Federal Test Method Standard 373
December 1, 1979

FEDERAL TEST METHOD STANDARD

INSTRUMENTAL COLOR MEASUREMENTS OF RETROREFLECTIVE MATERIALS AND DEVICES UNDER NIGHTTIME ILLUMINATING AND VIEWING CONDITIONS

This standard was approved by the Commissioner Federal Supply Service, General Services Administration, for the use of all Federal agencies.

1. SCOPE

1.1 This standard describes the instrumental determination of the chromaticity coordinates of retroreflective materials and devices under conditions which are characteristic of nighttime illuminating and viewing.

1.2 This standard is intended as a comprehensive guide to the geometric and colorimetric terminology useful in characterizing retroreflectors, and as a description of instrument requirements.

1.3 The requirements needed to stipulate specific tests and specifications for retroreflectors are included in section 4 of this standard.

2. DEFINITIONS

2.1 Retroreflective terms:

2.1.1 Retroreflection. Reflection in which radiation is returned in directions close to the direction from which it came.

2.1.2 Retroreflector. A surface or device which reflects and returns a relatively high proportion of light in a direction close to the direction from which it came. This characteristic is maintained over a wide variation of the angle made by the incident light ray and the reference axis.

2.1.3 Retroreflective element. One optical unit which by refraction and/or reflection produces the phenomenon of retroreflection.

2.1.4 Retroreflective device. A complete device, ready for use, consisting of one or more retroreflective elements.

2.1.5 Retroreflective material. A retroreflective material which consists of a thin continuous layer of small retroreflective elements on or very near the exposed surface (for example, retroreflective sheeting, beaded paint, highway sign surfaces, or pavement striping).

2.1.5.1 Retroreflective sheeting. A retroreflective material preassembled as a thin film ready for use.

2.2 Geometric terms (see figures 1 and 2):

2.2.1 Reference center (0). The defined center of a retroreflector.

2.2.2 Reference axis (ON). The defined axis used to determine the entrance angle in colormetric measurements and in practical use. This axis passes through the reference center (O) (see note 6).

2.2.3 Axis of incident light (OS). The line between the reference center and the center of the exit aperture of the light source.

2.2.4 Observation axis (OR). The line between the reference center and the center of the entrance aperature of the receptor.

2.2.5 Entrance angle (β). The angle between the reference axis and the axis of incident light. Counterclockwise rotation of the reference axis relative to the axis of incident light is considered positive, as shown in figure 1.

> NOTE 1: Entrance angles are normally in the range of 0 to 90°. However, negative entrance angles can be used to indicate a change of 180° in the presentation angle, provided the 0° orientation of the datum mark is defined relative to the observation plane.

