AMERICAN SOCIETY FOR TESTING AND MATERIALS
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Standard Practice for Color Measurement of Fluorescent Specimens[1]

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INTRODUCTION

The colors of fluorescent specimens should be measured under illuminating and viewing conditions (spectral and geometric) that duplicate those of anticipated use. The measurement of fluorescent specimens is more exacting than that of nonfluorescent specimens because the relative contributions of reflected and fluoresced radiation will vary with the spectral character of the source illuminating the specimen. This places important restrictions on the instrumentation used for measurement. This practice covers the instrumental appearance measurement of fluorescent materials using a one-monochromator spectrophotometer.[2]

1. Scope

1.1 This practice describes procedures for measuring the colors of fluorescent specimens as they would be perceived when illuminated by daylight, and for calculating tristimulus values and chromaticity coordinates for these conditions.

1.2 This practice applies to the use of one-monochromator spectrophotometer employing polychromatic illumination of the specimen and monochromatic detection of the radiant energy.

1.3 This practice can be used to provide specifications for fluorescent colors in either the 1931 or the 1964 CIE system.

1.4 This practice covers only fluorescent specimens that emit visible light. It is not intended for use with other types of luminescent materials such as phosphorescent, chemiluminescent, or electroluminescent.

1.5 *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:*

E 284 Terminology of Appearance[3]

E 308 Practice for Computing the Colors of Objects by Using the CIE System[3]

E 805 Practice for Identification of Instrumental Methods of Color or Color-Difference Measurement of Materials[3]

E 1164 Practice for Obtaining Spectrophotometric Data for Object-Color Evaluation[3]

E 1247 Test Method for Identifying Fluorescence in Object-Color Specimens by Spectrophotometry[3]

E 1349 Test Method for Reflectance Factor and Color by Spectrophotometry Using Bidirectional Geometry[3]

E 1767 Practice for Specifying the Geometry of Observations and Measurements to Characterize the Appearance of Materials[3]

2.2 *CIE Standards:*

CIE Publication No. 15.2, Colorimetry[4]

CIE Publication No. 51, A Method for Assessing the Quality of Daylight Simulators for Colorimetry[4]

CIE Publication No. 76, Intercomparison on Measurement of (Total) Spectral Radiance Factor of Luminescent Specimens[4]

3. Terminology

3.1 The terms and definitions in Terminology E 284 apply to this practice.

3.2 *Definitions:*

3.2.1 *fluorescence, n*—photoluminescence that ceases when excitation ceases.

3.2.1.1 *Discussion*—Fluorescence is distinguished from phosphorescence by a time delay generally less than 10 ns. See **photoluminescence** and **phosphorescence**.

3.2.2 *peak spectral radiance factor,* β_{peak}, *n*—largest measured spectral radiance factor of a specimen.

3.2.3 *source conformance factor, SCF, n*— the square root of the mean square deviation between the relative spectral irradiance distribution curves of an instrument illuminating source measured at the sample port and a specified CIE standard illuminant.

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[1] This practice is under the jurisdiction of ASTM Committee E-12 on Color and Appearance and is the direct responsibility of Subcommittee E12.05 on Fluorescence.

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[2] Measurement of the fluorescent properties of materials for the purpose of chemical analysis is not covered in this practice.

[3] *Annual Book of ASTM Standards*, Vol 06.01.

[4] The CIE documents can be obtained from USNC/CIE Publications, c/o TLA Lighting Consultants, 7 Pond St., Salem MA 01970.

3.2.3.1 *Discussion*—The ultraviolet source conformance factor, SCF_{uv}, is calculated over the range from 300 to 380 nm; the visible source conformance factor, SCF_{vis}, is calculated over the range from 380 to 700 nm.

3.2.4 *ultraviolet-activated fluorescence*, *n*— fluorescence resulting principally from absorption of ultraviolet radiant flux, shorter than 380 nm in wavelength.

3.2.5 *visible-activated fluorescence*, *n*— fluorescence resulting principally from absorption of visible radiant flux, approximately 380 to 780 nm in wavelength.

4. Significance and Use

4.1 This practice describes the color measurement of fluorescent specimens as they would appear when illuminated by CIE Illuminant D65. Since the CIE has not recommended a standard source corresponding to this illuminant, this practice requires that D65 be simulated within specified limits by the spectral power distribution illuminating the specimen.

