B matrix obtained by measurement, deriving an estimate of the reflection component which would be obtained in the ideal case, and recombining reflection and fluorescence components to obtain an estimate of the total Donaldson radiance factor.

A2.3 *Separation of Reflection and Fluorescence Components:*

A2.3.1 *Estimate Overspill Function*—The instrument's overspill distribution is approximated by the function f_m, derived from the discrete bispectral radiance factor matrix B_d obtained for the reflectance standard.

$$f_m(\mu,\lambda) \equiv \frac{B_d(\mu,\lambda)}{B_d(\lambda,\lambda)} \tag{A2.1}$$

NOTE A2.1—The matrix B_d is obtained by substituting S_d as defined in A1.2.3 for S in Eq A1.1.

A2.3.2 *Estimate Reflection Component ($B_R(\mu,\lambda)$)*—Estimate the reflection component of near-diagonal elements by using values for diagonal elements to normalize the overspill distribution function *(f_m)*. For the default approach described in A2.3.1, this calculation is represented by the following equation:

$$B_R(\mu,\lambda) \approx f_m(\mu,\lambda)\cdot B(\lambda,\lambda) \tag{A2.2}$$

A2.3.3 *Estimate Fluorescence Component ($B_R(\mu,\lambda)$)*—Estimate the fluorescence component of the discrete bispectral radiance factor as the residual value in each element, after subtraction of estimated reflection components.

$$B_F(\mu,\lambda) \approx B(\mu,\lambda) - B_R(\mu,\lambda) \tag{A2.3}$$

A2.4 *Estimation of Donaldson Radiance Factors:*

A2.4.1 *Estimation of Reflection Component*—Estimate the reflection component of each diagonal element of the Donaldson matrix *($D_R(\lambda,\lambda)$)* by summation over all the non-zero reflection components in the corresponding viewing band of the discrete bispectral radiance factor matrix obtained in section A2.3.2. (The reflection component of any off-diagonal element of the Donaldson matrix is equal to zero by definition.)

if $\mu = \lambda$ then:

$$D_R(\lambda,\lambda) \approx \sum_{\mu=\lambda-\Delta\lambda}^{\mu=\lambda+\Delta\lambda} B_R(\mu,\lambda) \tag{A2.4}$$

if $\mu \neq \lambda$ then:

$$D_R(\mu,\lambda) = 0 \tag{A2.5}$$

NOTE A2.2—For the approach defined in A2.3.1 and Annex A1, an equivalent result can be obtained more simply, by taking the direct ratio of diagonal elements of the matrices obtained for sample and reference:

$$\sum_{\mu=\lambda-\Delta\lambda}^{\mu=\lambda+\Delta\lambda} B_R(\mu,\lambda) = \frac{B(\lambda,\lambda)}{B_d(\lambda,\lambda)}\cdot R(\lambda) \tag{A2.6}$$

A2.4.2 *Estimation of Fluorescence Component*—Use the fluorescent component of the specimen's discrete bispectral radiance factor (obtained in A2.3.3) as an estimate of the fluorescent component of the Donaldson radiance factor.

$$D_F(\mu,\lambda) \approx B_F(\mu,\lambda) \tag{A2.7}$$

A2.4.3 *Combining Reflection and Fluorescence Components*—Estimate the total value of each element of the specimen's Donaldson radiance factor matrix by adding the reflection and fluorescence components obtained above.

$$D(\mu,\lambda) = D_R(\mu,\lambda) + D_F(\mu,\lambda) \tag{A2.8}$$

APPENDIXES

(Nonmandatory Information)

X1. REPORTING FORMAT

X2. ALTERNATIVE APPROACHES TO PHOTOMETRIC CALIBRATION

TABLE X1.1 Example Donaldson Matrix for a Fluorescent Specimen, Abridged

	300	320	340	360	380	400	420	440	460	480	500	520	540	560	580	600	620	640	660	680	700	720	740	760	780
380	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
420	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
440	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
460	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
480	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
500	0	0	0	0	0	0.000	0.010	0.013	0.010	0.014	0.028	0	0	0	0	0	0	0	0	0	0	0	0	0	0
520	0	0	0	0	0	0.029	0.054	0.060	0.059	0.066	0.067	0.330	0	0	0	0	0	0	0	0	0	0	0	0	0
540	0	0	0	0	0	0.034	0.072	0.078	0.081	0.087	0.086	0.027	0.509	0	0	0	0	0	0	0	0	0	0	0	0
560	0	0	0	0	0	0.025	0.048	0.054	0.058	0.061	0.022	0	0.529	0	0	0	0	0	0	0	0	0	0	0	0
580	0	0	0	0	0	0.012	0.025	0.028	0.029	0.031	0.032	0.013	0	0	0.497	0	0	0	0	0	0	0	0	0	0
600	0	0	0	0	0	0	0.014	0.016	0.016	0.018	0.021	0	0	0	0	0.491	0	0	0	0	0	0	0	0	0
620	0	0	0	0	0	0	0	0	0	0	0.012	0	0	0	0	0	0.480	0	0	0	0	0	0	0	0
640	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.475	0	0	0	0	0	0	0
660	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.473	0	0	0	0	0	0
680	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.467	0	0	0	0	0
700	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.461	0	0	0	0
720	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.452	0	0	0
740	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.449	0	0
760	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.441	0
780	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.438

NOTE 1—Column headings indicate irradiation wavelength; row headings indicate viewing wavelength.