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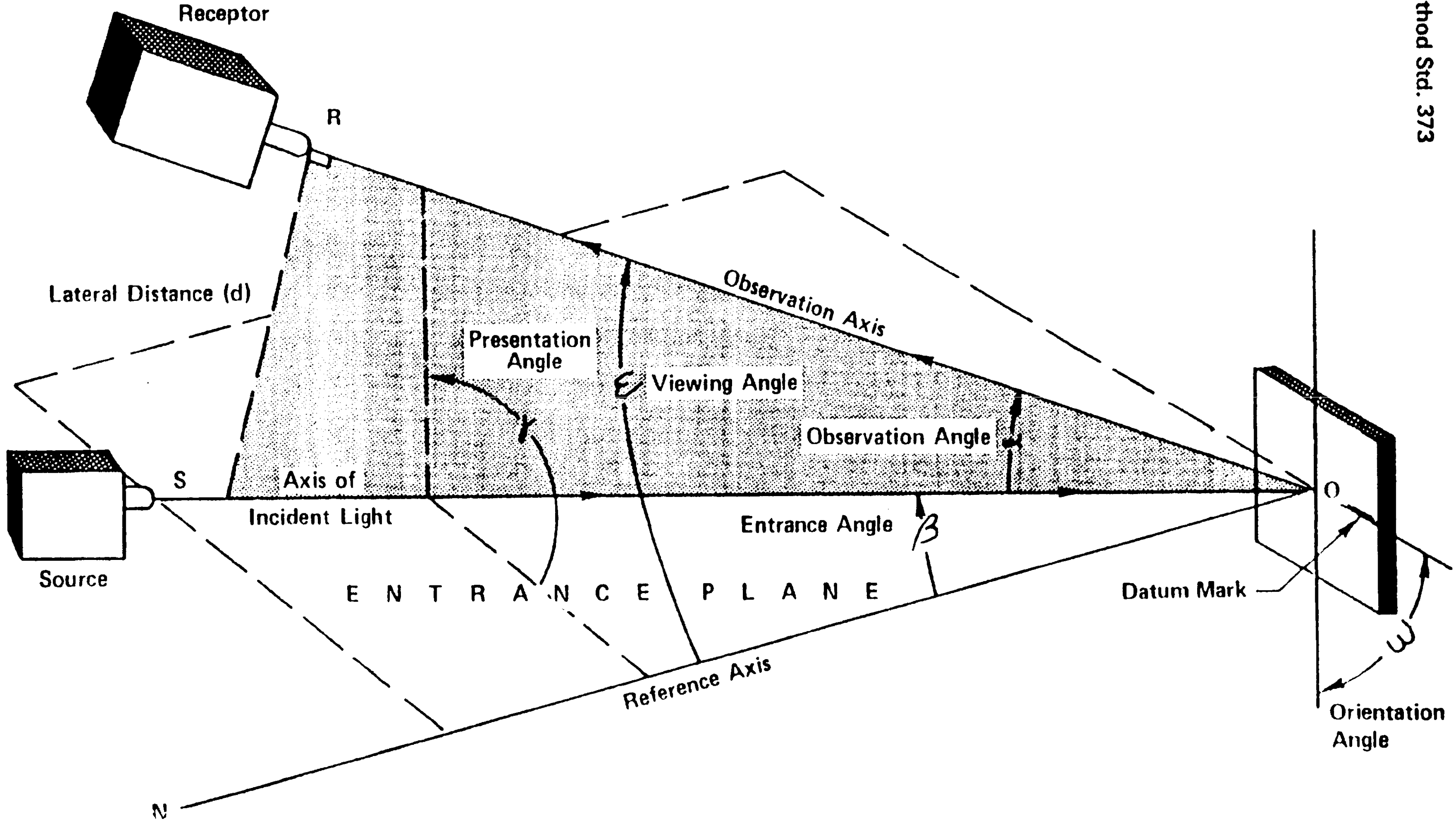

Figure 1

Pictorial view with the presentation angle (γ) illustrated at 90°

(A presentation angle of 0° is normally used)

