Designation: E810 − 20

# Standard Test Method for Coefficient of Retroreflection of Retroreflective Sheeting Utilizing the Coplanar Geometry[1]

This standard is issued under the fixed designation E810; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This test method describes an instrument measurement of the retroreflective performance of retroreflective sheeting.

1.2 The user of this test method must specify the entrance and observation angles to be used, and may specify the rotation angles.

1.3 This test method is intended as a laboratory test and requires a facility that can be darkened sufficiently so that stray light does not affect the test results. The testing apparatus must be able to achieve the coplanar geometry.

1.4 Portable and bench retroreflection measuring equipment may be used to determine $R_A$ values provided the geometry and appropriate substitution standard reference panels, measured in accordance with this test method, are utilized. In this case the methods of Procedure B in Practice E809 apply. Additional information on the use of portable retroreflectometers may be found in Test Method E1709.

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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E284 Terminology of Appearance

E308 Practice for Computing the Colors of Objects by Using the CIE System

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E808 Practice for Describing Retroreflection

E809 Practice for Measuring Photometric Characteristics of Retroreflectors

E1709 Test Method for Measurement of Retroreflective Signs Using a Portable Retroreflectometer at a 0.2 Degree Observation Angle

2.2 *Other Document:*

CIE Publication No 54 Retroreflection—Definition and Measurement[3]

## 3. Terminology

3.1 The terms and definitions in Terminology E284 and Practice E808 apply to this test method.

3.2 *Definitions:*

3.2.1 *coefficient of retroreflection, $R_A$—of a plane retroreflecting surface*, the ratio of the coefficient of luminous intensity ($R_I$) to the area ($A$), expressed in candelas per lux per square metre ($cd \cdot lx^{-1} \cdot m^{-2}$). $R_A = R_I/A$.

3.2.1.1 *Discussion*—The equivalent inch–pound units for coefficient of retroreflection are candelas per foot-candle per square foot ($cd \cdot fc^{-1} \cdot ft^{-2}$). The SI and inch pound units are numerically equal, because the units of $R_A$ reduce to 1/sr. An equivalent term used for coefficient of retroreflection is specific intensity per unit area, with symbol SIA or the CIE symbol R'. The term coefficient of retroreflection and the symbol $R_A$ along with the SI units of candelas per lux per square meter ($cd \cdot lx^{-1} \cdot m^{-2}$) are recommended by ASTM.

3.2.1.2 *Discussion*—$R_A$ is a useful engineering quantity for determining the photometric performance of such retroreflective surfaces as highway delineators or warning devices. $R_A$ may also be used to determine the minimum area of retroreflective sheeting necessary for a desired level of photometric

[1] This test method is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.10 on Retroreflection.

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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 U.S. National Committee of the CIE (International Commission on Illumination) (http://www.cie-usnc.org) or the CIE (cie.co.at) Webshop.

performance. $R_A$ has been used extensively in the specification of retroreflective sheeting.

3.2.2 *coplanar geometry, n*—retroreflection geometry in which the retroreflector axis, illumination axis, and observation axis lie in one plane.

3.2.2.1 *Discussion*—In the coplanar geometry: the second entrance angle component, $\beta_2$, is equal to 0°; presentation angle, γ, is equal to either 0° or 180°; orientation angle, $\omega_s$, is equal to either the rotation angle, ε, or to ε + 180° or ε − 180°.

3.2.3 *datum axis, n*—a designated half-line from the retroreflector center perpendicular to the retroreflector axis.

3.2.4 *datum mark, n*—an indication on the retroreflector, off the retroreflector axis, that establishes the direction of the datum axis.

3.2.5 *entrance angle, β, n*—the angle between the illumination axis and the retroreflector axis.

3.2.5.1 *Discussion*—The entrance angle is usually no larger than 90°, but for completeness its full range is defined as $0° \leq \beta \leq 180°$. In the CIE (goniometer system) β is resolved into two components $\beta_1$ and $\beta_2$. Since by definition β is always positive, the common practice of referring to the small entrance angles that direct specular reflections away from the photoreceptor as a negative value is deprecated by ASTM. The recommendation is to designate such negative values as belonging to $\beta_1$.

3.2.6 *goniometer, n*—an instrument for measuring or setting angles.

3.2.7 *illumination axis, n*—the half-line from the retroreflector center through the source point.

3.2.8 *observation angle, α, n*—the angle between the illumination axis and the observation axis.

3.2.8.1 *Discussion*—The observation angle is never negative and is almost always less than 10° and usually no more than 2°. The full range is defined as $0° \leq \alpha < 180°$.

3.2.9 *observation axis, n*—the half-line from the retroreflector center through the observation point.

3.2.10 *receiver, n*—the portion of a photometric instrument that receives the viewing beam from the specimen, including a collector such as an integrating sphere, if used, often the monochromator or spectral filters, the detector, and associated optics and electronics.

3.2.11 *retroreflection, n*—reflection in which the reflected rays are preferentially returned in directions close to the opposite of the direction of the incident rays, this property being maintained over wide variations of the direction of the incident rays. [CIE][B]

3.2.12 *retroreflective material, n*—a material that has a thin continuous layer of small retroreflective elements on or very near its exposed surface (for example, retroreflective sheeting, retroreflective fabrics, transfer films, beaded paint, highway surface signs, or pavement striping).

3.2.13 *retroreflective sheeting, n*—a retroreflective material preassembled as a thin film ready for use.

3.2.14 *retroreflector, n*—a reflecting surface or device from which, when directionally irradiated, the reflected rays are preferentially returned in directions close to the opposite of the direction of the incident rays, this property being maintained over wide variations of the direction of the incident rays. [CIE, 1982][B]

3.2.15 *retroreflector axis, n*—a designated half-line from the retroreflector center.

3.2.15.1 *Discussion*—The direction of the retroreflector axis is usually chosen centrally among the intended directions of illumination; for example, the direction of the road on which or with respect to which the retroreflector is intended to be positioned. The retroreflector axis usually coincides with the axis of symmetry of the retroreflector. For retroreflective sheeting the normal to the surface is chosen as the retroreflector axis.

3.2.16 *retroreflector center, n*—the point on or near a retroreflector that is designated to be the location of the device.

3.2.17 *rotation angle, ε, n*—the angle in a plane perpendicular to the retroreflector axis from the observation half-plane to the datum axis, measured counterclockwise from a viewpoint on the retroreflector axis.

3.2.17.1 *Discussion*—Range: $-180° < \varepsilon \leq 180°$. The definition is applicable when entrance angle and viewing angle are less than 90°. More generally, rotation angle is the angle from the positive part of second axis to the datum axis, measured counterclockwise from a viewpoint on the retroreflector axis.

3.2.17.2 *Discussion*—Rotation of the sample about the retroreflector axis while the source and receiver remain fixed in space changes the rotation angle (ε) and the orientation angle ($\omega_s$) equally.

3.2.18 *rotationally uniform, adj*—having substantially constant $R_A$, when rotated about the retroreflector axis, while the source, receiver, retroreflector center and retroreflector axis all remain in a fixed spatial relation.

3.2.18.1 *Discussion*—The degree of rotational uniformity can be specified numerically.

3.2.19 *source, n*—an object that produces light or other radiant flux.

## 4. Summary of Test Method

4.1 This test method involves the use of a light projector source, a receiver, a device to position the receiver with respect to the source and a test specimen holder in a suitable darkened area. The specimen holder is separated from the light source by 15 m.

4.2 The general procedure involved is to determine the ratio of the light retroreflected from the test surface to that incident on the test surface.

4.3 The photometric quantity, coefficient of retroreflection, is calculated from these measurements.

## 5. Significance and Use

5.1 Measurements made by this test method are related to visual observations of retroreflective sheeting as seen by the human eye when illuminated by tungsten-filament light sources such as a motor vehicle headlamp.

5.2 The values determined relate to the visual effects for a given geometric configuration as specified by the user of the test method. This test method has been found useful for tests at observation angles between 0.1 and 2.0° (observation angles between 0.1° and 0.2° may be achieved by careful design of source and receiver aperture configuration), and at entrance angles up to 60°. It has been used to determine coefficient of retroreflection values as low as 0.1 $cd \cdot lx^{-1} \cdot m^{-2}$, but for values less than 1 $cd \cdot lx^{-1} \cdot m^{-2}$ special attention must be given to the responsivity of the receiver and to the elimination of very small amounts of stray light.

## 6. Apparatus

6.1 *Light Source*—The light source shall be of the projector type and shall meet the following requirements (an illuminance at the 15 m specimen distance of about 10 lx is commonly available within these restrictions):

6.1.1 The spectral energy distribution of the source shall be proportional to CIE standard Source A (a correlated color temperature of 2856 K, see Practice E308). The projection lamp together with the projection optics shall be operated such that it illuminates the test specimen with this spectral power distribution.

6.1.2 An unpolarizing light source shall be used.

6.1.3 The source aperture shall be a standard circular aperture as defined in Practice E809. For measurements at observation angles (α) of $0.2° \leq \alpha \leq 2.0°$, the exit aperture of the source shall be uniformly radiant, circular and 26 mm (±2 mm) in diameter. This corresponds to 0.1° angular aperture at 15 m test distance. For measurements at observation angles (α) of $0.1° \leq \alpha < 0.2°$, the exit aperture of the source shall be uniformly radiant, circular and 13 mm (±1 mm) in diameter. This corresponds to 0.05° angular aperture at 15 m test distance.

6.1.4 The illumination at the sample produced by the projector shall be such that the test specimen and only a minimum of the background is illuminated. This is commonly accomplished by placing a restrictive aperture in the projector slide port.

6.1.5 The source shall be regulated such that the illuminance at the test surface does not change by more than ±1 % for the duration of the test.

6.1.6 The illuminance produced on the sample surface shall be uniform within ±5 % of the average illuminance normal to the source at the distance of 15 m.

6.2 *Receiver*—The receiver shall meet the requirements that follow. (In this test, for 10 lx incident upon a 1 $cd \cdot lx^{-1} \cdot m^{-2}$ retroreflective sheeting test specimen with area of 0.04 $m^2$, the incident normal illuminance at the receiver will be about $1.8 \times 10^{-3}$ lx).

6.2.1 The responsivity and range of the receiver shall be sufficient so that readings of both the incident normal illuminance (at the specimen) and the retroreflected light at the observation position can be measured with a resolution of at least 1 part in 50 on the readout scale.

6.2.2 The spectral responsivity of the receiver shall match that of the 1931 CIE Standard Photopic Observer (see Annex A1 of Practice E809).

6.2.3 The receiver shall be insensitive to the polarization of light.

6.2.4 The linearity of the photometric scale over the range of readings to be taken shall be within ±1 %. Correction factors may be used to ensure a linear response. Linearity verification tests must be made utilizing the entire receiver readout device including the detector, load, range selection system and readout display device.

6.2.5 The stability of the receiver shall be such that readings from a constant source do not vary any more than 1 % for the duration of the test.

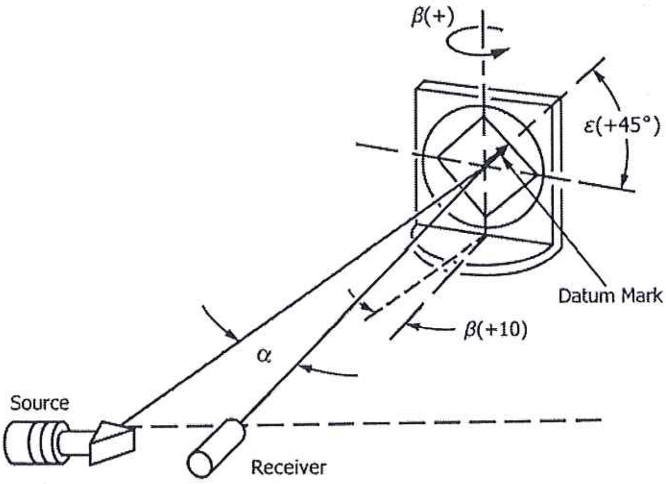
6.2.6 The field of view shall be limited by use of light baffles or a field aperture on the instrument so that the entire test sample is fully within the field of view, rejecting stray light as much as practical. A background light level $m_b$ less than 5 % of the smallest $m_1$ reading is acceptable.

6.2.7 The receiver aperture shall be a standard circular aperture as defined in Practice E809. For measurements at observation angles (α) of $0.2° \leq \alpha \leq 2.0°$, the receiver shall be provided with an entrance aperture 26 mm (±2 mm) in diameter. This corresponds to 0.1° angular aperture at 15 m test distance. For measurements at observation angles (α) of $0.1° \leq \alpha < 0.2°$, the receiver shall be provided with an entrance aperture 13 mm (±1 mm) in diameter. This corresponds to a 0.05° angular aperture at 15 m test distance. The size of the entrance aperture stop must be small so that the receiver may be positioned physically close to the source exit aperture without shadowing any of the illuminating light beam.

6.3 *Test Specimen Goniometer (Test Specimen Holder)*—The specimen holder must hold a 200 mm square specimen and meet the following requirements (see Fig. 1):

6.3.1 A means must be provided to rotate the specimen on an axis contained in the plane of the specimen surface if several entrance angles are to be used.

6.3.1.1 The entrance angle component $\beta_1$ is used to set the goniometer when no specific component is specified (see Practice E808).




NOTE 1—This view shows the source-receiver in a horizontal plane and the entrance angle $\beta$ ( = $\beta_1$) as a rotation about a vertical axis. The rotation angle ε is shown at +45° for illustration purposes— default position is ε = 0°.

**FIG. 1 Pictorial View of a Goniometer—Specimen Holder Assembly**

6.3.2 The specimen surface must be positionable so that the entrance angle is accurate to within 0.5 % of its complement (that is, for a 30° entrance angle this angle must be accurately set to ±0.005 × 60° = ±0.3°). This is obtainable by providing an accurate optical means to align the test surface to the " 0 degree" entrance angle and then adjusting the angular setting (within the required tolerance).

6.3.3 The specimen holder must be provided with a means of eliminating reflections from the edges of the specimen and the holder itself must be nonreflective (usually painted with a flat black paint).

6.3.4 The specimen holder should be constructed such that the receiver can easily be substituted for the specimen (required when incident light measurements are taken).

6.4 *Observer Goniometer (Device for Receiver/Light Source Separation)*—A device (sometimes called an observation angle positioner) must be provided to adequately support and separate the receiver from the source at the observation position. It must allow the observation angle to be varied (see Fig. 2). The usual range is at least 0.2° to 2.0°.

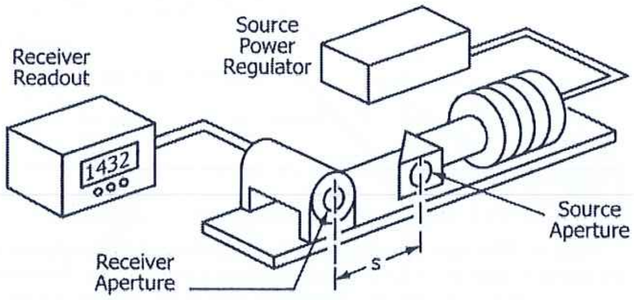
6.4.1 The accuracy of separation of the source exit aperture from the receiver entrance aperture is dependent on the test sample. For most materials, a positioning accuracy of ±0.1 mm (or ±0.5 % of the receiver angular subtense at 15 m distance) is adequate. A common method of fixing this distance is to provide a bar with holes machined in it at separations corresponding to the desired observation angles.

6.4.2 In this test method the minimum practical observation angle is approximately 0.2° using a receiver with an entrance aperture 26 mm (±2 mm) in diameter. If an observation angle (α) of $0.1° \leq \alpha < 0.2°$ is to be used, a smaller aperture is needed as explained in 6.2.7.

6.5 *Photometric Range*—Sufficient working space is required so that the projector and sample can be separated by a 15 m distance.

6.5.1 The stray light in this facility must be such that it does not appreciably influence the test results. Flat black paint, black curtains, black tape and other means shall be used to eliminate unwanted light.

6.5.2 A measuring system must be provided in the photometric range to measure the 15 m test distance (from the retroreflector center to the receiver entrance aperture) accurately to ±0.01 m.




NOTE 1—The distance *s* is adjusted to correspond to the desired observation angle.

**FIG. 2 Pictorial View of Observation Angle Positioning Device**

## 7. Sampling

7.1 The sampling procedure used for this test method shall be such that the test material is representative of the roll or batch.

7.2 When a roll of retroreflective sheeting is tested, at least three 0.2 by 0.2 m specimens shall be taken from the roll which are representative of crossweb and downweb variations if any. The average value of these three specimens will be reported. One method of meeting this requirement is to take three specimens—left, center, and right—diagonally across the roll.

7.2.1 If there is no datum mark already on the material and if the leading edge of the roll is not already indicated on the cut sample, then a datum mark should be made on the back of the sample at the time of cutting to indicate the leading edge of the roll. If not otherwise agreed, this datum mark shall indicate 0° rotation angle for the test.

7.2.2 If a datum mark is already indicated on the material, this mark shall be used to orient the material for test as in 10.7.

7.3 When sampling a number of cut sheets of material, a random selection procedure will be used to ensure the sample is representative of the lot. At least three 0.2 by 0.2 m specimens will be selected and the average value reported.

7.4 When the material to be tested is smaller than 0.2 by 0.2 m in any dimension, the 0.2 by 0.2 m test specimen shall be obtained by piecing several small uniformly retroreflective parts together, with identical orientation, to form the required 0.2 by 0.2 m size test specimen.

## 8. Test Specimen and Sample

8.1 The test specimen in this procedure shall be 200 ± 100 mm by 200 ± 100 mm in size.

8.1.1 *Discussion*—The 200 mm square specimen with an area of 0.04 $m^2$ is suitable for most testing and convenient for storing and handling. Historically a 300 mm square specimen (1 $ft^2$) has been used but this large a specimen can be clumsy to handle and does not significantly improve test accuracy. Specimens 100 mm square have been successfully used with modern receiver systems.

8.2 The specimen, when tested, shall be flat. This can be accomplished by applying the sample to a flat test panel or by providing a means of keeping the specimen adhered in a flat manner to the sample holder by tape, spray adhesive, mechanical means, or vacuum.

8.3 When it is desired to compare readings or individual panels between laboratories, a retroreflector datum mark should be provided on the sample to permit the same sample orientation between laboratories. This may be done by marking an arrow on the back of the specimen pointing toward the center of one of the 200 m sides. The direction of this arrow commonly corresponds to a "downweb" direction of manufacture.

## 9. Calibration and Standardization

9.1 Prior to performing any tests by this test method, the calibration of the apparatus must be verified.

9.2 The light source must be calibrated to match the spectral distribution of CIE Standard Source A. When the proper voltage or current has been established for this requirement, the values or setting shall be recorded and used during the measurement procedure (see Annex A3 of Practice E809).

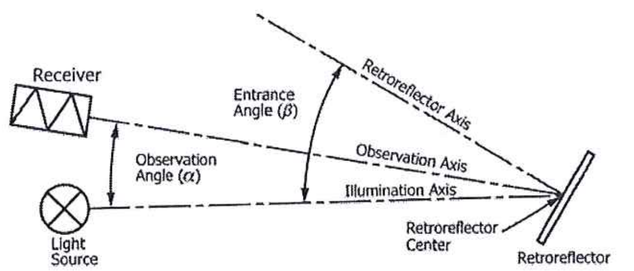
9.3 The linearity of the receiver must be established. Either a set of data indicating that the receiver and readout device combination is linear when used over the range of the readings or a set of correction factors must be established (see Practice E809, Annex A2) that correct the readings for nonlinearity.

9.4 The spectral responsivity of the receiver must be verified to be a sufficiently close match to the 1931 CIE photopic observer, for the color of the products to be measured (see Practice E809, Annex A1).

## 10. Procedure

10.1 Set up the sample holder so that the center of the test specimen will be separated by 15.0 ± 0.2 m from the exit aperture of the light source. Measure the actual distance to ±0.01 m and record this reading as "*d*." Align the sample holder by optical means (auto collimination) to the zero position so that the test surface is perpendicular to the source (that is, 0° entrance angle). In addition, align the sample holder so that the normal to the test surface is in the plane determined by the source exit aperture, receiver entrance aperture, and the sample center, as the entrance angle is changed (this corresponds to setting the second component of the entrance angle $\beta_2 = 0°$ (see Practice E808 and Fig. 3).

10.2 By substituting the light source for the sample (preferred method), measure the illumination at four quadrants representative of equal areas, in the sample position (that is, for a 200 mm square specimen, 50 mm to left and right and 50 mm up and down from sample center) and with the receiver entrance aperture in a plane normal to the source with this plane passing through the sample center position. When making this measurement, the source exit aperture is to be centered in the field of view of the receiver. Record the mean of the four readings as the initial incident illuminance, $m_2$. Individual readings must not vary by more than ±5 % from the mean. Background light from directions other than the projector exit aperture must be negligible (that is, less than 0.1 %) relative to the incident illuminance.




NOTE 1—This figure illustrates a simple test geometry for which the entrance half-plane and the observation half-plane are coplanar. In the CIE (goniometer) system this corresponds to the condition $\beta_2 = 0°$. The entrance angle β and the observation angle α are always positive. The figure does not show the rotation angle ε. In the CIE (goniometer) system, β would be labelled $\beta_1$ and shown with a single arrow ending at the retroreflector axis, and in this figure $\beta_1$ would be positive.

**FIG. 3 Coplanar Test Configuration**

10.3 Return the receiver or light source to the observation position with entrance aperture separated at the appropriate distance from the source exit aperture to obtain the desired observation angle.

10.4 Position the test specimen to the desired entrance angle.

10.4.1 *Discussion*—For this coplanar geometry test method, it is strictly sufficient to specify a single value for the entrance angle. According to the method, that value will be set for entrance angle component $\beta_1$, and entrance angle component $\beta_2$ will be set to zero. ASTM recommends that the test specifier provides explicit values $\beta_1$ and $\beta_2$, even when $\beta_2 = 0°$.

10.5 Position the receiver so that the sample, when it is placed on the holder, will be centered and entirely inside the receiver's field of view. With a black surface substituted for the test specimen, measure the background light level $m_b$.

10.6 Now replace the black surface with the test specimen and record the first retroreflected light reading (see 8.3 when datum mark is used). Make linearity corrections to this reading if required and record as $m_1$.

10.7 Rotation angle. In this test method, the setting of the rotation angle, ε, determines both the rotation angle, ε, and the orientation angle, $\omega_s$ and may influence the results of measurements. The rotation angle is changed by rotating the specimen about its own (retroreflector) axis relative to a fixed starting position. The datum mark may be provided at the time of sampling or may be implied by the production process. In some cases the datum mark is indicated directly on the material at time of manufacture. See Section 7. A 0° rotation angle is with the datum axis in the observation half-plane. The starting position is determined and indicated in Fig. 1 where it is to the right. It can be in any position as determined by the equipment configuration.

10.7.1 If no rotation angle is specified, the measurement is taken at rotation angles of 0° and 90° and the average of these two values is recorded as $m_1$.

10.7.2 If a rotation angle is specified, the measurement is made at that rotation and the value recorded as $m_1$. A specified rotation angle usually implies that the retroreflective material is designed to be applied in a particular orientation.

10.7.3 If the material is known to be rotationally uniform in retroreflectance, for example, glass bead optics, a single measurement of the reflected light $m_1$ may be all that is required. With rotational uniformity, no datum mark is needed.

10.7.4 If no rotation angle is specified, and no means of establishing a datum mark is available as by 7.2.1, it may be necessary to measure the retroreflectance at 15° intervals from 0° to 345° (24 measurements of $m_1$) and either record the average $m_1$ or lowest $m_1$ as required by the end user.

10.7.5 For interlaboratory test comparisons, materials with datum marks have been tested at rotation angles of 0 and 90 degrees and the average of these two values recorded as $m_1$. (See Section 13, which reports results of this test method.)

10.8 Rotate the sample holder to other entrance angles as required and repeat 10.6 and 10.7.

10.9 If additional observation angles are required, move the receiver to the next position desired and repeat 10.6 – 10.8. This will result in a series of $m_b$ and $m_1$ readings for the first specimen. Follow the same procedure for testing additional specimens.

10.10 When the series of retroreflected light readings has been completed, take four additional incident light readings in accordance with 10.2. The average of the four initial readings when compared to the four final readings, should not differ by more than 1 %. Average all eight readings, correct for linearity if required, and record as $m_2$.

10.11 Using measuring instruments suitable to provide a minimum accuracy of ±0.5 % in the result, measure the area of the actual effective retroreflective surface of the test sample in units of square metres. Record this as $A$.

## 11. Calculation

11.1 For each specimen and each combination of entrance and observation angles, calculate the coefficient of retroreflection of the retroreflective sheeting using the following equation:

$$R_A = \left[(m_1 - m_b)d^2/m_2A\right]$$

where:

$R_A$ = coefficient of retroreflection, in candelas per lux per square metre,
$m_b$ = background reading,
$m_1$ = reading of retroreflective test specimen measured at observation position,
$m_2$ = mean reading of source measured normal to the source at the specimen position,
$d$ = test distance, in metres, and
$A$ = area of samples, in square metres.

11.2 Average the $R_A$ values for each set of three specimens representing each roll or batch, at each set of angle combinations. These average values are to be reported, and used to determine conformance to specification requirements.

## 12. Report

12.1 The report shall contain the following:

12.1.1 Sample identification.

12.1.2 Average value of the coefficient of retroreflection for each combination of entrance and observation angles.

12.1.3 Any deviation from the requirements stated in this test method.

## 13. Precision and Bias

13.1 The precision of this test method is based on an interlaboratory study of ASTM E810, Test Method for Coefficient of Retroreflection of Retroreflective Sheeting Utilizing the Coplanar Geometry, conducted in 2019. Each of ten volunteer laboratories were asked to test 24 different materials. Identification of the samples tested is in Table 1. Every "test result" represents an individual determination, and all participants were instructed to report four replicate test results for each material. Practice E691 was followed for the design and analysis of the data; the details are given in ASTM Research Report No. E12-2000.[4]

13.1.1 *Repeatability Limit (r)*—The difference between repetitive results obtained by the same operator in a given laboratory applying the same test method with the same apparatus under constant operating conditions on identical test material within short intervals of time would in the long run, in the normal and correct operation of the test method, exceed the following values only in one case in 20.

13.1.1.1 Repeatability can be interpreted as maximum difference between two results, obtained under repeatability

[4] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:E12-2000. Contact ASTM Customer Service at service@astm.org.

**TABLE 1 Sample Identification**

| Sample | Type | Color | Description |
|---|---|---|---|
| 1 | III | White | Encapsulated Glassbead |
| 2 | III | Yellow | Encapsulated Glassbead |
| 3 | III | Orange | Encapsulated Glassbead |
| 4 | III | Green | Encapsulated Glassbead |
| 5 | III | Red | Encapsulated Glassbead |
| 6 | III | Blue | Encapsulated Glassbead |
| 7 | IV | Fl Orange | Microprismatic |
| 8 | IV | Fl Yellow-Green | Microprismatic |
| 9 | IV | White | Microprismatic |
| 10 | IV | White | Microprismatic |
| 11 | IV | Yellow | Microprismatic |
| 12 | IV | Orange | Microprismatic |
| 13 | IV | Green | Microprismatic |
| 14 | IV | Red | Microprismatic |
| 15 | IV | Blue | Microprismatic |
| 16 | XI | White | Microprismatic |
| 17 | XI | Yellow | Microprismatic |
| 18 | XI | Red | Microprismatic |
| 19 | XI | Green | Microprismatic |
| 20 | XI | Blue | Microprismatic |
| 21 | XI | Brown | Microprismatic |
| 22 | XI | Fl Orange | Microprismatic |
| 23 | XI | Fl Yellow | Microprismatic |
| 24 | XI | Fl Yellow-Green | Microprismatic |

conditions, that is accepted as plausible due to random causes under normal and correct operation of the test method.

13.1.1.2 Repeatability limits are listed in Tables 2-19.

13.1.2 *Reproducibility Limit (R)*—The difference between two single and independent results obtained by different operators applying the same test method in different laboratories using different apparatus on identical test material would, in the long run, in the normal and correct operation of the test method, exceed the following values only in one case in 20.

13.1.2.1 Reproducibility can be interpreted as maximum difference between two results, obtained under reproducibility conditions, that is accepted as plausible due to random causes under normal and correct operation of the test method.

13.1.2.2 Reproducibility limits are listed in Tables 2-19.

13.1.3 The above terms (repeatability limit and reproducibility limit) are used as specified in Practice E177.

13.2 *Bias*—At the time of the study, there was no accepted reference material suitable for determining the bias for this test method, therefore no statement on bias is being made.

13.3 The precision statement was determined through statistical examination of 17 280 results, from ten laboratories, on 24 materials.

13.4 The materials used to generate this precision and bias statement were chosen to evaluate this method. The data is intended to be used only to determine the reproducibility and repeatability of the method. The data is not to be used for establishing material performance or comparison.

**TABLE 2 0.20°,-4°,0° Coefficient of Retroreflection (cd•lx$^{-1}$•m$^{-2}$)**

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 264.778 | 1.997 | 13.323 | 5.591 | 37.306 | 2.1 | 14.1 |
| 2 | 10 | 244.479 | 1.332 | 8.803 | 3.728 | 24.649 | 1.5 | 10.1 |
| 3 | 10 | 130.821 | 0.834 | 3.358 | 2.335 | 9.402 | 1.8 | 7.2 |
| 4 | 10 | 55.791 | 0.302 | 1.745 | 0.845 | 4.887 | 1.5 | 8.8 |
| 5 | 10 | 61.171 | 0.378 | 2.098 | 1.058 | 5.875 | 1.7 | 9.6 |
| 6 | 10 | 20.887 | 0.184 | 1.461 | 0.516 | 4.090 | 2.5 | 19.6 |
| 7 | 10 | 227.148 | 4.417 | 14.122 | 12.368 | 39.541 | 5.4 | 17.4 |
| 8 | 10 | 396.335 | 5.233 | 24.726 | 14.651 | 69.232 | 3.7 | 17.5 |
| 9 | 10 | 598.984 | 8.064 | 28.820 | 22.580 | 80.695 | 3.8 | 13.5 |
| 10 | 10 | 622.929 | 4.579 | 14.447 | 12.822 | 40.450 | 2.1 | 6.5 |
| 11 | 10 | 492.156 | 12.945 | 18.303 | 36.245 | 51.247 | 7.4 | 10.4 |
| 12 | 10 | 287.659 | 4.596 | 7.527 | 12.868 | 21.076 | 4.5 | 7.3 |
| 13 | 10 | 125.378 | 3.585 | 4.379 | 10.037 | 12.260 | 8.0 | 9.8 |
| 14 | 10 | 182.651 | 1.951 | 4.229 | 5.462 | 11.842 | 3.0 | 6.5 |
| 15 | 10 | 80.010 | 1.624 | 3.657 | 4.547 | 10.241 | 5.7 | 12.8 |
| 16 | 10 | 964.280 | 6.999 | 23.030 | 19.598 | 64.483 | 2.0 | 6.7 |
| 17 | 10 | 808.027 | 7.243 | 18.266 | 20.280 | 51.145 | 2.5 | 6.3 |
| 18 | 10 | 217.363 | 2.417 | 6.078 | 6.769 | 17.017 | 3.1 | 7.8 |
| 19 | 10 | 167.047 | 4.209 | 4.447 | 11.786 | 12.452 | 7.1 | 7.5 |
| 20 | 10 | 84.614 | 1.214 | 3.248 | 3.398 | 9.094 | 4.0 | 10.7 |
| 21 | 10 | 46.065 | 0.818 | 1.683 | 2.292 | 4.713 | 5.0 | 10.2 |
| 22 | 10 | 386.042 | 6.523 | 13.625 | 18.266 | 38.150 | 4.7 | 9.9 |
| 23 | 10 | 664.920 | 4.368 | 15.149 | 12.230 | 42.418 | 1.8 | 6.4 |
| 24 | 10 | 872.579 | 5.257 | 17.459 | 14.718 | 48.886 | 1.7 | 5.6 |

[A] The average of the laboratories' calculated averages.

TABLE 3 0.20°,-4°,90° Coefficient of Retroreflection (cd•lx$^{-1}$•m$^{-2}$)

| Material | Number of Laboratories<br>n | Average[A]<br>$\bar{x}$ | Repeatability Standard Deviation<br>$s_r$ | Reproducibility Standard Deviation<br>$s_R$ | Repeatability Limit<br>r | Reproducibility Limit<br>R | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 262.416 | 2.037 | 14.278 | 5.703 | 39.978 | 2.2 | 15.2 |
| 2 | 10 | 242.777 | 1.589 | 8.914 | 4.450 | 24.958 | 1.8 | 10.3 |
| 3 | 10 | 128.351 | 1.733 | 4.482 | 4.851 | 12.548 | 3.8 | 9.8 |
| 4 | 10 | 55.576 | 0.353 | 1.858 | 0.989 | 5.203 | 1.8 | 9.4 |
| 5 | 10 | 60.873 | 0.350 | 2.040 | 0.980 | 5.712 | 1.6 | 9.4 |
| 6 | 10 | 20.143 | 0.187 | 1.547 | 0.523 | 4.330 | 2.6 | 21.5 |
| 7 | 10 | 243.385 | 5.110 | 8.106 | 14.309 | 22.696 | 5.9 | 9.3 |
| 8 | 10 | 471.572 | 6.608 | 17.083 | 18.504 | 47.833 | 3.9 | 10.1 |
| 9 | 10 | 618.617 | 9.661 | 12.520 | 27.052 | 35.057 | 4.4 | 5.7 |
| 10 | 10 | 608.390 | 5.288 | 15.288 | 14.806 | 42.807 | 2.4 | 7.0 |
| 11 | 10 | 473.126 | 5.692 | 14.696 | 15.938 | 41.148 | 3.4 | 8.7 |
| 12 | 10 | 270.227 | 5.175 | 8.759 | 14.489 | 24.524 | 5.4 | 9.1 |
| 13 | 10 | 124.034 | 3.292 | 3.549 | 9.217 | 9.938 | 7.4 | 8.0 |
| 14 | 10 | 175.012 | 2.163 | 4.910 | 6.056 | 13.748 | 3.5 | 7.9 |
| 15 | 10 | 75.744 | 1.137 | 4.454 | 3.182 | 12.472 | 4.2 | 16.5 |
| 16 | 10 | 660.556 | 16.009 | 32.048 | 44.825 | 89.736 | 6.8 | 13.6 |
| 17 | 10 | 506.336 | 10.891 | 23.336 | 30.495 | 65.340 | 6.0 | 12.9 |
| 18 | 10 | 120.280 | 3.173 | 6.521 | 8.883 | 18.259 | 7.4 | 15.2 |
| 19 | 10 | 126.818 | 3.149 | 4.978 | 8.817 | 13.939 | 7.0 | 11.0 |
| 20 | 10 | 68.405 | 1.861 | 4.676 | 5.211 | 13.094 | 7.6 | 19.1 |
| 21 | 10 | 24.738 | 0.562 | 1.822 | 1.574 | 5.103 | 6.4 | 20.6 |
| 22 | 10 | 211.579 | 3.559 | 12.229 | 9.964 | 34.240 | 4.7 | 16.2 |
| 23 | 10 | 410.774 | 9.389 | 20.521 | 26.289 | 57.459 | 6.4 | 14.0 |
| 24 | 10 | 538.104 | 6.855 | 23.679 | 19.195 | 66.302 | 3.6 | 12.3 |

[A] The average of the laboratories' calculated averages.