4.2 This practice applies to the instrumental color measurement of specimens exhibiting fluorescent emission within the visible range. For methods to determine whether specimens exhibit fluorescence, see Test Method E 1247.

4.3 The recommended measurement geometry for this practice is the 45/0[5] (or equivalent 0/45) illuminating and viewing geometry (see Practice E 805 and Test Method E 1349). It is the referee condition for this practice. The use of hemispherical geometry is not recommended. When hemispherical geometry using an integrating sphere is utilized, the light emission from the fluorescent specimen changes the spectral irradiance on the specimen from that of the required D65 **(1,2)**.[6]

4.3.1 The use of hemispherical geometry using an integrating sphere may be permissible if it can be shown that the spectral sphere error is negligible. The spectral sphere error associated with hemispherical geometry decreases as the measurement area relative to the internal area of the sphere is decreased. When the spectral sphere error is negligible, results obtained using hemispherical geometry may for some specimens under specific measurement conditions approach those obtained using 45/0 (0/45) geometry **(2)**.

NOTE 1—In addition to the spectral sphere error, there are also geometric differences between hemispherical geometry using an integrating sphere and 45/0 (0/45) geometry which can affect the measurement result for highly non-Lambertian materials.

4.4 While procedures are available in the literature to correct data obtained when the spectral irradiance on the specimen differs somewhat from that of illuminant D65 **(3, 4)**, the calculation and use of corrected spectral radiance factors of fluorescent materials for colorimetric purposes are not addressed by this practice.

4.5 When the fluorescent specimen has an angular subtense of <4° at the eye (for example, objects viewed from a distance such as a buoy at sea or a road sign on the roadway), use the CIE 1931 (2°) standard observer. When the fluorescent specimen has an angular subtense of >4° at the eye (for example, a large textile sample observed nearby), use the CIE 1964 (10°) supplementary standard observer.

4.6 While the two-monochromator method **(5,6,7)** is considered the referee procedure, this one-monochromator practice has found significant application for the color measurement of fluorescent specimens.

5. Instrument Requirements

5.1 The color measurement of fluorescent specimens under this practice requires the use of a one-monochromator spectrophotometer meeting the following minimum criteria:

5.1.1 The spectrophotometer shall illuminate the specimen with polychromatic illumination, usually by direct illumination from a daylight simulator.

5.1.2 The monochromator shall be located between the specimen and the detector system.

5.1.3 The wavelength measurement interval should be 10 nm or less. See Practice E 308 and Practice E 1164 for spectral bandpass recommendations.

5.2 *Requirements for CIE illuminant D65 Simulation*—The instrument source shall simulate CIE Illuminant D65, with a relative spectral irradiance distribution at the specimen port closely duplicating that of D65. Two alternative criteria are provided to determine whether the D65 simulation is adequate:

5.2.1 The ultraviolet source conformance factor, SCF_{uv}, over the range from 300 to 380 nm shall be less than 15.0 and the visible source conformance factor, SCF_{vis} over the range from 380 to 700 nm shall be less than 10.0 (see Appendix X1 for calculation of SCF_{uv} and SCF_{vis}).

$$SCF = \left[\frac{1}{n}\sum_{\lambda(1)}^{\lambda(2)} (S_{D65} - S_{INST})^2\right]^{1/2} \tag{1}$$

where:

λ **(1)** = minimum wavelength of the range evaluated,
λ**(2)** = maximum wavelength of the range evaluated,
n = number of sample points,
S_{D65} = relative spectral irradiance of CIE illuminant D65, normalized to 100.0 at 560 nm, and
S_{INST} = relative spectral irradiance incident on the specimen, determined by spectroradiometry and similarly normalized to 100.0 at 560 nm.

5.2.2 The D65 simulator shall have a rating not worse than BB (CIELAB) relative to D65 as determined by the method of CIE Publication No. 51.

5.2.3 In contrast to ultraviolet-activated fluorescent specimens, the ultraviolet content of the illuminant does not play a significant role in the color measurement of visible-activated fluorescent specimens **(8)**. For the instrumental color measurement of visible-activated fluorescent specimens, the instrument source shall only be required to have a SCF_{vis} less than 10.0, or a rating not worse than B (CIELAB) in the visible range relative to D65 as determined by the method of CIE Publication No. 51.

5.3 The instrument must be capable of producing as output spectral radiance factor as a function of wavelength over the range from 400 to 700 nm in increments of 10 nm or less. The preferred range is from 380 to 780 nm.