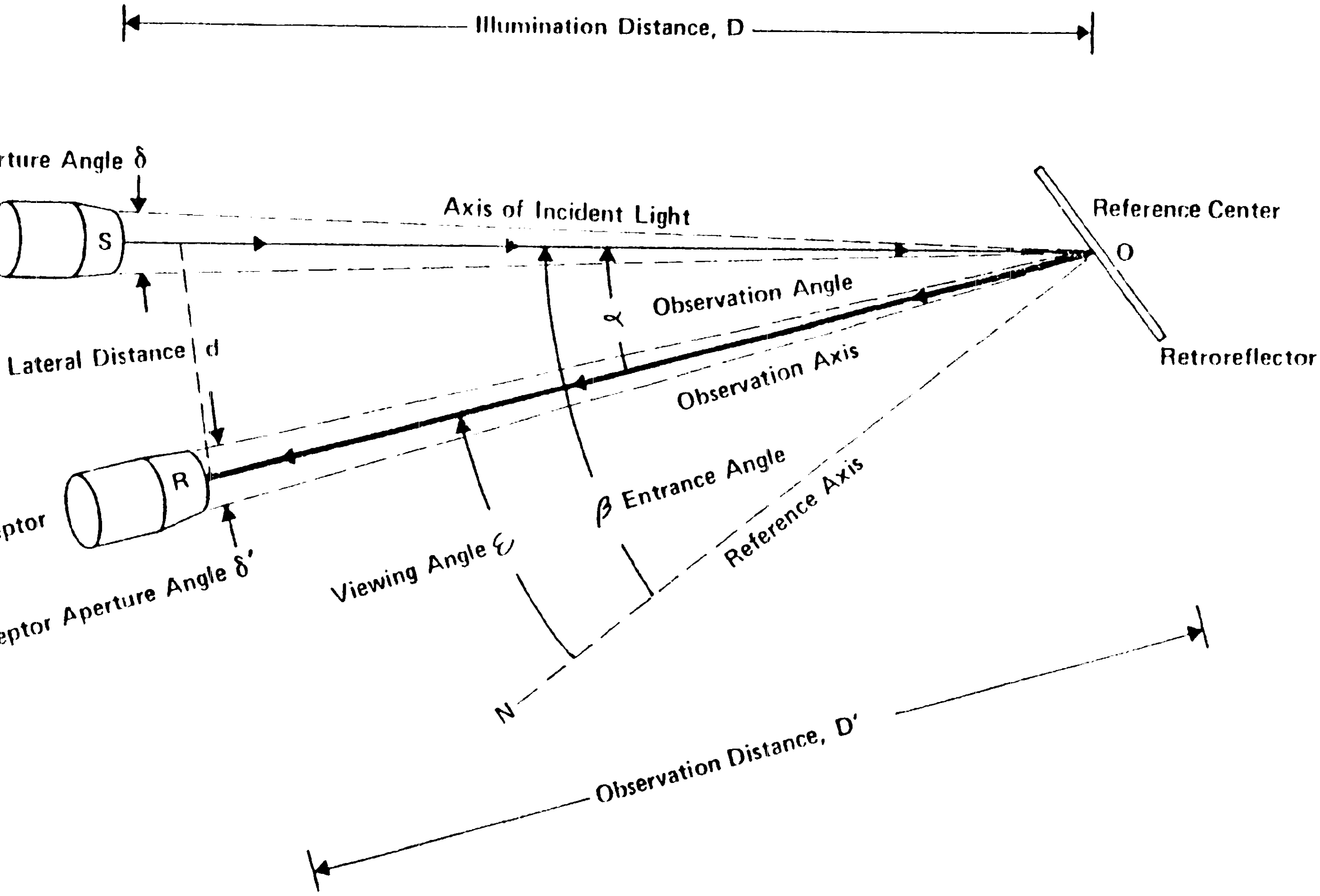

Figure 2

Plane view from above with the presentation angle illustrated at 0°

2.2.6 Viewing angle (ν). The angle between the observation axis and the reference axis.

NOTE 2: Since this angle is determined by other defined angles, the viewing angle is introduced for convenience.

2.2.7 Observation angle (α). The angle between the axis of incident light and the observation axis ("divergence angle" is an obsolete term for this angle).

2.2.8 Datum mark. The mark placed on the sample by the manufacturer which defines the initial (zero degree) orientation position and from which the orientation angle is measured.

2.2.9 Orientation angle (ω). The angle, when viewed from point N, through which the sample may be rotated about the reference axis, from the initial zero degree orientation of the datum mark. The initial zero degree orientation angle may be defined relative to either the observation plane or the entrance plane.

(a) When defined relative to the observation plane, the zero degree orientation is when the datum mark is in the observation plane and on the same side of the axis of incident light as the photoreceptor.

(b) When defined relative to the entrance plane, the zero degree orientation is when the datum mark is in the entrance plane and on the same side of the axis of incident light as the reference axis.

2.2.10 Presentation angle (γ). The dihedral angle between the entrance plane (formed by the axis of incident light and the reference axis) and the observation plane (formed by the axis of incident light and the observation axis). 0° is formed by the axis of incident light and the reference axis, with the receptor on the same side of the source as the reference axis. A presentation angle of 0° as shown in figure 2 is used, unless otherwise specified. Figure 1 shows the presentation angle at $+90^\circ$.

2.2.11 Illumination distance (D, equal to OS). The distance between the center of the exit aperture of the light source and the reference center.

2.2.12 Observation distance (D', equal to OR). The distance between the reference center and the center of the entrance aperture of the photoreceptor.

2.2.13 Lateral distance (d). The distance from the center of the entrance aperture of the photoreceptor to the axis of incident light, measured perpendicularly to the observation axis. It may be computed by multiplying the observation distance D' by the tangent of the observation angle.

$$d = D' \tan \alpha$$

2.2.14 Source aperture angle (δ). The angle at the sample subtended by a given dimension of the source aperture.

2.2.15 Receptor aperture angle (δ'). The angle at the sample subtended by a given dimension of the receptor aperture.

2.2.16 Angular aperture of an individual retroreflective optical unit. There is a maximum displacement distance between an incident light ray striking an individual retroreflective optical unit and the resultant retroreflected ray. When this maximum displacement distance is projected on a plane passing through the retroreflector center and perpendicular to the retroflector axis, the angle it then subtends at the center of the receptor is the angular aperture of the individual retroreflective optical unit.