TABLE 4 0.20°,-4°,0°+90° Coefficient of Retroreflection (cd•lx$^{-1}$•m$^{-2}$)

| Material | Number of Laboratories<br>n | Average[A]<br>$\bar{x}$ | Repeatability Standard Deviation<br>$s_r$ | Reproducibility Standard Deviation<br>$s_R$ | Repeatability Limit<br>r | Reproducibility Limit<br>R | r as % of mean | R as % of mean |
|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 263.597 | 1.907 | 13.714 | 5.339 | 38.400 | 2.0 | 14.6 |
| 2 | 10 | 243.628 | 1.358 | 8.842 | 3.802 | 24.757 | 1.6 | 10.2 |
| 3 | 10 | 129.586 | 1.156 | 3.811 | 3.238 | 10.672 | 2.5 | 8.2 |
| 4 | 10 | 55.684 | 0.305 | 1.793 | 0.853 | 5.020 | 1.5 | 9.0 |
| 5 | 10 | 61.022 | 0.336 | 2.057 | 0.941 | 5.759 | 1.5 | 9.4 |
| 6 | 10 | 20.515 | 0.160 | 1.487 | 0.449 | 4.164 | 2.2 | 20.3 |
| 7 | 10 | 235.266 | 4.617 | 10.773 | 12.928 | 30.166 | 5.5 | 12.8 |
| 8 | 10 | 433.954 | 4.763 | 18.829 | 13.338 | 52.723 | 3.1 | 12.1 |
| 9 | 10 | 608.800 | 8.062 | 17.372 | 22.573 | 48.641 | 3.7 | 8.0 |
| 10 | 10 | 615.659 | 4.525 | 13.817 | 12.669 | 38.689 | 2.1 | 6.3 |
| 11 | 10 | 482.641 | 9.047 | 15.395 | 25.330 | 43.106 | 5.2 | 8.9 |
| 12 | 10 | 278.943 | 4.651 | 7.599 | 13.022 | 21.276 | 4.7 | 7.6 |
| 13 | 10 | 124.706 | 3.413 | 3.829 | 9.557 | 10.721 | 7.7 | 8.6 |
| 14 | 10 | 178.831 | 2.030 | 4.311 | 5.685 | 12.070 | 3.2 | 6.7 |
| 15 | 10 | 77.877 | 1.330 | 4.022 | 3.725 | 11.262 | 4.8 | 14.5 |
| 16 | 10 | 812.418 | 9.884 | 24.645 | 27.674 | 69.005 | 3.4 | 8.5 |
| 17 | 10 | 657.182 | 7.295 | 18.528 | 20.425 | 51.880 | 3.1 | 7.9 |
| 18 | 10 | 168.822 | 1.699 | 5.641 | 4.756 | 15.795 | 2.8 | 9.4 |
| 19 | 10 | 146.933 | 3.510 | 4.002 | 9.828 | 11.205 | 6.7 | 7.6 |
| 20 | 10 | 76.509 | 1.423 | 3.771 | 3.986 | 10.559 | 5.2 | 13.8 |
| 21 | 10 | 35.401 | 0.609 | 1.583 | 1.705 | 4.432 | 4.8 | 12.5 |
| 22 | 10 | 298.811 | 4.585 | 12.116 | 12.839 | 33.924 | 4.3 | 11.4 |
| 23 | 10 | 537.847 | 5.894 | 16.139 | 16.502 | 45.191 | 3.1 | 8.4 |
| 24 | 10 | 705.342 | 4.140 | 18.071 | 11.592 | 50.599 | 1.6 | 7.2 |

[A] The average of the laboratories' calculated averages.

TABLE 5 0.20°,30°,0° Coefficient of Retroreflection (cd•lx⁻¹•m⁻²)

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | x̄ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 258.095 | 4.272 | 13.855 | 11.962 | 38.793 | 4.6 | 15.0 |
| 2 | 10 | 244.584 | 3.123 | 8.754 | 8.744 | 24.510 | 3.6 | 10.0 |
| 3 | 10 | 130.090 | 1.414 | 3.327 | 3.958 | 9.316 | 3.0 | 7.2 |
| 4 | 10 | 51.508 | 0.588 | 2.108 | 1.646 | 5.903 | 3.2 | 11.5 |
| 5 | 10 | 60.463 | 0.730 | 1.903 | 2.043 | 5.327 | 3.4 | 8.8 |
| 6 | 10 | 20.027 | 0.243 | 1.200 | 0.682 | 3.359 | 3.4 | 16.8 |
| 7 | 10 | 118.625 | 6.306 | 9.887 | 17.658 | 27.684 | 14.9 | 23.3 |
| 8 | 10 | 223.956 | 6.201 | 16.538 | 17.363 | 46.305 | 7.8 | 20.7 |
| 9 | 10 | 354.170 | 10.109 | 14.040 | 28.306 | 39.312 | 8.0 | 11.1 |
| 10 | 10 | 248.284 | 8.795 | 15.360 | 24.625 | 43.008 | 9.9 | 17.3 |
| 11 | 10 | 223.970 | 2.946 | 10.223 | 8.248 | 28.623 | 3.7 | 12.8 |
| 12 | 10 | 116.208 | 4.030 | 4.712 | 11.285 | 13.195 | 9.7 | 11.4 |
| 13 | 10 | 55.709 | 2.796 | 3.134 | 7.829 | 8.774 | 14.1 | 15.7 |
| 14 | 10 | 73.198 | 2.688 | 4.339 | 7.526 | 12.148 | 10.3 | 16.6 |
| 15 | 10 | 38.397 | 0.595 | 1.270 | 1.666 | 3.555 | 4.3 | 9.3 |
| 16 | 10 | 429.554 | 15.912 | 16.818 | 44.553 | 47.091 | 10.4 | 11.0 |
| 17 | 10 | 368.348 | 8.286 | 10.273 | 23.202 | 28.764 | 6.3 | 7.8 |
| 18 | 10 | 98.147 | 3.146 | 3.301 | 8.808 | 9.244 | 9.0 | 9.4 |
| 19 | 10 | 71.780 | 3.053 | 3.173 | 8.549 | 8.884 | 11.9 | 12.4 |
| 20 | 10 | 34.270 | 0.459 | 1.155 | 1.286 | 3.233 | 3.8 | 9.4 |
| 21 | 10 | 16.770 | 0.801 | 1.109 | 2.242 | 3.104 | 13.4 | 18.5 |
| 22 | 10 | 180.344 | 7.347 | 8.289 | 20.571 | 23.210 | 11.4 | 12.9 |
| 23 | 10 | 299.918 | 8.275 | 8.876 | 23.170 | 24.853 | 7.7 | 8.3 |
| 24 | 10 | 412.415 | 9.383 | 12.153 | 26.271 | 34.029 | 6.4 | 8.3 |

[A] The average of the laboratories' calculated averages.

TABLE 6 0.20°,30°,90° Coefficient of Retroreflection (cd•lx⁻¹•m⁻²)

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | x̄ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 251.065 | 3.944 | 14.315 | 11.042 | 40.082 | 4.4 | 16.0 |
| 2 | 10 | 244.533 | 4.720 | 9.848 | 13.216 | 27.574 | 5.4 | 11.3 |
| 3 | 10 | 127.718 | 1.874 | 4.258 | 5.247 | 11.921 | 4.1 | 9.3 |
| 4 | 10 | 51.535 | 0.813 | 2.439 | 2.276 | 6.829 | 4.4 | 13.3 |
| 5 | 10 | 60.945 | 0.904 | 2.153 | 2.530 | 6.029 | 4.2 | 9.9 |
| 6 | 10 | 19.849 | 0.288 | 1.459 | 0.805 | 4.084 | 4.1 | 20.6 |
| 7 | 10 | 167.467 | 8.419 | 15.574 | 23.573 | 43.609 | 14.1 | 26.0 |
| 8 | 10 | 336.103 | 15.179 | 23.009 | 42.500 | 64.426 | 12.6 | 19.2 |
| 9 | 10 | 405.022 | 19.434 | 33.344 | 54.415 | 93.363 | 13.4 | 23.1 |
| 10 | 10 | 267.621 | 8.424 | 15.407 | 23.587 | 43.141 | 8.8 | 16.1 |
| 11 | 10 | 185.896 | 6.744 | 11.584 | 18.883 | 32.436 | 10.2 | 17.4 |
| 12 | 10 | 114.547 | 4.470 | 7.173 | 12.516 | 20.083 | 10.9 | 17.5 |
| 13 | 10 | 54.495 | 2.645 | 3.074 | 7.405 | 8.607 | 13.6 | 15.8 |
| 14 | 10 | 68.256 | 3.110 | 3.996 | 8.707 | 11.189 | 12.8 | 16.4 |
| 15 | 10 | 33.048 | 0.839 | 2.089 | 2.349 | 5.848 | 7.1 | 17.7 |
| 16 | 10 | 175.162 | 6.687 | 6.954 | 18.724 | 19.472 | 10.7 | 11.1 |
| 17 | 10 | 147.917 | 4.744 | 5.248 | 13.282 | 14.694 | 9.0 | 9.9 |
| 18 | 10 | 43.065 | 1.460 | 1.511 | 4.087 | 4.232 | 9.5 | 9.8 |
| 19 | 10 | 29.616 | 1.247 | 1.630 | 3.493 | 4.564 | 11.8 | 15.4 |
| 20 | 10 | 12.469 | 0.317 | 0.730 | 0.889 | 2.044 | 7.1 | 16.4 |
| 21 | 10 | 6.575 | 0.294 | 0.473 | 0.822 | 1.325 | 12.5 | 20.2 |
| 22 | 10 | 82.187 | 3.842 | 4.266 | 10.759 | 11.945 | 13.1 | 14.5 |
| 23 | 10 | 112.926 | 3.252 | 3.448 | 9.105 | 9.654 | 8.1 | 8.5 |
| 24 | 10 | 178.333 | 5.778 | 5.947 | 16.178 | 16.653 | 9.1 | 9.3 |

[A] The average of the laboratories' calculated averages.

TABLE 7 0.20°,30°,0°+90° Coefficient of Retroreflection ($cd•lx^{-1}•m^{-2}$)

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 254.580 | 3.962 | 14.051 | 11.094 | 39.341 | 4.4 | 15.5 |
| 2 | 10 | 244.558 | 3.846 | 9.244 | 10.768 | 25.883 | 4.4 | 10.6 |
| 3 | 10 | 128.904 | 1.631 | 3.775 | 4.566 | 10.570 | 3.5 | 8.2 |
| 4 | 10 | 51.521 | 0.698 | 2.270 | 1.954 | 6.355 | 3.8 | 12.3 |
| 5 | 10 | 60.704 | 0.812 | 2.019 | 2.274 | 5.654 | 3.7 | 9.3 |
| 6 | 10 | 19.938 | 0.261 | 1.323 | 0.731 | 3.704 | 3.7 | 18.6 |
| 7 | 10 | 143.046 | 7.158 | 12.330 | 20.044 | 34.524 | 14.0 | 24.1 |
| 8 | 10 | 280.029 | 10.274 | 18.365 | 28.767 | 51.421 | 10.3 | 18.4 |
| 9 | 10 | 379.596 | 12.837 | 19.329 | 35.943 | 54.122 | 9.5 | 14.3 |
| 10 | 10 | 257.953 | 7.781 | 14.127 | 21.787 | 39.554 | 8.4 | 15.3 |
| 11 | 10 | 204.933 | 3.797 | 9.799 | 10.632 | 27.437 | 5.2 | 13.4 |
| 12 | 10 | 115.378 | 4.138 | 5.228 | 11.587 | 14.640 | 10.0 | 12.7 |
| 13 | 10 | 55.102 | 2.690 | 3.011 | 7.532 | 8.431 | 13.7 | 15.3 |
| 14 | 10 | 70.727 | 2.611 | 3.643 | 7.310 | 10.199 | 10.3 | 14.4 |
| 15 | 10 | 35.722 | 0.690 | 1.464 | 1.932 | 4.099 | 5.4 | 11.5 |
| 16 | 10 | 302.358 | 11.082 | 11.502 | 31.031 | 32.204 | 10.3 | 10.7 |
| 17 | 10 | 258.132 | 5.948 | 7.080 | 16.656 | 19.825 | 6.5 | 7.7 |
| 18 | 10 | 70.606 | 2.254 | 2.305 | 6.311 | 6.454 | 8.9 | 9.1 |
| 19 | 10 | 50.698 | 2.123 | 2.201 | 5.944 | 6.162 | 11.7 | 12.2 |
| 20 | 10 | 23.370 | 0.329 | 0.891 | 0.920 | 2.494 | 3.9 | 10.7 |
| 21 | 10 | 11.673 | 0.537 | 0.770 | 1.504 | 2.155 | 12.9 | 18.5 |
| 22 | 10 | 131.266 | 5.514 | 6.071 | 15.439 | 16.999 | 11.8 | 13.0 |
| 23 | 10 | 206.422 | 5.512 | 5.771 | 15.434 | 16.160 | 7.5 | 7.8 |
| 24 | 10 | 295.374 | 7.207 | 8.214 | 20.180 | 22.999 | 6.8 | 7.8 |

[A] The average of the laboratories' calculated averages.

TABLE 8 0.50°,-4°,0° Coefficient of Retroreflection ($cd•lx^{-1}•m^{-2}$)

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 85.660 | 0.809 | 3.840 | 2.266 | 10.753 | 2.6 | 12.6 |
| 2 | 10 | 81.080 | 0.671 | 2.359 | 1.879 | 6.605 | 2.3 | 8.1 |
| 3 | 10 | 45.485 | 0.410 | 0.989 | 1.147 | 2.770 | 2.5 | 6.1 |
| 4 | 10 | 18.856 | 0.239 | 0.658 | 0.669 | 1.842 | 3.5 | 9.8 |
| 5 | 10 | 21.877 | 0.558 | 1.624 | 1.564 | 4.547 | 7.1 | 20.8 |
| 6 | 10 | 4.921 | 0.087 | 0.335 | 0.242 | 0.938 | 4.9 | 19.1 |
| 7 | 10 | 151.413 | 7.323 | 10.276 | 20.505 | 28.772 | 13.5 | 19.0 |
| 8 | 10 | 297.766 | 9.414 | 17.002 | 26.359 | 47.607 | 8.9 | 16.0 |
| 9 | 10 | 475.529 | 10.148 | 16.791 | 28.414 | 47.014 | 6.0 | 9.9 |
| 10 | 10 | 437.683 | 4.934 | 15.702 | 13.815 | 43.966 | 3.2 | 10.0 |
| 11 | 10 | 357.380 | 3.038 | 13.656 | 8.507 | 38.237 | 2.4 | 10.7 |
| 12 | 10 | 209.493 | 3.684 | 8.640 | 10.314 | 24.191 | 4.9 | 11.5 |
| 13 | 10 | 99.683 | 4.582 | 5.054 | 12.830 | 14.150 | 12.9 | 14.2 |
| 14 | 10 | 121.461 | 4.472 | 9.313 | 12.522 | 26.077 | 10.3 | 21.5 |
| 15 | 10 | 63.024 | 0.689 | 2.759 | 1.930 | 7.727 | 3.1 | 12.3 |
| 16 | 10 | 585.611 | 9.158 | 13.039 | 25.643 | 36.510 | 4.4 | 6.2 |
| 17 | 10 | 491.953 | 5.651 | 9.656 | 15.822 | 27.035 | 3.2 | 5.5 |
| 18 | 10 | 126.854 | 4.709 | 8.613 | 13.184 | 24.116 | 10.4 | 19.0 |
| 19 | 10 | 108.229 | 4.556 | 4.789 | 12.758 | 13.410 | 11.8 | 12.4 |
| 20 | 10 | 54.288 | 0.627 | 1.805 | 1.756 | 5.054 | 3.2 | 9.3 |
| 21 | 10 | 31.972 | 0.680 | 1.056 | 1.905 | 2.956 | 6.0 | 9.2 |
| 22 | 10 | 234.111 | 4.312 | 7.505 | 12.075 | 21.015 | 5.2 | 9.0 |
| 23 | 10 | 404.169 | 4.589 | 9.077 | 12.849 | 25.416 | 3.2 | 6.3 |
| 24 | 10 | 546.843 | 5.539 | 11.831 | 15.510 | 33.128 | 2.8 | 6.1 |

[A] The average of the laboratories' calculated averages.

TABLE 9 0.50°,-4°,90° Coefficient of Retroreflection (cd•lx$^{-1}$•m$^{-2}$)

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 82.518 | 1.287 | 4.172 | 3.603 | 11.681 | 4.4 | 14.2 |
| 2 | 10 | 80.568 | 0.707 | 2.410 | 1.981 | 6.749 | 2.5 | 8.4 |
| 3 | 10 | 45.173 | 0.316 | 1.211 | 0.884 | 3.392 | 2.0 | 7.5 |
| 4 | 10 | 18.501 | 0.336 | 0.700 | 0.941 | 1.959 | 5.1 | 10.6 |
| 5 | 10 | 21.718 | 0.209 | 1.719 | 0.586 | 4.813 | 2.7 | 22.2 |
| 6 | 10 | 4.680 | 0.125 | 0.324 | 0.350 | 0.909 | 7.5 | 19.4 |
| 7 | 10 | 161.320 | 3.754 | 12.056 | 10.512 | 33.756 | 6.5 | 20.9 |
| 8 | 10 | 317.709 | 4.042 | 21.357 | 11.316 | 59.798 | 3.6 | 18.8 |
| 9 | 10 | 474.591 | 12.395 | 27.903 | 34.706 | 78.127 | 7.3 | 16.5 |
| 10 | 10 | 451.083 | 5.682 | 13.043 | 15.911 | 36.521 | 3.5 | 8.1 |
| 11 | 10 | 354.296 | 2.698 | 9.875 | 7.555 | 27.650 | 2.1 | 7.8 |
| 12 | 10 | 209.127 | 4.736 | 7.322 | 13.262 | 20.501 | 6.3 | 9.8 |
| 13 | 10 | 98.445 | 4.384 | 4.384 | 12.276 | 12.276 | 12.5 | 12.5 |
| 14 | 10 | 120.952 | 4.159 | 8.076 | 11.646 | 22.611 | 9.6 | 18.7 |
| 15 | 10 | 61.032 | 0.774 | 2.622 | 2.168 | 7.342 | 3.6 | 12.0 |
| 16 | 10 | 486.600 | 7.723 | 11.787 | 21.625 | 33.002 | 4.4 | 6.8 |
| 17 | 10 | 408.542 | 4.943 | 10.762 | 13.840 | 30.134 | 3.4 | 7.4 |
| 18 | 10 | 110.419 | 3.338 | 7.496 | 9.346 | 20.988 | 8.5 | 19.0 |
| 19 | 10 | 88.895 | 3.492 | 3.492 | 9.778 | 9.778 | 11.0 | 11.0 |
| 20 | 10 | 46.930 | 0.609 | 2.565 | 1.705 | 7.183 | 3.6 | 15.3 |
| 21 | 10 | 25.224 | 0.632 | 1.159 | 1.770 | 3.246 | 7.0 | 12.9 |
| 22 | 10 | 187.194 | 4.224 | 7.994 | 11.828 | 22.383 | 6.3 | 12.0 |
| 23 | 10 | 321.567 | 4.255 | 8.390 | 11.915 | 23.493 | 3.7 | 7.3 |
| 24 | 10 | 428.033 | 3.239 | 10.956 | 9.070 | 30.677 | 2.1 | 7.2 |

[A] The average of the laboratories' calculated averages.

TABLE 10 0.50°,-4°,0°+90° Coefficient of Retroreflection (cd•lx$^{-1}$•m$^{-2}$)

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 84.089 | 0.822 | 3.944 | 2.302 | 11.042 | 2.7 | 13.1 |
| 2 | 10 | 80.824 | 0.631 | 2.368 | 1.766 | 6.629 | 2.2 | 8.2 |
| 3 | 10 | 45.329 | 0.342 | 1.083 | 0.959 | 3.033 | 2.1 | 6.7 |
| 4 | 10 | 18.678 | 0.232 | 0.653 | 0.650 | 1.827 | 3.5 | 9.8 |
| 5 | 10 | 21.797 | 0.345 | 1.651 | 0.966 | 4.623 | 4.4 | 21.2 |
| 6 | 10 | 4.800 | 0.096 | 0.323 | 0.268 | 0.903 | 5.6 | 18.8 |
| 7 | 10 | 156.366 | 4.408 | 10.331 | 12.342 | 28.927 | 7.9 | 18.5 |
| 8 | 10 | 307.738 | 5.286 | 17.656 | 14.802 | 49.436 | 4.8 | 16.1 |
| 9 | 10 | 475.060 | 8.028 | 19.311 | 22.479 | 54.072 | 4.7 | 11.4 |
| 10 | 10 | 444.383 | 4.942 | 13.998 | 13.836 | 39.196 | 3.1 | 8.8 |
| 11 | 10 | 355.838 | 2.750 | 11.592 | 7.700 | 32.457 | 2.2 | 9.1 |
| 12 | 10 | 209.310 | 4.150 | 7.847 | 11.621 | 21.971 | 5.6 | 10.5 |
| 13 | 10 | 99.064 | 4.476 | 4.618 | 12.534 | 12.931 | 12.7 | 13.1 |
| 14 | 10 | 121.207 | 4.306 | 8.666 | 12.057 | 24.264 | 9.9 | 20.0 |
| 15 | 10 | 62.028 | 0.713 | 2.658 | 1.997 | 7.443 | 3.2 | 12.0 |
| 16 | 10 | 536.106 | 8.150 | 12.041 | 22.821 | 33.716 | 4.3 | 6.3 |
| 17 | 10 | 450.248 | 5.028 | 9.946 | 14.077 | 27.849 | 3.1 | 6.2 |
| 18 | 10 | 118.636 | 4.009 | 8.013 | 11.224 | 22.435 | 9.5 | 18.9 |
| 19 | 10 | 98.562 | 4.020 | 4.030 | 11.256 | 11.283 | 11.4 | 11.4 |
| 20 | 10 | 50.609 | 0.604 | 2.123 | 1.690 | 5.945 | 3.3 | 11.7 |
| 21 | 10 | 28.598 | 0.651 | 1.020 | 1.823 | 2.857 | 6.4 | 10.0 |
| 22 | 10 | 210.652 | 4.243 | 7.662 | 11.882 | 21.455 | 5.6 | 10.2 |
| 23 | 10 | 362.868 | 4.320 | 8.446 | 12.097 | 23.648 | 3.3 | 6.5 |
| 24 | 10 | 487.438 | 3.504 | 10.969 | 9.810 | 30.713 | 2.0 | 6.3 |

[A] The average of the laboratories' calculated averages.

TABLE 11 0.50°,30°,0° Coefficient of Retroreflection ($cd{\cdot}lx^{-1}{\cdot}m^{-2}$)

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 94.678 | 1.625 | 3.620 | 4.549 | 10.137 | 4.8 | 10.7 |
| 2 | 10 | 85.385 | 1.260 | 2.618 | 3.529 | 7.330 | 4.1 | 8.6 |
| 3 | 10 | 46.803 | 0.570 | 1.093 | 1.596 | 3.060 | 3.4 | 6.5 |
| 4 | 10 | 19.348 | 0.228 | 0.704 | 0.638 | 1.972 | 3.3 | 10.2 |
| 5 | 10 | 24.045 | 0.300 | 0.761 | 0.840 | 2.130 | 3.5 | 8.9 |
| 6 | 10 | 6.228 | 0.104 | 0.196 | 0.290 | 0.549 | 4.7 | 8.8 |
| 7 | 10 | 39.252 | 2.141 | 3.115 | 5.994 | 8.723 | 15.3 | 22.2 |
| 8 | 10 | 74.115 | 1.975 | 6.235 | 5.529 | 17.459 | 7.5 | 23.6 |
| 9 | 10 | 124.452 | 5.334 | 6.104 | 14.934 | 17.090 | 12.0 | 13.7 |
| 10 | 10 | 120.643 | 5.326 | 7.875 | 14.912 | 22.051 | 12.4 | 18.3 |
| 11 | 10 | 104.801 | 2.645 | 4.246 | 7.406 | 11.890 | 7.1 | 11.3 |
| 12 | 10 | 58.856 | 2.370 | 2.377 | 6.637 | 6.656 | 11.3 | 11.3 |
| 13 | 10 | 24.506 | 1.474 | 1.651 | 4.128 | 4.622 | 16.8 | 18.9 |
| 14 | 10 | 36.428 | 1.085 | 1.299 | 3.038 | 3.638 | 8.3 | 10.0 |
| 15 | 10 | 15.899 | 0.487 | 0.684 | 1.363 | 1.915 | 8.6 | 12.0 |
| 16 | 10 | 248.228 | 8.971 | 9.232 | 25.118 | 25.851 | 10.1 | 10.4 |
| 17 | 10 | 205.428 | 6.015 | 6.113 | 16.841 | 17.116 | 8.2 | 8.3 |
| 18 | 10 | 50.137 | 1.020 | 1.607 | 2.856 | 4.499 | 5.7 | 9.0 |
| 19 | 10 | 45.801 | 2.341 | 2.341 | 6.555 | 6.555 | 14.3 | 14.3 |
| 20 | 10 | 22.797 | 0.582 | 0.825 | 1.629 | 2.310 | 7.1 | 10.1 |
| 21 | 10 | 9.295 | 0.465 | 0.543 | 1.301 | 1.521 | 14.0 | 16.4 |
| 22 | 10 | 93.620 | 6.247 | 6.285 | 17.492 | 17.599 | 18.7 | 18.8 |
| 23 | 10 | 165.789 | 4.470 | 4.470 | 12.517 | 12.517 | 7.5 | 7.5 |
| 24 | 10 | 230.594 | 5.095 | 5.758 | 14.267 | 16.123 | 6.2 | 7.0 |

[A] The average of the laboratories' calculated averages.

TABLE 12 0.50°,30°,90° Coefficient of Retroreflection ($cd{\cdot}lx^{-1}{\cdot}m^{-2}$)

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 92.355 | 1.890 | 4.129 | 5.291 | 11.561 | 5.7 | 12.5 |
| 2 | 10 | 85.480 | 1.586 | 2.844 | 4.439 | 7.964 | 5.2 | 9.3 |
| 3 | 10 | 46.135 | 0.623 | 1.333 | 1.744 | 3.733 | 3.8 | 8.1 |
| 4 | 10 | 19.294 | 0.283 | 0.756 | 0.794 | 2.117 | 4.1 | 11.0 |
| 5 | 10 | 23.842 | 0.376 | 0.797 | 1.052 | 2.233 | 4.4 | 9.4 |
| 6 | 10 | 6.258 | 0.090 | 0.247 | 0.252 | 0.693 | 4.0 | 11.1 |
| 7 | 10 | 61.602 | 3.310 | 6.198 | 9.269 | 17.355 | 15.0 | 28.2 |
| 8 | 10 | 126.977 | 5.600 | 9.871 | 15.679 | 27.639 | 12.3 | 21.8 |
| 9 | 10 | 132.584 | 6.920 | 10.003 | 19.376 | 28.008 | 14.6 | 21.1 |
| 10 | 10 | 118.451 | 5.938 | 7.099 | 16.625 | 19.878 | 14.0 | 16.8 |
| 11 | 10 | 85.077 | 2.862 | 4.821 | 8.013 | 13.498 | 9.4 | 15.9 |
| 12 | 10 | 48.617 | 2.329 | 2.956 | 6.521 | 8.278 | 13.4 | 17.0 |
| 13 | 10 | 22.705 | 1.342 | 1.490 | 3.759 | 4.171 | 16.6 | 18.4 |
| 14 | 10 | 29.939 | 0.948 | 1.715 | 2.656 | 4.803 | 8.9 | 16.0 |
| 15 | 10 | 12.882 | 0.514 | 0.871 | 1.439 | 2.439 | 11.2 | 18.9 |
| 16 | 10 | 149.625 | 5.738 | 5.854 | 16.068 | 16.391 | 10.7 | 11.0 |
| 17 | 10 | 120.322 | 3.484 | 4.402 | 9.755 | 12.325 | 8.1 | 10.2 |
| 18 | 10 | 31.674 | 0.825 | 1.326 | 2.310 | 3.713 | 7.3 | 11.7 |
| 19 | 10 | 28.394 | 1.430 | 1.617 | 4.005 | 4.529 | 14.1 | 16.0 |
| 20 | 10 | 14.611 | 0.449 | 0.804 | 1.258 | 2.250 | 8.6 | 15.4 |
| 21 | 10 | 6.702 | 0.350 | 0.421 | 0.980 | 1.180 | 14.6 | 17.6 |
| 22 | 10 | 64.072 | 7.317 | 7.317 | 20.488 | 20.488 | 32.0 | 32.0 |
| 23 | 10 | 97.178 | 2.915 | 3.259 | 8.161 | 9.126 | 8.4 | 9.4 |
| 24 | 10 | 146.928 | 4.129 | 5.355 | 11.562 | 14.993 | 7.9 | 10.2 |

[A] The average of the laboratories' calculated averages.

TABLE 13 0.50°,30°,0°+90° Coefficient of Retroreflection (cd•lx$^{-1}$•m$^{-2}$)

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 93.517 | 1.723 | 3.861 | 4.824 | 10.810 | 5.2 | 11.6 |
| 2 | 10 | 85.432 | 1.419 | 2.723 | 3.974 | 7.625 | 4.7 | 8.9 |
| 3 | 10 | 46.469 | 0.595 | 1.206 | 1.665 | 3.378 | 3.6 | 7.3 |
| 4 | 10 | 19.321 | 0.251 | 0.728 | 0.703 | 2.040 | 3.6 | 10.6 |
| 5 | 10 | 23.944 | 0.330 | 0.775 | 0.923 | 2.171 | 3.9 | 9.1 |
| 6 | 10 | 6.243 | 0.095 | 0.217 | 0.267 | 0.609 | 4.3 | 9.8 |
| 7 | 10 | 50.427 | 2.401 | 4.364 | 6.723 | 12.220 | 13.3 | 24.2 |
| 8 | 10 | 100.546 | 3.672 | 7.916 | 10.281 | 22.166 | 10.2 | 22.0 |
| 9 | 10 | 128.518 | 5.243 | 7.288 | 14.680 | 20.407 | 11.4 | 15.9 |
| 10 | 10 | 119.547 | 5.519 | 6.920 | 15.453 | 19.376 | 12.9 | 16.2 |
| 11 | 10 | 94.939 | 2.653 | 4.360 | 7.428 | 12.208 | 7.8 | 12.9 |
| 12 | 10 | 53.737 | 2.319 | 2.368 | 6.494 | 6.631 | 12.1 | 12.3 |
| 13 | 10 | 23.606 | 1.398 | 1.535 | 3.914 | 4.298 | 16.6 | 18.2 |
| 14 | 10 | 33.184 | 0.950 | 1.067 | 2.659 | 2.988 | 8.0 | 9.0 |
| 15 | 10 | 14.390 | 0.483 | 0.736 | 1.351 | 2.062 | 9.4 | 14.3 |
| 16 | 10 | 198.927 | 7.138 | 7.301 | 19.987 | 20.442 | 10.0 | 10.3 |
| 17 | 10 | 162.875 | 4.516 | 4.892 | 12.645 | 13.699 | 7.8 | 8.4 |
| 18 | 10 | 40.906 | 0.883 | 1.385 | 2.472 | 3.878 | 6.0 | 9.5 |
| 19 | 10 | 37.098 | 1.871 | 1.871 | 5.237 | 5.237 | 14.1 | 14.1 |
| 20 | 10 | 18.704 | 0.470 | 0.756 | 1.316 | 2.116 | 7.0 | 11.3 |
| 21 | 10 | 7.999 | 0.402 | 0.457 | 1.124 | 1.279 | 14.1 | 16.0 |
| 22 | 10 | 78.846 | 3.260 | 3.497 | 9.129 | 9.790 | 11.6 | 12.4 |
| 23 | 10 | 131.483 | 3.393 | 3.493 | 9.500 | 9.780 | 7.2 | 7.4 |
| 24 | 10 | 188.761 | 4.359 | 4.966 | 12.205 | 13.906 | 6.5 | 7.4 |

[A] The average of the laboratories' calculated averages.

TABLE 14 1.00°,-4°,0° Coefficient of Retroreflection (cd•lx$^{-1}$•m$^{-2}$)

| Material | Number of Laboratories | Average[A] | Repeatability Standard Deviation | Reproducibility Standard Deviation | Repeatability Limit | Reproducibility Limit | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| | n | $\bar{x}$ | $s_r$ | $s_R$ | r | R | | |
| 1 | 10 | 18.309 | 0.139 | 0.927 | 0.390 | 2.595 | 2.1 | 14.2 |
| 2 | 10 | 17.014 | 0.361 | 0.796 | 1.010 | 2.230 | 5.9 | 13.1 |
| 3 | 10 | 10.955 | 0.083 | 0.383 | 0.232 | 1.072 | 2.1 | 9.8 |
| 4 | 10 | 3.078 | 0.061 | 0.249 | 0.172 | 0.698 | 5.6 | 22.7 |
| 5 | 10 | 5.791 | 0.418 | 0.462 | 1.170 | 1.292 | 20.2 | 22.3 |
| 6 | 10 | 1.837 | 0.099 | 0.331 | 0.278 | 0.926 | 15.1 | 50.4 |
| 7 | 10 | 22.125 | 3.557 | 3.557 | 9.959 | 9.959 | 45.0 | 45.0 |
| 8 | 10 | 61.780 | 2.622 | 2.622 | 7.341 | 7.341 | 11.9 | 11.9 |
| 9 | 10 | 47.068 | 2.096 | 2.103 | 5.868 | 5.888 | 12.5 | 12.5 |
| 10 | 10 | 74.989 | 3.983 | 4.871 | 11.152 | 13.639 | 14.9 | 18.2 |
| 11 | 10 | 78.934 | 3.069 | 3.375 | 8.594 | 9.449 | 10.9 | 12.0 |
| 12 | 10 | 48.693 | 0.863 | 1.793 | 2.416 | 5.022 | 5.0 | 10.3 |
| 13 | 10 | 12.380 | 0.409 | 0.574 | 1.145 | 1.608 | 9.3 | 13.0 |
| 14 | 10 | 28.290 | 0.951 | 1.434 | 2.664 | 4.014 | 9.4 | 14.2 |
| 15 | 10 | 8.830 | 0.353 | 0.732 | 0.990 | 2.050 | 11.2 | 23.2 |
| 16 | 10 | 162.645 | 7.758 | 7.758 | 21.723 | 21.723 | 13.4 | 13.4 |
| 17 | 10 | 132.319 | 4.986 | 4.986 | 13.960 | 13.960 | 10.6 | 10.6 |
| 18 | 10 | 36.796 | 1.146 | 1.152 | 3.208 | 3.225 | 8.7 | 8.8 |
| 19 | 10 | 27.742 | 0.190 | 0.514 | 0.533 | 1.440 | 1.9 | 5.2 |
| 20 | 10 | 14.677 | 0.512 | 0.598 | 1.433 | 1.675 | 9.8 | 11.4 |
| 21 | 10 | 8.712 | 0.096 | 0.456 | 0.268 | 1.278 | 3.1 | 14.7 |
| 22 | 10 | 67.317 | 1.177 | 1.740 | 3.295 | 4.873 | 4.9 | 7.2 |
| 23 | 10 | 110.055 | 4.028 | 4.326 | 11.279 | 12.112 | 10.2 | 11.0 |
| 24 | 10 | 145.594 | 5.297 | 5.482 | 14.832 | 15.350 | 10.2 | 10.5 |

[A] The average of the laboratories' calculated averages.