X2.1 *Overview*—Four different approaches to photometric calibration of a bispectrometer are theoretically consistent with this practice. These are listed in the table below. Of these four approaches, approach #3 has been selected as the default recommendation, and is summarized in Annex A1. The alternative approaches may also be employed. Though the methods outlined below are approximately equivalent, differences in the systematic errors associated with each approach may result in some bias between these calibration methods. When an alternative to approach #3 is employed, it is the responsibility of the user to assess the significance of this bias for the purpose for which data are obtained.

#	Physical Standards Required	Type of Calibration	Notation
1	Set of Fluorescent Materials	Donaldson Radiance Factor	$D_{std}(\mu,\lambda)$
2	Non-Fluorescent White Diffuser	Spectral Reflectance Factor	$R(\lambda)$
	Source (at Sample Position)	Relative Spectral Radiance	$L(\lambda)$
3	Non-Fluorescent White Diffuser	Spectral Reflectance Factor	$R(\lambda)$
	Reference Detector (at Sample Position)	Relative Spectral Responsivity	$K(\lambda)$
4	Non-Fluorescent White Diffuser	Spectral Reflectance Factor at reference wavelength (λ_o)	$R(\lambda_o)$
	Reference Detector (at Sample Position)	Relative Spectral Responsivity	$K(\lambda)$
	Source (at Sample Position)	Relative Spectral Radiance	$L(\lambda)$

X2.2 *Calibration Procedures:*

X2.2.1 *Sample Measurement*—Place specimen in sample position, and collect sample readings $S(\mu,\lambda)$ for all irradiation and viewing wavelengths within range of the two monochromators.

X2.2.1.1 *Sample Reading*—The bispectrometer sample reading ($S(\mu,\lambda)$) represents the ratio of the signal ($j_m(\mu,\lambda)$) recorded by the instrument detection system for viewing wavelength λ when the specimen is irradiated monochromatically at wavelength μ, to the signal ($j_r(\mu)$) simultaneously recorded by the reference detector which monitors the sample irradiation.

X2.2.2 *Reflectance Factor Calibration*—Place reflectance standard in sample position, and collect reflectance calibration readings $S_d(\mu,\lambda)$ for all wavelengths μ within range of the irradiation monochromators, and all viewing wavelengths in the near-diagonal region. In other words, for each irradiation wavelength μ, collect readings for all viewing wavelengths λ within $\Delta\lambda$ of μ.

X2.2.2.1 *Spectral Range*—For approach (3), defined above, reflectance calibration must be performed over the spectral range of the viewing monochromator only. For approach (2), reflectance calibration must be performed over the entire spectral range of the irradiation monochromator.

X2.2.2.2 *Reflectance Calibration Reading*—The reflectance calibration reading ($S_d(\mu,\lambda)$) is identical to the sample reading, as described above, except for the specimen in sample position during measurement.

X2.2.3 *Irradiation Calibration*—Place standard detector in sample position, and collect irradiation calibration readings $S_x(\mu)$for all wavelengths μ in the spectral range of the irradiation monochromator.

X2.2.3.1 *Irradiation Calibration Reading*—The irradiation calibration reading ($S_x(\mu)$) represents the ratio of the signal ($j_x(\mu)$) recorded by the standard detector mounted in sample position when the irradiation monochromator is positioned at wavelength μ, to the signal ($j_r(\mu)$) simultaneously recorded by the reference detector.

X2.2.4 *Viewing Calibration*—Place source of known relative spectral radiance in sample position, and collect viewing calibration readings $S_v(\lambda)$ for all wavelengths λ in the spectral range of the viewing monochromator.

X2.2.4.1 *Viewing Calibration Reading*—The viewing calibration reading ($S_v(\lambda)$) represents the signal ($j_v(\mu,\lambda)$) recorded by the instrument detection system for viewing wavelength λ.