2.2.17 Angular aperture of the retroreflector at the source (η). The angle subtended at the center of the source by the greatest dimension of the active area of the retroreflector.

2.2.18 Angular aperture of the retroreflector at the receptor (η'). The angle subtended at the center of the receptor by the greatest dimension of the active area of the retroreflector. Because, in practice, the receptor is always close to the source, the angular apertures of the retroreflector at the source and at the receptor do not differ significantly.

2.3 Colorimetric terms.

2.3.1 CIE standard illuminant A. Standard sources of light have been established and specified by the International Commission on Illumination, known by the official abbreviation CIE which is adopted from the French name, Commission Internationale de l'Eclairage. For nighttime color measurement, the CIE light source used is CIE standard source A (a tungsten lamp operated at a color temperature of 2856 K). Other CIE standard sources and their energy distributions (referred to as standard illuminants) are defined in reference 8.1. The energy distribution of CIE standard illuminant A is given in table I.

TABLE 1. Energy distribution of CIE standard illuminant A (ref. 8.1)

Wavelength, nm	Relative energy	Wavelength, nm	Relative energy
380	9.79	580	114.44
390	12.09	590	121.73
400	14.71	600	129.04
410	17.68	610	136.34
420	21.00	620	143.62
430	24.67	630	150.83
440	28.70	640	157.98
450	33.09	650	165.03
460	37.82	660	171.96
470	42.87	670	178.77
480	48.25	680	185.43
490	53.91	690	191.93
500	59.86	700	198.26
510	66.06	710	204.41
520	72.50	720	210.36
530	79.13	730	216.12
540	85.95	740	221.66
550	92.91	750	227.00
560	100.00	760	232.11
570	107.18		

2.3.2 Tristimulus values of the spectrum colors for the 1931 CIE standard colorimetric observer. The basis for the tristimulus system of colorimetry is defined by the 1931 CIE standard colorimetric observer. (A detailed explanation of the development of the system may be found in reference 8.2.) Figure 3 and table II give the spectral tristimulus values of the 1931 Standard Colormetric Observer. These functions have been chosen so that $y(\lambda) \equiv V(\lambda)$, the spectral luminous efficiency function for photopic vision (see 8.3).

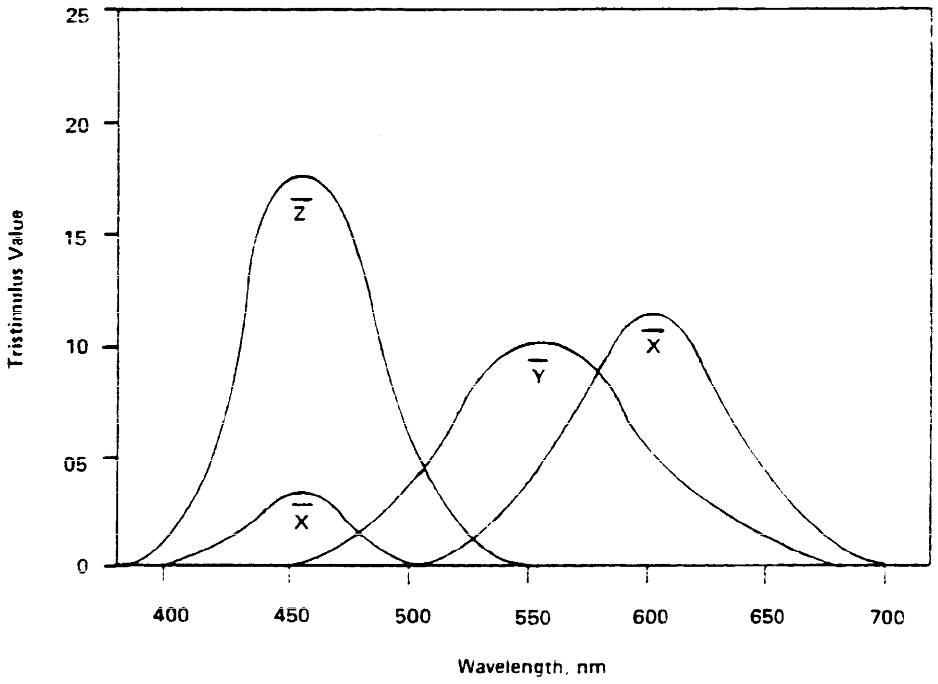

FIGURE 3

Spectral tristimulus values (for equal spectral energy source) of the 1931 CIE standard colorimetric observer