TABLE 15 1.00°,-4°,90° Coefficient of Retroreflection (cd•lx$^{-1}$•m$^{-2}$)

| Material | Number of Laboratories n | Average[A] $\bar{x}$ | Repeatability Standard Deviation $s_r$ | Reproducibility Standard Deviation $s_R$ | Repeatability Limit r | Reproducibility Limit R | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 18.669 | 0.083 | 0.899 | 0.232 | 2.516 | 1.2 | 13.5 |
| 2 | 10 | 17.752 | 0.088 | 0.754 | 0.246 | 2.111 | 1.4 | 11.9 |
| 3 | 10 | 11.435 | 0.054 | 0.372 | 0.150 | 1.040 | 1.3 | 9.1 |
| 4 | 10 | 3.026 | 0.039 | 0.212 | 0.108 | 0.594 | 3.6 | 19.6 |
| 5 | 10 | 6.056 | 0.429 | 0.447 | 1.200 | 1.253 | 19.8 | 20.7 |
| 6 | 10 | 1.729 | 0.083 | 0.296 | 0.232 | 0.830 | 13.4 | 48.0 |
| 7 | 10 | 33.522 | 9.784 | 9.784 | 27.396 | 27.396 | 81.7 | 81.7 |
| 8 | 10 | 103.453 | 4.249 | 8.832 | 11.897 | 24.730 | 11.5 | 23.9 |
| 9 | 10 | 71.343 | 3.335 | 4.968 | 9.339 | 13.909 | 13.1 | 19.5 |
| 10 | 10 | 78.231 | 3.839 | 4.012 | 10.750 | 11.234 | 13.7 | 14.4 |
| 11 | 10 | 65.023 | 2.592 | 2.802 | 7.258 | 7.845 | 11.2 | 12.1 |
| 12 | 10 | 38.991 | 0.804 | 1.071 | 2.251 | 2.999 | 5.8 | 7.7 |
| 13 | 10 | 12.492 | 0.481 | 0.546 | 1.346 | 1.529 | 10.8 | 12.2 |
| 14 | 10 | 23.825 | 0.896 | 0.896 | 2.508 | 2.508 | 10.5 | 10.5 |
| 15 | 10 | 7.214 | 0.280 | 0.642 | 0.783 | 1.797 | 10.8 | 24.9 |
| 16 | 10 | 157.692 | 7.629 | 7.629 | 21.362 | 21.362 | 13.5 | 13.5 |
| 17 | 10 | 124.916 | 4.787 | 5.828 | 13.402 | 16.318 | 10.7 | 13.1 |
| 18 | 10 | 35.759 | 1.153 | 1.609 | 3.229 | 4.506 | 9.0 | 12.6 |
| 19 | 10 | 26.228 | 0.169 | 0.730 | 0.472 | 2.045 | 1.8 | 7.8 |
| 20 | 10 | 13.871 | 0.463 | 0.633 | 1.296 | 1.774 | 9.3 | 12.8 |
| 21 | 10 | 7.418 | 0.149 | 0.509 | 0.418 | 1.424 | 5.6 | 19.2 |
| 22 | 10 | 59.000 | 1.583 | 2.187 | 4.431 | 6.125 | 7.5 | 10.4 |
| 23 | 10 | 99.340 | 4.761 | 4.761 | 13.332 | 13.332 | 13.4 | 13.4 |
| 24 | 10 | 127.298 | 5.683 | 5.683 | 15.911 | 15.911 | 12.5 | 12.5 |

[A] The average of the laboratories' calculated averages.

TABLE 16 1.00°,-4°,0°+90° Coefficient of Retroreflection (cd•lx$^{-1}$•m$^{-2}$)

| Material | Number of Laboratories n | Average[A] $\bar{x}$ | Repeatability Standard Deviation $s_r$ | Reproducibility Standard Deviation $s_R$ | Repeatability Limit r | Reproducibility Limit R | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 18.489 | 0.088 | 0.905 | 0.246 | 2.535 | 1.3 | 13.7 |
| 2 | 10 | 17.383 | 0.192 | 0.752 | 0.537 | 2.106 | 3.1 | 12.1 |
| 3 | 10 | 11.195 | 0.055 | 0.371 | 0.154 | 1.038 | 1.4 | 9.3 |
| 4 | 10 | 3.052 | 0.049 | 0.230 | 0.136 | 0.644 | 4.5 | 21.1 |
| 5 | 10 | 5.924 | 0.423 | 0.452 | 1.185 | 1.266 | 20.0 | 21.4 |
| 6 | 10 | 1.783 | 0.090 | 0.313 | 0.251 | 0.876 | 14.1 | 49.1 |
| 7 | 10 | 27.823 | 6.199 | 6.199 | 17.358 | 17.358 | 62.4 | 62.4 |
| 8 | 10 | 82.616 | 3.415 | 4.953 | 9.561 | 13.870 | 11.6 | 16.8 |
| 9 | 10 | 59.205 | 2.651 | 3.097 | 7.423 | 8.672 | 12.5 | 14.6 |
| 10 | 10 | 76.610 | 3.849 | 3.849 | 10.778 | 10.778 | 14.1 | 14.1 |
| 11 | 10 | 71.979 | 2.785 | 2.936 | 7.798 | 8.222 | 10.8 | 11.4 |
| 12 | 10 | 43.842 | 0.796 | 1.101 | 2.228 | 3.082 | 5.1 | 7.0 |
| 13 | 10 | 12.436 | 0.438 | 0.514 | 1.226 | 1.440 | 9.9 | 11.6 |
| 14 | 10 | 26.057 | 0.902 | 1.033 | 2.527 | 2.891 | 9.7 | 11.1 |
| 15 | 10 | 8.022 | 0.314 | 0.665 | 0.880 | 1.863 | 11.0 | 23.2 |
| 16 | 10 | 160.169 | 7.655 | 7.655 | 21.434 | 21.434 | 13.4 | 13.4 |
| 17 | 10 | 128.617 | 4.866 | 5.175 | 13.624 | 14.491 | 10.6 | 11.3 |
| 18 | 10 | 36.277 | 1.139 | 1.291 | 3.188 | 3.615 | 8.8 | 10.0 |
| 19 | 10 | 26.985 | 0.166 | 0.531 | 0.465 | 1.488 | 1.7 | 5.5 |
| 20 | 10 | 14.274 | 0.480 | 0.578 | 1.344 | 1.620 | 9.4 | 11.3 |
| 21 | 10 | 8.065 | 0.119 | 0.473 | 0.332 | 1.324 | 4.1 | 16.4 |
| 22 | 10 | 63.159 | 1.366 | 1.941 | 3.824 | 5.435 | 6.1 | 8.6 |
| 23 | 10 | 104.697 | 4.356 | 4.441 | 12.196 | 12.434 | 11.6 | 11.9 |
| 24 | 10 | 136.446 | 5.411 | 5.411 | 15.150 | 15.150 | 11.1 | 11.1 |

[A] The average of the laboratories' calculated averages.

TABLE 17 1.00°,30°,0° Coefficient of Retroreflection ($cd•lx^{-1}•m^{-2}$)

| Material | Number of Laboratories<br>n | Average[A]<br>x̄ | Repeatability Standard Deviation<br>$s_r$ | Reproducibility Standard Deviation<br>$s_R$ | Repeatability Limit<br>r | Reproducibility Limit<br>R | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 16.759 | 0.134 | 0.701 | 0.375 | 1.961 | 2.2 | 11.7 |
| 2 | 10 | 14.883 | 0.134 | 0.568 | 0.374 | 1.590 | 2.5 | 10.7 |
| 3 | 10 | 10.146 | 0.089 | 0.285 | 0.248 | 0.798 | 2.4 | 7.9 |
| 4 | 10 | 2.331 | 0.039 | 0.216 | 0.109 | 0.605 | 4.7 | 26.0 |
| 5 | 10 | 4.949 | 0.041 | 0.207 | 0.116 | 0.580 | 2.3 | 11.7 |
| 6 | 10 | 0.987 | 0.022 | 0.329 | 0.061 | 0.921 | 6.2 | 93.4 |
| 7 | 10 | 13.982 | 0.626 | 1.464 | 1.753 | 4.100 | 12.5 | 29.3 |
| 8 | 10 | 32.780 | 0.715 | 1.418 | 2.002 | 3.971 | 6.1 | 12.1 |
| 9 | 10 | 32.396 | 0.812 | 2.365 | 2.275 | 6.622 | 7.0 | 20.4 |
| 10 | 10 | 27.145 | 1.338 | 2.537 | 3.747 | 7.104 | 13.8 | 26.2 |
| 11 | 10 | 27.737 | 1.932 | 2.869 | 5.411 | 8.032 | 19.5 | 29.0 |
| 12 | 10 | 14.454 | 0.919 | 1.363 | 2.573 | 3.816 | 17.8 | 26.4 |
| 13 | 10 | 5.145 | 0.124 | 0.350 | 0.349 | 0.981 | 6.8 | 19.1 |
| 14 | 10 | 8.932 | 0.861 | 1.360 | 2.411 | 3.807 | 27.0 | 42.6 |
| 15 | 10 | 3.819 | 0.691 | 1.094 | 1.935 | 3.062 | 50.7 | 80.2 |
| 16 | 10 | 92.188 | 4.204 | 4.204 | 11.770 | 11.770 | 12.8 | 12.8 |
| 17 | 10 | 75.895 | 2.162 | 2.405 | 6.053 | 6.733 | 8.0 | 8.9 |
| 18 | 10 | 20.417 | 1.236 | 1.307 | 3.461 | 3.660 | 16.9 | 17.9 |
| 19 | 10 | 13.512 | 0.227 | 0.380 | 0.637 | 1.063 | 4.7 | 7.9 |
| 20 | 10 | 7.154 | 1.031 | 1.477 | 2.887 | 4.136 | 40.3 | 57.8 |
| 21 | 10 | 3.510 | 0.110 | 0.421 | 0.309 | 1.179 | 8.8 | 33.6 |
| 22 | 10 | 33.137 | 1.432 | 1.704 | 4.011 | 4.771 | 12.1 | 14.4 |
| 23 | 10 | 61.413 | 2.085 | 2.085 | 5.838 | 5.838 | 9.5 | 9.5 |
| 24 | 10 | 72.479 | 2.404 | 2.404 | 6.733 | 6.733 | 9.3 | 9.3 |

[A] The average of the laboratories' calculated averages.

TABLE 18 1.00°,30°,90° Coefficient of Retroreflection ($cd•lx^{-1}•m^{-2}$)

| Material | Number of Laboratories<br>n | Average[A]<br>x̄ | Repeatability Standard Deviation<br>$s_r$ | Reproducibility Standard Deviation<br>$s_R$ | Repeatability Limit<br>r | Reproducibility Limit<br>R | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 16.295 | 0.144 | 0.656 | 0.404 | 1.837 | 2.5 | 11.3 |
| 2 | 10 | 15.426 | 0.159 | 0.607 | 0.446 | 1.700 | 2.9 | 11.0 |
| 3 | 10 | 10.071 | 0.111 | 0.319 | 0.311 | 0.893 | 3.1 | 8.9 |
| 4 | 10 | 2.356 | 0.047 | 0.211 | 0.132 | 0.589 | 5.6 | 25.0 |
| 5 | 10 | 4.822 | 0.052 | 0.201 | 0.147 | 0.564 | 3.0 | 11.7 |
| 6 | 10 | 0.960 | 0.037 | 0.298 | 0.103 | 0.833 | 10.7 | 86.8 |
| 7 | 10 | 17.152 | 0.968 | 1.228 | 2.709 | 3.439 | 15.8 | 20.1 |
| 8 | 10 | 44.304 | 1.398 | 2.156 | 3.913 | 6.035 | 8.8 | 13.6 |
| 9 | 10 | 41.342 | 1.960 | 2.813 | 5.487 | 7.877 | 13.3 | 19.1 |
| 10 | 10 | 32.026 | 2.232 | 2.497 | 6.250 | 6.992 | 19.5 | 21.8 |
| 11 | 10 | 21.045 | 0.726 | 2.048 | 2.033 | 5.735 | 9.7 | 27.3 |
| 12 | 10 | 12.623 | 0.893 | 1.149 | 2.500 | 3.218 | 19.8 | 25.5 |
| 13 | 10 | 5.814 | 0.075 | 0.227 | 0.210 | 0.635 | 3.6 | 10.9 |
| 14 | 10 | 8.050 | 0.765 | 1.010 | 2.141 | 2.829 | 26.6 | 35.1 |
| 15 | 10 | 3.579 | 0.682 | 0.996 | 1.909 | 2.789 | 53.3 | 77.9 |
| 16 | 10 | 39.904 | 1.732 | 1.732 | 4.848 | 4.848 | 12.1 | 12.1 |
| 17 | 10 | 33.915 | 1.114 | 1.340 | 3.118 | 3.752 | 9.2 | 11.1 |
| 18 | 10 | 10.463 | 0.592 | 0.768 | 1.658 | 2.149 | 15.8 | 20.5 |
| 19 | 10 | 7.155 | 0.110 | 0.336 | 0.307 | 0.942 | 4.3 | 13.2 |
| 20 | 10 | 4.090 | 0.655 | 0.938 | 1.835 | 2.627 | 44.9 | 64.2 |
| 21 | 10 | 1.911 | 0.050 | 0.273 | 0.139 | 0.765 | 7.3 | 40.0 |
| 22 | 10 | 17.690 | 0.782 | 1.061 | 2.191 | 2.970 | 12.4 | 16.8 |
| 23 | 10 | 25.999 | 0.756 | 1.063 | 2.116 | 2.977 | 8.1 | 11.4 |
| 24 | 10 | 38.980 | 1.495 | 1.595 | 4.186 | 4.467 | 10.7 | 11.5 |

[A] The average of the laboratories' calculated averages.

TABLE 19 1.00°,30°,0°+90° Coefficient of Retroreflection (cd•lx$^{-1}$•m$^{-2}$)

| Material | Number of Laboratories n | Average[A] $\bar{x}$ | Repeatability Standard Deviation $s_r$ | Reproducibility Standard Deviation $s_R$ | Repeatability Limit r | Reproducibility Limit R | r as a % of mean | R as a % of mean |
|---|---|---|---|---|---|---|---|---|
| 1 | 10 | 16.527 | 0.137 | 0.670 | 0.382 | 1.877 | 2.3 | 11.4 |
| 2 | 10 | 15.154 | 0.133 | 0.584 | 0.373 | 1.635 | 2.5 | 10.8 |
| 3 | 10 | 10.109 | 0.097 | 0.300 | 0.270 | 0.840 | 2.7 | 8.3 |
| 4 | 10 | 2.343 | 0.039 | 0.213 | 0.109 | 0.595 | 4.7 | 25.4 |
| 5 | 10 | 4.885 | 0.045 | 0.204 | 0.125 | 0.570 | 2.6 | 11.7 |
| 6 | 10 | 0.974 | 0.026 | 0.313 | 0.073 | 0.876 | 7.5 | 90.0 |
| 7 | 10 | 15.567 | 0.736 | 0.907 | 2.060 | 2.540 | 13.2 | 16.3 |
| 8 | 10 | 38.542 | 0.921 | 1.466 | 2.578 | 4.103 | 6.7 | 10.6 |
| 9 | 10 | 36.869 | 1.144 | 1.482 | 3.203 | 4.149 | 8.7 | 11.3 |
| 10 | 10 | 29.585 | 1.711 | 2.282 | 4.791 | 6.388 | 16.2 | 21.6 |
| 11 | 10 | 24.391 | 1.274 | 2.354 | 3.568 | 6.592 | 14.6 | 27.0 |
| 12 | 10 | 13.538 | 0.869 | 1.198 | 2.433 | 3.355 | 18.0 | 24.8 |
| 13 | 10 | 5.479 | 0.084 | 0.250 | 0.236 | 0.700 | 4.3 | 12.8 |
| 14 | 10 | 8.491 | 0.767 | 1.138 | 2.147 | 3.186 | 25.3 | 37.5 |
| 15 | 10 | 3.699 | 0.685 | 1.036 | 1.917 | 2.902 | 51.8 | 78.5 |
| 16 | 10 | 66.046 | 2.947 | 2.947 | 8.253 | 8.253 | 12.5 | 12.5 |
| 17 | 10 | 54.905 | 1.547 | 1.648 | 4.331 | 4.614 | 7.9 | 8.4 |
| 18 | 10 | 15.440 | 0.913 | 1.026 | 2.555 | 2.874 | 16.6 | 18.6 |
| 19 | 10 | 10.334 | 0.151 | 0.320 | 0.423 | 0.896 | 4.1 | 8.7 |
| 20 | 10 | 5.622 | 0.838 | 1.203 | 2.347 | 3.370 | 41.7 | 59.9 |
| 21 | 10 | 2.711 | 0.078 | 0.341 | 0.217 | 0.955 | 8.0 | 35.2 |
| 22 | 10 | 25.414 | 1.091 | 1.355 | 3.055 | 3.793 | 12.0 | 14.9 |
| 23 | 10 | 43.706 | 1.386 | 1.386 | 3.880 | 3.880 | 8.9 | 8.9 |
| 24 | 10 | 55.730 | 1.922 | 1.922 | 5.382 | 5.382 | 9.7 | 9.7 |

[A] The average of the laboratories' calculated averages.

## 14. Keywords

14.1 coefficient of retroreflection; light—transmission and reflection; retroreflection/retroreflectors; retroreflective sheeting

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*This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.*

Designation: E308 − 22

# Standard Practice for Computing the Colors of Objects by Using the CIE System[1]

This standard is issued under the fixed designation E308; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

*This standard has been approved for use by agencies of the U.S. Department of Defense.*

## INTRODUCTION

Standard tables (Tables 1–4) of color matching functions and illuminant spectral power distributions have since 1931 been defined by the CIE, but the CIE has eschewed the role of preparing tables of tristimulus weighting factors for the convenient calculation of tristimulus values. There have subsequently appeared numerous compilations of tristimulus weighting factors in the literature with disparity of data resulting from, for example, different selections of wavelength intervals and methods of truncating abbreviated wavelength ranges. In 1970, Foster et al. **(1)**[2] proposed conventions to standardize these two features, and Stearns **(2)** published a more complete set of tables. Stearns' work and later publications such as the 1985 revision of E308 have greatly reduced the substantial variations in methods for tristimulus computation that existed several decades ago.

The disparities among earlier tables were largely caused by the introduction of computations based on 20-nm wavelength intervals. With the increasing precision of modern instruments, there is a likelihood of a need for tables for narrower wavelength intervals. Stearns' tables, based on a 10-nm interval, did not allow the derivation of consistent tables with wavelength intervals less than 10 nm. The 1-nm table must be designated the basic table if others with greater wavelength intervals are to have the same white point, and this was the reason for the 1985 revision of E308, resulting in tables that are included in the present revision as Tables 5.

## 1. Scope

1.1 This practice provides the values and practical computation procedures needed to obtain CIE tristimulus values from spectral reflectance, transmittance, or radiance data for object-color specimens.

1.2 Procedures and tables of standard values are given for computing from spectral measurements the CIE tristimulus values $X$, $Y$, $Z$, and chromaticity coordinates $x$, $y$ for the CIE 1931 standard observer and $X_{10}$, $Y_{10}$, $Z_{10}$ and $x_{10}$, $y_{10}$ for the CIE 1964 supplementary standard observer.

1.3 Standard values are included for the spectral power of six CIE standard illuminants and three CIE recommended fluorescent illuminants. Weight sets are included for tristimulus integration of nine standard or recommended CIE LED illuminants combined with the two standard CIE observers.

1.4 Procedures are included for cases in which data are available only in more limited wavelength ranges than those recommended, or for a measurement interval wider than that recommended by the CIE. This practice is applicable to spectral data obtained in accordance with Practice E1164 with 1-, 5-, 10-, or 20-nm measurement interval.

1.5 This practice includes procedures for conversion of results to color spaces that are part of the CIE system, such as CIELAB and CIELUV **(3)**. Equations for calculating color differences in these and other systems are given in Practice D2244.

1.6 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.7 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.8 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the*

[1] This practice is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.04 on Color and Appearance Analysis.

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

*Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[3]

D2244 Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates

E284 Terminology of Appearance

E313 Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Color Coordinates

E1164 Practice for Obtaining Spectrometric Data for Object-Color Evaluation

E2022 Practice for Calculation of Weighting Factors for Tristimulus Integration

E2729 Practice for Rectification of Spectrophotometric Bandpass Differences

2.2 *ANSI Standard:*[4]

PH2.23 Lighting Conditions for Viewing Photographic Color Prints and Transparencies

2.3 *CIE/ISO Standards:*

ISO Standard 11664-1:2007(E)/CIE S 014-1/E:2006 Standard Colorimetric Observers[4,5]

ISO Standard 11664-2:2007(E)/CIE S 014-2/E:2006 Colorimetric Illuminants[4,5]

CIE Standard D 001 Colorimetric Illuminants and Observers (Disk)[5]

2.4 *ASTM Adjuncts:*

Electronic file containing Tables 5[6]

## 3. Terminology

3.1 Definitions of terms in Terminology E284 are applicable to this practice (see also Ref (**4**)).

3.2 *Definitions*—Definitions are listed in dictionary alphabetical order which makes no distinction between capital and lower-case ordering of the letters of the alphabet, and disregards spaces between multiple-word definiens. Otherwise, order is determined by the UTF-8 value of the letter or symbol involved. Definitions that have the same meaning, but are not necessarily word-for-word identities as that contained in the committee terminology document, are notated with the designation of that document after the definition.

3.2.1 *bandpass, adj*—having to do with a passband. **E284**

3.2.2 *bandwidth, n*—the width of a passband at its half-peak transmittance. **E284**

3.2.3 *chromaticity, n*—the color quality of a color stimulus definable by its chromaticity coordinates. **E284**

3.2.4 *chromaticity coordinates, n*—the ratio of each of the tristimulus values of a psychophysical color to the sum of the tristimulus values. **E284**

3.2.4.1 *Discussion*—In the CIE 1931 standard colorimetric system, the chromaticity coordinates are: $x = X/(X + Y + Z)$, $y = Y/(X + Y + Z)$, $z = Z/(X + Y + Z)$; in the CIE 1964 colorimetric system, the same equations apply with all symbols having the subscript 10 (see 3.2.10).

3.2.5 *CIE, n*—the abbreviation for the French title of the International Commission on Illumination, Commission Internationale de l'Éclairage. **E284**

3.2.6 *CIE 1931 (x, y) chromaticity diagram, n*—chromaticity diagram for the CIE 1931 standard observer, in which the CIE 1931 chromaticity coordinates are plotted, with *x* as abscissa and *y* as ordinate. **E284**

3.2.7 *CIE 1931 standard colorimetric system, n*—a system for determining the tristimulus values of any spectral power distribution using the set of reference color stimuli, *X, Y, Z* and the three CIE color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ adopted by the CIE in 1931. **E284**

3.2.8 *CIE 1931 standard observer, n*—ideal colorimetric observer with color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ corresponding to a field of view subtending a 2° angle on the retina; commonly called the "2° standard observer." **E284**

3.2.9 *CIE 1964 ($x_{10}$, $y_{10}$) chromaticity diagram, n*—chromaticity diagram for the CIE 1964 standard observer, in which the CIE 1964 chromaticity coordinates are plotted, with $x_{10}$ as abscissa and $y_{10}$ as ordinate. **E284**

3.2.9.1 *Discussion*—Fig. 1 shows the CIE 1931 and 1964 chromaticity diagrams, including the locations of the spectrum locus and the connecting purple boundary.

3.2.10 *CIE 1964 standard colorimetric system, n*—a system for determining the tristimulus values of any spectral power distribution using the set of reference color stimuli $X_{10}$, $Y_{10}$, $Z_{10}$ and the three CIE color-matching functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$ adopted by the CIE in 1964 (see Note 1). **E284**

NOTE 1—Users should be aware that the CIE 1964 (10°) system and standard observer assume no contribution or constant contribution of rods to vision. Under some circumstances, such as in viewing highly metameric pairs in very low light levels (where the rods are unsaturated), the amount of rod participation can vary between the members of the pair. This is not accounted for by any trichromatic system of colorimetry. The 10° system and observer should be used with caution in such circumstances.

3.2.11 *CIE 1964 standard observer, n*—ideal colorimetric observer with color-matching functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$ corresponding to a field of view subtending a 10° angle on the retina; commonly called the "10° standard observer" (see Note 1). **E284**

3.2.12 *CIE 1976 (u', v') or ($u'_{10}$, $v'_{10}$) chromaticity diagram, n*—the uniform-chromaticity-scale diagram produced by plotting in rectangular coordinates v' against u', quantities defined as follows:

$$u' = 4X/(X + 15Y + 3Z) = 4x/(-2x + 12y + 3) \quad (1)$$

[3] 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.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[5] Available from CIE (International Commission on Illumination), http://www.cie.co.at or http://www.techstreet.com.

[6] Electronically readable tables of tristimulus weight sets are available from ASTM Headquarters. Request Adjunct No. ADJE0308-EA. Originally approved in 2022.

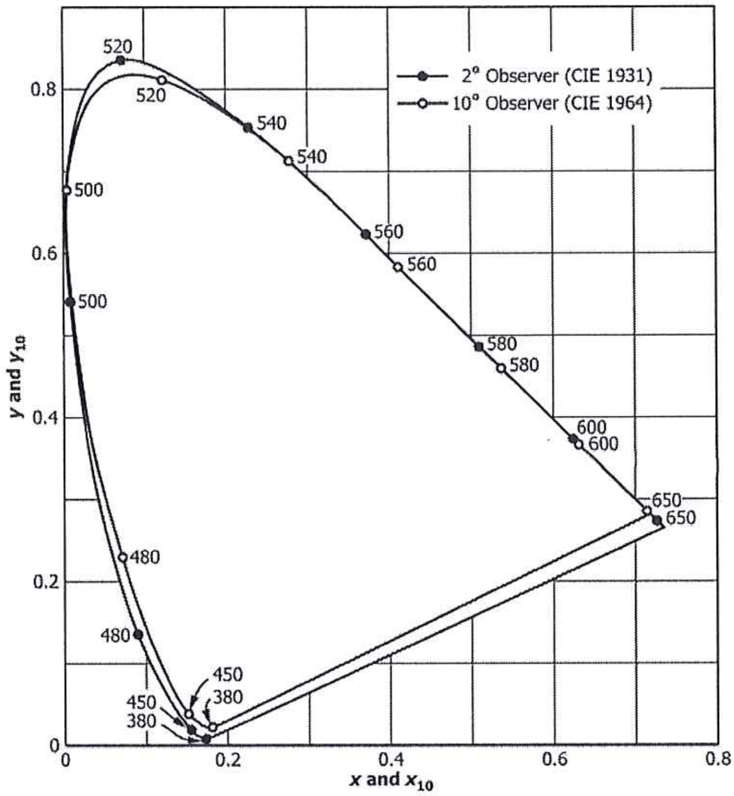


**FIG. 1 The CIE 1931 *x, y* and 1964 $x_{10}$, $y_{10}$ Chromaticity Diagrams Ref (5) (see Note 2)**

$$v' = 9Y/(X + 15Y + 3Z) = 9y/(-2x + 12y+3) \quad (2)$$

for the CIE 1931 standard colorimetric system, or $v'_{10}$ against $u'_{10}$ for the CIE 1964 standard colorimetric system, in which case in the above formulae $X_{10}$, $Y_{10}$, $Z_{10}$ are used instead of X, Y, Z and $x_{10}$, $y_{10}$ instead of x, y. **E284**

3.2.13 *CIE recommended fluorescent illuminants, n*—a set of spectral power distributions of 12 types of fluorescent lamps, the most important of which are *FL2*, representing a cool white fluorescent lamp with correlated color temperature 4200 K, *FL7*, a broad-band (continuous-spectrum) daylight lamp (6500 K), and *FL11*, a narrow-band (line-spectrum) white fluorescent lamp (4000 K).

3.2.14 *CIE standard illuminant A, n*—colorimetric illuminant, representing the full radiator at 2855.6 K, defined by the CIE in terms of a relative spectral power distribution. **E284**

3.2.15 *CIE standard illuminant C, n*—colorimetric illuminant, representing daylight with a correlated color temperature of 6774 K, defined by the CIE in terms of a relative spectral power distribution. **E284**

3.2.16 *CIE standard illuminant $D_{65}$, n*—colorimetric illuminant, representing daylight with a correlated color temperature of 6504 K, defined by the CIE in terms of a relative spectral power distribution. **E284**

3.2.16.1 *Discussion*—Other illuminants of importance defined by the CIE include the daylight illuminants $D_{50}$, $D_{55}$, and $D_{75}$. Illuminant $D_{50}$ is used by the graphic arts industry for viewing colored transparencies and prints (see ANSI PH2.23).

3.2.17 *CIELAB color scales, n*—CIE 1976 $L^*$, $a^*$, $b^*$ opponent-color scales, in which $a^*$ is positive in the red direction and negative in the green direction, and $b^*$ is positive in the yellow direction and negative in the blue direction.

3.2.18 *CIELUV color scales, n*—CIE 1976 $L^*$, $u^*$, $v^*$ opponent-color scales, in which $u^*$ is positive in the red direction and negative in the green direction, and $v^*$ is positive in the yellow direction and negative in the blue direction.

3.2.19 *color, n—of an object,* aspect of object appearance distinct from form, shape, size, position or gloss that depends upon the spectral composition of the incident light, the spectral reflectance, transmittance, or radiance of the object, and the spectral response of the observer, as well as the illuminating and viewing geometry.

3.2.20 *color, n—psychophysical,* characteristics of a color stimulus (that is, light producing a visual sensation of color) denoted by a colorimetric specification with three values, such as tristimulus values.

3.2.21 *color–matching functions, n*—the amounts, in any trichromatic system, of three reference color stimuli needed to match, by additive mixing, monochromatic components of an equal–energy spectrum. **E284**

3.2.22 *fluorescent illuminant, n*—illuminant representing the spectral distribution of the radiation from a specified type of fluorescent lamp. **E284**

3.2.23 *luminous, adj*—weighted according to the spectral luminous efficiency function $V(\lambda)$ of the CIE. **E284**

3.2.24 *opponent-color scales, n*—scales that denote one color by positive scale values, the neutral axis by zero value, and an approximately complementary color by negative scale values, common examples being scales that are positive in the red direction and negative in the green direction, and those that are positive in the yellow direction and negative in the blue direction. **E284**

3.2.25 *passband, n*—a contiguous band of wavelengths in which at least a fraction of the incident light is selectively transmitted by a light-modulating device or medium. **E284**

3.2.26 *spectral, adj—for radiometric quantities,* pertaining to monochromatic radiation at a specified wavelength or, by extension, to radiation within a narrow wavelength band about a specified wavelength. **E284**

3.2.27 *standard illuminant, n*—a luminous flux, specified by its spectral distribution, meeting specifications adopted by a standardizing organization. **E284**

3.2.28 *tristimulus values, n—of a color stimulus,* three amounts of the primary color stimuli required to make an additive match to the color stimulus under consideration. **E284**

3.2.29 *tristimulus weighting factors, $S\bar{x}$, $S\bar{y}$, $S\bar{z}$, n*—factors obtained from products of the spectral power S of an illuminant and the spectral color-matching functions $\bar{x}$, $\bar{y}$, $\bar{z}$ (or $\bar{x}_{10}$, $\bar{y}_{10}$, $\bar{z}_{10}$) of an observer, usually tabulated at wavelength intervals of 10 nm, used to compute tristimulus values by multiplication by the spectral reflectance, transmittance, or radiance (or the corresponding factors) and summation. **E284**

3.2.29.1 *Discussion*—Proper account should be taken of the spectral bandpass of the measuring instrument. See Practice E2729.

## 4. Summary of Practice

4.1 *Selection of Parameters*—The user of this practice must select values of the following parameters:

4.1.1 *Observer*—Select either the CIE 1931 standard colorimetric observer (2° observer) or the CIE 1964 supplementary standard observer (10° observer), tabulated in this practice, CIE Standard S 013 or D 001, or Ref **(3)** (see Note 1).

4.1.2 *Illuminant*—Select one of the CIE standard or recommended illuminants tabulated in this practice, CIE Standard S 014 or D 001, or Ref **(3)** (see 3.2.22).

4.1.3 *Measurement Interval*—Select the measurement interval of the available spectral data. This practice provides for 1-, 5-, 10-, or 20-nm measurement intervals. For best practice the measurement interval should be selected to be as nearly as possible equal to the instrument bandpass.

4.2 *Procedures*—For data obtained at 1- or 5-nm measurement intervals, the procedures of 7.2 should be followed.

4.3 For data obtained at 10- or 20-nm measurement intervals, the tables of tristimulus weighting factors contained in Tables 5 should be used with spectral data that have been corrected for bandpass dependence. For standard methods of making such a correction see Practice E2729.

4.4 A flow chart to ensure the use of proper combinations of data and tables is given in Fig. 2. The procedures of the practice are given in detail in 7.1.

4.5 *Calculations*—CIE tristimulus values *X, Y, Z* or $X_{10}$, $Y_{10}$, $Z_{10}$ are calculated by numerical summation of the products of tristimulus weighting factors for selected illuminants and observers with the reflectance factors (or transmittance or radiance factors) making up the spectral data.

4.6 The tristimulus values so calculated may be further converted to coordinates in a more nearly uniform color space such as CIELAB or CIELUV.

## 5. Significance and Use

5.1 The CIE colorimetric systems provide numerical specifications that are meant to indicate whether or not pairs of color stimuli match when viewed by a CIE standard observer. The CIE color systems are not intended to provide visually uniform scales of color difference or to describe visually perceived color appearances.

5.2 This practice provides for the calculation of tristimulus values *X, Y, Z* and chromaticity coordinates *x, y* that can be used directly for psychophysical color stimulus specification or that can be transformed to nearly visually uniform color scales, such as CIELAB and CIELUV. Uniform color scales are preferred for research, production control, color-difference calculation, color specification, and setting color tolerances. The appearance of a material or an object is not completely specified by the numerical evaluation of its psychophysical color, because appearance can be influenced by other properties such as gloss or texture.

## 6. Procedure

6.1 *Selecting Standard Observer*—When colorimetric results are required that will be compared with previous results obtained for the CIE 1931 standard observer, use the values in Table 1 for that observer. When new results are being computed, consider using the values in Table 2 for the CIE 1964 standard observer, but see Note 1.

6.1.1 Whenever correlation with visual observations using fields of angular subtense between about 1° and about 4° at the eye of the observer is desired, select the CIE 1931 standard colorimetric observer.

6.1.2 Whenever correlation with visual observations using fields of angular subtense greater than 4° at the eye of the observer is desired, select the CIE 1964 supplementary standard colorimetric observer (but see Note 1).

6.2 *Selecting Standard or Recommended Illuminants*—Select illuminants according to the type of light(s) under which objects will be viewed or for which their colors will be specified or evaluated.

6.2.1 When incandescent (tungsten) lamplight is involved, use values for CIE illuminant *A*.

6.2.2 When daylight is involved, use values for CIE illuminant *C* or $D_{65}$.

6.2.3 When fluorescent-lamp illumination is involved, use 4200 K standard cool white (*FL2*) unless results are desired for 6500 K broad-band daylight (*FL7*) or 4000 K narrow-band white (*FL11*) fluorescent illumination.