X2.3 *Basic Measurement Equations*—The discrete bispectral radiance factor of the specimen under test is determined by one of the following equations, depending on the calibration approach chosen:

X2.3.1 *Approach (1):*

$$B(\mu,\lambda) \approx \frac{S(\mu,\lambda)}{S_{std}(\mu,\lambda)} \cdot D_{std}(\mu,\lambda) \qquad \text{(X2.1)}$$

X2.3.2 *Approach (2):*

$$B(\mu,\lambda) \approx \frac{S(\mu,\lambda)}{S'_{d2}(\mu)} \cdot \frac{S_m(\mu)}{S_m(\lambda)} \cdot R(\mu) \cdot \frac{L(\lambda)}{L(\mu)} \qquad \text{(X2.2)}$$

where:

$$S'_{d2}(\mu) \equiv \sum_{\lambda=\mu-\Delta\mu}^{\mu+\Delta\mu} S_d(\mu,\lambda) \cdot \frac{S_m(\mu)}{S_m(\lambda)} \frac{\Phi_c(\lambda)}{\Phi_c(\mu)} \qquad \text{(X2.3)}$$

X2.3.3 *Approach (3):*

$$B(\mu,\lambda) \approx \frac{S(\mu,\lambda)}{S'_{d3}(\lambda)} \cdot \frac{S_x(\lambda)}{S_x(\mu)} \cdot R(\lambda) \frac{K(\mu)}{K(\lambda)} \qquad \text{(X2.4)}$$

where:

$$S'_{d3}(\lambda) \equiv \sum_{\mu=\lambda-\Delta\lambda}^{\lambda+\Delta\lambda} S_d(\mu,\lambda) \cdot \frac{S_x(\lambda)}{S_x(\mu)} \frac{K(\mu)}{K(\lambda)} \qquad \text{(X2.5)}$$

X2.3.4 *Approach (4)*—May be implemented in various ways. The equation below represents an approach similar to that described by Zwinkels et al. (**4, 5**):

$$B(\mu,\lambda) \approx \frac{S(\mu,\lambda)}{S'_{d4}(\lambda_0)} \cdot \frac{S_x(\lambda_0)}{S_x(\mu)} \cdot \frac{S_m(\lambda_0)}{S_m(\lambda)} R(\lambda) \cdot \frac{K(\mu)}{K(\lambda_0)} \cdot \frac{L(\lambda)}{L(\lambda_0)} \qquad \text{(X2.6)}$$

where:

$$S'_{d4}(\lambda_0) \equiv \sum_{\mu=\lambda_0-\Delta\lambda}^{\lambda_0+\Delta\lambda} S_d(\mu,\lambda_0) \cdot \frac{S_x(\lambda_0)}{S_x(\mu)} \frac{K(\mu)}{K(\lambda_0)} \qquad \text{(X2.7)}$$

or:

$$S'_{d4}(\lambda_0) \equiv \sum_{\lambda=\lambda_0-\Delta\mu}^{\lambda_0+\Delta\mu} S_d(\lambda_0,\lambda) \cdot \frac{S_m(\lambda_0)}{S_m(\lambda)} \frac{\Phi_c(\lambda)}{\Phi_c(\lambda_0)} \qquad \text{(X2.8)}$$

REFERENCES

(1) Donaldson, R., "Spectrophotometry of fluorescent pigments," British Journal of Applied Physics, 5, 210 (1954).

(2) Mielenz, K.D., "Photoluminescence Spectrometry," in *Measurement of Photoluminescence*, K.D. Mielenz, ed., Vol. 3 of Optical Radiation Measurements (Academic Press, Inc. New York, 1982).

(3) Williams, D.C., "Fluorescent Standards for Surface Color," *NPL Report QU 111*, National Physical Laboratory, Division of Quantum Metrology, (NPL, August 1995).

(4) Zwinkels, J.C., and Gignac, D.S., "Development of a new reference spectrofluorimeter," in Spectrophotometry, Luminescence and Colour; Science and Compliance, C. Burgess and D.G. Jones, eds. (Elsevier, Amsterdam, 1995).

(5) Zwinkels, J.C., Gignac, D.S., Nevins, M., Powell, I., and Bewsher, A., "Design and testing of a two-monochromator reference spectrofluorimeter for high-accuracy total radiance factor measurements," Applied Optics, Vol. 36, No. 4, 892 (1997).

(6) Leland, J., Johnson, N., and Arecchi, A., "Principles of Bispectral Fluorescence Colorimetry," *Photometric Engineering of Sources and Systems*, Angelo V. Arecchi, Editor, Proceedings of SPIE Vol. 3140, 76-87 (1997).

(7) Van den Akker, J.A., "Wave-length Calibration of Spectrophotometers," Journal, Optical Society of America, Vol. 33, 1943, pp.257-259.

(8) "New Series of Ceramic Colour Standards," Color Research & Application, Vol 9, 1984, pp.119-120.

(9) Gundlach, D., "Bispektrale Lumineszenzmessung mit Kugelgeometrien. Möglich oder nict möglich?" dfwg Report, 1999, Number 2, pp.20-27.

(10) Alman, D.H., and Billmeyer, Jr., F.W., "Integrating-Sphere Errors in the Colorimetry of Fluorescent Materials," Color Research and Application, 1:141-145 (1976).