[5] The illuminating and viewing geometry denoted by 45/0 (0/45) in this practice is equivalent to the 45:0 (0:45) notation in Practice E 1767. The use of Practice E 1767 notation is recommended for the complete description of measurement geometry including aperture size, etc.

[6] The boldface numbers in parentheses refer to the list of references at the end of this practice.

5.4 For geometrically sensitive fluorescent specimens, the illuminating and viewing geometry shall consist of direct specimen irradiation by the illuminator system at an angle of 45 ± 2° from the normal, with an aperture angle not exceeding 4°, and viewing at an angle of 0 ± 2° (along the normal) with an aperture angle not exceeding 4° (the combination denoted by 45/0) **(9)** or the equivalent 0/45 geometry.

5.4.1 For specimens known to be relatively insensitive to measurement geometry, the illuminating and viewing geometry should consist of direct specimen irradiation by the illuminator system at an angle of 45 ± 2° from the normal to the specimen surface. The angle between the direction of viewing and the normal to the specimen surface should not exceed 10°. The angle between the axis and any ray of an illuminating beam should not exceed 8°. The same restriction applies to the viewing beam. The equivalent 0/45° geometry is allowed (see Practice E 1164).

6. Procedure

6.1 Operate the spectrophotometer in accordance with Practice E 1164 and Test Method E 1349. This includes mandatory standardization of the following:

6.1.1 Zero setting of the reflectance scale,

6.1.2 Full-scale value of the reflectance scale of the instrument by use of the white standard. Follow the instrument manufacturer's instructions.

6.2 Express spectral radiances obtained as radiance factors relative to the perfect reflecting diffuser assigned a value of 1.000 (100.0 %) at each wavelength.

7. Calculation

7.1 Calculate CIE tristimulus values and chromaticity coordinates for CIE Illuminant D65 and either the CIE 1931 (2°) standard observer or the CIE 1964 (10°) supplementary standard observer (see Practice E 308).

8. Standardization and Verification

8.1 Standardization of zero and full-scale values is required at the time of measurement.

8.2 *System Verification* (see Practice E 1164, Section 9):

8.2.1 Verify the calibration of the wavelength scale (recommended).

8.2.2 The precision and bias of the entire measurement system, including verification of total spectral radiance factors and calculation of CIE tristimulus values, should be determined by periodic measurement of calibrated fluorescent reference materials (recommended). The calibration of these reference materials should be traceable to national standardizing laboratories.

NOTE 2—If retroreflective specimens are to be measured, the set of calibrated reference materials should include appropriate retroreflective product standards.

8.3 The accuracy with which the illuminating source simulates CIE Illuminant D65 must be determined periodically by measurement of the spectral distribution of irradiance at the specimen port of the instrument.

NOTE 3—Possibly the greatest single source of variability in fluorescent color measurement is differences between the spectral distribution of the source illuminating the specimen at the sample port and the specified CIE illuminant.

9. Report

9.1 Report the following information (see Practices E 805 and E 1164):

9.1.1 *Specimen Description*—Include the following:

9.1.1.1 Specimen identification and type, for example whether the sample is opaque, translucent or transparent, a textile or plastic, retroreflective, ultraviolet-activated or visible-activated.

9.1.1.2 *Specimen Substrate*—The instrumental color measurement of specimens that are not opaque can be influenced by the spectral reflectance of the material behind the specimen **(10)**. Specimens are typically measured mounted on the substrate upon which they are to used.

9.1.2 *Instrument Parameters*—Including the following:

9.1.2.1 *Measurement Conditions*—Indicate whether annular, circumferential, or uniplanar measurement conditions.

9.1.2.2 The spectral parameters, including the wavelength range, wavelength measurement interval, and spectral bandpass.

9.1.2.3 The adequacy of the D65 simulation of the instrument source at the sample port as determined in 5.2 of this practice in terms of *SCF*, or CIELAB rating in accordance with the method of Publication CIE No. 51.

9.2 *Measurement Results*:

9.2.1 The CIE tristimulus values (X, Y, Z) or chromaticity coordinates (x, y, Y) for CIE Illuminant D65 for either the CIE 1931 (2°) standard observer or the CIE 1964 (10°) supplementary standard observer.