6.3 *Selecting the Measurement Interval*—For greater accuracy select the 5-nm measurement interval over the 10-nm

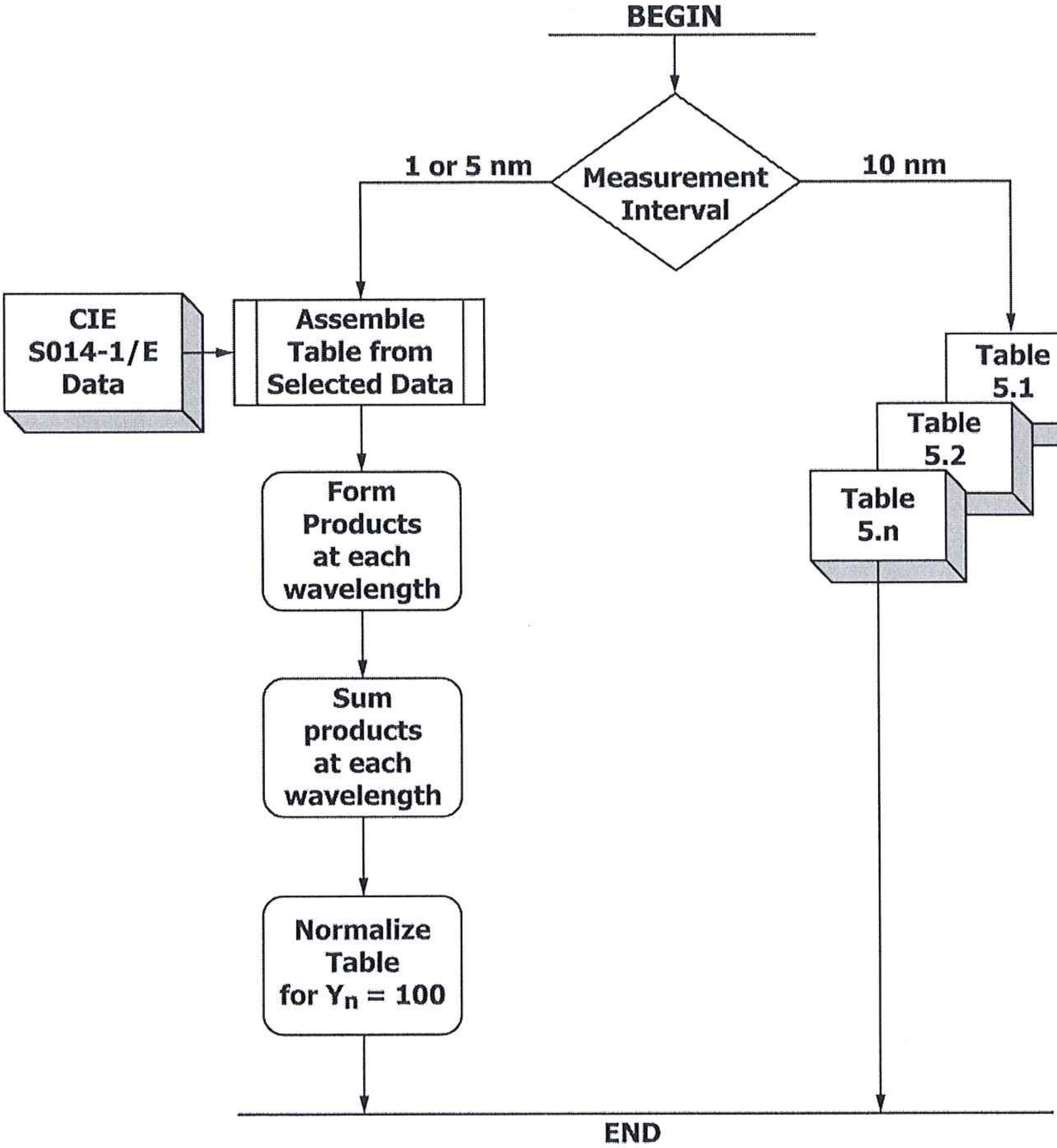


*Figure Note*—References to Section 7. Calculations are included.

**FIG. 2 Flow Chart for Selecting Methods and Tables for Tristimulus Integration**

TABLE 1 Spectral Tristimulus Values (Color-Matching Functions) $\bar{x}$, $\bar{y}$, $\bar{z}$, of the CIE 1931 Standard (2°) Observer, at 5 nm Intervals from 380 to 780 nm (See Note 2 and Ref (3))

| λ(nm) | $\bar{x}(\lambda)$ | $\bar{y}(\lambda)$ | $\bar{z}(\lambda)$ |
|---|---|---|---|
| 380 | 0.0014 | 0.0000 | 0.0065 |
| 385 | 0.0022 | 0.0001 | 0.0105 |
| 390 | 0.0042 | 0.0001 | 0.0201 |
| 395 | 0.0076 | 0.0002 | 0.0362 |
| 400 | 0.0143 | 0.0004 | 0.0679 |
| 405 | 0.0232 | 0.0006 | 0.1102 |
| 410 | 0.0435 | 0.0012 | 0.2074 |
| 415 | 0.0776 | 0.0022 | 0.3713 |
| 420 | 0.1344 | 0.0040 | 0.6456 |
| 425 | 0.2148 | 0.0073 | 1.0391 |
| 430 | 0.2839 | 0.0116 | 1.3856 |
| 435 | 0.3285 | 0.0168 | 1.6230 |
| 440 | 0.3483 | 0.0230 | 1.7471 |
| 445 | 0.3481 | 0.0298 | 1.7826 |
| 450 | 0.3362 | 0.0380 | 1.7721 |
| 455 | 0.3187 | 0.0480 | 1.7441 |
| 460 | 0.2908 | 0.0600 | 1.6692 |
| 465 | 0.2511 | 0.0739 | 1.5281 |
| 470 | 0.1954 | 0.0910 | 1.2876 |
| 475 | 0.1421 | 0.1126 | 1.0419 |
| 480 | 0.0956 | 0.1390 | 0.8130 |
| 485 | 0.0580 | 0.1693 | 0.6162 |
| 490 | 0.0320 | 0.2080 | 0.4652 |
| 495 | 0.0147 | 0.2586 | 0.3533 |
| 500 | 0.0049 | 0.3230 | 0.2720 |
| 505 | 0.0024 | 0.4073 | 0.2123 |
| 510 | 0.0093 | 0.5030 | 0.1582 |
| 515 | 0.0291 | 0.6082 | 0.1117 |
| 520 | 0.0633 | 0.7100 | 0.0782 |
| 525 | 0.1096 | 0.7932 | 0.0573 |
| 530 | 0.1655 | 0.8620 | 0.0422 |
| 535 | 0.2257 | 0.9149 | 0.0298 |
| 540 | 0.2904 | 0.9540 | 0.0203 |
| 545 | 0.3597 | 0.9803 | 0.0134 |
| 550 | 0.4334 | 0.9950 | 0.0087 |
| 555 | 0.5121 | 1.0000 | 0.0057 |
| 560 | 0.5945 | 0.9950 | 0.0039 |
| 565 | 0.6784 | 0.9786 | 0.0027 |
| 570 | 0.7621 | 0.9520 | 0.0021 |
| 575 | 0.8425 | 0.9154 | 0.0018 |
| 580 | 0.9163 | 0.8700 | 0.0017 |
| 585 | 0.9786 | 0.8163 | 0.0014 |
| 590 | 1.0263 | 0.7570 | 0.0011 |
| 595 | 1.0567 | 0.6949 | 0.0010 |
| 600 | 1.0622 | 0.6310 | 0.0008 |
| 605 | 1.0456 | 0.5668 | 0.0006 |
| 610 | 1.0026 | 0.5030 | 0.0003 |
| 615 | 0.9384 | 0.4412 | 0.0002 |
| 620 | 0.8544 | 0.3810 | 0.0002 |
| 625 | 0.7514 | 0.3210 | 0.0001 |
| 630 | 0.6424 | 0.2650 | 0.0000 |
| 635 | 0.5419 | 0.2170 | 0.0000 |
| 640 | 0.4479 | 0.1750 | 0.0000 |
| 645 | 0.3608 | 0.1382 | 0.0000 |
| 650 | 0.2835 | 0.1070 | 0.0000 |
| 655 | 0.2187 | 0.0816 | 0.0000 |
| 660 | 0.1649 | 0.0610 | 0.0000 |
| 665 | 0.1212 | 0.0446 | 0.0000 |
| 670 | 0.0874 | 0.0320 | 0.0000 |
| 675 | 0.0636 | 0.0232 | 0.0000 |
| 680 | 0.0468 | 0.0170 | 0.0000 |
| 685 | 0.0329 | 0.0119 | 0.0000 |

TABLE 1 *Continued*

| λ(nm) | $\bar{x}(\lambda)$ | $\bar{y}(\lambda)$ | $\bar{z}(\lambda)$ |
|---|---|---|---|
| 690 | 0.0227 | 0.0082 | 0.0000 |
| 695 | 0.0158 | 0.0057 | 0.0000 |
| 700 | 0.0114 | 0.0041 | 0.0000 |
| 705 | 0.0081 | 0.0029 | 0.0000 |
| 710 | 0.0058 | 0.0021 | 0.0000 |
| 715 | 0.0041 | 0.0015 | 0.0000 |
| 720 | 0.0029 | 0.0010 | 0.0000 |
| 725 | 0.0020 | 0.0007 | 0.0000 |
| 730 | 0.0014 | 0.0005 | 0.0000 |
| 735 | 0.0010 | 0.0004 | 0.0000 |
| 740 | 0.0007 | 0.0002 | 0.0000 |
| 745 | 0.0005 | 0.0002 | 0.0000 |
| 750 | 0.0003 | 0.0001 | 0.0000 |
| 755 | 0.0002 | 0.0001 | 0.0000 |
| 760 | 0.0002 | 0.0001 | 0.0000 |
| 765 | 0.0001 | 0.0000 | 0.0000 |
| 770 | 0.0001 | 0.0000 | 0.0000 |
| 775 | 0.0001 | 0.0000 | 0.0000 |
| 780 | 0.0000 | 0.0000 | 0.0000 |
| Summation at 5 nm intervals: | | | |
| $\sum\bar{x}(\lambda) = 21.3714$ | | | |
| $\sum\bar{y}(\lambda) = 21.3711$ | | | |
| $\sum\bar{z}(\lambda) = 21.3715$ | | | |

interval where spectral data are available at 5-nm intervals. Likewise, select the 10-nm measurement interval over the 20-nm interval where spectral data are available at 10-nm intervals. If the 20-nm interval is selected, users should assure themselves that the resulting accuracy is sufficient for the purpose for which the results are intended.

6.3.1 If the instrument used has a selectable measurement interval, select the interval that most nearly equals the bandwidth of the instrument throughout the spectrum. If the instrument has an adjustable bandwidth, adjust the bandwidth to be approximately equal to the measurement interval.

6.3.2 The measurement interval should be commensurate with the bandwidth. A much greater interval would undersample the spectrum, and a much smaller interval would not improve the accuracy of the computation.

6.4 *Other Miscellaneous Conditions*—While the above selections cover the majority of industrial practices, the possibility exists that other conditions could be encountered. Therefore, other procedures than those included in this practice may be used provided that the results are consistent with those obtained by use of the procedures in the practice.

## 7. Calculations

7.1 *General Procedures*—The general procedures for computing CIE tristimulus values are summarized as follows:

7.1.1 *Procedures as Specified by the CIE*—The CIE procedures are specified in Ref **(3)** and summarized in Refs **(5-9)**. The fundamental definition is in terms of integrals,

$$X = k \int_{\lambda} R(\lambda)\, S(\lambda)\, \bar{x}(\lambda)\, d\lambda \quad (3)$$

$$Y = k \int_{\lambda} R(\lambda)\, S(\lambda)\, \bar{y}(\lambda)\, d\lambda$$

$$Z = k \int_{\lambda} R(\lambda)\, S(\lambda)\, \bar{z}(\lambda)\, d\lambda$$

where:

$R(\lambda)$ = the reflectance, transmittance, or radiance factor (on a scale of zero to one for the perfect reflecting diffuser),

$S(\lambda)$ = the relative spectral power of a CIE standard illuminant, and

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ = the color-matching functions of one of the CIE standard observers.

The integration is carried out over the entire wavelength region in which the color-matching functions are defined, 360 to 830 nm. The normalizing factor $k$ is defined as

$$k = 100 / \int_{\lambda} S(\lambda)\, \bar{y}(\lambda)\, d\lambda \quad (4)$$

The CIE notes that in all practical calculations of tristimulus values the integration is approximated by a summation, giving the equations as follows:

$$X = k \sum_{\lambda} R(\lambda)\, S(\lambda)\, \bar{x}(\lambda)\, \Delta\lambda \quad (5)$$

$$Y = k \sum_{\lambda} R(\lambda)\, S(\lambda)\, \bar{y}(\lambda)\, \Delta\lambda$$

$$Z = k \sum_{\lambda} R(\lambda)\, S(\lambda)\, \bar{z}(\lambda)\, \Delta\lambda$$

with:

$$k = 100 / \sum_{\lambda} S(\lambda) \bar{y}(\lambda)\, \Delta\lambda \quad (6)$$

7.1.2 *Procedure Using Tristimulus Weighting Factors*—It is common industrial practice to carry out the summation to

TABLE 2 Spectral Tristimulus Values (Color-Matching Functions) $\bar{x}_{10}$, $\bar{y}_{10}$, $\bar{z}_{10}$, of the CIE 1964 Supplementary Standard (10°) Observer, At 5 nm Intervals from 380 to 780 nm (See Note 2 and Ref (3))

| λ(nm) | $\bar{x}_{10}(\lambda)$ | $\bar{y}_{10}(\lambda)$ | $\bar{z}_{10}(\lambda)$ |
|---|---|---|---|
| 380 | 0.0002 | 0.0000 | 0.0007 |
| 385 | 0.0007 | 0.0001 | 0.0029 |
| 390 | 0.0024 | 0.0003 | 0.0105 |
| 395 | 0.0072 | 0.0008 | 0.0323 |
| 400 | 0.0191 | 0.0020 | 0.0860 |
| 405 | 0.0434 | 0.0045 | 0.1971 |
| 410 | 0.0847 | 0.0088 | 0.3894 |
| 415 | 0.1406 | 0.0145 | 0.6568 |
| 420 | 0.2045 | 0.0214 | 0.9725 |
| 425 | 0.2647 | 0.0295 | 1.2825 |
| 430 | 0.3147 | 0.0387 | 1.5535 |
| 435 | 0.3577 | 0.0496 | 1.7985 |
| 440 | 0.3837 | 0.0621 | 1.9673 |
| 445 | 0.3867 | 0.0747 | 2.0273 |
| 450 | 0.3707 | 0.0895 | 1.9948 |
| 455 | 0.3430 | 0.1063 | 1.9007 |
| 460 | 0.3023 | 0.1282 | 1.7454 |
| 465 | 0.2541 | 0.1528 | 1.5549 |
| 470 | 0.1956 | 0.1852 | 1.3176 |
| 475 | 0.1323 | 0.2199 | 1.0302 |
| 480 | 0.0805 | 0.2536 | 0.7721 |
| 485 | 0.0411 | 0.2977 | 0.5701 |
| 490 | 0.0162 | 0.3391 | 0.4153 |
| 495 | 0.0051 | 0.3954 | 0.3024 |
| 500 | 0.0038 | 0.4608 | 0.2185 |
| 505 | 0.0154 | 0.5314 | 0.1592 |
| 510 | 0.0375 | 0.6067 | 0.1120 |
| 515 | 0.0714 | 0.6857 | 0.0822 |
| 520 | 0.1177 | 0.7618 | 0.0607 |
| 525 | 0.1730 | 0.8233 | 0.0431 |
| 530 | 0.2365 | 0.8752 | 0.0305 |
| 535 | 0.3042 | 0.9238 | 0.0206 |
| 540 | 0.3768 | 0.9620 | 0.0137 |
| 545 | 0.4516 | 0.9822 | 0.0079 |
| 550 | 0.5298 | 0.9918 | 0.0040 |
| 555 | 0.6161 | 0.9991 | 0.0011 |
| 560 | 0.7052 | 0.9973 | 0.0000 |
| 565 | 0.7938 | 0.9824 | 0.0000 |
| 570 | 0.8787 | 0.9556 | 0.0000 |
| 575 | 0.9512 | 0.9152 | 0.0000 |
| 580 | 1.0142 | 0.8689 | 0.0000 |
| 585 | 1.0743 | 0.8256 | 0.0000 |
| 590 | 1.1185 | 0.7774 | 0.0000 |
| 595 | 1.1343 | 0.7204 | 0.0000 |
| 600 | 1.1240 | 0.6583 | 0.0000 |
| 605 | 1.0891 | 0.5939 | 0.0000 |
| 610 | 1.0305 | 0.5280 | 0.0000 |
| 615 | 0.9507 | 0.4618 | 0.0000 |
| 620 | 0.8563 | 0.3981 | 0.0000 |
| 625 | 0.7549 | 0.3396 | 0.0000 |
| 630 | 0.6475 | 0.2835 | 0.0000 |
| 635 | 0.5351 | 0.2283 | 0.0000 |
| 640 | 0.4316 | 0.1798 | 0.0000 |
| 645 | 0.3437 | 0.1402 | 0.0000 |
| 650 | 0.2683 | 0.1076 | 0.0000 |
| 655 | 0.2043 | 0.0812 | 0.0000 |
| 660 | 0.1526 | 0.0603 | 0.0000 |
| 665 | 0.1122 | 0.0441 | 0.0000 |
| 670 | 0.0813 | 0.0318 | 0.0000 |
| 675 | 0.0579 | 0.0226 | 0.0000 |
| 680 | 0.0409 | 0.0159 | 0.0000 |
| 685 | 0.0286 | 0.0111 | 0.0000 |

TABLE 2 *Continued*

| λ(nm) | $\bar{x}_{10}(\lambda)$ | $\bar{y}_{10}(\lambda)$ | $\bar{z}_{10}(\lambda)$ |
|---|---|---|---|
| 690 | 0.0199 | 0.0077 | 0.0000 |
| 695 | 0.0138 | 0.0054 | 0.0000 |
| 700 | 0.0096 | 0.0037 | 0.0000 |
| 705 | 0.0066 | 0.0026 | 0.0000 |
| 710 | 0.0046 | 0.0018 | 0.0000 |
| 715 | 0.0031 | 0.0012 | 0.0000 |
| 720 | 0.0022 | 0.0008 | 0.0000 |
| 725 | 0.0015 | 0.0006 | 0.0000 |
| 730 | 0.0010 | 0.0004 | 0.0000 |
| 735 | 0.0007 | 0.0003 | 0.0000 |
| 740 | 0.0005 | 0.0002 | 0.0000 |
| 745 | 0.0004 | 0.0001 | 0.0000 |
| 750 | 0.0003 | 0.0001 | 0.0000 |
| 755 | 0.0002 | 0.0001 | 0.0000 |
| 760 | 0.0001 | 0.0000 | 0.0000 |
| 765 | 0.0001 | 0.0000 | 0.0000 |
| 770 | 0.0001 | 0.0000 | 0.0000 |
| 775 | 0.0000 | 0.0000 | 0.0000 |
| 780 | 0.0000 | 0.0000 | 0.0000 |
| Summation at 5 nm intervals: | | | |
| $\sum\bar{x}_{10}(\lambda) = 23.3294$ | | | |
| $\sum\bar{y}_{10}(\lambda) = 23.3324$ | | | |
| $\sum\bar{z}_{10}(\lambda) = 23.3343$ | | | |

tristimulus values in two steps. In the first of these, a set of normalized tristimulus weighting factors $W_x$, $W_y$, $W_z$ is calculated as follows:

$$W_x(\lambda) = k\,S(\lambda)\,\bar{x}(\lambda)\Delta\lambda \quad (7)$$

$$W_y(\lambda) = kS(\lambda)\,\bar{y}(\lambda)\,\Delta\lambda$$

$$W_z(\lambda) = kS(\lambda)\,\bar{z}(\lambda)\,\Delta\lambda$$

for λ = 360, ... 780 nm, (see Note 2), and where:

$$k = 100/\sum_{360}^{780} S(\lambda)\,\bar{y}(\lambda)\,\Delta\lambda \quad (8)$$

For a given selection of illuminant, observer, measurement interval Δλ, and measurement bandpass, this calculation needs to be done only once, since the spectral reflectance (or transmittance or radiance) factor $R(\lambda)$ is not included in the weighting factors $W$. In the second step, tristimulus values $X$, $Y$, $Z$ (or $X_{10}$, $Y_{10}$, $Z_{10}$) are calculated using the values of $W$ and $R(\lambda)$ in the following equations:

$$X = \Sigma_{360}^{780} W_x(\lambda)R(\lambda) \quad (9)$$

$$Y = \Sigma_{360}^{780} W_y(\lambda)R(\lambda)$$

$$Z = \Sigma_{360}^{780} W_z(\lambda)R(\lambda)$$

NOTE 2—While 360 nm is recommended as the starting wavelength for summation and elsewhere in this practice, CIE data reproduced in Tables 1-4, and the spectrum locus scale of Fig. 1, begin only at 380 nm; since the missing data cannot be supplied in all cases, these references to 380 nm should remain. In the region between 360 and 379 nm, values of color matching functions are so small that their inclusion or omission in the calculations would not lead to significant differences in the resulting tristimulus values.

7.1.3 For methods of calculating weighting factors from custom sources, see Practice E2022.

7.2 *Summary of Calculations* (see Note 2)—A general outline of the procedure is given in Fig. 2 in the form of a flow chart.

NOTE 3—For reflecting materials, calculate tristimulus values from spectral data obtained relative to the perfect reflecting diffuser. For transmitting materials, calculate by use of the incident light as the reference.

7.2.1 *Procedure for 1-nm Measurement Interval*—Use the 1-nm spectral data in CIE S 014 and S 013 (or on CIE D 001 Disk) and (Eq 6) and (Eq 7).

7.2.2 *Procedures for Spectral Data:*

7.2.2.1 *Procedure for Data Obtained at 5-nm Measurement Intervals*—Prepare tables of tristimulus weighting factors for desired illuminant-observer combinations, using the spectral data in Tables 1-4 (see Note 2), and (Eq 8) and (Eq 9). Use the tables so prepared as described in 7.3 (see Note 4).

NOTE 4—Using the previous procedure at 10 nm or 20 nm intervals by omitting intermediate tabulated values is not allowed. Use the procedures of 7.3 instead.

7.2.2.2 *Procedures for Data Obtained at 10- or 20-nm Measurement Intervals*—Select the appropriate tables of tristimulus weighting factors from those in Tables 5 and use them as described in 7.3.

7.3 *Use of Tristimulus Weighting Factors:*

7.3.1 *Use of Data Obtained at 5-nm Measurement Intervals*—Use the color-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$, from Table 1, for the 1931 CIE standard colorimetric observer, or when desired the functions $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$, from Table 2, for the 1964 CIE supplementary standard colorimetric observer. Select the desired CIE standard or recommended illuminant, for example *A*, *C*, or one of the *D* or *F* illuminants from Table 3 or Table 4. At each wavelength multiply the

TABLE 3 Relative Spectral Power Distributions S(λ) of CIE Standard Illuminants *A*, *C*, $D_{50}$, $D_{55}$, $D_{65}$, and $D_{75}$ at 5-nm Intervals from 380 to 780 nm (See Note 2 and Ref (3))

| λ (nm) | *A* S(λ) | *C* S(λ) | $D_{50}$ S(λ) | $D_{55}$ S(λ) | $D_{65}$ S(λ) | $D_{75}$ S(λ) |
|---|---|---|---|---|---|---|
| 380 | 9.80 | 33.00 | 24.49 | 32.58 | 49.98 | 66.70 |
| 385 | 10.90 | 39.92 | 27.18 | 35.34 | 52.31 | 68.33 |
| 390 | 12.09 | 47.40 | 29.87 | 38.09 | 54.65 | 69.96 |
| 395 | 13.35 | 55.17 | 39.59 | 49.52 | 68.70 | 85.95 |
| 400 | 14.71 | 63.30 | 49.31 | 60.95 | 82.75 | 101.93 |
| 405 | 16.15 | 71.81 | 52.91 | 64.75 | 87.12 | 106.91 |
| 410 | 17.68 | 80.60 | 56.51 | 68.55 | 91.49 | 111.89 |
| 415 | 19.29 | 89.53 | 58.27 | 70.07 | 92.46 | 112.35 |
| 420 | 20.99 | 98.10 | 60.03 | 71.58 | 93.43 | 112.80 |
| 425 | 22.79 | 105.80 | 58.93 | 69.75 | 90.06 | 107.94 |
| 430 | 24.67 | 112.40 | 57.82 | 67.91 | 86.68 | 103.09 |
| 435 | 26.64 | 117.75 | 66.32 | 76.76 | 95.77 | 112.14 |
| 440 | 28.70 | 121.50 | 74.82 | 85.61 | 104.86 | 121.20 |
| 445 | 30.85 | 123.45 | 81.04 | 91.80 | 110.94 | 127.10 |
| 450 | 33.09 | 124.00 | 87.25 | 97.99 | 117.01 | 133.01 |
| 455 | 35.41 | 123.60 | 88.93 | 99.23 | 117.41 | 132.68 |
| 460 | 37.81 | 123.10 | 90.61 | 100.46 | 117.81 | 132.36 |
| 465 | 40.30 | 123.30 | 90.99 | 100.19 | 116.34 | 129.84 |
| 470 | 42.87 | 123.80 | 91.37 | 99.91 | 114.86 | 127.32 |
| 475 | 45.52 | 124.09 | 93.24 | 101.33 | 115.39 | 127.06 |
| 480 | 48.24 | 123.90 | 95.11 | 102.74 | 115.92 | 126.80 |
| 485 | 51.04 | 122.92 | 93.54 | 100.41 | 112.37 | 122.29 |
| 490 | 53.91 | 120.70 | 91.96 | 98.08 | 108.81 | 117.78 |
| 495 | 56.85 | 116.90 | 93.84 | 99.38 | 109.08 | 117.19 |
| 500 | 59.86 | 112.10 | 95.72 | 100.68 | 109.35 | 116.59 |
| 505 | 62.93 | 106.98 | 96.17 | 100.69 | 108.58 | 115.15 |
| 510 | 66.06 | 102.30 | 96.61 | 100.70 | 107.80 | 113.70 |
| 515 | 69.25 | 98.81 | 96.87 | 100.34 | 106.30 | 111.18 |
| 520 | 72.50 | 96.90 | 97.13 | 99.99 | 104.79 | 108.56 |
| 525 | 75.79 | 96.78 | 99.61 | 102.10 | 106.24 | 109.55 |
| 530 | 79.13 | 98.00 | 102.10 | 104.21 | 107.69 | 110.44 |
| 535 | 82.52 | 99.94 | 101.43 | 103.16 | 106.05 | 108.37 |
| 540 | 85.95 | 102.10 | 100.75 | 102.10 | 104.41 | 106.29 |
| 545 | 89.41 | 103.95 | 101.54 | 102.53 | 104.23 | 105.60 |
| 550 | 92.91 | 105.20 | 102.32 | 102.97 | 104.05 | 104.90 |
| 555 | 96.44 | 105.67 | 101.16 | 101.48 | 102.02 | 102.45 |
| 560 | 100.00 | 105.30 | 100.00 | 100.00 | 100.00 | 100.00 |
| 565 | 103.58 | 104.11 | 98.87 | 98.61 | 98.17 | 97.81 |
| 570 | 107.18 | 102.30 | 97.74 | 97.22 | 96.33 | 95.62 |
| 575 | 110.80 | 100.15 | 98.33 | 97.48 | 96.06 | 94.91 |
| 580 | 114.44 | 97.80 | 98.92 | 97.75 | 95.79 | 94.21 |
| 585 | 118.08 | 95.43 | 96.21 | 94.59 | 92.24 | 90.60 |
| 590 | 121.73 | 93.20 | 93.50 | 91.43 | 88.69 | 87.00 |
| 595 | 125.39 | 91.22 | 95.59 | 92.93 | 89.35 | 87.11 |
| 600 | 129.04 | 89.70 | 97.69 | 94.42 | 90.01 | 87.23 |
| 605 | 132.70 | 88.83 | 98.48 | 94.78 | 89.80 | 86.68 |
| 610 | 136.35 | 88.40 | 99.27 | 95.14 | 89.60 | 86.14 |
| 615 | 139.99 | 88.19 | 99.16 | 94.68 | 88.65 | 84.86 |
| 620 | 143.62 | 88.10 | 99.04 | 94.22 | 87.70 | 83.58 |
| 625 | 147.24 | 88.06 | 97.38 | 92.33 | 85.49 | 81.16 |
| 630 | 150.84 | 88.00 | 95.72 | 90.45 | 83.29 | 78.75 |
| 635 | 154.42 | 87.86 | 97.29 | 91.39 | 83.49 | 78.59 |
| 640 | 157.98 | 87.80 | 98.86 | 92.33 | 83.70 | 78.43 |
| 645 | 161.52 | 87.99 | 97.26 | 90.59 | 81.86 | 76.61 |
| 650 | 165.03 | 88.20 | 95.67 | 88.85 | 80.03 | 74.80 |
| 655 | 168.51 | 88.20 | 96.93 | 89.59 | 80.12 | 74.56 |
| 660 | 171.96 | 87.90 | 98.19 | 90.32 | 80.21 | 74.32 |
| 665 | 175.38 | 87.22 | 100.60 | 92.13 | 81.25 | 74.87 |
| 670 | 178.77 | 86.30 | 103.00 | 93.95 | 82.28 | 75.42 |
| 675 | 182.12 | 85.30 | 101.07 | 91.95 | 80.28 | 73.50 |
| 680 | 185.43 | 84.00 | 99.13 | 89.96 | 78.28 | 71.58 |
| 685 | 188.70 | 82.21 | 93.26 | 84.82 | 74.00 | 67.71 |
| 690 | 191.93 | 80.20 | 87.38 | 79.68 | 69.72 | 63.85 |
| 695 | 195.12 | 78.24 | 89.49 | 81.26 | 70.67 | 64.46 |
| 700 | 198.26 | 76.30 | 91.60 | 82.84 | 71.61 | 65.08 |
| 705 | 201.36 | 74.36 | 92.25 | 83.84 | 72.98 | 66.57 |
| 710 | 204.41 | 72.40 | 92.89 | 84.84 | 74.35 | 68.07 |
| 715 | 207.41 | 70.40 | 84.87 | 77.54 | 67.98 | 62.26 |
| 720 | 210.36 | 68.30 | 76.85 | 70.24 | 61.60 | 56.44 |
| 725 | 213.27 | 66.30 | 81.68 | 74.77 | 65.74 | 60.34 |
| 730 | 216.12 | 64.40 | 86.51 | 79.30 | 69.89 | 64.24 |
| 735 | 218.92 | 62.80 | 89.55 | 82.15 | 72.49 | 66.70 |
| 740 | 221.67 | 61.50 | 92.58 | 84.99 | 75.09 | 69.15 |

TABLE 3 *Continued*

| λ (nm) | A S(λ) | C S(λ) | $D_{50}$ S(λ) | $D_{55}$ S(λ) | $D_{65}$ S(λ) | $D_{75}$ S(λ) |
|---|---|---|---|---|---|---|
| 745 | 224.36 | 60.20 | 85.40 | 78.44 | 69.34 | 63.89 |
| 750 | 227.00 | 59.20 | 78.23 | 71.88 | 63.59 | 58.63 |
| 755 | 229.59 | 58.50 | 67.96 | 62.34 | 55.01 | 50.62 |
| 760 | 232.12 | 58.10 | 57.69 | 52.79 | 46.42 | 42.62 |
| 765 | 234.59 | 58.00 | 70.31 | 64.36 | 56.61 | 51.98 |
| 770 | 237.01 | 58.20 | 82.92 | 75.93 | 66.81 | 61.35 |
| 775 | 239.37 | 58.50 | 80.60 | 73.87 | 65.09 | 59.84 |
| 780 | 241.68 | 59.10 | 78.27 | 71.82 | 63.38 | 58.32 |

tabulated value of the observer color-matching functions by the tabulated value of the relative spectral power of the illuminant $S(\lambda)$, and by the spectral reflectance (or transmittance) factor $R(\lambda)$ (or $T(\lambda)$) of the specimen. Obtain the sum of these products at 5 nm intervals over the wavelength range 360 to 780 nm and use (Eq 6) and (Eq 7).

7.3.2 *Use of Data Obtained at 10 nm Measurement Intervals:*

7.3.2.1 *Data Available over the Wavelength Range 360 to 780 nm*—Select the appropriate table of tristimulus weighting factors, computed for triangular bandpass and 10 nm measurement intervals, for the desired illuminant and observer, from the nine sets included in Tables 5 (**10**).

7.3.2.2 *Data Available only for Wavelength Ranges Shorter than 360 to 780 nm*—When data for $R(\lambda)$, $T(\lambda)$, or $\beta(\lambda)$ are not available for the full wavelength range, add the weights at the wavelengths for which data are not available to the weights at the shortest and longest wavelength for which spectral data are available. That is: add the weights for wavelengths 360, ..., up to the last wavelength for which measured data are not available, to the next higher weight, for which such data are available; add the weights for wavelengths of 780, ..., down to the last wavelength for which measured data are not available, to the next lower weight, for which such data are available.

7.3.3 *Use of Data Obtained at 20 nm Measurement Intervals:*

7.3.3.1 *Data Available Over the Wavelength Range 360 to 780 nm*—Copy the 20 nm spectrum into a 10 nm framework whose indices, at 10 nm intervals, will run from 0 to 46 by copying the 22 values available to the even indices between 360 nm (index 2) and 780 nm (index 44). Extrapolate the 20 nm data to a range of 340 to 800 nm by use of the following equations:

$$R_0 = 3R_2 - 3R_4 + R_6 \quad (10)$$

$$R_n = R_{n-6} - 3R_{n-4} + 3R_{n-2} \quad (11)$$

where $R$ refers to the measured reflectance or transmittance and the index *zero* refers to an extrapolated value at 340 nm and the index $n$ refers to the extrapolated value at 800 nm of the 10 nm interval spectrum. Use these values to calculate the missing 10 nm intervals between 360 and 780 nm, but discard these values immediately after the interpolation and use these values for no other purpose.

With the extrapolated spectrum extended to indices 0 to 46, interpolate the missing 10 nm values by use of the following equation:

$$R_j = -0.0625R_{j-3} + 0.5625R_{j-1} + 0.5625R_{j+1} - 0.0625R_{j+3} \quad (12)$$

where the range of interpolation is for every odd numbered value of $j$ between 3 and 43 inclusive.

Should any interpolated value be less than zero, such value should be set to zero.

Select the appropriate table of tristimulus weighting factors, computed for triangular bandpass and 10 nm measurement intervals, for the desired illuminant and observer, from the nine sets included in Tables 5. Integrate the interpolated spectrum from index 2 to 44 (360 to 780 nm) with the chosen 10 nm table of tristimulus weighting factors, being sure to match the indices of the two multiplicative factors, spectral value and weighting factor, appropriately. The accuracy of doing so has been found to be approximately as accurate as 20 nm interpolation itself because each of the 19 missing 1-nm intervals is interpolated in each case, but in a different order.

7.3.3.2 *Data Available Only for Wavelength Ranges Shorter than 360 to 780 nm*—Interpolate the spectrum using equations Eq 10 through Eq 12 with the number of intervals and indices appropriate to the range of the present spectrum. Follow the teachings of 7.3.2.2 for the purpose of shortening the weighting factors to the appropriate range.

7.3.4 *Tristimulus Values*—Obtain the products of $R(\lambda)$, $T(\lambda)$ or $\beta(\lambda)$ and the weights selected in 7.3.1 or 7.3.2, including any modifications, and sum to obtain the CIE tristimulus values $X$, $Y$, $Z$ , or $X_{10}$, $Y_{10}$, $Z_{10}$.