TABLE II. Spectral tristimulus values (for equal spectral energy source) of the 1931 CIE Standard Colorimetric Observer

Wavelength (nm)	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$	Wavelength (nm)	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$
380	0.0014	0.0000	0.0065	580	0.9163	0.8700	0.0017
390	0.0042	0.0001	0.0201	590	1.0263	0.7570	0.0011
400	0.0143	0.0004	0.0679	600	1.0622	0.6310	0.0008
410	0.0435	0.0012	0.2074	610	1.0026	0.5030	0.0003
420	0.1344	0.0040	0.6456	620	0.8544	0.3810	0.0002
430	0.2839	0.0116	1.3856	630	0.6424	0.2650	0.0000
440	0.3483	0.0230	1.7471	640	0.4479	0.1750	0.0000
450	0.3362	0.0380	1.7721	650	0.2835	0.1070	0.0000
460	0.2908	0.0600	1.6692	660	0.1649	0.0610	0.0000
470	0.1954	0.0910	1.2876	670	0.0874	0.0320	0.0000
480	0.0954	0.1390	0.8130	680	0.0468	0.0170	0.0000
490	0.0320	0.2080	0.4652	690	0.0227	0.0082	0.0000
500	0.0049	0.3230	0.2720	700	0.0114	0.0041	0.0000
510	0.0093	0.5030	0.1582	710	0.0058	0.0021	0.0000
520	0.0633	0.7100	0.0782	720	0.0029	0.0010	0.0000
530	0.1655	0.8620	0.0422	730	0.0014	0.0005	0.0000
540	0.2904	0.9540	0.0203	740	0.0007	0.0003	0.0000
550	0.4334	0.9950	0.0084	750	0.0003	0.0001	0.0000
560	0.5945	0.9950	0.0039	760	0.0002	0.0001	0.0000
570	0.7621	0.9520	0.0021				
580	0.9163	0.8700	0.0017				

2.3.3 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, $S_A(\lambda)$, and $R(\lambda)$ are used to calculate three numbers, the tristimulus values X, Y, and Z, as follows:

$$X = k\int S_A(\lambda)\, R(\lambda)\, \bar{x}(\lambda)\, d\lambda$$

$$Y = k\int S_A(\lambda)\, R(\lambda)\, \bar{y}(\lambda)\, d\lambda$$

$$Z = k\int S_A(\lambda)\, R(\lambda)\, \bar{z}(\lambda)\, d\lambda$$

Where: $S_A(\lambda)$ = the spectral distribution of illuminant A.

$R(\lambda)$ = the spectral reflectance of the sample.

$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ = the spectral tristimulus values of the CIE standard observer.

$$100/k = \int S_A(\lambda)\, \bar{y}(\lambda)\, d\lambda$$

Integration of each curve across the visible region (380 to 760 nm) gives the numerical value for the corresponding tristimulus value X, Y, or Z.

2.3.4 Chromaticity coordinates. The chromaticity coordinates x, y, and z are computed from the tristimulus values X, Y, and Z as follows:

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X - Y - Z}$$

$$z = \frac{Z}{X + Y + Z}$$

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 chromaticity of the reflected light without regard to its brightness. 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.

2.3.5 CIE 1931 (x, y)-chromaticity diagram. The chromaticity coordinates x and y can be plotted as shown in figure 4. The outline in the figure encloses the entire range of combinations of x and y which correspond to real colors. The chromaticity coordinates for monochromatic radiation fall on the upper curved boundary, called the "spectrum locus." The points at which monochromatic radiation of various wavelengths fall are indicated on this boundary. The chromaticity coordinates for polychromatic radiation fall within the boundary, with the more nearly neutral colors being represented by points toward the center of the bounded region. The dotted line in figure 4 is called the Plankian locus and indicates the chromaticity coordinates for radiation emitted at various temperatures from a blackbody. The chromaticity coordinates for illuminant A are indicated in figure 4.