9.2.2 The wavelength of peak spectral radiance factor from the measured spectral radiance factors obtained.

10. Precision and Bias

10.1 The precision and bias of the procedure in this practice is being determined.

10.2 In the interim, the following assessment of repeatability and reproducibility is provided for illustrative purposes. These results are based on experiments that tested the entire procedure for the color measurement of fluorescent specimens, including the calculation of spectral radiance factors corrected for differences between the spectral distribution of the instrument source and CIE illuminant D65. The calculation and use of corrected spectral radiance factors of fluorescent materials for colorimetric purposes are not addressed by this practice.

10.2.1 *Repeatability*:

10.2.1.1 The short-term repeatability of a single spectrophotometer[7] suitable for use in accordance with this practice was tested by measuring each chromatic fluorescent specimen ten times. The means and standard deviations of the CIE tristimulus values, XYZ are given in Table 1. The standard deviation of the tristimulus values of 10 nonfluorescent colored tiles determined on the same instrument are included for comparison.

10.2.1.2 The same fluorescent and nonfluorescent specimens were measured ten times on the same instrument[7] during

[7] The instrument used to determine repeatability was a spectrophotometer utilizing 45/0 geometry and a xenon arc lamp, suitably filtered. The 1931 (2°) CIE standard observer was used in the calculations.

TABLE 1 Comparison of Short-Term Repeatability for Measurements on Fluorescent and Nonfluorescent Specimens

Specimen		Mean (x) and Standard Deviation (d)		
		X	Y	Z
Yellow-green fluorescent	x	87.06	118.06	5.59
	d	0.30	0.38	0.05
Red-orange fluorescent	x	68.42	33.54	0.35
	d	0.27	0.15	0.01
10 nonfluorescent	d	0.05	0.05	0.04

a one-month period **(11)**. Table 2 gives the results expressed as Mean CIELAB Color Differences from the Mean (MCDM) (see Practice E 308 and CIE Publication No. 15.2) of the earlier set of measurements.

10.2.2 *Reproducibility*—The reproducibility of color measurement of other fluorescent specimens was studied for an international intercomparison (see CIE Publication No. 76). Results from four U.S. laboratories are given in Table 3, expressed as MCDM over all laboratories **(12)**.

TABLE 2 Comparison of Long-Term Repeatability[A] for Measurements on Fluorescent and Nonfluorescent Specimens

Specimen	MCDM
Yellow-green fluorescent	0.28
Red-orange fluorescent	0.28
Mean of 10 nonfluorescent	0.10

[A]Mean of 10 measurements on one instrument over a one-month period.

NOTE 4—The MCDMs of the fluorescent specimens from the intercomparison are 2 to 3 times larger than for the nonfluorescent specimens measured.

11. Keywords

11.1 appearance; color; fluorescence; measurement

TABLE 3 Comparison of Reproducibility Between Four Laboratories for Measurements on Fluorescent and Nonfluorescent Specimens

Specimen	MCDM
White fluorescent 1	2.0
White fluorescent 2	1.9
Green fluorescent	3.2
Yellow-green fluorescent	3.4
Yellow-orange fluorescent	2.7
Red-orange fluorescent	2.3
Red fluorescent	2.6
Five nonfluorescent	1.0

APPENDIX

(Nonmandatory Information)

X1. CALCULATION OF THE SPECTRAL CONFORMANCE FACTORS (SCF) OF A ONE-MONOCHROMATOR SPECTROPHOTOMETER

X1.1 This appendix provides a step-by-step guide for determining the spectral conformance factors SCF_{uv} and SCF_{vis} of a spectrophotometer source using the equation in 5.2.1 and the sample data in Table X1.1 as an example.

X1.2 Procedure

X1.2.1 Measure the spectral irradiance (E_c, W/m^2 nm) of the source at the sample port using a calibrated spectroradiometer equipped with a cosine receptor. Record the source irradiance at 10-nm intervals over the range from 300 to 700 nm. See Table X1.1, Column 2.

X1.2.2 Normalize the spectral distribution of the source to 100.0 at 560 nm using the following equation (see Table X1.1, Column 3):

$$S_{INST} = [E_c(\lambda)/E_c\ (560\ \text{nm})] \times \tag{X1.1}$$

X1.2.3 At each wavelength, calculate the square of the difference between S_{INST} and S_{D65}, the relative spectral distribution of CIE illuminant D65 similarly normalized to 100.0 at 560 nm **(11)** (see Table X1.1, Column 5):

$$(S_{D65} - S_{INST})^2 \tag{X1.2}$$

X1.2.4 *Ultraviolet Source Conformance Factor, SCF_{uv}*—Calculate the SCF_{uv} for the ultraviolet range from 300 to 380 nm in the following manner:

X1.2.4.1 Sum the quantities $(S_{D65} - S_{INST})^2$ over the range from 300 to 380 nm (the sum of Table X1.1, Column 5, Rows 1 to 9 in the example).