7.4 *Chromaticity Coordinates*—Obtain chromaticity coordinates $x$, $y$, $z$ (for the CIE 1931 standard observer) by dividing each tristimulus value $X$, $Y$, $Z$ by the sum of all three: $x = X/(X + Y + Z)$; $y = Y/(X + Y + Z)$; and $z = Z/(X + Y + Z)$, or use the same procedure with all quantities having the subscript 10 for the CIE 1964 standard observer.

7.5 *CIE 1976 Uniform Color Spaces*—When a color space more nearly uniform than $X$, $Y$, $Z$ is desired, use CIELAB or CIELUV.

7.5.1 *CIELAB or $L^*a^*b^*$*—This approximately uniform color space is produced by plotting in rectangular coordinates the quantities $L^*$, $a^*$, $b^*$ defined as follows (**3**):

$$L^* = 116f(Q_Y) - 16 \quad (13)$$

$$a^* = 500[f(Q_X) - f(Q_Y)] \quad (14)$$

$$b^* = 200[f(Q_Y) - f(Q_Z)] \quad (15)$$

where:

TABLE 4 Relative Spectral Power Distributions S(λ) of CIE Fluorescent Illuminants *F2, F7,*, and *F11* at 5-nm Intervals from 380 to 780 nm (See Note 2 and Ref (3))

| λ(nm) | *F2* | *F7* | *F11* |
|---|---|---|---|
| 380 | 1.18 | 2.56 | 0.91 |
| 385 | 1.48 | 3.18 | 0.63 |
| 390 | 1.84 | 3.84 | 0.46 |
| 395 | 2.15 | 4.53 | 0.37 |
| 400 | 3.44 | 6.15 | 1.29 |
| 405 | 15.69 | 19.37 | 12.68 |
| 410 | 3.85 | 7.37 | 1.59 |
| 415 | 3.74 | 7.05 | 1.79 |
| 420 | 4.19 | 7.71 | 2.46 |
| 425 | 4.62 | 8.41 | 3.38 |
| 430 | 5.06 | 9.15 | 4.49 |
| 435 | 34.98 | 44.14 | 33.94 |
| 440 | 11.81 | 17.52 | 12.13 |
| 445 | 6.27 | 11.35 | 6.95 |
| 450 | 6.63 | 12.00 | 7.19 |
| 455 | 6.93 | 12.58 | 7.12 |
| 460 | 7.19 | 13.08 | 6.72 |
| 465 | 7.40 | 13.45 | 6.13 |
| 470 | 7.54 | 13.71 | 5.46 |
| 475 | 7.62 | 13.88 | 4.79 |
| 480 | 7.65 | 13.95 | 5.66 |
| 485 | 7.62 | 13.93 | 14.29 |
| 490 | 7.62 | 13.82 | 14.96 |
| 495 | 7.45 | 13.64 | 8.97 |
| 500 | 7.28 | 13.43 | 4.72 |
| 505 | 7.15 | 13.25 | 2.33 |
| 510 | 7.05 | 13.08 | 1.47 |
| 515 | 7.04 | 12.93 | 1.10 |
| 520 | 7.16 | 12.78 | 0.89 |
| 525 | 7.47 | 12.60 | 0.83 |
| 530 | 8.04 | 12.44 | 1.18 |
| 535 | 8.88 | 12.33 | 4.90 |
| 540 | 10.01 | 12.26 | 39.59 |
| 545 | 24.88 | 29.52 | 72.84 |
| 550 | 16.64 | 17.05 | 32.61 |
| 555 | 14.59 | 12.44 | 7.52 |
| 560 | 16.16 | 12.58 | 2.83 |
| 565 | 17.56 | 12.72 | 1.96 |
| 570 | 18.62 | 12.83 | 1.67 |
| 575 | 21.47 | 15.46 | 4.43 |
| 580 | 22.79 | 16.75 | 11.28 |
| 585 | 19.29 | 12.83 | 14.76 |
| 590 | 18.66 | 12.67 | 12.73 |
| 595 | 17.73 | 12.45 | 9.74 |
| 600 | 16.54 | 12.19 | 7.33 |
| 605 | 15.21 | 11.89 | 9.72 |
| 610 | 13.80 | 11.60 | 55.27 |
| 615 | 12.36 | 11.35 | 42.58 |
| 620 | 10.95 | 11.12 | 13.18 |
| 625 | 9.65 | 10.95 | 13.16 |
| 630 | 8.40 | 10.76 | 12.26 |
| 635 | 7.32 | 10.42 | 5.11 |
| 640 | 6.31 | 10.11 | 2.07 |
| 645 | 5.43 | 10.04 | 2.34 |
| 650 | 4.68 | 10.02 | 3.58 |
| 655 | 4.02 | 10.11 | 3.01 |
| 660 | 3.45 | 9.87 | 2.48 |
| 665 | 2.96 | 8.65 | 2.14 |
| 670 | 2.55 | 7.27 | 1.54 |
| 675 | 2.19 | 6.44 | 1.33 |
| 680 | 1.89 | 5.83 | 1.46 |
| 685 | 1.64 | 5.41 | 1.94 |

TABLE 4 *Continued*

| λ(nm) | F2 | F7 | F11 |
|---|---|---|---|
| 690 | 1.53 | 5.04 | 2.00 |
| 695 | 1.27 | 4.57 | 1.20 |
| 700 | 1.10 | 4.12 | 1.35 |
| 705 | 0.99 | 3.77 | 4.10 |
| 710 | 0.88 | 3.46 | 5.58 |
| 715 | 0.76 | 3.08 | 2.51 |
| 720 | 0.68 | 2.73 | 0.57 |
| 725 | 0.61 | 2.47 | 0.27 |
| 730 | 0.56 | 2.25 | 0.23 |
| 735 | 0.54 | 2.06 | 0.21 |
| 740 | 0.51 | 1.90 | 0.24 |
| 745 | 0.47 | 1.75 | 0.24 |
| 750 | 0.47 | 1.62 | 0.20 |
| 755 | 0.43 | 1.54 | 0.24 |
| 760 | 0.46 | 1.45 | 0.32 |
| 765 | 0.47 | 1.32 | 0.26 |
| 770 | 0.40 | 1.17 | 0.16 |
| 775 | 0.33 | 0.99 | 0.12 |
| 780 | 0.27 | 0.81 | 0.09 |

$$Q_X = (X/X_n);\ Q_Y = (Y/Y_n);\ Q_Z = (Z/Z_n) \quad (16)$$

and

$$f(Q_i) = Q_i^{1/3} \ \ if\ Q_i > (6/29)^3 \quad (17)$$

else

$$f(Q_i) = (841/108)Q_i + 4/29 \ \ if\ Q_i \leq (6/29)^3 \quad (18)$$

where *i* varies as *X, Y,* and *Z*.

The tristimulus values $X_n$, $Y_n$, $Z_n$ define the color of the normally white object-color stimulus. Usually, the white object-color stimulus is given by the spectral radiant power of one of the CIE standard illuminants, for example, *C*, $D_{65}$ or another of daylight quality, reflected into the observer's eye by the perfect reflecting diffuser. Under these conditions, $X_n$, $Y_n$, $Z_n$ are the tristimulus values of the standard illuminant with $Y_n$ equal to 100 obtained by use of the same method used to obtain *X, Y, Z* (see 7.6).

7.5.2 *CIELUV or L*u*v**—This approximately uniform color space is produced by plotting in rectangular coordinates the quantities $L^*$, $u^*$, $v^*$ defined as follows (see also Note 5):

$$L^* = 116\,(Y/Y_n)^{1/3} - 16 \qquad Y/Y_n > (6/29)^3 \quad (19)$$

$$u^* = 13L^*(u' - u'_n)$$

$$v^* = 13L^*(v' - v'_n)$$

with:

$$u' = \frac{4X}{X + 15Y + 3Z} \quad (20)$$

$$v' = \frac{9Y}{X + 15Y + 3Z}$$

$$u'_n = \frac{4X_n}{X_n + 15Y_n + 3Z_n}$$

$$v'_n = \frac{9Y_n}{X_n + 15Y_n + 3Z_n}$$

7.5.2.1 In calculating $L^*$ values for $Y/Y_n$ less than $(6/29)^3$, use the equation given in 7.5.1.

NOTE 5—The CIE 1976 $L^*u^*v^*$ space incorporates, for constant $L^*$, a ($u'$, $v'$) chromaticity diagram which is a projective transformation of the CIE 1931 (*x, y*) chromaticity diagram. Straight lines in the (*x, y*) chromaticity diagram remain straight in the ($u'$, $v'$) diagram.

7.5.3 *LCH Versions of CIELAB and CIELUV:*

7.5.3.1 It may be useful to calculate CIE 1976 hue and chroma coordinates as follows, combining them with $L^*$ to provide alternative sets of LCH coordinates within the CIELAB and CIELUV spaces: CIE 1976 hue angles:

$$h_{ab} = \tan^{-1}(b^*/a^*) \quad \text{or} \quad h_{uv} = \tan^{-1}(v^*/u^*) \quad (21)$$

NOTE 6—As stated here, the arctangent formula for h as a function of a* and b*, $\tan^{-1}(b^*/a^*)$, is a shorthand for a four-quadrant arctangent that has the range [0, 360] degrees. Computation of h or of ΔH* is recommended only outside the 0.1-radius domain about a*, b* = 0. The following pseudo-code applies.

```
if b* = 0 then
    h = 90 – 90 sign(a*)
else
    h = 180 – (180/π) tan⁻¹(a*/b*) – 90 sign(b*)
end if.
```

CIE 1976 chroma:

$$C^*_{ab} = [(a^*)^2 + (b^*)^2]^{1/2} \quad \text{or} \quad C^*_{uv} = [(u^*)^2 + (v^*)^2]^{1/2} \quad (22)$$

7.5.3.2 Differences in hue angle between two specimens can be correlated with differences in their visually perceived hue, and differences in their chroma can similarly be correlated with differences in their visually perceived chroma (see also Practice D2244).

7.6 *Tristimulus Values* $X_n$, $Y_n$, $Z_n$:

7.6.1 It is emphasized that the tristimulus values of the nominally white object-color stimulus must always be calculated by the same method used to calculate tristimulus values for other colors with which they are to be used. This implies not only use of the same illuminant and observer, but also of the same measurement interval, bandpass, band shape, and method of summation. When using Tables 5, the values tabulated as "White Point" at the bottoms of the tables must always be the ones used for $X_n$, $Y_n$, and $Z_n$.

7.6.2 Use values of $X_n$, $Y_n$, and $Z_n$ meeting the above requirements in the calculation of CIELAB coordinates and in some single-number color scales such as those for indexes of yellowness and whiteness, among others (see Practice E313).

7.7 *Inverse Transformations from CIE Notations to Tristimulus Values:*

7.7.1 *Transformation from L*, a* b* to X, Y, Z.* There are times when it is desirable to transform from CIE notation $L^*$, $a^*$, $b^*$ to CIE $X$, $Y$, and $Z$. To do so, use the following pseudocode.

$$P_Y = \left(\frac{L^* + 16}{116}\right)$$

$$P_X = \frac{a^*}{500} + P_Y$$

$$P_Z = P_Y - \frac{b^*}{200}$$

*If* $P_X > \left(\frac{6}{29}\right)$ *then*

$$X = X_n P_X{}^3$$

*Else*

$$X = X_n\left(\frac{108}{841}\right)\left(P_X - \frac{4}{29}\right)$$

*End if.*

*If* $P_Y > \left(\frac{6}{29}\right)$ *then*

$$Y = Y_n P_Y{}^3$$

*Else*

$$Y = Y_n\left(\frac{108}{841}\right)\left(P_Y - \frac{4}{29}\right)$$

*End if.*

*If* $P_Z > \left(\frac{6}{29}\right)$ *then*

$$Z = Z_n P_Z{}^3$$

*Else*

$$Z = Z_n\left(\frac{108}{841}\right)\left(P_Z - \frac{4}{29}\right)$$

*End if.*

Here the symbols $P_X$, $P_Y$, $P_Z$ are intermediate values that act as placeholders for values being carried to further calculations. The unknowns are X, Y, and Z and the values $L^*$, $a^*$, $b^*$ and $X_n$, $Y_n$, and $Z_n$ are known. The actual values of $X_n$, $Y_n$, and $Z_n$ may be found in Tables 5 in rows labeled "White Point" while paying particular attention to the fact that the illuminant-observer combination chosen here must be identical to those from which the CIELAB notation was originally calculated.

7.7.2 *Transformation from L*, u* v* to X, Y, Z.* There are times when it is desirable to transform from CIE notation $L^*$, $u^*$, $v^*$ to CIE $X$, $Y$, and $Z$. To do so, use the following pseudocode.

$$P_Y = \left(\frac{L^* + 16}{116}\right)$$

*If* $P_Y > \left(\frac{6}{29}\right)$ *Then*

$$Y = Y_n P_Y{}^3$$

*Else*

$$Y = Y_n\left(\frac{108}{841}\right)\left(P_Y - \frac{4}{29}\right)$$

*End if.*

$$u' = \frac{u^*}{13L^*} + u'_n$$

$$v' = \frac{v^*}{13L^*} + v'_n$$

$$x = \frac{9u'}{(6u' - 16v' + 12)}$$

$$y = \frac{4v'}{6u' - 16v' + 12}$$

$$X = \frac{xY}{y}$$

$$Z = \frac{(1 - x - y)Y}{y}$$

The symbols used are similar to those of 7.7.1 except that the known values are $L^*$, $u^*$, and $v^*$. The values u' and v' are here used as placeholders and the values $u'_n$ and $v'_n$ may be calculated from Eq 21 in 7.5.2 replacing the values $X$, $Y$, and $Z$ with the white point values $X_n$, $Y_n$, and $Z_n$ from Tables 5 with the previously mentioned precautions as to compatibility of illuminant-observer.

7.7.3 It may be noted that the condition $P_Y > \left(\frac{6}{29}\right)$ used in both of the above sections in the derivation of Y is equivalent to $L^* > 8$.

## 8. Report

8.1 The report of color calculations shall include the following:

8.1.1 *Specimen Identification:*

8.1.2 *Source of Data*—Give instrument identification, illuminating and viewing geometry, spectral bandpass, and date of measurement.

8.1.3 *Standard Observers*—Indicate whether the reported data were computed for the CIE 1931 standard observer (2°) or the CIE 1964 standard observer (10°), or specify any other observers that were used.

8.1.4 *Standard or Recommended Illuminants*—Indicate which of the following illuminants were used, or specify any other illuminants that were used: *A, C,* $D_{50}$, $D_{55}$, $D_{65}$, $D_{75}$, *FL2, FL7, FL11.*

8.1.5 *Bandpass Correction*—Because rectification of bandpass dependence is now specified by Practice E2729, it is no longer necessary to report the selection of bandpass correction as only one option remains.

8.1.6 *Method of Calculation*—Indicate whether the procedures for 1-nm bandpass and measurement interval, or for 5-nm triangular bandpass and measurement interval, or a specific abridged procedure (for 10- or 20-nm triangular bandpass and measurement interval) were used, and give the wavelength range of the spectral data used.

8.1.7 *Tristimulus Values*—Report as *X, Y, Z* or $X_{10}$, $Y_{10}$, $Z_{10}$.

8.1.8 *Chromaticity Coordinates*—Report as *x, y* or $x_{10}$, $y_{10}$.

8.1.9 As an alternative to 8.1.7 or 8.1.8, report CIELAB results as $L^*a^*b^*$ or $L^*C^*_{ab}h_{ab}$, or CIELUV results as $L^*u^*v^*$ or $L^*C^*_{uv}\ h_{uv}$.

## 9. Precision and Bias

9.1 *Precision*—The precision of results calculated by use of Tables 5 is limited by the precision of the measured spectral data and round-off of the data used in the calculations.

9.2 *Bias*—In the calculation procedures of 7.2, the bias is the same as the precision when the same spectral data are used. Bias of the abridged calculation procedures of 7.3 depends on the measurement interval and wavelength range, the complexity of the spectral character of the specimen, and the degree to which the passband of the measuring instrument conforms to the width and ideal triangular shape assumed in computing the tables. Least bias is obtained with the smallest measurement interval, the largest wavelength range, and the best correspondence of passband width and shape.

9.2.1 The uncertainty of the tristimulus values depends on the uncertainty of the spectral measurements.

9.2.2 The bias introduced by conversion of text to numeric formats, and that introduced by floating-point processor noise, are mostly insignificant.

## 10. Keywords

10.1 CIELAB; CIELUV; CIE system; color coordinates; tristimulus integration; tristimulus values; tristimulus weighting factors

## INTRODUCTION TO TABLES 5

Tables 5 consist of sets of 36 tables each, containing tristimulus weighting factors for a variety of CIE standard and recommended illuminants and the CIE 1931 and 1964 standard observers. The tables are presented with three decimal digits of precision. These digits should be carried in the calculations until the final values sought are calculated, and only then should the results be rounded to the appropriate number of significant digits available in the measured data.

Note that in the case of the values in Tables 5 the approximating procedure, lead to some small values with a negative sign. This sign is correct, and the corresponding entry must be carried in the calculations as a negative number.

The data labeled "Check Sum" at the bottom of each column in each table of Tables 5 is the algebraic sum of the entries above. It provides as a convenience the assurance that the tables have been copied correctly should copying be required. These check sums may not be identical to the "White Point" data located below them because of roundoff. Each value in a column has been rounded to three decimal digits. The "White Point" is the analytic total of the double-precision values at each wavelength, rounded to three decimal digits. It is these "White Point" data, and no others, that must be used as $X_n$, $Y_n$, $Z_n$ when converting tristimulus values calculated by use of these tables to CIELAB or CIELUV coordinates or for any other purpose requiring the ratio of the tristimulus value of the specimen to that of the white point.

The tables of Tables 5 have been prepared for use with spectral measurement data that have previously been corrected for spectral bandpass dependence.

The tables presented here were calculated from the data on CIE Standard D 001 (see 2.3) and have been reproduced here photographically to avoid any possible transcription errors.

Tables 5.1 through Tables 5.71 are indexed by illuminant, observer, and measurement interval in the accompanying Index to Table 5.

**TABLE 5 Index for Tables 5.1 to 5.71**

| Tables | Illuminant | Observer | Measurement Interval (nm) | Tables | Illuminant | Observer | Measurement Interval (nm) |
|---|---|---|---|---|---|---|---|
| 5.1 | A | 1931 | 10 | 5.37 | LED-B1 | 1931 | 10 |
| 5.3 | A | 1964 | 10 | 5.39 | LED-B1 | 1964 | 10 |
| 5.5 | C | 1931 | 10 | 5.41 | LED-B2 | 1931 | 10 |
| 5.7 | C | 1964 | 10 | 5.43 | LED-B2 | 1964 | 10 |
| 5.9 | D50 | 1931 | 10 | 5.45 | LED-B3 | 1931 | 10 |
| 5.11 | D50 | 1964 | 10 | 5.47 | LED-B3 | 1964 | 10 |
| 5.13 | D55 | 1931 | 10 | 5.49 | LED-B4 | 1931 | 10 |
| 5.15 | D55 | 1964 | 10 | 5.51 | LED-B4 | 1964 | 10 |
| 5.17 | D65 | 1931 | 10 | 5.53 | LED-B5 | 1931 | 10 |
| 5.19 | D65 | 1964 | 10 | 5.55 | LED-B5 | 1964 | 10 |
| 5.21 | D75 | 1931 | 10 | 5.57 | LED-BH1 | 1931 | 10 |
| 5.23 | D75 | 1964 | 10 | 5.59 | LED-BH1 | 1964 | 10 |
| 5.25 | F2 | 1931 | 10 | 5.61 | LED-RGB1 | 1931 | 10 |
| 5.27 | F2 | 1964 | 10 | 5.63 | LED-RGB1 | 1964 | 10 |
| 5.29 | F7 | 1931 | 10 | 5.65 | LED-V1 | 1931 | 10 |
| 5.31 | F7 | 1964 | 10 | 5.67 | LED-V1 | 1964 | 10 |
| 5.33 | F11 | 1931 | 10 | 5.69 | LED-V2 | 1931 | 10 |
| 5.35 | F11 | 1964 | 10 | 5.71 | LED-V2 | 1964 | 10 |

**Table 5.1 Illuminant A, 1931 Observer 10 nm Interval**

| nm | $W_x$ | $W_y$ | $W_z$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.001 |
| 380 | 0.001 | 0.000 | 0.005 |
| 390 | 0.005 | 0.000 | 0.021 |
| 400 | 0.017 | 0.000 | 0.083 |
| 410 | 0.070 | 0.002 | 0.333 |
| 420 | 0.272 | 0.008 | 1.309 |
| 430 | 0.644 | 0.027 | 3.144 |
| 440 | 0.924 | 0.061 | 4.635 |
| 450 | 1.036 | 0.117 | 5.461 |
| 460 | 1.017 | 0.209 | 5.838 |
| 470 | 0.779 | 0.362 | 5.128 |
| 480 | 0.428 | 0.618 | 3.639 |
| 490 | 0.160 | 1.039 | 2.332 |
| 500 | 0.024 | 1.802 | 1.513 |
| 510 | 0.059 | 3.091 | 0.962 |
| 520 | 0.428 | 4.756 | 0.533 |
| 530 | 1.210 | 6.320 | 0.305 |
| 540 | 2.313 | 7.599 | 0.162 |
| 550 | 3.735 | 8.571 | 0.075 |
| 560 | 5.511 | 9.219 | 0.036 |
| 570 | 7.573 | 9.456 | 0.021 |
| 580 | 9.718 | 9.224 | 0.017 |
| 590 | 11.583 | 8.543 | 0.013 |
| 600 | 12.706 | 7.547 | 0.010 |
| 610 | 12.671 | 6.360 | 0.005 |
| 620 | 11.347 | 5.061 | 0.002 |
| 630 | 9.010 | 3.716 | 0.001 |
| 640 | 6.551 | 2.559 | 0.000 |
| 650 | 4.345 | 1.639 | 0.000 |
| 660 | 2.626 | 0.971 | 0.000 |
| 670 | 1.457 | 0.533 | 0.000 |
| 680 | 0.794 | 0.289 | 0.000 |
| 690 | 0.406 | 0.147 | 0.000 |
| 700 | 0.207 | 0.075 | 0.000 |
| 710 | 0.109 | 0.039 | 0.000 |
| 720 | 0.056 | 0.020 | 0.000 |
| 730 | 0.029 | 0.010 | 0.000 |
| 740 | 0.014 | 0.005 | 0.000 |
| 750 | 0.007 | 0.003 | 0.000 |
| 760 | 0.004 | 0.001 | 0.000 |
| 770 | 0.002 | 0.001 | 0.000 |
| 780 | 0.001 | 0.000 | 0.000 |
| **Check Sum** | **109.849** | **100.000** | **35.584** |
| **White Point** | **109.850** | **100.000** | **35.585** |

**Table 5.3 Illuminant A, 1964 Observer 10 nm Interval**

| nm | $W_{10,x}$ | $W_{10,y}$ | $W_{10,z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.002 | 0.000 | 0.008 |
| 400 | 0.025 | 0.003 | 0.110 |
| 410 | 0.134 | 0.014 | 0.615 |
| 420 | 0.377 | 0.039 | 1.792 |
| 430 | 0.686 | 0.084 | 3.386 |
| 440 | 0.964 | 0.156 | 4.944 |
| 450 | 1.080 | 0.259 | 5.806 |
| 460 | 1.006 | 0.424 | 5.812 |
| 470 | 0.731 | 0.696 | 4.919 |
| 480 | 0.343 | 1.082 | 3.300 |
| 490 | 0.078 | 1.616 | 1.973 |
| 500 | 0.022 | 2.422 | 1.152 |
| 510 | 0.218 | 3.529 | 0.658 |
| 520 | 0.750 | 4.840 | 0.382 |
| 530 | 1.642 | 6.100 | 0.211 |
| 540 | 2.842 | 7.250 | 0.102 |
| 550 | 4.336 | 8.114 | 0.032 |
| 560 | 6.200 | 8.758 | 0.001 |
| 570 | 8.262 | 8.988 | 0.000 |
| 580 | 10.227 | 8.760 | 0.000 |
| 590 | 11.945 | 8.304 | 0.000 |
| 600 | 12.746 | 7.468 | 0.000 |
| 610 | 12.337 | 6.323 | 0.000 |
| 620 | 10.817 | 5.033 | 0.000 |
| 630 | 8.560 | 3.744 | 0.000 |
| 640 | 6.014 | 2.506 | 0.000 |
| 650 | 3.887 | 1.560 | 0.000 |
| 660 | 2.309 | 0.911 | 0.000 |
| 670 | 1.276 | 0.499 | 0.000 |
| 680 | 0.666 | 0.259 | 0.000 |
| 690 | 0.336 | 0.130 | 0.000 |
| 700 | 0.166 | 0.065 | 0.000 |
| 710 | 0.082 | 0.032 | 0.000 |
| 720 | 0.040 | 0.016 | 0.000 |
| 730 | 0.020 | 0.008 | 0.000 |
| 740 | 0.010 | 0.004 | 0.000 |
| 750 | 0.005 | 0.002 | 0.000 |
| 760 | 0.003 | 0.001 | 0.000 |
| 770 | 0.001 | 0.001 | 0.000 |
| 780 | 0.001 | 0.000 | 0.000 |
| **Check Sum** | **111.146** | **100.000** | **35.203** |
| **White Point** | **111.144** | **100.000** | **35.200** |

**Table 5.5 Illuminant C, 1931 Observer 10 nm Interval**

| nm | $W_x$ | $W_y$ | $W_z$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.001 | 0.000 | 0.004 |
| 380 | 0.004 | 0.000 | 0.017 |
| 390 | 0.018 | 0.001 | 0.084 |
| 400 | 0.076 | 0.002 | 0.358 |
| 410 | 0.325 | 0.009 | 1.547 |
| 420 | 1.292 | 0.038 | 6.207 |
| 430 | 2.968 | 0.123 | 14.496 |
| 440 | 3.959 | 0.261 | 19.860 |
| 450 | 3.931 | 0.443 | 20.728 |
| 460 | 3.360 | 0.692 | 19.286 |
| 470 | 2.283 | 1.061 | 15.022 |
| 480 | 1.116 | 1.612 | 9.479 |
| 490 | 0.363 | 2.358 | 5.286 |
| 500 | 0.048 | 3.414 | 2.868 |
| 510 | 0.092 | 4.842 | 1.512 |
| 520 | 0.578 | 6.449 | 0.720 |
| 530 | 1.519 | 7.936 | 0.381 |
| 540 | 2.786 | 9.145 | 0.195 |
| 550 | 4.285 | 9.831 | 0.086 |
| 560 | 5.877 | 9.834 | 0.038 |
| 570 | 7.323 | 9.148 | 0.020 |
| 580 | 8.414 | 7.990 | 0.015 |
| 590 | 8.985 | 6.629 | 0.010 |
| 600 | 8.958 | 5.321 | 0.007 |
| 610 | 8.324 | 4.177 | 0.003 |
| 620 | 7.055 | 3.146 | 0.001 |
| 630 | 5.327 | 2.196 | 0.000 |
| 640 | 3.692 | 1.442 | 0.000 |
| 650 | 2.352 | 0.887 | 0.000 |
| 660 | 1.360 | 0.503 | 0.000 |
| 670 | 0.713 | 0.261 | 0.000 |
| 680 | 0.364 | 0.132 | 0.000 |
| 690 | 0.172 | 0.062 | 0.000 |
| 700 | 0.080 | 0.029 | 0.000 |
| 710 | 0.039 | 0.014 | 0.000 |
| 720 | 0.019 | 0.007 | 0.000 |
| 730 | 0.009 | 0.003 | 0.000 |
| 740 | 0.004 | 0.001 | 0.000 |
| 750 | 0.002 | 0.001 | 0.000 |
| 760 | 0.001 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **98.074** | **100.000** | **118.230** |
| **White Point** | **98.074** | **100.000** | **118.232** |

**Table 5.7 Illuminant C, 1964 Observer 10 nm Interval**

| nm | $W_{10,x}$ | $W_{10,y}$ | $W_{10,z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | −0.002 |
| 390 | 0.006 | 0.001 | 0.025 |
| 400 | 0.102 | 0.011 | 0.457 |
| 410 | 0.594 | 0.060 | 2.728 |
| 420 | 1.705 | 0.179 | 8.117 |
| 430 | 3.025 | 0.372 | 14.933 |
| 440 | 3.944 | 0.638 | 20.229 |
| 450 | 3.919 | 0.941 | 21.068 |
| 460 | 3.178 | 1.340 | 18.361 |
| 470 | 2.047 | 1.948 | 13.768 |
| 480 | 0.856 | 2.695 | 8.218 |
| 490 | 0.171 | 3.502 | 4.273 |
| 500 | 0.040 | 4.387 | 2.088 |
| 510 | 0.325 | 5.291 | 0.986 |
| 520 | 0.970 | 6.274 | 0.493 |
| 530 | 1.971 | 7.319 | 0.252 |
| 540 | 3.271 | 8.339 | 0.117 |
| 550 | 4.755 | 8.896 | 0.035 |
| 560 | 6.319 | 8.928 | 0.001 |
| 570 | 7.637 | 8.311 | 0.000 |
| 580 | 8.464 | 7.253 | 0.000 |
| 590 | 8.855 | 6.158 | 0.000 |
| 600 | 8.589 | 5.032 | 0.000 |
| 610 | 7.747 | 3.969 | 0.000 |
| 620 | 6.427 | 2.990 | 0.000 |
| 630 | 4.837 | 2.116 | 0.000 |
| 640 | 3.240 | 1.350 | 0.000 |
| 650 | 2.011 | 0.807 | 0.000 |
| 660 | 1.143 | 0.451 | 0.000 |
| 670 | 0.597 | 0.234 | 0.000 |
| 680 | 0.292 | 0.114 | 0.000 |
| 690 | 0.136 | 0.053 | 0.000 |
| 700 | 0.062 | 0.024 | 0.000 |
| 710 | 0.028 | 0.011 | 0.000 |
| 720 | 0.013 | 0.005 | 0.000 |
| 730 | 0.006 | 0.002 | 0.000 |
| 740 | 0.003 | 0.001 | 0.000 |
| 750 | 0.001 | 0.000 | 0.000 |
| 760 | 0.001 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **97.287** | **100.002** | **116.147** |
| **White Point** | **97.285** | **100.000** | **116.145** |

**Table 5.9 Illuminant D50, 1931 Observer 10 nm Interval**

| nm | $W_x$ | $W_y$ | $W_z$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.001 |
| 370 | 0.001 | 0.000 | 0.005 |
| 380 | 0.003 | 0.000 | 0.013 |
| 390 | 0.012 | 0.000 | 0.057 |
| 400 | 0.060 | 0.002 | 0.285 |
| 410 | 0.234 | 0.006 | 1.113 |
| 420 | 0.775 | 0.023 | 3.723 |
| 430 | 1.610 | 0.066 | 7.862 |
| 440 | 2.453 | 0.162 | 12.309 |
| 450 | 2.777 | 0.313 | 14.647 |
| 460 | 2.500 | 0.514 | 14.346 |
| 470 | 1.717 | 0.798 | 11.299 |
| 480 | 0.861 | 1.239 | 7.309 |
| 490 | 0.283 | 1.839 | 4.128 |
| 500 | 0.040 | 2.948 | 2.466 |
| 510 | 0.088 | 4.632 | 1.447 |
| 520 | 0.593 | 6.587 | 0.736 |
| 530 | 1.590 | 8.308 | 0.401 |
| 540 | 2.799 | 9.197 | 0.196 |
| 550 | 4.207 | 9.650 | 0.085 |
| 560 | 5.657 | 9.471 | 0.037 |
| 570 | 7.132 | 8.902 | 0.020 |
| 580 | 8.540 | 8.112 | 0.015 |
| 590 | 9.255 | 6.829 | 0.010 |
| 600 | 9.835 | 5.838 | 0.007 |
| 610 | 9.469 | 4.753 | 0.004 |
| 620 | 8.009 | 3.573 | 0.002 |
| 630 | 5.926 | 2.443 | 0.001 |
| 640 | 4.171 | 1.629 | 0.000 |
| 650 | 2.609 | 0.984 | 0.000 |
| 660 | 1.541 | 0.570 | 0.000 |
| 670 | 0.855 | 0.313 | 0.000 |
| 680 | 0.434 | 0.158 | 0.000 |
| 690 | 0.194 | 0.070 | 0.000 |
| 700 | 0.097 | 0.035 | 0.000 |
| 710 | 0.050 | 0.018 | 0.000 |
| 720 | 0.022 | 0.008 | 0.000 |
| 730 | 0.012 | 0.004 | 0.000 |
| 740 | 0.006 | 0.002 | 0.000 |
| 750 | 0.002 | 0.001 | 0.000 |
| 760 | 0.001 | 0.000 | 0.000 |
| 770 | 0.001 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **96.421** | **99.997** | **82.524** |
| **White Point** | **96.422** | **100.000** | **82.521** |

**Table 5.11 Illuminant D50, 1964 Observer 10 nm Interval**

| nm | $W_{10,x}$ | $W_{10,y}$ | $W_{10,z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | –0.002 |
| 390 | 0.004 | 0.000 | 0.017 |
| 400 | 0.083 | 0.009 | 0.371 |
| 410 | 0.427 | 0.044 | 1.966 |
| 420 | 1.049 | 0.110 | 4.989 |
| 430 | 1.668 | 0.204 | 8.231 |
| 440 | 2.487 | 0.403 | 12.758 |
| 450 | 2.814 | 0.677 | 15.129 |
| 460 | 2.404 | 1.012 | 13.886 |
| 470 | 1.565 | 1.490 | 10.528 |
| 480 | 0.671 | 2.108 | 6.442 |
| 490 | 0.135 | 2.779 | 3.392 |
| 500 | 0.035 | 3.850 | 1.824 |
| 510 | 0.317 | 5.143 | 0.960 |
| 520 | 1.010 | 6.513 | 0.513 |
| 530 | 2.098 | 7.791 | 0.269 |
| 540 | 3.341 | 8.525 | 0.120 |
| 550 | 4.745 | 8.877 | 0.035 |
| 560 | 6.183 | 8.742 | 0.001 |
| 570 | 7.560 | 8.222 | 0.000 |
| 580 | 8.733 | 7.485 | 0.000 |
| 590 | 9.273 | 6.449 | 0.000 |
| 600 | 9.586 | 5.613 | 0.000 |
| 610 | 8.959 | 4.592 | 0.000 |
| 620 | 7.419 | 3.452 | 0.000 |
| 630 | 5.471 | 2.392 | 0.000 |
| 640 | 3.721 | 1.550 | 0.000 |
| 650 | 2.268 | 0.910 | 0.000 |
| 660 | 1.316 | 0.519 | 0.000 |
| 670 | 0.728 | 0.285 | 0.000 |
| 680 | 0.354 | 0.138 | 0.000 |
| 690 | 0.155 | 0.060 | 0.000 |
| 700 | 0.076 | 0.029 | 0.000 |
| 710 | 0.036 | 0.014 | 0.000 |
| 720 | 0.015 | 0.006 | 0.000 |
| 730 | 0.008 | 0.003 | 0.000 |
| 740 | 0.004 | 0.002 | 0.000 |
| 750 | 0.002 | 0.001 | 0.000 |
| 760 | 0.001 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **96.721** | **99.999** | **81.429** |
| **White Point** | **96.720** | **100.000** | **81.427** |