2.3.6 Tristimulus colorimeter. For the purposes of this method, a tristimulus colorimeter is defined as an instrument for measuring colorimetric quantities by means of detectors. The spectral response of the detectors has been made to simulate the standard observer spectral tristimulus functions. Such an instrument produces values approximately proportional to X, Y, and Z directly without need for numerical integration. For practical reasons, the X response is often broken up into two parts, X_{red} and X_{blue}, representing the separate contributions from each of the two peaks on the $\bar{x}(\lambda)$ curve (see figure 3).

2.3.7 Telecolorimeter. An instrument for measuring the tristimulus values or chromaticity coordinates of a color stimulus at appreciable distances from that stimulus.

2.3.8 Spectroradiometer. An instrument for measuring the spectral distribution of radiant energy (see 8.4).

2.3.9 Goniometer. An instrument for supporting the retroreflective material or device and adjusting its angular setting with respect to the illuminating and measuring instruments.

3. USE OF THE CIE CHROMATICITY DIAGRAM FOR THE SPECIFICATION OF COLOR

3.1 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.

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.

4. REQUIREMENTS TO BE STATED IN SPECIFICATIONS

4.1 When stating colorimetric retroreflective requirements, the following requirements shall be specified in the specification for the material:

(a) The 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).

(b) The chromaticity coordinate limits of the standard filter(s) (when it is necessary to calibrate the receptor relative to a standard colored filter(s)).

NOTE 3: It is necessary to calibrate the receptor relative to (a) standard colored filter(s), except when using the spectroradiometer method (no filter used). The chromaticity coordinate limits of the standard filter(s) must be specified by stipulating the filter glass type or the manufacturer's part number of the filter.

(c) The observation angle (α).

(d) The entrance angle (β).
NOTE 4: When specifying an entrance angle of 0°, care must be taken to prevent specular reflection from entering the receptor. In this case, the entrance angle should be specified so that specular light will be reflected away from the receptor.

(e) The orientation angle (ω), and the 0° orientation of the datum mark, if random orientation of the sample is not suitable.

(f) The presentation angle (γ).

(g) The observation distance (D') (see 4.2.3).