X1.2.4.2 Calculate SCF_{uv} where $n = 9$ in accordance with the following equation:

$$SCF_{uv} = \left[\frac{\sum_{300}^{380} (S_{D65} - S_{INST})^2}{9} \right]^{1/2} \tag{X1.3}$$

X1.2.5 *Visible Source Conformance Factor, SCF_{vis}*—Calculate the SCF_{vis} for the visible range from 380 to 700 nm in the following manner:

X1.2.5.1 Sum the quantities $(S_{D65} - S_{INST})^2$ over the range from 380 to 700 nm (the sum of Table X1.1, Column 5, Rows 9 to 41 in the example).

X1.2.5.2 Calculate SCF_{vis} where $n = 33$ in accordance with the following equation:

$$SCF_{vis} = \left[\frac{\sum_{380}^{700} (S_{D65} - S_{INST})^2}{33} \right]^{1/2} \tag{X1.4}$$

X1.2.6 *Calculation Results:*

X1.2.6.1 For the spectrophotometer in the example in Table X1.1:

$$SCF_{uv} = \left[\frac{\sum_{300}^{380} (S_{D65} - S_{INST})^2}{9} \right]^{1/2} = [8867.0/9]^{1/2} = 31.4 \tag{X1.5}$$

TABLE X1.1 Sample Data and Calculation of the SCF of a Spectrophotometer

nm	Irradiance, E_c, W/m^2 nm	$S_{INST}(S_{560} = 100.00)$	S_{D65}	$(S_{D65} - S_{INST})^2$
300	0.0000	0.00	0.03	0.0
310	0.0000	0.00	3.29	10.8
320	0.0000	0.00	20.24	409.7
330	0.0000	0.00	37.05	372.7
340	0.0000	0.00	39.95	596.0
350	0.0002	0.17	44.91	2001.3
360	0.0051	4.44	46.64	1781.0
370	0.0182	15.84	52.09	1314.2
380	0.0350	30.46	49.98	381.2
390	0.0574	49.92	54.65	22.4
400	0.0791	68.81	82.75	194.3
410	0.0974	84.72	91.49	45.8
420	0.1137	98.98	93.43	30.8
430	0.1270	110.49	86.68	567.0
440	0.1364	118.70	104.86	191.5
450	0.1395	121.39	117.01	19.2
460	0.1365	118.74	117.81	0.9
470	0.1318	114.66	114.86	0.0
480	0.1275	110.97	115.92	24.5
490	0.1264	109.98	108.81	1.4
500	0.1237	107.62	109.35	3.0
510	0.1201	104.51	107.80	10.8
520	0.1148	99.93	104.79	23.6
530	0.1123	97.75	107.69	98.7
540	0.1148	99.93	104.41	20.0
550	0.1184	103.04	104.05	1.0
560	0.1149	100.00	100.00	0.0
570	0.1030	89.65	96.33	44.6
580	0.0945	82.25	95.79	183.3
590	0.0943	82.06	88.69	43.9
600	0.0969	84.30	90.01	32.6
610	0.0968	84.25	89.60	28.6
620	0.0936	81.44	87.70	39.2
630	0.0910	79.17	83.29	16.9
640	0.0923	80.32	83.70	11.4
650	0.0959	83.48	80.03	11.9
660	0.0990	86.14	80.21	35.2
670	0.0977	85.06	82.28	7.7
680	0.0924	80.36	78.28	4.3
690	0.0833	72.49	69.72	7.7
700	0.0724	63.01	71.61	74.0

$$SCF_{\text{vis}} = \left[\frac{\sum_{380}^{700} (S_{D65} - S_{INST})^2}{33} \right]^{1/2} = [2177.5/33]^{1/2} = 8.1 \tag{X1.6}$$

X1.2.6.2 Based on the data in Table X1.1, the spectrophotometer in the example meets the source requirement of this practice for specimens having visible-activated fluorescence ($SCF_{\text{vis}} < 10.0$), but does not meet the source requirement for specimens having ultraviolet-activated fluorescence ($SCF_{\text{uv}} < 15.0$ and $SCF_{\text{vis}} < 10.0$).

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