**Table 5.13 Illuminant D55, 1931 Observer 10 nm Interval**

| nm | $W_x$ | $W_y$ | $W_z$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.001 |
| 370 | 0.001 | 0.000 | 0.006 |
| 380 | 0.004 | 0.000 | 0.017 |
| 390 | 0.015 | 0.000 | 0.073 |
| 400 | 0.074 | 0.002 | 0.353 |
| 410 | 0.284 | 0.008 | 1.350 |
| 420 | 0.924 | 0.027 | 4.440 |
| 430 | 1.886 | 0.077 | 9.208 |
| 440 | 2.805 | 0.186 | 14.076 |
| 450 | 3.119 | 0.352 | 16.447 |
| 460 | 2.769 | 0.570 | 15.893 |
| 470 | 1.877 | 0.872 | 12.353 |
| 480 | 0.929 | 1.338 | 7.891 |
| 490 | 0.301 | 1.960 | 4.399 |
| 500 | 0.042 | 3.101 | 2.593 |
| 510 | 0.092 | 4.822 | 1.506 |
| 520 | 0.610 | 6.779 | 0.758 |
| 530 | 1.622 | 8.476 | 0.409 |
| 540 | 2.835 | 9.314 | 0.199 |
| 550 | 4.231 | 9.706 | 0.085 |
| 560 | 5.654 | 9.467 | 0.037 |
| 570 | 7.089 | 8.848 | 0.020 |
| 580 | 8.431 | 8.009 | 0.015 |
| 590 | 9.044 | 6.674 | 0.010 |
| 600 | 9.503 | 5.641 | 0.007 |
| 610 | 9.070 | 4.553 | 0.003 |
| 620 | 7.616 | 3.398 | 0.002 |
| 630 | 5.593 | 2.306 | 0.000 |
| 640 | 3.897 | 1.522 | 0.000 |
| 650 | 2.420 | 0.913 | 0.000 |
| 660 | 1.416 | 0.524 | 0.000 |
| 670 | 0.779 | 0.285 | 0.000 |
| 680 | 0.394 | 0.143 | 0.000 |
| 690 | 0.176 | 0.064 | 0.000 |
| 700 | 0.088 | 0.032 | 0.000 |
| 710 | 0.046 | 0.016 | 0.000 |
| 720 | 0.020 | 0.007 | 0.000 |
| 730 | 0.011 | 0.004 | 0.000 |
| 740 | 0.005 | 0.002 | 0.000 |
| 750 | 0.002 | 0.001 | 0.000 |
| 760 | 0.001 | 0.000 | 0.000 |
| 770 | 0.001 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **95.676** | **99.999** | **92.151** |
| **White Point** | **95.682** | **100.000** | **92.149** |

**Table 5.15 Illuminant D55, 1964 Observer 10 nm Interval**

| nm | $W_{10,x}$ | $W_{10,y}$ | $W_{10,z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | −0.002 |
| 390 | 0.005 | 0.001 | 0.022 |
| 400 | 0.102 | 0.011 | 0.457 |
| 410 | 0.515 | 0.053 | 2.370 |
| 420 | 1.245 | 0.130 | 5.922 |
| 430 | 1.944 | 0.238 | 9.596 |
| 440 | 2.829 | 0.459 | 14.517 |
| 450 | 3.144 | 0.757 | 16.906 |
| 460 | 2.651 | 1.116 | 15.309 |
| 470 | 1.703 | 1.621 | 11.453 |
| 480 | 0.721 | 2.265 | 6.921 |
| 490 | 0.143 | 2.947 | 3.597 |
| 500 | 0.037 | 4.029 | 1.908 |
| 510 | 0.329 | 5.329 | 0.995 |
| 520 | 1.034 | 6.671 | 0.525 |
| 530 | 2.130 | 7.910 | 0.273 |
| 540 | 3.367 | 8.592 | 0.121 |
| 550 | 4.749 | 8.885 | 0.035 |
| 560 | 6.151 | 8.696 | 0.001 |
| 570 | 7.479 | 8.133 | 0.000 |
| 580 | 8.580 | 7.355 | 0.000 |
| 590 | 9.019 | 6.272 | 0.000 |
| 600 | 9.218 | 5.398 | 0.000 |
| 610 | 8.540 | 4.377 | 0.000 |
| 620 | 7.020 | 3.267 | 0.000 |
| 630 | 5.139 | 2.247 | 0.000 |
| 640 | 3.459 | 1.441 | 0.000 |
| 650 | 2.094 | 0.840 | 0.000 |
| 660 | 1.204 | 0.475 | 0.000 |
| 670 | 0.660 | 0.258 | 0.000 |
| 680 | 0.319 | 0.124 | 0.000 |
| 690 | 0.141 | 0.055 | 0.000 |
| 700 | 0.068 | 0.027 | 0.000 |
| 710 | 0.033 | 0.013 | 0.000 |
| 720 | 0.014 | 0.005 | 0.000 |
| 730 | 0.007 | 0.003 | 0.000 |
| 740 | 0.004 | 0.001 | 0.000 |
| 750 | 0.002 | 0.001 | 0.000 |
| 760 | 0.001 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **95.800** | **100.002** | **90.926** |
| **White Point** | **95.799** | **100.000** | **90.926** |

**Table 5.17 Illuminant D65, 1931 Observer 10 nm Interval**

| nm | $W_x$ | $W_y$ | $W_z$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.001 |
| 370 | 0.002 | 0.000 | 0.010 |
| 380 | 0.006 | 0.000 | 0.026 |
| 390 | 0.022 | 0.001 | 0.104 |
| 400 | 0.101 | 0.003 | 0.477 |
| 410 | 0.376 | 0.010 | 1.788 |
| 420 | 1.200 | 0.035 | 5.765 |
| 430 | 2.396 | 0.098 | 11.698 |
| 440 | 3.418 | 0.226 | 17.150 |
| 450 | 3.699 | 0.417 | 19.506 |
| 460 | 3.227 | 0.664 | 18.520 |
| 470 | 2.149 | 0.998 | 14.137 |
| 480 | 1.042 | 1.501 | 8.850 |
| 490 | 0.333 | 2.164 | 4.856 |
| 500 | 0.045 | 3.352 | 2.802 |
| 510 | 0.098 | 5.129 | 1.602 |
| 520 | 0.637 | 7.076 | 0.791 |
| 530 | 1.667 | 8.708 | 0.420 |
| 540 | 2.884 | 9.474 | 0.202 |
| 550 | 4.250 | 9.752 | 0.086 |
| 560 | 5.626 | 9.419 | 0.037 |
| 570 | 6.988 | 8.722 | 0.019 |
| 580 | 8.214 | 7.802 | 0.014 |
| 590 | 8.730 | 6.442 | 0.010 |
| 600 | 9.015 | 5.351 | 0.007 |
| 610 | 8.492 | 4.263 | 0.003 |
| 620 | 7.050 | 3.145 | 0.001 |
| 630 | 5.124 | 2.113 | 0.000 |
| 640 | 3.516 | 1.373 | 0.000 |
| 650 | 2.167 | 0.818 | 0.000 |
| 660 | 1.252 | 0.463 | 0.000 |
| 670 | 0.678 | 0.248 | 0.000 |
| 680 | 0.341 | 0.124 | 0.000 |
| 690 | 0.153 | 0.055 | 0.000 |
| 700 | 0.076 | 0.027 | 0.000 |
| 710 | 0.040 | 0.014 | 0.000 |
| 720 | 0.018 | 0.006 | 0.000 |
| 730 | 0.009 | 0.003 | 0.000 |
| 740 | 0.005 | 0.002 | 0.000 |
| 750 | 0.002 | 0.001 | 0.000 |
| 760 | 0.001 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **95.049** | **99.999** | **108.882** |
| **White Point** | **95.047** | **100.000** | **108.883** |

**Table 5.19 Illuminant D65, 1964 Observer 10 nm Interval**

| nm | $W_{10,x}$ | $W_{10,y}$ | $W_{10,z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | −0.002 |
| 390 | 0.008 | 0.001 | 0.033 |
| 400 | 0.137 | 0.014 | 0.612 |
| 410 | 0.676 | 0.069 | 3.110 |
| 420 | 1.603 | 0.168 | 7.627 |
| 430 | 2.451 | 0.300 | 12.095 |
| 440 | 3.418 | 0.554 | 17.537 |
| 450 | 3.699 | 0.890 | 19.888 |
| 460 | 3.064 | 1.290 | 17.695 |
| 470 | 1.933 | 1.838 | 13.000 |
| 480 | 0.802 | 2.520 | 7.699 |
| 490 | 0.156 | 3.226 | 3.938 |
| 500 | 0.039 | 4.320 | 2.046 |
| 510 | 0.347 | 5.621 | 1.049 |
| 520 | 1.070 | 6.907 | 0.544 |
| 530 | 2.170 | 8.059 | 0.278 |
| 540 | 3.397 | 8.668 | 0.122 |
| 550 | 4.732 | 8.855 | 0.035 |
| 560 | 6.070 | 8.581 | 0.001 |
| 570 | 7.311 | 7.951 | 0.000 |
| 580 | 8.291 | 7.106 | 0.000 |
| 590 | 8.634 | 6.004 | 0.000 |
| 600 | 8.672 | 5.079 | 0.000 |
| 610 | 7.930 | 4.065 | 0.000 |
| 620 | 6.446 | 2.999 | 0.000 |
| 630 | 4.669 | 2.042 | 0.000 |
| 640 | 3.095 | 1.290 | 0.000 |
| 650 | 1.859 | 0.746 | 0.000 |
| 660 | 1.056 | 0.417 | 0.000 |
| 670 | 0.570 | 0.223 | 0.000 |
| 680 | 0.274 | 0.107 | 0.000 |
| 690 | 0.121 | 0.047 | 0.000 |
| 700 | 0.058 | 0.023 | 0.000 |
| 710 | 0.028 | 0.011 | 0.000 |
| 720 | 0.012 | 0.005 | 0.000 |
| 730 | 0.006 | 0.002 | 0.000 |
| 740 | 0.003 | 0.001 | 0.000 |
| 750 | 0.001 | 0.001 | 0.000 |
| 760 | 0.001 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **94.809** | **100.000** | **107.307** |
| **White Point** | **94.811** | **100.000** | **107.304** |

**Table 5.21 Illuminant D75, 1931 Observer 10 nm Interval**

| nm | $W_x$ | $W_y$ | $W_z$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.002 |
| 370 | 0.003 | 0.000 | 0.013 |
| 380 | 0.007 | 0.000 | 0.035 |
| 390 | 0.028 | 0.001 | 0.132 |
| 400 | 0.124 | 0.003 | 0.587 |
| 410 | 0.457 | 0.012 | 2.176 |
| 420 | 1.439 | 0.043 | 6.916 |
| 430 | 2.809 | 0.115 | 13.714 |
| 440 | 3.926 | 0.260 | 19.702 |
| 450 | 4.182 | 0.472 | 22.055 |
| 460 | 3.600 | 0.741 | 20.660 |
| 470 | 2.364 | 1.098 | 15.551 |
| 480 | 1.133 | 1.632 | 9.621 |
| 490 | 0.357 | 2.321 | 5.209 |
| 500 | 0.048 | 3.551 | 2.967 |
| 510 | 0.103 | 5.365 | 1.676 |
| 520 | 0.655 | 7.281 | 0.814 |
| 530 | 1.698 | 8.873 | 0.427 |
| 540 | 2.912 | 9.567 | 0.204 |
| 550 | 4.256 | 9.766 | 0.086 |
| 560 | 5.584 | 9.350 | 0.036 |
| 570 | 6.879 | 8.586 | 0.019 |
| 580 | 8.032 | 7.629 | 0.014 |
| 590 | 8.478 | 6.256 | 0.010 |
| 600 | 8.677 | 5.151 | 0.006 |
| 610 | 8.105 | 4.068 | 0.003 |
| 620 | 6.673 | 2.977 | 0.001 |
| 630 | 4.804 | 1.981 | 0.000 |
| 640 | 3.274 | 1.279 | 0.000 |
| 650 | 2.008 | 0.757 | 0.000 |
| 660 | 1.151 | 0.426 | 0.000 |
| 670 | 0.618 | 0.226 | 0.000 |
| 680 | 0.309 | 0.112 | 0.000 |
| 690 | 0.139 | 0.050 | 0.000 |
| 700 | 0.068 | 0.025 | 0.000 |
| 710 | 0.036 | 0.013 | 0.000 |
| 720 | 0.016 | 0.006 | 0.000 |
| 730 | 0.008 | 0.003 | 0.000 |
| 740 | 0.004 | 0.002 | 0.000 |
| 750 | 0.002 | 0.001 | 0.000 |
| 760 | 0.001 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **94.967** | **99.999** | **122.636** |
| **White Point** | **94.972** | **100.000** | **122.638** |

**Table 5.23 Illuminant D75, 1964 Observer 10 nm Interval**

| nm | $W_{10,x}$ | $W_{10,y}$ | $W_{10,z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | −0.002 |
| 390 | 0.010 | 0.001 | 0.042 |
| 400 | 0.167 | 0.018 | 0.749 |
| 410 | 0.816 | 0.083 | 3.755 |
| 420 | 1.911 | 0.200 | 9.091 |
| 430 | 2.855 | 0.350 | 14.089 |
| 440 | 3.900 | 0.632 | 20.011 |
| 450 | 4.155 | 1.000 | 22.341 |
| 460 | 3.396 | 1.430 | 19.612 |
| 470 | 2.112 | 2.008 | 14.205 |
| 480 | 0.866 | 2.721 | 8.316 |
| 490 | 0.167 | 3.438 | 4.197 |
| 500 | 0.041 | 4.546 | 2.151 |
| 510 | 0.360 | 5.842 | 1.090 |
| 520 | 1.094 | 7.061 | 0.556 |
| 530 | 2.197 | 8.158 | 0.281 |
| 540 | 3.408 | 8.696 | 0.122 |
| 550 | 4.708 | 8.809 | 0.034 |
| 560 | 5.985 | 8.462 | 0.001 |
| 570 | 7.150 | 7.776 | 0.000 |
| 580 | 8.055 | 6.903 | 0.000 |
| 590 | 8.329 | 5.793 | 0.000 |
| 600 | 8.293 | 4.857 | 0.000 |
| 610 | 7.519 | 3.854 | 0.000 |
| 620 | 6.060 | 2.820 | 0.000 |
| 630 | 4.349 | 1.902 | 0.000 |
| 640 | 2.864 | 1.193 | 0.000 |
| 650 | 1.711 | 0.687 | 0.000 |
| 660 | 0.964 | 0.380 | 0.000 |
| 670 | 0.516 | 0.202 | 0.000 |
| 680 | 0.247 | 0.096 | 0.000 |
| 690 | 0.109 | 0.042 | 0.000 |
| 700 | 0.052 | 0.020 | 0.000 |
| 710 | 0.026 | 0.010 | 0.000 |
| 720 | 0.011 | 0.004 | 0.000 |
| 730 | 0.006 | 0.002 | 0.000 |
| 740 | 0.003 | 0.001 | 0.000 |
| 750 | 0.001 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **94.413** | **99.997** | **120.641** |
| **White Point** | **94.416** | **100.000** | **120.641** |

**Table 5.25 Illuminant F2, 1931 Observer 10 nm Interval**

| nm | $W_x$ | $W_y$ | $W_z$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.001 | 0.000 | 0.003 |
| 390 | −0.001 | 0.000 | −0.006 |
| 400 | 0.082 | 0.002 | 0.391 |
| 410 | 0.169 | 0.005 | 0.802 |
| 420 | 0.173 | 0.001 | 0.806 |
| 430 | 2.860 | 0.136 | 14.065 |
| 440 | 3.931 | 0.234 | 19.588 |
| 450 | 1.338 | 0.162 | 7.114 |
| 460 | 1.421 | 0.294 | 8.161 |
| 470 | 1.011 | 0.470 | 6.652 |
| 480 | 0.502 | 0.723 | 4.257 |
| 490 | 0.166 | 1.078 | 2.418 |
| 500 | 0.022 | 1.614 | 1.356 |
| 510 | 0.045 | 2.425 | 0.757 |
| 520 | 0.310 | 3.466 | 0.387 |
| 530 | 0.793 | 4.424 | 0.223 |
| 540 | 2.935 | 9.137 | 0.175 |
| 550 | 5.305 | 12.533 | 0.122 |
| 560 | 6.428 | 10.676 | 0.039 |
| 570 | 10.089 | 12.520 | 0.028 |
| 580 | 13.508 | 12.872 | 0.024 |
| 590 | 13.082 | 9.655 | 0.015 |
| 600 | 11.989 | 7.125 | 0.009 |
| 610 | 9.453 | 4.746 | 0.004 |
| 620 | 6.393 | 2.850 | 0.001 |
| 630 | 3.711 | 1.529 | 0.000 |
| 640 | 1.929 | 0.753 | 0.000 |
| 650 | 0.906 | 0.341 | 0.000 |
| 660 | 0.387 | 0.143 | 0.000 |
| 670 | 0.152 | 0.055 | 0.000 |
| 680 | 0.059 | 0.021 | 0.000 |
| 690 | 0.023 | 0.008 | 0.000 |
| 700 | 0.008 | 0.003 | 0.000 |
| 710 | 0.003 | 0.001 | 0.000 |
| 720 | 0.001 | 0.000 | 0.000 |
| 730 | 0.001 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **99.185** | **100.002** | **67.391** |
| **White Point** | **99.186** | **100.000** | **67.393** |

**Table 5.27 Illuminant F2, 1964 Observer 10 nm Interval**

| nm | $W_{10,x}$ | $W_{10,y}$ | $W_{10,z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | −0.001 |
| 390 | −0.009 | −0.001 | −0.041 |
| 400 | 0.133 | 0.014 | 0.603 |
| 410 | 0.311 | 0.032 | 1.425 |
| 420 | 0.310 | 0.025 | 1.418 |
| 430 | 2.977 | 0.395 | 14.861 |
| 440 | 4.074 | 0.617 | 20.711 |
| 450 | 1.393 | 0.354 | 7.553 |
| 460 | 1.402 | 0.593 | 8.103 |
| 470 | 0.946 | 0.900 | 6.363 |
| 480 | 0.401 | 1.261 | 3.852 |
| 490 | 0.081 | 1.671 | 2.039 |
| 500 | 0.019 | 2.165 | 1.030 |
| 510 | 0.169 | 2.764 | 0.515 |
| 520 | 0.543 | 3.517 | 0.277 |
| 530 | 1.093 | 4.262 | 0.154 |
| 540 | 3.562 | 8.685 | 0.107 |
| 550 | 6.166 | 11.838 | 0.055 |
| 560 | 7.209 | 10.117 | −0.001 |
| 570 | 10.967 | 11.867 | 0.000 |
| 580 | 14.182 | 12.191 | 0.000 |
| 590 | 13.453 | 9.357 | 0.000 |
| 600 | 11.997 | 7.032 | 0.000 |
| 610 | 9.183 | 4.707 | 0.000 |
| 620 | 6.075 | 2.825 | 0.000 |
| 630 | 3.517 | 1.537 | 0.000 |
| 640 | 1.767 | 0.736 | 0.000 |
| 650 | 0.808 | 0.324 | 0.000 |
| 660 | 0.339 | 0.134 | 0.000 |
| 670 | 0.133 | 0.052 | 0.000 |
| 680 | 0.049 | 0.019 | 0.000 |
| 690 | 0.019 | 0.007 | 0.000 |
| 700 | 0.007 | 0.003 | 0.000 |
| 710 | 0.003 | 0.001 | 0.000 |
| 720 | 0.001 | 0.000 | 0.000 |
| 730 | 0.000 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **103.280** | **100.001** | **69.023** |
| **White Point** | **103.279** | **100.000** | **69.027** |

**Table 5.29 Illuminant F7, 1931 Observer**
**10 nm Interval**

| nm | $W_x$ | $W_y$ | $W_z$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | −0.001 |
| 380 | 0.001 | 0.000 | 0.007 |
| 390 | 0.004 | 0.000 | 0.019 |
| 400 | 0.110 | 0.003 | 0.521 |
| 410 | 0.269 | 0.007 | 1.282 |
| 420 | 0.475 | 0.009 | 2.249 |
| 430 | 3.951 | 0.183 | 19.408 |
| 440 | 5.466 | 0.331 | 27.269 |
| 450 | 2.547 | 0.300 | 13.501 |
| 460 | 2.585 | 0.534 | 14.846 |
| 470 | 1.840 | 0.854 | 12.103 |
| 480 | 0.915 | 1.318 | 7.764 |
| 490 | 0.302 | 1.964 | 4.405 |
| 500 | 0.041 | 2.979 | 2.499 |
| 510 | 0.087 | 4.507 | 1.404 |
| 520 | 0.556 | 6.177 | 0.691 |
| 530 | 1.258 | 6.924 | 0.347 |
| 540 | 3.644 | 11.327 | 0.217 |
| 550 | 5.522 | 13.146 | 0.130 |
| 560 | 4.932 | 8.167 | 0.029 |
| 570 | 7.145 | 8.839 | 0.019 |
| 580 | 9.610 | 9.176 | 0.017 |
| 590 | 8.888 | 6.553 | 0.010 |
| 600 | 8.828 | 5.241 | 0.007 |
| 610 | 7.951 | 3.991 | 0.003 |
| 620 | 6.485 | 2.892 | 0.001 |
| 630 | 4.721 | 1.947 | 0.000 |
| 640 | 3.106 | 1.213 | 0.000 |
| 650 | 1.949 | 0.735 | 0.000 |
| 660 | 1.093 | 0.404 | 0.000 |
| 670 | 0.449 | 0.164 | 0.000 |
| 680 | 0.181 | 0.066 | 0.000 |
| 690 | 0.078 | 0.028 | 0.000 |
| 700 | 0.032 | 0.011 | 0.000 |
| 710 | 0.013 | 0.005 | 0.000 |
| 720 | 0.005 | 0.002 | 0.000 |
| 730 | 0.002 | 0.001 | 0.000 |
| 740 | 0.001 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **95.042** | **99.998** | **108.747** |
| **White Point** | **95.041** | **100.000** | **108.747** |

**Table 5.31 Illuminant F7, 1964 Observer**
**10 nm Interval**

| nm | $W_{10,x}$ | $W_{10,y}$ | $W_{10,z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | −0.001 |
| 390 | −0.007 | −0.001 | −0.034 |
| 400 | 0.168 | 0.017 | 0.757 |
| 410 | 0.486 | 0.050 | 2.229 |
| 420 | 0.715 | 0.067 | 3.341 |
| 430 | 4.000 | 0.524 | 19.933 |
| 440 | 5.496 | 0.842 | 27.981 |
| 450 | 2.569 | 0.639 | 13.889 |
| 460 | 2.473 | 1.046 | 14.292 |
| 470 | 1.669 | 1.587 | 11.224 |
| 480 | 0.709 | 2.230 | 6.810 |
| 490 | 0.144 | 2.951 | 3.603 |
| 500 | 0.035 | 3.873 | 1.840 |
| 510 | 0.308 | 4.979 | 0.927 |
| 520 | 0.943 | 6.080 | 0.479 |
| 530 | 1.674 | 6.466 | 0.232 |
| 540 | 4.286 | 10.438 | 0.129 |
| 550 | 6.229 | 12.041 | 0.059 |
| 560 | 5.360 | 7.501 | −0.002 |
| 570 | 7.528 | 8.122 | 0.000 |
| 580 | 9.783 | 8.424 | 0.000 |
| 590 | 8.861 | 6.158 | 0.000 |
| 600 | 8.563 | 5.015 | 0.000 |
| 610 | 7.486 | 3.837 | 0.000 |
| 620 | 5.977 | 2.780 | 0.000 |
| 630 | 4.337 | 1.897 | 0.000 |
| 640 | 2.757 | 1.149 | 0.000 |
| 650 | 1.685 | 0.676 | 0.000 |
| 660 | 0.929 | 0.367 | 0.000 |
| 670 | 0.380 | 0.149 | 0.000 |
| 680 | 0.147 | 0.057 | 0.000 |
| 690 | 0.062 | 0.024 | 0.000 |
| 700 | 0.025 | 0.010 | 0.000 |
| 710 | 0.010 | 0.004 | 0.000 |
| 720 | 0.004 | 0.001 | 0.000 |
| 730 | 0.001 | 0.001 | 0.000 |
| 740 | 0.001 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **95.793** | **100.001** | **107.688** |
| **White Point** | **95.792** | **100.000** | **107.686** |

**Table 5.33 Illuminant F11, 1931 Observer 10 nm Interval**

| nm | $W_x$ | $W_y$ | $W_z$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.001 | 0.000 | 0.002 |
| 390 | −0.005 | 0.000 | −0.022 |
| 400 | 0.059 | 0.002 | 0.281 |
| 410 | 0.097 | 0.003 | 0.463 |
| 420 | 0.024 | −0.004 | 0.087 |
| 430 | 2.687 | 0.128 | 13.207 |
| 440 | 3.952 | 0.237 | 19.705 |
| 450 | 1.471 | 0.177 | 7.819 |
| 460 | 1.328 | 0.274 | 7.621 |
| 470 | 0.723 | 0.295 | 4.685 |
| 480 | 0.448 | 0.803 | 4.044 |
| 490 | 0.326 | 1.905 | 4.458 |
| 500 | 0.020 | 1.104 | 1.005 |
| 510 | 0.006 | 0.499 | 0.121 |
| 520 | −0.012 | 0.244 | 0.038 |
| 530 | −0.155 | 0.163 | 0.037 |
| 540 | 8.983 | 26.955 | 0.483 |
| 550 | 10.520 | 26.054 | 0.291 |
| 560 | 0.993 | 1.348 | −0.007 |
| 570 | 1.064 | 1.283 | 0.002 |
| 580 | 6.717 | 6.191 | 0.011 |
| 590 | 8.697 | 6.590 | 0.010 |
| 600 | 6.188 | 3.669 | 0.005 |
| 610 | 27.072 | 13.415 | 0.009 |
| 620 | 13.847 | 6.329 | 0.003 |
| 630 | 4.003 | 1.614 | 0.000 |
| 640 | 0.864 | 0.335 | 0.000 |
| 650 | 0.541 | 0.203 | 0.000 |
| 660 | 0.301 | 0.111 | 0.000 |
| 670 | 0.096 | 0.035 | 0.000 |
| 680 | 0.046 | 0.017 | 0.000 |
| 690 | 0.028 | 0.010 | 0.000 |
| 700 | 0.014 | 0.005 | 0.000 |
| 710 | 0.018 | 0.007 | 0.000 |
| 720 | 0.002 | 0.001 | 0.000 |
| 730 | 0.000 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **100.964** | **100.002** | **64.358** |
| **White Point** | **100.962** | **100.000** | **64.350** |

**Table 5.35 Illuminant F11, 1964 Observer 10 nm Interval**

| nm | $W_{10,x}$ | $W_{10,y}$ | $W_{10,z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | −0.010 | −0.001 | −0.044 |
| 400 | 0.099 | 0.010 | 0.451 |
| 410 | 0.182 | 0.019 | 0.829 |
| 420 | 0.098 | 0.003 | 0.415 |
| 430 | 2.796 | 0.372 | 13.964 |
| 440 | 4.103 | 0.625 | 20.873 |
| 450 | 1.534 | 0.388 | 8.310 |
| 460 | 1.314 | 0.554 | 7.586 |
| 470 | 0.681 | 0.578 | 4.498 |
| 480 | 0.343 | 1.380 | 3.625 |
| 490 | 0.176 | 2.955 | 3.789 |
| 500 | 0.009 | 1.506 | 0.773 |
| 510 | 0.034 | 0.564 | 0.074 |
| 520 | 0.005 | 0.257 | 0.028 |
| 530 | −0.145 | 0.170 | 0.027 |
| 540 | 10.852 | 25.656 | 0.293 |
| 550 | 12.320 | 24.661 | 0.148 |
| 560 | 1.096 | 1.274 | −0.010 |
| 570 | 1.157 | 1.214 | 0.000 |
| 580 | 7.036 | 5.881 | 0.000 |
| 590 | 8.982 | 6.382 | 0.000 |
| 600 | 6.204 | 3.629 | 0.000 |
| 610 | 26.264 | 13.321 | 0.000 |
| 620 | 13.228 | 6.279 | 0.000 |
| 630 | 3.797 | 1.631 | 0.000 |
| 640 | 0.794 | 0.329 | 0.000 |
| 650 | 0.481 | 0.192 | 0.000 |
| 660 | 0.264 | 0.104 | 0.000 |
| 670 | 0.084 | 0.033 | 0.000 |
| 680 | 0.038 | 0.015 | 0.000 |
| 690 | 0.023 | 0.009 | 0.000 |
| 700 | 0.011 | 0.004 | 0.000 |
| 710 | 0.014 | 0.005 | 0.000 |
| 720 | 0.002 | 0.001 | 0.000 |
| 730 | 0.000 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **Check Sum** | **103.866** | **100.000** | **65.629** |
| **White Point** | **103.863** | **100.000** | **65.607** |

Table 5.37 LED Illuminant B1, 1931 Observer
10 nm Interval

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | 0.000 | 0.000 | 0.000 |
| 410 | 0.002 | 0.000 | 0.009 |
| 420 | 0.048 | 0.001 | 0.231 |
| 430 | 0.300 | 0.011 | 1.460 |
| 440 | 1.030 | 0.070 | 5.180 |
| 450 | 1.741 | 0.199 | 9.191 |
| 460 | 1.277 | 0.258 | 7.298 |
| 470 | 0.590 | 0.270 | 3.878 |
| 480 | 0.240 | 0.350 | 2.051 |
| 490 | 0.091 | 0.605 | 1.346 |
| 500 | 0.015 | 1.199 | 1.005 |
| 510 | 0.044 | 2.310 | 0.718 |
| 520 | 0.347 | 3.859 | 0.433 |
| 530 | 1.049 | 5.481 | 0.265 |
| 540 | 2.133 | 7.008 | 0.150 |
| 550 | 3.667 | 8.415 | 0.074 |
| 560 | 5.778 | 9.664 | 0.038 |
| 570 | 8.438 | 10.532 | 0.023 |
| 580 | 11.354 | 10.774 | 0.020 |
| 590 | 13.865 | 10.225 | 0.016 |
| 600 | 15.084 | 8.962 | 0.011 |
| 610 | 14.355 | 7.208 | 0.005 |
| 620 | 11.781 | 5.256 | 0.002 |
| 630 | 8.264 | 3.407 | 0.001 |
| 640 | 5.132 | 2.004 | 0.000 |
| 650 | 2.814 | 1.061 | 0.000 |
| 660 | 1.367 | 0.505 | 0.000 |
| 670 | 0.596 | 0.218 | 0.000 |
| 680 | 0.250 | 0.091 | 0.000 |
| 690 | 0.098 | 0.035 | 0.000 |
| 700 | 0.037 | 0.013 | 0.000 |
| 710 | 0.015 | 0.005 | 0.000 |
| 720 | 0.006 | 0.002 | 0.000 |
| 730 | 0.002 | 0.001 | 0.000 |
| 740 | 0.001 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **111.811** | **99.999** | **33.405** |
| **WP** | **111.811** | **100.000** | **33.406** |

Table 5.39 LED Illuminant B1, 1964 Observer
10 nm Interval

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | 0.000 | 0.000 | -0.001 |
| 410 | 0.007 | 0.001 | 0.030 |
| 420 | 0.068 | 0.007 | 0.322 |
| 430 | 0.319 | 0.038 | 1.571 |
| 440 | 1.087 | 0.180 | 5.594 |
| 450 | 1.828 | 0.445 | 9.836 |
| 460 | 1.278 | 0.527 | 7.352 |
| 470 | 0.558 | 0.523 | 3.742 |
| 480 | 0.192 | 0.619 | 1.873 |
| 490 | 0.043 | 0.949 | 1.147 |
| 500 | 0.014 | 1.625 | 0.770 |
| 510 | 0.164 | 2.657 | 0.496 |
| 520 | 0.613 | 3.958 | 0.313 |
| 530 | 1.435 | 5.332 | 0.184 |
| 540 | 2.640 | 6.739 | 0.095 |
| 550 | 4.291 | 8.029 | 0.031 |
| 560 | 6.552 | 9.254 | 0.001 |
| 570 | 9.277 | 10.088 | 0.000 |
| 580 | 12.043 | 10.314 | 0.000 |
| 590 | 14.410 | 10.018 | 0.000 |
| 600 | 15.251 | 8.937 | 0.000 |
| 610 | 14.090 | 7.223 | 0.000 |
| 620 | 11.319 | 5.267 | 0.000 |
| 630 | 7.914 | 3.461 | 0.000 |
| 640 | 4.750 | 1.979 | 0.000 |
| 650 | 2.537 | 1.018 | 0.000 |
| 660 | 1.211 | 0.478 | 0.000 |
| 670 | 0.526 | 0.206 | 0.000 |
| 680 | 0.212 | 0.082 | 0.000 |
| 690 | 0.081 | 0.032 | 0.000 |
| 700 | 0.030 | 0.012 | 0.000 |
| 710 | 0.011 | 0.004 | 0.000 |
| 720 | 0.004 | 0.002 | 0.000 |
| 730 | 0.001 | 0.001 | 0.000 |
| 740 | 0.001 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **114.757** | **100.005** | **33.356** |
| **WP** | **114.757** | **100.000** | **33.356** |

Table 5.41 LED Illuminant B2, 1931 Observer
10 nm Interval

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | 0.000 | 0.000 | -0.001 |
| 410 | 0.000 | 0.000 | 0.002 |
| 420 | 0.047 | 0.001 | 0.222 |
| 430 | 0.325 | 0.012 | 1.580 |
| 440 | 1.200 | 0.082 | 6.035 |
| 450 | 2.294 | 0.264 | 12.125 |
| 460 | 1.652 | 0.330 | 9.424 |
| 470 | 0.697 | 0.320 | 4.581 |
| 480 | 0.261 | 0.381 | 2.238 |
| 490 | 0.097 | 0.652 | 1.447 |
| 500 | 0.017 | 1.322 | 1.106 |
| 510 | 0.049 | 2.565 | 0.798 |
| 520 | 0.380 | 4.228 | 0.475 |
| 530 | 1.133 | 5.918 | 0.286 |
| 540 | 2.278 | 7.483 | 0.160 |
| 550 | 3.866 | 8.870 | 0.078 |
| 560 | 5.968 | 9.980 | 0.039 |
| 570 | 8.477 | 10.583 | 0.024 |
| 580 | 11.072 | 10.508 | 0.019 |
| 590 | 13.203 | 9.738 | 0.015 |
| 600 | 14.151 | 8.407 | 0.011 |
| 610 | 13.337 | 6.696 | 0.005 |
| 620 | 10.902 | 4.863 | 0.002 |
| 630 | 7.641 | 3.150 | 0.001 |
| 640 | 4.743 | 1.852 | 0.000 |
| 650 | 2.606 | 0.983 | 0.000 |
| 660 | 1.267 | 0.469 | 0.000 |
| 670 | 0.554 | 0.203 | 0.000 |
| 680 | 0.233 | 0.085 | 0.000 |
| 690 | 0.091 | 0.033 | 0.000 |
| 700 | 0.035 | 0.012 | 0.000 |
| 710 | 0.014 | 0.005 | 0.000 |
| 720 | 0.005 | 0.002 | 0.000 |
| 730 | 0.002 | 0.001 | 0.000 |
| 740 | 0.001 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **108.598** | **99.998** | **40.672** |
| **WP** | **108.597** | **100.000** | **40.671** |