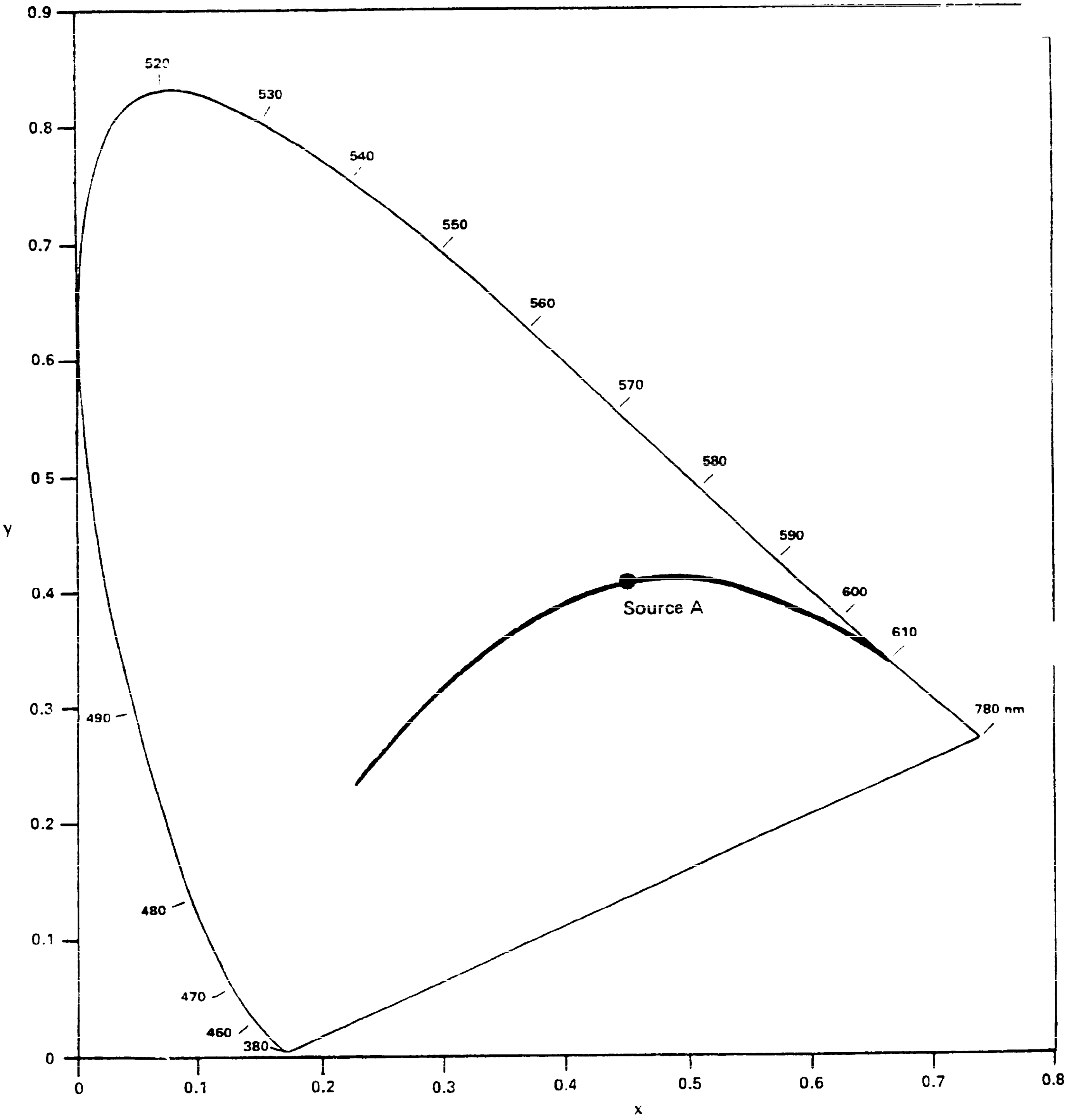

Figure 4.

The 1931 CIE (x,y) - Chromaticity Diagram

(h) Sample dimensions and shape.

(i) The maximum receptor angular aperture [the angle at the sample (δ' in figure 2) subtended by the maximum dimension of this aperture]. The solid angle subtended by the receptor aperture at the reference center shall be specified. This can be accomplished by specifying the receptor dimensions and observation distance (D') or the maximum receptor aperture angle (generally 6 minutes of arc).

NOTE 5: The maximum value of the angle at the sample subtended by the maximum aperture diameter of the receptor should be specified in the material specification: it should be in the order of 6 minutes of arc (see figure 2). However, the maximum diameter of both apertures varies with the test distance.

(j) The maximum angular aperture of the light projector [the angle at the sample (δ in figure 2) subtended by the maximum dimension of this aperture]. The solid angle subtended by the light source aperture at the reference center shall be specified. This can be accomplished by specifying the source aperture dimensions and illumination distance (D), or the maximum source aperture angle (generally 10 minutes of arc).

(k) The reference center.

(l) The reference axis.

NOTE 6: The reference axis usually is 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.

NOTE 7: When evaluation requirements are different from those stated in this standard, it is recommended that the variations be defined relative to the test conditions used in this standard.

4.2 Guidelines for the selection of colorimetric parameters. The following information is provided as a guide to the selection of test distances and apertures. These guidelines are based on the experience of several laboratories which test retroreflectors.

4.2.1 Angular apertures. Useful angular apertures are shown in table III. High resolution tests require observation angles as small as 0.1°. Moderate resolution tests require observation angles no smaller than 0.2°, and low resolution tests require observation angles of 0.33° or greater. It must be noted that, in theory, retroreflected radiant energy is measured with infinitely small apertures, or apertures at least as small as those encountered in practical application. The angular apertures in table III have been found to be useful approximations of these requirements, while still allowing for sufficient sensitivity to realize a practical measurement in the laboratory.

TABLE III. Useful angular apertures for colorimetric testing

	High resolution	Moderate resolution	Low resolution
Sum of angular aperture of source plus receptor ($\delta + \delta'$)*	0.1 ± .02°	0.2 ± .04°	0.33 ± .06°
angular aperture of retroreflector (η or η')	0.4° max.	1.8° max.	3.5° max.
angular aperture of an individual retroreflective optical unit	0.01° max.	0.02° max.	0.04° max.

*Maximum system sensitivity is obtained when the angular apertures of the source (δ) and of the receptor (δ') are equal.