Table 5.43 LED Illuminant B2, 1964 Observer
10 nm Interval

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | 0.000 | 0.000 | -0.001 |
| 410 | 0.004 | 0.000 | 0.018 |
| 420 | 0.065 | 0.006 | 0.308 |
| 430 | 0.345 | 0.040 | 1.693 |
| 440 | 1.264 | 0.209 | 6.501 |
| 450 | 2.400 | 0.588 | 12.927 |
| 460 | 1.649 | 0.674 | 9.475 |
| 470 | 0.656 | 0.617 | 4.403 |
| 480 | 0.209 | 0.673 | 2.037 |
| 490 | 0.046 | 1.020 | 1.228 |
| 500 | 0.016 | 1.785 | 0.845 |
| 510 | 0.182 | 2.941 | 0.549 |
| 520 | 0.669 | 4.322 | 0.342 |
| 530 | 1.545 | 5.739 | 0.199 |
| 540 | 2.811 | 7.173 | 0.101 |
| 550 | 4.509 | 8.437 | 0.033 |
| 560 | 6.745 | 9.526 | 0.001 |
| 570 | 9.291 | 10.105 | 0.000 |
| 580 | 11.706 | 10.027 | 0.000 |
| 590 | 13.678 | 9.509 | 0.000 |
| 600 | 14.261 | 8.357 | 0.000 |
| 610 | 13.048 | 6.689 | 0.000 |
| 620 | 10.440 | 4.858 | 0.000 |
| 630 | 7.293 | 3.190 | 0.000 |
| 640 | 4.375 | 1.823 | 0.000 |
| 650 | 2.341 | 0.939 | 0.000 |
| 660 | 1.119 | 0.441 | 0.000 |
| 670 | 0.487 | 0.191 | 0.000 |
| 680 | 0.196 | 0.076 | 0.000 |
| 690 | 0.075 | 0.029 | 0.000 |
| 700 | 0.028 | 0.011 | 0.000 |
| 710 | 0.010 | 0.004 | 0.000 |
| 720 | 0.004 | 0.001 | 0.000 |
| 730 | 0.001 | 0.001 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **111.468** | **100.001** | **40.659** |
| **WP** | **111.470** | **100.000** | **40.657** |

**Table 5.45 LED Illuminant B3, 1931 Observer**
**10 nm Interval**

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | 0.000 | 0.000 | -0.002 |
| 410 | 0.000 | 0.000 | 0.000 |
| 420 | 0.110 | 0.002 | 0.525 |
| 430 | 0.838 | 0.032 | 4.082 |
| 440 | 2.972 | 0.206 | 14.965 |
| 450 | 4.121 | 0.463 | 21.710 |
| 460 | 2.113 | 0.422 | 12.056 |
| 470 | 0.797 | 0.368 | 5.256 |
| 480 | 0.330 | 0.490 | 2.840 |
| 490 | 0.144 | 0.964 | 2.136 |
| 500 | 0.027 | 1.983 | 1.662 |
| 510 | 0.070 | 3.623 | 1.131 |
| 520 | 0.500 | 5.563 | 0.625 |
| 530 | 1.393 | 7.282 | 0.352 |
| 540 | 2.641 | 8.674 | 0.185 |
| 550 | 4.223 | 9.690 | 0.085 |
| 560 | 6.123 | 10.242 | 0.040 |
| 570 | 8.183 | 10.218 | 0.023 |
| 580 | 10.128 | 9.614 | 0.018 |
| 590 | 11.568 | 8.532 | 0.013 |
| 600 | 11.965 | 7.109 | 0.009 |
| 610 | 10.952 | 5.498 | 0.004 |
| 620 | 8.714 | 3.887 | 0.002 |
| 630 | 5.941 | 2.449 | 0.001 |
| 640 | 3.582 | 1.399 | 0.000 |
| 650 | 1.912 | 0.721 | 0.000 |
| 660 | 0.905 | 0.334 | 0.000 |
| 670 | 0.384 | 0.140 | 0.000 |
| 680 | 0.157 | 0.057 | 0.000 |
| 690 | 0.060 | 0.022 | 0.000 |
| 700 | 0.022 | 0.008 | 0.000 |
| 710 | 0.009 | 0.003 | 0.000 |
| 720 | 0.003 | 0.001 | 0.000 |
| 730 | 0.001 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **100.888** | **99.996** | **67.718** |
| **WP** | **100.891** | **100.000** | **67.718** |

**Table 5.47 LED Illuminant B3, 1964 Observer**
**10 nm Interval**

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | -0.001 | 0.000 | -0.004 |
| 410 | 0.008 | 0.001 | 0.034 |
| 420 | 0.154 | 0.015 | 0.724 |
| 430 | 0.877 | 0.104 | 4.318 |
| 440 | 3.086 | 0.516 | 15.891 |
| 450 | 4.263 | 1.022 | 22.902 |
| 460 | 2.083 | 0.850 | 11.971 |
| 470 | 0.739 | 0.702 | 4.978 |
| 480 | 0.259 | 0.853 | 2.549 |
| 490 | 0.068 | 1.487 | 1.790 |
| 500 | 0.025 | 2.642 | 1.255 |
| 510 | 0.255 | 4.103 | 0.769 |
| 520 | 0.869 | 5.616 | 0.445 |
| 530 | 1.877 | 6.972 | 0.241 |
| 540 | 3.218 | 8.208 | 0.115 |
| 550 | 4.863 | 9.099 | 0.036 |
| 560 | 6.832 | 9.651 | 0.001 |
| 570 | 8.855 | 9.634 | 0.000 |
| 580 | 10.573 | 9.057 | 0.000 |
| 590 | 11.832 | 8.226 | 0.000 |
| 600 | 11.906 | 6.977 | 0.000 |
| 610 | 10.579 | 5.423 | 0.000 |
| 620 | 8.238 | 3.833 | 0.000 |
| 630 | 5.599 | 2.448 | 0.000 |
| 640 | 3.263 | 1.359 | 0.000 |
| 650 | 1.696 | 0.680 | 0.000 |
| 660 | 0.789 | 0.311 | 0.000 |
| 670 | 0.334 | 0.130 | 0.000 |
| 680 | 0.131 | 0.051 | 0.000 |
| 690 | 0.049 | 0.019 | 0.000 |
| 700 | 0.018 | 0.007 | 0.000 |
| 710 | 0.006 | 0.002 | 0.000 |
| 720 | 0.002 | 0.001 | 0.000 |
| 730 | 0.001 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **103.346** | **99.999** | **68.015** |
| **WP** | **103.345** | **100.000** | **68.014** |

Table 5.49 LED Illuminant B4, 1931 Observer
10 nm Interval

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | -0.001 | 0.000 | -0.003 |
| 410 | -0.003 | 0.000 | -0.015 |
| 420 | 0.124 | 0.003 | 0.588 |
| 430 | 0.977 | 0.037 | 4.754 |
| 440 | 3.335 | 0.228 | 16.773 |
| 450 | 5.666 | 0.652 | 29.930 |
| 460 | 3.630 | 0.721 | 20.681 |
| 470 | 1.159 | 0.535 | 7.636 |
| 480 | 0.313 | 0.462 | 2.702 |
| 490 | 0.085 | 0.590 | 1.309 |
| 500 | 0.013 | 1.288 | 1.069 |
| 510 | 0.059 | 3.096 | 0.953 |
| 520 | 0.531 | 5.852 | 0.657 |
| 530 | 1.612 | 8.414 | 0.409 |
| 540 | 3.081 | 10.122 | 0.217 |
| 550 | 4.787 | 10.985 | 0.097 |
| 560 | 6.666 | 11.152 | 0.043 |
| 570 | 8.517 | 10.636 | 0.024 |
| 580 | 9.998 | 9.493 | 0.017 |
| 590 | 10.762 | 7.940 | 0.012 |
| 600 | 10.469 | 6.221 | 0.008 |
| 610 | 9.068 | 4.552 | 0.003 |
| 620 | 6.905 | 3.079 | 0.001 |
| 630 | 4.574 | 1.885 | 0.000 |
| 640 | 2.725 | 1.064 | 0.000 |
| 650 | 1.457 | 0.549 | 0.000 |
| 660 | 0.699 | 0.258 | 0.000 |
| 670 | 0.302 | 0.111 | 0.000 |
| 680 | 0.127 | 0.046 | 0.000 |
| 690 | 0.050 | 0.018 | 0.000 |
| 700 | 0.019 | 0.007 | 0.000 |
| 710 | 0.008 | 0.003 | 0.000 |
| 720 | 0.003 | 0.001 | 0.000 |
| 730 | 0.001 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **97.718** | **100.000** | **87.865** |
| **WP** | **97.719** | **100.000** | **87.865** |

Table 5.51 LED Illuminant B4, 1964 Observer
10 nm Interval

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | -0.001 | 0.000 | -0.005 |
| 410 | 0.004 | 0.000 | 0.015 |
| 420 | 0.171 | 0.016 | 0.806 |
| 430 | 1.021 | 0.120 | 5.029 |
| 440 | 3.464 | 0.573 | 17.820 |
| 450 | 5.852 | 1.432 | 31.509 |
| 460 | 3.580 | 1.452 | 20.550 |
| 470 | 1.075 | 1.017 | 7.227 |
| 480 | 0.247 | 0.805 | 2.427 |
| 490 | 0.037 | 0.915 | 1.093 |
| 500 | 0.012 | 1.719 | 0.803 |
| 510 | 0.218 | 3.498 | 0.648 |
| 520 | 0.919 | 5.904 | 0.468 |
| 530 | 2.170 | 8.055 | 0.280 |
| 540 | 3.754 | 9.578 | 0.135 |
| 550 | 5.511 | 10.314 | 0.040 |
| 560 | 7.437 | 10.506 | 0.001 |
| 570 | 9.215 | 10.026 | 0.000 |
| 580 | 10.436 | 8.942 | 0.000 |
| 590 | 11.005 | 7.653 | 0.000 |
| 600 | 10.416 | 6.105 | 0.000 |
| 610 | 8.758 | 4.489 | 0.000 |
| 620 | 6.526 | 3.036 | 0.000 |
| 630 | 4.310 | 1.884 | 0.000 |
| 640 | 2.481 | 1.034 | 0.000 |
| 650 | 1.292 | 0.518 | 0.000 |
| 660 | 0.609 | 0.240 | 0.000 |
| 670 | 0.263 | 0.103 | 0.000 |
| 680 | 0.106 | 0.041 | 0.000 |
| 690 | 0.041 | 0.016 | 0.000 |
| 700 | 0.015 | 0.006 | 0.000 |
| 710 | 0.006 | 0.002 | 0.000 |
| 720 | 0.002 | 0.001 | 0.000 |
| 730 | 0.001 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **100.953** | **100.000** | **88.846** |
| **WP** | **100.954** | **100.000** | **88.844** |

**Table 5.53 LED Illuminant B5, 1931 Observer**
**10 nm Interval**

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | -0.001 | 0.000 | -0.003 |
| 410 | 0.000 | 0.000 | 0.000 |
| 420 | 0.154 | 0.003 | 0.735 |
| 430 | 1.155 | 0.044 | 5.620 |
| 440 | 4.026 | 0.274 | 20.242 |
| 450 | 7.097 | 0.818 | 37.505 |
| 460 | 4.830 | 0.962 | 27.534 |
| 470 | 1.635 | 0.750 | 10.753 |
| 480 | 0.464 | 0.684 | 3.993 |
| 490 | 0.133 | 0.917 | 2.024 |
| 500 | 0.021 | 1.804 | 1.500 |
| 510 | 0.072 | 3.759 | 1.162 |
| 520 | 0.585 | 6.462 | 0.726 |
| 530 | 1.688 | 8.813 | 0.427 |
| 540 | 3.135 | 10.299 | 0.220 |
| 550 | 4.771 | 10.950 | 0.096 |
| 560 | 6.536 | 10.934 | 0.042 |
| 570 | 8.213 | 10.257 | 0.023 |
| 580 | 9.481 | 9.003 | 0.017 |
| 590 | 10.027 | 7.399 | 0.011 |
| 600 | 9.589 | 5.698 | 0.007 |
| 610 | 8.158 | 4.095 | 0.003 |
| 620 | 6.101 | 2.720 | 0.001 |
| 630 | 3.964 | 1.634 | 0.000 |
| 640 | 2.315 | 0.904 | 0.000 |
| 650 | 1.214 | 0.458 | 0.000 |
| 660 | 0.571 | 0.211 | 0.000 |
| 670 | 0.243 | 0.089 | 0.000 |
| 680 | 0.101 | 0.037 | 0.000 |
| 690 | 0.039 | 0.014 | 0.000 |
| 700 | 0.015 | 0.005 | 0.000 |
| 710 | 0.006 | 0.002 | 0.000 |
| 720 | 0.002 | 0.001 | 0.000 |
| 730 | 0.001 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **96.341** | **100.000** | **112.638** |
| **WP** | **96.342** | **100.000** | **112.641** |

**Table 5.55 LED Illuminant B5, 1964 Observer**
**10 nm Interval**

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | -0.001 |
| 400 | -0.001 | 0.000 | -0.005 |
| 410 | 0.011 | 0.001 | 0.048 |
| 420 | 0.212 | 0.020 | 0.997 |
| 430 | 1.191 | 0.140 | 5.860 |
| 440 | 4.123 | 0.680 | 21.208 |
| 450 | 7.226 | 1.772 | 38.917 |
| 460 | 4.696 | 1.910 | 26.962 |
| 470 | 1.496 | 1.408 | 10.042 |
| 480 | 0.360 | 1.174 | 3.537 |
| 490 | 0.058 | 1.398 | 1.667 |
| 500 | 0.019 | 2.371 | 1.113 |
| 510 | 0.261 | 4.190 | 0.779 |
| 520 | 0.999 | 6.429 | 0.509 |
| 530 | 2.240 | 8.318 | 0.289 |
| 540 | 3.766 | 9.607 | 0.135 |
| 550 | 5.416 | 10.136 | 0.040 |
| 560 | 7.189 | 10.156 | 0.001 |
| 570 | 8.761 | 9.533 | 0.000 |
| 580 | 9.757 | 8.360 | 0.000 |
| 590 | 10.109 | 7.030 | 0.000 |
| 600 | 9.406 | 5.513 | 0.000 |
| 610 | 7.768 | 3.981 | 0.000 |
| 620 | 5.685 | 2.644 | 0.000 |
| 630 | 3.683 | 1.610 | 0.000 |
| 640 | 2.078 | 0.866 | 0.000 |
| 650 | 1.061 | 0.426 | 0.000 |
| 660 | 0.491 | 0.194 | 0.000 |
| 670 | 0.208 | 0.081 | 0.000 |
| 680 | 0.083 | 0.032 | 0.000 |
| 690 | 0.032 | 0.012 | 0.000 |
| 700 | 0.012 | 0.005 | 0.000 |
| 710 | 0.004 | 0.002 | 0.000 |
| 720 | 0.002 | 0.001 | 0.000 |
| 730 | 0.001 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **98.403** | **100.000** | **112.098** |
| **WP** | **98.401** | **100.000** | **112.097** |

**Table 5.57 LED Illuminant BH1, 1931 Observer 10 nm Interval**

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | -0.001 | 0.000 | -0.004 |
| 410 | 0.006 | 0.000 | 0.027 |
| 420 | 0.187 | 0.005 | 0.897 |
| 430 | 0.845 | 0.035 | 4.125 |
| 440 | 1.666 | 0.112 | 8.369 |
| 450 | 1.759 | 0.198 | 9.270 |
| 460 | 1.037 | 0.210 | 5.926 |
| 470 | 0.399 | 0.183 | 2.623 |
| 480 | 0.128 | 0.184 | 1.098 |
| 490 | 0.046 | 0.305 | 0.692 |
| 500 | 0.008 | 0.904 | 0.751 |
| 510 | 0.049 | 2.590 | 0.794 |
| 520 | 0.476 | 5.234 | 0.588 |
| 530 | 1.471 | 7.676 | 0.373 |
| 540 | 2.778 | 9.127 | 0.196 |
| 550 | 4.230 | 9.707 | 0.085 |
| 560 | 5.759 | 9.637 | 0.037 |
| 570 | 7.192 | 8.984 | 0.020 |
| 580 | 8.349 | 7.932 | 0.015 |
| 590 | 9.227 | 6.815 | 0.010 |
| 600 | 10.387 | 6.173 | 0.008 |
| 610 | 13.534 | 6.775 | 0.005 |
| 620 | 19.616 | 8.721 | 0.004 |
| 630 | 15.323 | 6.357 | 0.001 |
| 640 | 3.870 | 1.507 | 0.000 |
| 650 | 0.955 | 0.355 | 0.000 |
| 660 | 0.437 | 0.161 | 0.000 |
| 670 | 0.183 | 0.067 | 0.000 |
| 680 | 0.076 | 0.028 | 0.000 |
| 690 | 0.030 | 0.011 | 0.000 |
| 700 | 0.011 | 0.004 | 0.000 |
| 710 | 0.005 | 0.002 | 0.000 |
| 720 | 0.002 | 0.001 | 0.000 |
| 730 | 0.001 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **110.041** | **100.000** | **35.910** |
| **WP** | **110.040** | **100.000** | **35.912** |

**Table 5.59 LED Illuminant BH1, 1964 Observer 10 nm Interval**

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | -0.001 |
| 400 | -0.001 | 0.000 | -0.006 |
| 410 | 0.020 | 0.002 | 0.090 |
| 420 | 0.256 | 0.026 | 1.215 |
| 430 | 0.904 | 0.111 | 4.466 |
| 440 | 1.756 | 0.288 | 9.019 |
| 450 | 1.851 | 0.445 | 9.949 |
| 460 | 1.038 | 0.429 | 5.978 |
| 470 | 0.377 | 0.354 | 2.530 |
| 480 | 0.103 | 0.328 | 1.005 |
| 490 | 0.020 | 0.484 | 0.589 |
| 500 | 0.008 | 1.228 | 0.574 |
| 510 | 0.187 | 2.975 | 0.550 |
| 520 | 0.837 | 5.373 | 0.426 |
| 530 | 2.015 | 7.479 | 0.260 |
| 540 | 3.443 | 8.788 | 0.124 |
| 550 | 4.956 | 9.274 | 0.036 |
| 560 | 6.538 | 9.239 | 0.001 |
| 570 | 7.919 | 8.619 | 0.000 |
| 580 | 8.869 | 7.602 | 0.000 |
| 590 | 9.605 | 6.684 | 0.000 |
| 600 | 10.518 | 6.165 | 0.000 |
| 610 | 13.287 | 6.795 | 0.000 |
| 620 | 18.869 | 8.757 | 0.000 |
| 630 | 14.710 | 6.466 | 0.000 |
| 640 | 3.596 | 1.496 | 0.000 |
| 650 | 0.853 | 0.337 | 0.000 |
| 660 | 0.387 | 0.152 | 0.000 |
| 670 | 0.161 | 0.063 | 0.000 |
| 680 | 0.064 | 0.025 | 0.000 |
| 690 | 0.025 | 0.010 | 0.000 |
| 700 | 0.009 | 0.004 | 0.000 |
| 710 | 0.003 | 0.001 | 0.000 |
| 720 | 0.001 | 0.001 | 0.000 |
| 730 | 0.000 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **113.184** | **100.000** | **36.805** |
| **WP** | **113.186** | **100.000** | **36.804** |

**Table 5.61 LED Illuminant RGB1, 1931 Observer**
**10 nm Interval**

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | 0.000 | 0.000 | -0.001 |
| 410 | 0.001 | 0.000 | 0.002 |
| 420 | 0.049 | 0.001 | 0.233 |
| 430 | 0.314 | 0.013 | 1.530 |
| 440 | 0.824 | 0.055 | 4.137 |
| 450 | 1.277 | 0.147 | 6.746 |
| 460 | 0.853 | 0.169 | 4.862 |
| 470 | 0.369 | 0.169 | 2.434 |
| 480 | 0.197 | 0.281 | 1.686 |
| 490 | 0.117 | 0.777 | 1.755 |
| 500 | 0.028 | 2.476 | 2.045 |
| 510 | 0.133 | 6.237 | 1.914 |
| 520 | 0.892 | 9.845 | 1.123 |
| 530 | 1.893 | 9.982 | 0.488 |
| 540 | 2.507 | 8.252 | 0.175 |
| 550 | 2.942 | 6.755 | 0.058 |
| 560 | 3.491 | 5.840 | 0.022 |
| 570 | 4.276 | 5.338 | 0.012 |
| 580 | 5.270 | 5.003 | 0.009 |
| 590 | 6.479 | 4.779 | 0.007 |
| 600 | 8.041 | 4.777 | 0.006 |
| 610 | 10.513 | 5.276 | 0.004 |
| 620 | 15.403 | 6.857 | 0.003 |
| 630 | 22.302 | 9.182 | 0.002 |
| 640 | 15.809 | 6.208 | 0.001 |
| 650 | 3.238 | 1.215 | 0.000 |
| 660 | 0.635 | 0.232 | 0.000 |
| 670 | 0.226 | 0.083 | 0.000 |
| 680 | 0.089 | 0.032 | 0.000 |
| 690 | 0.034 | 0.012 | 0.000 |
| 700 | 0.013 | 0.005 | 0.000 |
| 710 | 0.005 | 0.002 | 0.000 |
| 720 | 0.002 | 0.001 | 0.000 |
| 730 | 0.001 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **108.223** | **100.001** | **29.253** |
| **WP** | **108.219** | **100.000** | **29.257** |

**Table 5.63 LED Illuminant RGB1, 1964 Observer**
**10 nm Interval**

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | 0.000 |
| 390 | 0.000 | 0.000 | 0.000 |
| 400 | 0.000 | 0.000 | -0.001 |
| 410 | 0.004 | 0.000 | 0.018 |
| 420 | 0.066 | 0.007 | 0.315 |
| 430 | 0.328 | 0.040 | 1.621 |
| 440 | 0.854 | 0.140 | 4.388 |
| 450 | 1.318 | 0.323 | 7.098 |
| 460 | 0.841 | 0.340 | 4.826 |
| 470 | 0.343 | 0.323 | 2.307 |
| 480 | 0.155 | 0.493 | 1.514 |
| 490 | 0.052 | 1.209 | 1.471 |
| 500 | 0.030 | 3.290 | 1.537 |
| 510 | 0.454 | 7.033 | 1.303 |
| 520 | 1.542 | 9.942 | 0.798 |
| 530 | 2.554 | 9.552 | 0.335 |
| 540 | 3.053 | 7.800 | 0.108 |
| 550 | 3.385 | 6.338 | 0.024 |
| 560 | 3.892 | 5.498 | 0.000 |
| 570 | 4.623 | 5.029 | 0.000 |
| 580 | 5.497 | 4.709 | 0.000 |
| 590 | 6.623 | 4.605 | 0.000 |
| 600 | 7.995 | 4.686 | 0.000 |
| 610 | 10.140 | 5.196 | 0.000 |
| 620 | 14.561 | 6.765 | 0.000 |
| 630 | 20.978 | 9.163 | 0.000 |
| 640 | 14.432 | 6.044 | 0.000 |
| 650 | 2.857 | 1.140 | 0.000 |
| 660 | 0.549 | 0.214 | 0.000 |
| 670 | 0.196 | 0.077 | 0.000 |
| 680 | 0.074 | 0.029 | 0.000 |
| 690 | 0.027 | 0.011 | 0.000 |
| 700 | 0.010 | 0.004 | 0.000 |
| 710 | 0.004 | 0.001 | 0.000 |
| 720 | 0.001 | 0.001 | 0.000 |
| 730 | 0.000 | 0.000 | 0.000 |
| 740 | 0.000 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **107.438** | **100.002** | **27.662** |
| **WP** | **107.440** | **100.000** | **27.661** |

**Table 5.65 LED Illuminant V1, 1931 Observer 10 nm Interval**

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | -0.001 |
| 390 | -0.004 | 0.000 | -0.021 |
| 400 | 0.024 | 0.001 | 0.114 |
| 410 | 0.524 | 0.014 | 2.501 |
| 420 | 1.003 | 0.030 | 4.818 |
| 430 | 0.665 | 0.026 | 3.244 |
| 440 | 0.493 | 0.032 | 2.473 |
| 450 | 0.615 | 0.069 | 3.247 |
| 460 | 0.722 | 0.148 | 4.145 |
| 470 | 0.646 | 0.301 | 4.255 |
| 480 | 0.417 | 0.606 | 3.551 |
| 490 | 0.177 | 1.148 | 2.572 |
| 500 | 0.029 | 2.042 | 1.718 |
| 510 | 0.064 | 3.356 | 1.049 |
| 520 | 0.437 | 4.863 | 0.545 |
| 530 | 1.184 | 6.190 | 0.299 |
| 540 | 2.217 | 7.280 | 0.155 |
| 550 | 3.531 | 8.103 | 0.071 |
| 560 | 5.145 | 8.609 | 0.033 |
| 570 | 7.040 | 8.792 | 0.020 |
| 580 | 9.205 | 8.736 | 0.016 |
| 590 | 11.492 | 8.471 | 0.013 |
| 600 | 13.395 | 7.954 | 0.010 |
| 610 | 14.062 | 7.058 | 0.005 |
| 620 | 13.023 | 5.810 | 0.003 |
| 630 | 10.346 | 4.267 | 0.001 |
| 640 | 7.234 | 2.826 | 0.000 |
| 650 | 4.427 | 1.670 | 0.000 |
| 660 | 2.369 | 0.876 | 0.000 |
| 670 | 1.122 | 0.410 | 0.000 |
| 680 | 0.505 | 0.183 | 0.000 |
| 690 | 0.208 | 0.075 | 0.000 |
| 700 | 0.082 | 0.030 | 0.000 |
| 710 | 0.033 | 0.012 | 0.000 |
| 720 | 0.013 | 0.005 | 0.000 |
| 730 | 0.005 | 0.002 | 0.000 |
| 740 | 0.002 | 0.001 | 0.000 |
| 750 | 0.001 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **112.453** | **99.996** | **34.836** |
| **WP** | **112.451** | **100.000** | **34.835** |

**Table 5.67 LED Illuminant V1, 1964 Observer 10 nm Interval**

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | -0.001 |
| 390 | -0.009 | -0.001 | -0.042 |
| 400 | 0.039 | 0.004 | 0.170 |
| 410 | 0.943 | 0.097 | 4.360 |
| 420 | 1.453 | 0.153 | 6.890 |
| 430 | 0.708 | 0.086 | 3.490 |
| 440 | 0.509 | 0.082 | 2.614 |
| 450 | 0.640 | 0.154 | 3.441 |
| 460 | 0.712 | 0.299 | 4.112 |
| 470 | 0.604 | 0.577 | 4.071 |
| 480 | 0.332 | 1.058 | 3.209 |
| 490 | 0.087 | 1.779 | 2.171 |
| 500 | 0.026 | 2.736 | 1.305 |
| 510 | 0.236 | 3.823 | 0.715 |
| 520 | 0.764 | 4.936 | 0.390 |
| 530 | 1.603 | 5.956 | 0.206 |
| 540 | 2.715 | 6.926 | 0.097 |
| 550 | 4.088 | 7.650 | 0.030 |
| 560 | 5.771 | 8.156 | 0.001 |
| 570 | 7.658 | 8.332 | 0.000 |
| 580 | 9.660 | 8.274 | 0.000 |
| 590 | 11.816 | 8.211 | 0.000 |
| 600 | 13.397 | 7.848 | 0.000 |
| 610 | 13.651 | 6.996 | 0.000 |
| 620 | 12.380 | 5.761 | 0.000 |
| 630 | 9.801 | 4.288 | 0.000 |
| 640 | 6.622 | 2.759 | 0.000 |
| 650 | 3.949 | 1.585 | 0.000 |
| 660 | 2.077 | 0.819 | 0.000 |
| 670 | 0.980 | 0.383 | 0.000 |
| 680 | 0.422 | 0.164 | 0.000 |
| 690 | 0.171 | 0.066 | 0.000 |
| 700 | 0.066 | 0.026 | 0.000 |
| 710 | 0.025 | 0.010 | 0.000 |
| 720 | 0.009 | 0.004 | 0.000 |
| 730 | 0.003 | 0.001 | 0.000 |
| 740 | 0.001 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **113.909** | **99.998** | **37.229** |
| **WP** | **113.912** | **100.000** | **37.227** |

## Table 5.69 LED Illuminant V2, 1931 Observer 10 nm Interval

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | -0.001 |
| 390 | -0.005 | 0.000 | -0.025 |
| 400 | 0.046 | 0.001 | 0.217 |
| 410 | 0.612 | 0.017 | 2.917 |
| 420 | 1.287 | 0.039 | 6.185 |
| 430 | 1.150 | 0.046 | 5.606 |
| 440 | 1.164 | 0.077 | 5.839 |
| 450 | 1.597 | 0.181 | 8.431 |
| 460 | 1.789 | 0.369 | 10.274 |
| 470 | 1.412 | 0.656 | 9.291 |
| 480 | 0.777 | 1.124 | 6.604 |
| 490 | 0.284 | 1.844 | 4.133 |
| 500 | 0.042 | 2.947 | 2.477 |
| 510 | 0.086 | 4.493 | 1.403 |
| 520 | 0.553 | 6.158 | 0.690 |
| 530 | 1.430 | 7.475 | 0.360 |
| 540 | 2.561 | 8.409 | 0.179 |
| 550 | 3.898 | 8.944 | 0.079 |
| 560 | 5.419 | 9.067 | 0.035 |
| 570 | 7.036 | 8.788 | 0.019 |
| 580 | 8.653 | 8.215 | 0.015 |
| 590 | 10.113 | 7.457 | 0.011 |
| 600 | 11.056 | 6.566 | 0.008 |
| 610 | 10.980 | 5.511 | 0.004 |
| 620 | 9.710 | 4.331 | 0.002 |
| 630 | 7.455 | 3.075 | 0.001 |
| 640 | 5.081 | 1.985 | 0.000 |
| 650 | 3.052 | 1.151 | 0.000 |
| 660 | 1.611 | 0.596 | 0.000 |
| 670 | 0.754 | 0.276 | 0.000 |
| 680 | 0.337 | 0.122 | 0.000 |
| 690 | 0.138 | 0.050 | 0.000 |
| 700 | 0.055 | 0.020 | 0.000 |
| 710 | 0.022 | 0.008 | 0.000 |
| 720 | 0.009 | 0.003 | 0.000 |
| 730 | 0.003 | 0.001 | 0.000 |
| 740 | 0.001 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **100.168** | **100.002** | **64.754** |
| **WP** | **100.164** | **100.000** | **64.756** |

## Table 5.71 Led Illuminant V2, 1964 Observer 10 nm Interval

| nm | $W_{10,X}$ | $W_{10,Y}$ | $W_{10,Z}$ |
|---|---|---|---|
| 360 | 0.000 | 0.000 | 0.000 |
| 370 | 0.000 | 0.000 | 0.000 |
| 380 | 0.000 | 0.000 | -0.001 |
| 390 | -0.012 | -0.001 | -0.053 |
| 400 | 0.072 | 0.008 | 0.317 |
| 410 | 1.085 | 0.111 | 5.009 |
| 420 | 1.804 | 0.190 | 8.566 |
| 430 | 1.202 | 0.145 | 5.919 |
| 440 | 1.182 | 0.191 | 6.069 |
| 450 | 1.625 | 0.393 | 8.745 |
| 460 | 1.728 | 0.729 | 9.986 |
| 470 | 1.294 | 1.231 | 8.706 |
| 480 | 0.608 | 1.921 | 5.848 |
| 490 | 0.137 | 2.798 | 3.415 |
| 500 | 0.036 | 3.868 | 1.843 |
| 510 | 0.310 | 5.013 | 0.936 |
| 520 | 0.947 | 6.121 | 0.482 |
| 530 | 1.896 | 7.044 | 0.243 |
| 540 | 3.071 | 7.834 | 0.110 |
| 550 | 4.419 | 8.269 | 0.032 |
| 560 | 5.953 | 8.412 | 0.001 |
| 570 | 7.496 | 8.157 | 0.000 |
| 580 | 8.893 | 7.619 | 0.000 |
| 590 | 10.183 | 7.078 | 0.000 |
| 600 | 10.830 | 6.345 | 0.000 |
| 610 | 10.440 | 5.350 | 0.000 |
| 620 | 9.039 | 4.206 | 0.000 |
| 630 | 6.917 | 3.026 | 0.000 |
| 640 | 4.555 | 1.898 | 0.000 |
| 650 | 2.666 | 1.070 | 0.000 |
| 660 | 1.383 | 0.546 | 0.000 |
| 670 | 0.645 | 0.252 | 0.000 |
| 680 | 0.276 | 0.107 | 0.000 |
| 690 | 0.111 | 0.043 | 0.000 |
| 700 | 0.043 | 0.017 | 0.000 |
| 710 | 0.016 | 0.006 | 0.000 |
| 720 | 0.006 | 0.002 | 0.000 |
| 730 | 0.002 | 0.001 | 0.000 |
| 740 | 0.001 | 0.000 | 0.000 |
| 750 | 0.000 | 0.000 | 0.000 |
| 760 | 0.000 | 0.000 | 0.000 |
| 770 | 0.000 | 0.000 | 0.000 |
| 780 | 0.000 | 0.000 | 0.000 |
| **CS** | **100.859** | **100.000** | **66.173** |
| **WP** | **100.859** | **100.000** | **66.171** |

## REFERENCES


(1) Foster, W. H., Jr., Gans, R., Stearns, E. I., and Stearns, R. E., "Weights for Calculation of Tristimulus Values from Sixteen Reflectance Values," *Color Engineering*, Vol 8, No. 3, 1970, pp. 35–47.

(2) Stearns, E. I., "Weights for Calculation of Tristimulus Values," *Clemson Review of Industrial Management and Textile Science*, Vol 14, No. 1, 1975, pp. 79–113.

(3) Commission Internationale de l'Éclairage, Publication CIE No. 15.2004, *Colorimetry*, Central Bureau of the CIE, Vienna, 2018.

(4) Commission Internationale de l'Éclairage, *ILV-International Lighting Vocabulary*, 2nd ed., 2020. Central Bureau of the CIE, Vienna.

(5) Judd, D. B., and Wyszecki, G., "Calculation of Tristimulus Values and Chromaticity Coordinates," *Color in Business, Science and Industry*, 3rd ed., John Wiley and Sons, New York, 1975, pp. 139–149.

(6) Billmeyer, F. W., and Saltzman, M., *Principles of Color Technology*, 2nd ed., John Wiley and Sons, New York, 1981.

(7) Hunter, R. S., and Harold, R. W., *The Measurement of Appearance*, 2nd ed., John Wiley and Sons, New York, 1987.

(8) Wyszecki, G., and Stiles, W. S., *Color Science*, 2nd ed., John Wiley and Sons, New York, 1982.

(9) Billmeyer, F. W., and Fairman, H. S., "CIE Method for Calculating Tristimulus Values," *Color Research and Application*, Vol 12, 1987, pp. 27–36.

(10) Fairman, H. S., "The Calculation of Weight Factors for Tristimulus Integration," *Color Research and Application*, Vol 10, 1985, pp. 199–203.

(11) Stearns, E. I., and Stearns, R. E., "An Example of a Method for Correcting Radiance Data for Bandpass Error," *Color Research and Application*, Vol 13, 1988, pp. 257–259.

(12) Venable, W. H.,"Accurate Tristimulus Values from Spectral Data," *Color Research and Application*, Vol 14, 1989, pp. 260–267.

Designation: E811 – 09 (Reapproved 2020)ε1

# Standard Practice for Measuring Colorimetric Characteristics of Retroreflectors Under Nighttime Conditions[1]

This standard is issued under the fixed designation E811; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε1 NOTE—Editorial changes were made in Sections 2, 3, and 5 in June 2020.

## 1. Scope

1.1 This practice describes the instrumental determination of retroreflected chromaticity coordinates of retroreflectors. It includes the techniques used in a photometric range to measure retroreflected (nighttime) chromaticity with either a telecolorimeter or telespectroradiometer.

1.2 This practice covers the general measurement procedures. Additional requirements for specific tests and specifications are described in Section 7.

1.3 The description of the geometry used in the nighttime colorimetry of retroreflectors is described in Practice E808 and the methods for calculation of chromaticity are contained in Practice E308.

1.4 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

## 2. Referenced Documents

2.1 *ASTM Standards:*[2]

E284 Terminology of Appearance

E308 Practice for Computing the Colors of Objects by Using the CIE System

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E808 Practice for Describing Retroreflection

E809 Practice for Measuring Photometric Characteristics of Retroreflectors

2.2 *CIE Documents:*[3]

CIE Publication No. 15 Colorimetry

ISO/CIE 11664-1:2019(E) Colorimetry — Part 1: CIE standard colorimetric observers

ISO 11664-2:2007(E)/CIE S 014-2/E:2006 Colorimetry — Part 2: CIE Standard Illuminants for Colorimetry

CIE Technical Report 54.2 Retroreflection: Definition and Measurement

## 3. Terminology

3.1 The terms and definitions in Terminology E284 apply to this practice.

3.2 *Definitions:*

3.2.1 *chromaticity coordinates, n*—the ratios of each of the tristimulus values of a psychophysical color to the sum of the tristimulus values.

3.2.1.1 *Discussion*—Chromaticity coordinates in the CIE 1931 system of color specification are designated by $x$, $y$, $z$ and in the CIE 1964 supplementary system by $x_{10}$, $y_{10}$, $z_{10}$.

3.2.2 *CIE 1931 (x, y)-chromaticity diagram*—the chromaticity diagram for the CIE 1931 standard observer, in which the CIE 1931 chromaticity coordinates are plotted with $x$ as the abscissa and $y$ as the ordinate.

3.2.3 *CIE 1931 standard observer, n*—ideal colorimetric observer with color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ corresponding to a field of view subtending a 2° angle on the retina; commonly called the "2° standard observer."

3.2.3.1 *Discussion*—The color matching functions of the CIE 1931 standard observer are tabulated in Practice E308, CIE Publication No. 15, and ISO/CIE 11664-1:2019(E).

[1] This practice is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.10 on Retroreflection.

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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 U.S. National Committee of the CIE (International Commission on Illumination) (http://www.cie-usnc.org) or the CIE (cie.co.at) Webshop.

3.2.4 *CIE standard illuminant A, n*—colorimetric illuminant, representing the full radiation at 2855.6 K, defined by the CIE in terms of a relative spectral power distribution.

3.2.4.1 *Discussion*—The relative spectral power distribution of CIE standard illuminant *A* is tabulated in Practice E308, CIE Publication No. 15, and ISO 11664-2:2007(E)/CIE S 014-2/E:2006.

3.2.5 *CIE standard source A, n*—a gas-filled tungsten-filament lamp operated at a correlated color temperature of 2855.6 K. [CIE][B]

3.2.6 *entrance angle, β, n*—the angle between the illumination axis and the retroreflector axis.

3.2.6.1 *Discussion*—The entrance angle is usually no larger than 90°, but for completeness its full range is defined as $0° \leq \beta \leq 180°$. In the CIE (goniometer) system β is resolved into two components, $\beta_1$ and $\beta_2$. Since by definition β is always positive, the common practice of referring to the small entrance angles that direct specular reflections away from the photoreceptor as negative valued is deprecated by ASTM. The recommendation is to designate such negative values as belonging to $\beta_1$.

3.2.7 *goniometer, n*—an instrument for measuring or setting angles.

3.2.8 *illumination axis, n—in retroreflection*, a line from the effective center of the source aperture to the retroreflector center.

3.2.9 *observation angle, n*—angle between the axes of the incident beam and the observed (reflected) beam, (*in retroreflection*, α, angle between the illumination axis and the observation axis).

3.2.10 *observation axis, n—in retroreflection*, a line from the effective center of the receiver aperture to the retroreflector center.

3.2.11 *retroreflection, n*—reflection in which the reflected rays are preferentially returned in directions close to the opposite of the direction of the incident rays, this property being maintained over wide variations of the direction of the incident rays.

3.2.12 *retroreflective device, n*—deprecated term; use *retroreflector*.

3.2.13 *retroreflective sheeting, n*—a retroreflective material preassembled as a thin film ready for use.

3.2.14 *retroreflector, n*—a reflecting surface or device from which, when directionally irradiated, the reflected rays are preferentially returned in directions close to the opposite of the direction of the incident rays, this property being maintained over wide variations of the direction of the incident rays.

3.2.15 *retroreflector axis, n*—a designated line segment from the retroreflector center that is used to describe the angular position of the retroreflector.

3.2.15.1 *Discussion*—The direction of the retroreflector axis is usually chosen centrally among the intended directions of illumination; for example, the direction of the road on which or with respect to which the retroreflector is intended to be positioned. In testing horizontal road markings the retroreflector axis is usually the normal to the test surface.

3.2.16 *retroreflector center, n*—a point on or near a retroreflector that is designated to be the center of the device for the purpose of specifying its performance.

3.2.17 *rotation angle, ε, n*—the angle in a plane perpendicular to the retroreflector axis from the observation halfplane to the datum axis, measured counter-clockwise from a viewpoint on the retroreflector axis.

3.2.17.1 *Discussion*—Range: $-180° < \varepsilon \leq 180°$. The definition is applicable when entrance angle and viewing angle are less than 90°. More generally, rotation angle is the angle from the positive part of second axis to the datum axis, measured counterclockwise from a viewpoint on the retroreflector axis.

3.2.17.2 *Discussion*—Rotation of the sample about the retroreflector axis while the source and receiver remain fixed in space changes the rotation angle (ε) and the orientation angle ($\omega_s$) equally.

3.2.18 *spectroradiometer, n*—an instrument for measuring the spectral distribution of radiant energy or power.

3.2.19 *tristimulus colorimeter, n*—instrument that measures psychophysical color, in terms of tristimulus values, by the use of filters to convert the relative spectral power distribution of the illuminator to that of a standard illuminant, and to convert the relative spectral responsivity of the receiver to the responsivities prescribed for a standard observer.

3.2.19.1 *Discussion*—In some instruments, the filters may be combined into one set placed in the receiver; in such cases, caution should be observed when measuring fluorescent specimens.

3.2.20 *viewing angle, v, n*—in retroreflection, the angle between the retroreflector axis and the observation axis.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *telecolorimeter, n*—a tristimulus colorimeter equipped with collection optics for viewing a limited area at a distance from the instrument.

3.3.2 *telespectroradiometer, n*—a spectroradiometer equipped with collection optics for viewing a limited area at a distance from the instrument.

## 4. Summary of Practice

4.1 Two procedures are described in this practice (see also Practice E809). Procedure A is based on a calibrated light source, colored reference filters, a white reference standard and a telecolorimeter equipped with tristimulus filters. In this procedure, measurements of the incident light on the white standard at the specimen position are made using the colored filters and correction factors developed. Then the retroreflected light is measured under the test geometry and the corrected relative tristimulus values are computed. In Procedure B, spectral measurements are made of the incident light and of the retroreflected light under the test geometry required. From these spectral measurements, the relative tristimulus values are determined. In both procedures, the chromaticity coordinates *x*, *y* are based on the CIE 1931 Standard Color Observer.

## 5. Significance and Use

5.1 This practice describes a procedure for measuring the chromaticity of retroreflectors in a nighttime, that is, retroreflective, geometry of illumination and observation. CIE Standard Source A has been chosen to represent a tungsten automobile headlamp. Although the geometry must be specified by the user of this practice, it will, in general, correspond to the relationship between the vehicle headlamp, the retroreflector, and the vehicle driver's eyes. Thus, the chromaticity coordinates determined by the procedures in this practice describe numerically the nighttime appearance of the retroreflector.

## 6. Use of the CIE Chromaticity Diagram for the Specification of Color

6.1 *Tristimulus Values for a Colored Sample*—The spectral nature of the light coming to the eye from a retroreflector depends upon the spectral distribution of the radiation from the source, $S(\lambda)$, and a quantity proportional to the spectral reflectance of the retroreflector, $R(\lambda)$. For nighttime colorimetric measurements of retroreflectors, $S(\lambda)$ is Illuminant A. The spectral tristimulus values, $\bar{x}$, $\bar{y}$, *and* $\bar{z}$, the illuminant power $S(\lambda)$, and the reflectance quantity $R(\lambda)$ are used together to calculate three numbers, the tristimulus values $X$, $Y$, and $Z$ as follows:

$$X = k \int_{380}^{740} S_A(\lambda)\, R(\lambda)\, \bar{x}(\lambda) d\lambda$$

$$Y = k \int_{380}^{740} S_A(\lambda)\, R(\lambda)\, \bar{y}(\lambda) d\lambda$$

$$Z = k \int_{380}^{740} S_A(\lambda)\, R(\lambda)\, \bar{z}(\lambda) d\lambda$$

where:

$S_A(\lambda)$ = spectral power distribution of Illuminant A,

$R(\lambda)$ = spectral reflectance factor of the sample, and

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ = color matching functions of the CIE standard observer.

$$100/k = \int_{380}^{740} S_A\, \bar{y}(\lambda) d\lambda$$

Integration of each curve across the visible region (380 to 740 nm) give the numerical value for the corresponding tristimulus value $X$, $Y$, or $Z$.

6.2 *Chromaticity Coordinates*—The chromaticity coordinates $x$, $y$, and $z$ are computed from the tristimulus values $X$, $Y$, and $Z$ as follows:

$$x = X/(X+Y+Z)$$
$$y = Y/(X+Y+Z)$$
$$z = Z/(X+Y+Z)$$

The normalization constant $k$ in the equations for $X$, $Y$, and $Z$ cancels out in calculating $x$, $y$, and $z$. Thus, $x$, $y$, and $z$ express the color of the reflected light without regard to its intensity. Because the sum of $x$, $y$, and $z$ is always equal to one, only two of these quantities are needed to describe the chromaticity of a light. The chromaticity coordinates $x$ and $y$ are chosen for this purpose.

6.3 *CIE 1931 (x, y) Chromaticity Diagram*—The chromaticity coordinates $x$ and $y$ can be plotted as shown in Practice E308, Fig. 1. The outline in the figure encloses the entire range of combinations of $x$ and $y$ that correspond to real colors. The points at which monochromatic radiation of various wavelengths falls are indicated on this boundary, with the more nearly neutral colors being represented by points toward the center of the bounded region.

6.4 *Specifying Color Limits*—A color point representing the $x$ and $y$ chromaticity coordinates of a test sample can be located on the CIE diagram. A specification for a specific retroreflective color limit would require that the color point for a sample of this color fall within specified boundaries of the diagram. The area within these boundaries is referred to as a color area, and is defined exactly by specifying four sets of chromaticity coordinates in the specification.

6.5 *Daytime versus Nighttime Color Limits*—Different color limits are required to specify daytime and nighttime color. Nighttime and daytime color limits are different for two major reasons: the quality of the illuminating light and the geometry or direction of the illuminating light. Daytime color is viewed under a source of daylight quality, and nighttime color is viewed under Source A (a CIE source corresponding to an incandescent lamp, such as an automobile headlamp). Illumination in the daytime is from skylight, and diffusely reflected light is observed; illumination in the nighttime comes from a point very near the observer, and retroreflected light is observed.

## 7. Requirements to be Stated in Specifications

7.1 When stating colorimetric retroreflective requirements, the following requirements shall be given in the specification for the material:

7.1.1 Limits of the color area on the 1931 CIE chromaticity diagram (usually four pairs of chromaticity coordinates ($x$ and $y$) are required to define an area on the diagram).

7.1.2 Chromaticity coordinate limits and spectral transmittance limits of the standard filter when Procedure A is used. (These may be specified by giving the filter glass type and thickness or the manufacturer's part number of the filter.)

7.1.3 Observation angle (α).

7.1.4 Entrance angle (β) and when required the components of the entrance angle $\beta_1$, and $\beta_2$. (When specifying entrance angles near 0°, care must be taken to prevent "white" specular reflection from entering the receptor. Therefore, instead of specifying 0°, the entrance angle is usually specified so that specular light is reflected away from the receptor.)

7.1.5 Rotation angle (ε) and the location of the datum mark, if random orientation of the test specimen is not suitable.

7.1.6 Observation distance (*d*).

7.1.7 Test specimen dimensions and shape.

7.1.8 Receptor angular aperture, usually either 6 min or 10 min of arc.

7.1.9 Source angular aperture, usually either 6 min or 10 min of arc.

7.1.10 Reference center of the retroreflector.

7.1.11 Reference axis of the retroreflector. (The reference axis is usually perpendicular to the surface of sheeting. In such complex devices as automobile or bicycle reflectors, the reference axis and reference center may be defined with respect to the viewing direction.)

## 8. Apparatus

8.1 The apparatus shall consist of either a spectroradiometer equipped with collection optics or a telecolorimeter, a regulated light projector source, a goniometer sample holder, a photometric range, and calibration standards.

8.2 *Telecolorimeter*—The telecolorimeter shall be equipped with three or more filters having spectral transmittances such that the spectral products of CIE Illuminant A with CIE tristimulus functions x-bar, y-bar, and z-bar are each linear combinations of the spectral products of the instrument illumination, the instrument detector sensitivity, and the three or more filters transmittances.

8.2.1 Discussion—If the Instrument illumination matches CIE Illuminant A, then the condition simplifies to the CIE Tristimulus functions x-bar, y-bar, and z-bar each being linear combinations of the spectral products of the instrument detector sensitivity and the three or more filters transmittances.

8.2.2 *Stability and Linearity*—The linearity of the scale reading shall be within 1.0 % over the range to be measured.

8.2.3 *Light Filter Holder Attachment*—If the filter correction factor is to be used, the telecolorimeter shall be equipped with an attachment to mount filters in a way that prevents interreflection between the filter and the telecolorimeter.

8.2.4 *Means to Eliminate Stray Light*—Stray light shall be reduced to a negligible level by use of a field aperture on the telecolorimeter. The field aperture may be omitted if baffling of the photometric range is carefully employed. Elimination of stray light is particularly important when a photometertype instrument is used.

8.3 *Spectroradiometer*—The spectroradiometer shall be equipped with the following:

8.3.1 *Dispersive Element*—A device that separates the incident radiant flux into narrow bands of wavelength. It shall consist of a monochromator or a series of narrow-band interference filters. The stray light shall be sufficiently small to permit an accuracy of ±0.005 in the measured values of *x* and *y*. The wavelength reproducibility shall be ±1 nm or better.

8.3.2 *Receptor Stability and Linearity*—The receptor shall be stable and linear to within ±1 % over the range to be measured.

8.3.3 *Output*—The spectroradiometer shall be capable of providing either graphical or digital information from which chromaticity coordinates can be computed.

8.3.4 *Collection Optics*—The radiant flux shall be collected by either limiting the acceptance cone to narrow angles or by such optical means as are used in a telecolorimeter.

8.4 *Light Projector Source*—The light source shall be a lamp with appropriate reflector and lenses to provide normal illumination on the test sample with a continuous spectral energy distribution having adequate power over the range 380 nm to 780 nm.

8.5 *Goniometer Sample Holder and Other Supports*—Suitable supports shall be provided for the source, telecolorimeter, and test samples as required so that the geometric arrangement required for calibration and measurements can be achieved and maintained.

8.6 *Photometric Range*—The background behind the sample shall be flat black to minimize the effect of stray light. Light baffles shall be located, as necessary, between the projector and the test sample. Goniometer parts, range wall, ceiling, and floor exposed to the light beam shall be painted flat black.

## 9. Test Specimen and Sample

9.1 The test specimen is the unit on which the test is made. The specimen is the material selected by a sampling process which is not part of this practice.

9.2 The test specimen should be one entire retroreflector (a large retroreflector may be tested by summing the effects of smaller segments).

9.3 When testing retroreflective sheeting, a minimum area of 0.1 (±0.05) $m^2$ should be used. This may be accomplished by testing a single specimen of this area or by averaging measurements of several smaller areas totaling 0.1 (±0.05) $m^2$.

9.4 When testing retroreflective sheeting, the test specimen must be held flat by vacuum or some other means. It may be applied to a flat aluminum backing panel so that the entrance angle is consistent across the test specimen. Aluminum panels flat to ±0.015 in. have been found satisfactory for this purpose.

## 10. Calibration and Standardization

10.1 *Light Source*—The projector light source used in Procedure B must be calibrated to a correlated color temperature of 2856 K. This may be accomplished by comparing the tristimulus values of the projector source to those of a reference lamp calibrated by a recognized agency or by measurement of the spectral power distribution of the projector source.

10.2 *Telecolorimeter*—The telecolorimeter must be calibrated before each measurement or series of measurements by using the method outlined in Procedure A.

10.3 *Telespectroradiometer*—The telespectroradiometer must be calibrated for wave-length accuracy and photometric scale linearity. An effective means to test the calibration of the unit is to measure the reference light level from the $BaSO_4$ standard and then to insert into the optical system colored filters of known chromaticity and then, by transmittance, measure the chromaticity of the standard filters. Filters specifically designed to test the accuracy of spectrophotometer systems are available and should be used for this purpose.

10.4 *Goniometer:*

10.4.1 Calibrate the goniometer at the 0° entrance angle position in the vertical and horizontal planes of the test sample. Take all measurements relative to this point and check each time the goniometer or light projector is moved. If measurements are to be made at extreme angles of 75 to near 90°, it is recommended to calibrate the goniometer at the 90° entrance angle position for greatest accuracy.

10.4.2 Accomplish calibration by locating a 300-mm (12-in.) square, high-quality, plane mirror in place of the sample. A

300-mm cross, centered on the surface of the mirror, can be made with photographic black tape. A 600-mm square piece of white construction paper, with a hole in the center, can be placed over the exit aperture of the projector. By observing the white paper, the goniometer can be adjusted so that the shadow of the cross is reflected directly on the exit aperture of the projector. This horizontal position of the goniometer is the 0° entrance angle of the test sample.

## 11. Procedure

11.1 *General*—The geometry used to determine the performance of retroreflective materials shall be in accordance with Practice E808, for both Procedures A and B.

11.2 *Procedure A—Telecolorimeter Method:*

11.2.1 *Effective Responses*—The instrument makes N reading $R_1$, $R_2$,....$R_N$ each using a different filter (N≥3). The spectral designs of the filters, the detector (or detectors), and the light source are such that some linear combination of these N readings yields the CIE $\bar{x}$ response to the specimen when illuminated by CIE Illuminant A, another linear combination of these readings yields the CIE $\bar{y}$ response to the specimen when illuminated by CIE Illuminant A, and another linear combination of these readings yields the CIE $\bar{z}$ response to the specimen when illuminated by CIE Illuminant A. For example, the three effective responses, $R_X$, $R_Y$, and $R_Z$, of a three-filter instrument are given by the following three equations based on nine coefficients.

$$R_X = a_1R_1 + a_2R_2 + a_3R_3$$
$$R_Y = b_1R_1 + b_2R_2 + b_3R_3$$
$$R_Z = c_1R_1 + c_2R_2 + c_3R_3$$

The three effective responses of a four-filter instrument are given by the following three equations based on twelve coefficients.

$$R_X = a_1R_1 + a_2R_2 + a_3R_3 + a_4R_4$$
$$R_Y = b_1R_1 + b_2R_2 + b_3R_3 + b_4R_4$$
$$R_Z = c_1R_1 + c_2R_2 + c_3R_3 + c_4R_4$$

For instruments based on five or more filters the three equations will be written analogously to these examples. All the coefficient values should be provided to the instrument user by the instrument maker.

NOTE 1—For the four-filter instrument described in E811 - 95 the coefficients have the following simple values:

$$a_1 = 1$$
$$a_2 = 1$$
$$a_3 = 0$$
$$a_4 = 0$$
$$b_1 = 0$$
$$b_2 = 0$$
$$b_3 = 1$$
$$b_4 = 0$$
$$c_1 = 0$$
$$c_2 = 0$$
$$c_3 = 0$$
$$c_4 = 1$$

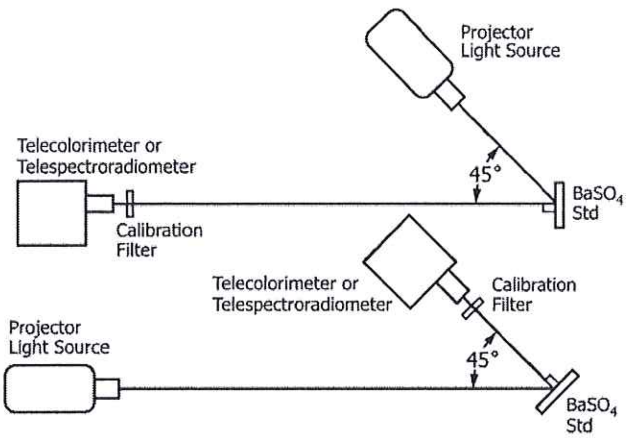


**FIG. 1 Two Arrangements Suitable for Calibration of Telecolorimeter or Telespectroradiometer**

11.2.2 *Calibration of the Telecolorimeter*—Place a spectrally flat (white) diffusing surface in the sample position as shown in Fig. 1. Focus the telecolorimeter, equipped with the field aperture to be used during the color measurements, on the white surface. Obtain N readings $R_1$, $R_2$,....$R_N$ with the telecolorimeter for the N instrument filters and calculate the three corresponding effective responses $R_X$, $R_Y$, and $R_Z$ according to the equations in 11.2.1. The three responses should be found to be approximately in the ratio

1:0.910:0.324

Next insert into the auxiliary filter holder the reference filter of color similar to the specimen's, which has been measured with a spectrophotometer to have tristimulus values $X_{ref}$, $Y_{ref}$, and $Z_{ref}$ for Illuminant A. Obtain N new readings $R_{1,ref}$, $R_{2,ref}$, ....$R_{N,ref}$ with the telecolorimeter for the N instrument filters and calculate the three corresponding effective responses $R_{X,ref}$, $R_{Y,ref}$, and $R_{Z,ref}$, according to the equations in 11.2.1.

11.2.2.1 Calculate the color correction factors $CF_X$, $CF_Y$, and $CF_Z$ as follows:

$$CF_X = X_{ref}/R_{X,ref}$$
$$CF_Y = Y_{ref}/R_{Y,ref}$$
$$CF_Z = Z_{ref}/R_{Z,ref}$$

where:

$CF_X$, $CF_Y$, $CF_Z$ = correction factors
$X_{ref}$, $Y_{ref}$, $Z_{ref}$ = the *X*, *Y* and *Z* values assigned to the reference filter. These values are determined with a spectrophotometer for Illuminant A and the 1931 Standard Observer.
$R_{X,ref}$, $R_{Y,ref}$, $R_{Z,ref}$ = telecolorimeter effective responses with the reference filter inserted calculated according to the equations in 11.2.1

11.2.3 *Color Measurement*—Reposition the telecolorimeter to achieve the geometric arrangement specified for the test material. No changes in the adjustment of the telecolorimeter shall be made, but the range scale of the instrument may be used. The same light source must be used for both calibration and color measurements. Focus the telecolorimeter on the test

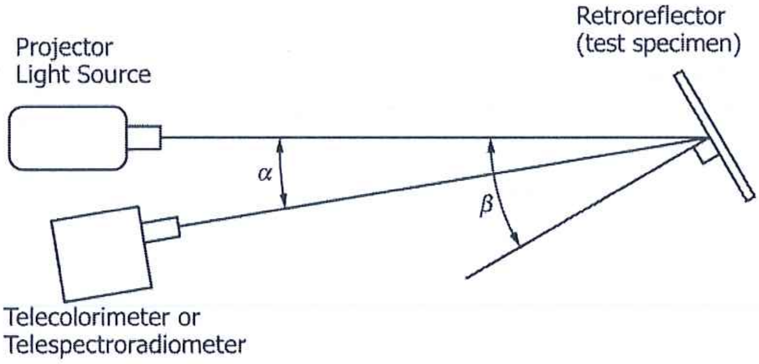


**FIG. 2 Simplified Geometric Arrangement of Apparatus for Measurement of Chromaticity of Test Specimen**

surface and ensure that the field stop aperture of the telecolorimeter is completely filled with light. Obtain N readings $R_1$, $R_2$,....$R_N$ from the specimen by positioning each of the N instrument filters in turn before the photoreceptor. Calculate the three effective responses $R_X$, $R_Y$, and $R_Z$ according to the equations in 11.2.1. Then correct these values by the following equations:

$$X_{test} = R_X \cdot CF_X$$
$$Y_{test} = R_Y \cdot CF_Y$$
$$Z_{test} = R_Z \cdot CF_Z$$

11.2.3.1 Compute the chromaticity coordinates (*x*, *y*) of the test specimen by the following equations:

$$x_{test} = \frac{X_{test}}{X_{test}+Y_{test}+Z_{test}}$$
$$y_{test} = \frac{Y_{test}}{X_{test}+Y_{test}+Z_{test}}$$

11.3 *Procedure B—Telespectroradiometer Method:*

11.3.1 *Use of Spectroradiometer*—This method employs a spectroradiometer to measure the spectral distribution of the irradiance on the specimen and the irradiance at the receptor. Use of this method does not require that the source be at the proper color temperature or that the intensity scale of the spectroradiometer be properly calibrated. However, the spectroradiometer must be linear, and its wavelength scale must be calibrated. The collection optics of the spectroradiometer must be adjusted so that, when placed in the receptor position, either the entire retroreflecting specimen is contained within its field of view or the entire field of view is contained within the uniform specimen surface. In the case of retroreflecting devices, the first of these conditions is recommended. When the entire specimen is included in the field of view, the field of view should be sufficiently larger than the specimen to avoid problems in alignment, but not so large as to cause difficulty by collecting stray radiation. When the entire field of view is within the retroreflection specimen area, its size should be sufficiently smaller than the specimen area in order to avoid problems with misalignment, but should not be so small as to cause difficulty with specimen nonuniformity.

11.3.2 *Color Measurement:*

11.3.2.1 Place the spectroradiometer in the specimen position, ensuring that the entire source exit aperture is contained within the field of view of the spectroradiometer, and take readings $m_2(\lambda)$ at each wavelength from 380 to 780 nm at 10-nm intervals. Then return the spectroradiometer to the receptor position and take readings $m_1(\lambda)$ of the light reflected from the retroreflector being measured at each wavelength from 380 to 780 nm at 10-nm intervals.

11.3.2.2 An alternative set of $m_2(\lambda)$ readings can be obtained by viewing the radiation reflected from a $BaSO_4$ plaque as shown in Fig. 1. This method has the advantage that $m_1(\lambda)$ and $m_2(\lambda)$ can be made to be approximately the same magnitude by properly choosing the distance between the receptor and the white standard. However, in both methods, the position of the spectroradiometer must be held constant during the entire series of measurements of $m_2(\lambda)$ and its collection optics must not be changed from that used when $m_1(\lambda)$ is measured.

11.3.2.3 Calculate the tristimulus values *X*, *Y*, and *Z* by the following equations:

$$X = k\sum_{380}^{780}[m_1(\lambda)/m_2(\lambda)]S_A(\lambda)\bar{x}(\lambda)\Delta\lambda$$
$$Y = k\sum_{380}^{780}[m_1(\lambda)/m_2(\lambda)]S_A(\lambda)\bar{y}(\lambda)\Delta\lambda$$
$$Z = k\sum_{380}^{780}[m_1(\lambda)/m_2(\lambda)]S_A(\lambda)\bar{z}(\lambda)\Delta\lambda$$

where:

$m_1$ = reading of the sample
$m_2$ = reading of the incident radiation, either directly or reflected from a $BaSO_4$ plaque

11.3.2.4 The chromaticity coordinates *x* and *y* are given by:

$$x = X/(X+Y+Z)$$
$$y = Y/(X+Y+Z)$$

## 12. Precision and Bias

12.1 The precision and bias information contained in this section is based on the work of the International Commission on Illumination (CIE) and technical committee TC 2-19. The measurements were made on various grades and colors of retroreflective sheeting materials using spectral radiometers. The data is based on measurements at an entrance angle of 5 degrees of arc and an observation angle of 0.33 degrees of arc. The aperture size for both source and receptor is 10 minutes of arc. Table 1 shows the mean values of the chromaticity coordinates x, y, from measurements on the test specimens made in the 6 laboratories that participated in the international intercomparision. Included for reference in this table is the

TABLE 1 Mean of Normalized Data — Retroreflectance [RA] and Chromaticity x, y values

| TC 2–19 Panel Designation | | $R_A$ | x | y |
|---|---|---|---|---|
| Enclosed Lens | | | | |
| 1 | A(White) | 96 | 0.4572 | 0.4305 |
| 2 | B(Yellow) | 48 | 0.5463 | 0.4451 |
| 3 | C(Red) | 25 | 0.6564 | 0.3421 |
| 4 | D(Blue) | 6 | 0.1094 | 0.2826 |
| 5 | E(Green) | 10 | 0.1852 | 0.5937 |
| 6 | F(Brown) | 5 | 0.5972 | 0.3904 |
| 7 | G(Orange) | 30 | 0.6165 | 0.3712 |
| Encapsulated Lens | | | | |
| 8 | H(White) | 233 | 0.4589 | 0.4289 |
| 9 | J(Yellow) | 161 | 0.5549 | 0.4415 |
| 10 | K(Red) | 49 | 0.6769 | 0.3202 |
| 11 | L(Blue) | 23 | 0.1596 | 0.3161 |
| 12 | M(Green) | 43 | 0.1689 | 0.6020 |
| 13 | N(Brown) | 10 | 0.6136 | 0.3795 |
| 14 | P(Orange) | 92 | 0.5977 | 0.3940 |
| Prismatic Materials | | | | |
| 15 | R(White) | 783 | 0.4500 | 0.4065 |
| 16 | S(Yellow) | 648 | 0.5478 | 0.4478 |
| 17 | T(Red) | 172 | 0.6792 | 0.3186 |
| 18 | U(Blue) | 53 | 0.1386 | 0.2509 |
| 19 | V(Green) | 70 | 0.1751 | 0.6857 |
| 20 | W(Orange) | 385 | 0.6161 | 0.3828 |

TABLE 2 The Pooled Standard Deviation From the Mean of Chromaticity Measurements From Each of the 6 Laboratories

| TC 2–19 Panel Designation | | x | y |
|---|---|---|---|
| Enclosed Lens | | | |
| 1 | A(White) | 0.0005 | 0.0003 |
| 2 | B(Yellow) | 0.0003 | 0.0003 |
| 3 | C(Red) | 0.0003 | 0.0001 |
| 4 | D(Blue) | 0.0007 | 0.0015 |
| 5 | E(Green) | 0.0004 | 0.0016 |
| 6 | F(Brown) | 0.0025 | 0.0007 |
| 7 | G(Orange) | 0.0004 | 0.0002 |
| Encapsulated Lens | | | |
| 8 | H(White) | 0.0009 | 0.0001 |
| 9 | J(Yellow) | 0.0003 | 0.0003 |
| 10 | K(Red) | 0.0003 | 0.0001 |
| 11 | L(Blue) | 0.0007 | 0.0010 |
| 12 | M(Green) | 0.0004 | 0.0011 |
| 13 | N(Brown) | 0.0007 | 0.0002 |
| 14 | P(Orange) | 0.0003 | 0.0002 |
| Prismatic Material | | | |
| 15 | R(White) | 0.0005 | 0.0002 |
| 16 | S(Yellow) | 0.0002 | 0.0002 |
| 17 | T(Red) | 0.0002 | 0.0001 |
| 18 | U(Blue) | 0.0002 | 0.0006 |
| 19 | V(Green) | 0.0004 | 0.0004 |
| 20 | W(Orange) | 0.0002 | 0.0002 |

mean value of the retroreflectance, $R_A$, of the test specimen calculated from the spectral measurements as described in CIE Technical Report 54.2.

12.2 *Precision*—Table 2 shows the average precision of the nighttime chromaticity coordinates x, y, measurements expressed as the mean standard deviation from the mean of repeat measurements in the individual laboratories.

TABLE 3 95 % Repeatability Interval (Repeat Measurements Within a Single Laboratory)

| TC 2–19 Panel Designation | | x | y |
|---|---|---|---|
| Enclosed Lens | | | |
| 1 | A(White) | 0.0015 | 0.0007 |
| 2 | B(Yellow) | 0.0008 | 0.0008 |
| 3 | C(Red) | 0.0010 | 0.0004 |
| 4 | D(Blue) | 0.0021 | 0.0042 |
| 5 | E(Green) | 0.0012 | 0.0046 |
| 6 | F(Brown) | 0.0070 | 0.0019 |
| 7 | G(Orange) | 0.0011 | 0.0004 |
| Encapsulated Lens | | | |
| 8 | H(White) | 0.0024 | 0.0004 |
| 9 | J(Yellow) | 0.0009 | 0.0009 |
| 10 | K(Red) | 0.0007 | 0.0004 |
| 11 | L(Blue) | 0.0018 | 0.0028 |
| 12 | M(Green) | 0.0011 | 0.0030 |
| 13 | N(Brown) | 0.0019 | 0.0006 |
| 14 | P(Orange) | 0.0008 | 0.0005 |
| Prismatic Materials | | | |
| 15 | R(White) | 0.0015 | 0.0006 |
| 16 | S(Yellow) | 0.0005 | 0.0005 |
| 17 | T(Red) | 0.0006 | 0.0003 |
| 18 | U(Blue) | 0.0005 | 0.0017 |
| 19 | V(Green) | 0.0012 | 0.0012 |
| 20 | W(Orange) | 0.0006 | 0.0007 |

TABLE 4 95 % Reproducibility Interval (Between Laboratories)

| TC 2–19 Panel Designation | | x | y |
|---|---|---|---|
| Enclosed Lens | | | |
| 1 | A(White) | 0.0045 | 0.0026 |
| 2 | B(Yellow) | 0.0040 | 0.0022 |
| 3 | C(Red) | 0.0054 | 0.0031 |
| 4 | D(Blue) | 0.0099 | 0.0114 |
| 5 | E(Green) | 0.0109 | 0.0139 |
| 6 | F(Brown) | 0.0104 | 0.0030 |
| 7 | G(Orange) | 0.0063 | 0.0029 |
| Encapsulated Lens | | | |
| 8 | H(White) | 0.0049 | 0.0013 |
| 9 | J(Yellow) | 0.0037 | 0.0028 |
| 10 | K(Red) | 0.0050 | 0.0032 |
| 11 | L(Blue) | 0.0064 | 0.0116 |
| 12 | M(Green) | 0.0089 | 0.0098 |
| 13 | N(Brown) | 0.0069 | 0.0044 |
| 14 | P(Orange) | 0.0028 | 0.0033 |
| Prismatic Materials | | | |
| 15 | R(White) | 0.0067 | 0.0051 |
| 16 | S(Yellow) | 0.0082 | 0.0105 |
| 17 | T(Red) | 0.0042 | 0.0037 |
| 18 | U(Blue) | 0.0057 | 0.0160 |
| 19 | V(Green) | 0.0115 | 0.0132 |
| 20 | W(Orange) | 0.0039 | 0.0045 |

12.3 *Repeatability*—Table 3 shows the expected repeatability, at the 95 % confidence interval, within laboratories using the methods of Practice E691.

12.4 *Reproducibility*—Table 4 shows the expected reproducibility, at the 95 % confidence interval, between laboratories expressed using the methods of Practice E691. It is based on measurements in 6 laboratories.

## 13. Keywords

13.1 chromaticity; retroreflector