4.2.2 Sample size selection. The recommended minimum sample is one entire retroreflector (a large retroreflector may be tested by summing the effects of smaller segments), or, when testing retroreflective sheeting, a minimum area of 0.09 m^2 (1 ft^2). This can be accomplished, for example, by measuring a single square sample 0.3 m (1 ft) on a side or by averaging the measurements of several smaller pieces totaling 0.09 m^2 (1 ft^2) in area.

4.2.3 Observation distance. The observation distance and illumination distance must be specified in this test metho They are limited by angular aperture requirements, by the requirement to test a minimum sample area, or by the desire to test an entire retroreflector at once. However, the illumination distance must be within ± 1 percent of the observation distance. If it is not possible to have the illumination and observation distances equal, a restrictive opening must be placed in the incident light beam at the observation distance. The angular aperture of the source is then measured at this restrictive aperture.

4.2.4 Photometric range.

4.2.4.1 High resolution test. A 30-m illumination distance with source and receiver angular apertures meeting the tolerance of table III is recommended. With this arrangement, if the sample retroreflector is contained within a circle 18 cm in diameter, the maximum angular aperture of the retroreflector (0.4°) will not be exceeded. However, this method does not exclude the use of shorter illumination distances (or longer if needed when the angular aperture of the elemental optical unit is large), provided the angular requirements and minimum sample sizes are within the stated tolerances.

4.2.4.2 Moderate resolution test. A 15-m illumination distance with a 25-mm diameter receptor aperture is recommended. With this arrangement, the sample retroreflector must be within a circle 45 cm in diameter in order not to exceed the maximum angular aperture limit. However, this method does not exclude the use of shorter illumination distances, provided the tolerances for the angular apertures of the source, the photoreceptor, the retroreflector, and the elemental retroreflective optical unit are not exceeded. However, shorter illumination distances may necessitate testing and averaging the readings on several smaller samples of the retroreflector in order to meet the sample size requirement.

4.2.4.3 Low resolution test. An 8.7-m illumination distance with source and receiver angular apertures meeting the tolerances of table III is recommended. At this distance, a 0.46-m specimen will be within the angular tolerances for sample specified in table III. This geometry allows for greater sensitivity to low reflectivity materials or for tests at larg observation angles (e.g., α = 2.0 or 8.0°). Other distances may be used for the low resolution test, provided the angular requirements and samples sizes are within the tolerances of table III.

5. APPARATUS

5.1 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.

5.2 Telecolorimeter. The telecolorimeter shall be equipped with:

a. CIE 1931 Tristimulus Value filters :

- An $\bar{x}_{red}$ filter for the long wave portion of the $\bar{x}$ function
- An $\bar{x}_{blue}$ filter for the short wave portion of the $\bar{x}$ functio
- A $\bar{y}$ filter for the $\bar{y}$ function (spectral luminous efficiency function)
- A $\bar{z}$ filter for the $\bar{z}$ function

b. Stability and linearity. The linearity of the scale reading shall be within ± 0.3 percent over the range to be measured. The stability and readability shall be ± 0.1 percent over the range to be measured.

c. 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 which prevents interreflection between the filter and the telecolorimeter.

d. 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 photometer-type instrument is used.

NOTE 8: A selection of angular field apertures from 2 minutes to 3° may be necessary, because retroreflective material specifications require various test distances which affect the actual field aperture. The field of view should be limited to the smallest aperture that includes the entire sample.

e. Objective lens. If the telecolorimeter is equipped with an objective lens, it shall focus at the test distance.

5.3 Spectroradiometer. The spectroradiometer shall be equipped with:

a. Dispersive element. A device which 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, and the half-power bandwidth shall be between 4 and 8 nm.

b. Receptor stability and linearity. The receptor shall be stable and linear to within ± 1 percent over the range to be measured.

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

d. 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.

5.4 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 spectral energy distribution conforming to CIE Standard Source A (a tungsten filament lamp operated at a color temperature of 2856 K). The normal illuminance (see 8.3) on the sample shall be uniform within 5 percent of the average normal illuminance over the area of the retroreflector at the test distance. The light projector shall be equipped with an adjustable iris diaphragm or a selection of fixed apertures. The intensity of the light shall be regulated and shall not vary more than 1 percent for the duration of the test.

NOTE 9: Many projection lamps are designed to operate at color temperatures higher than 2856 K. In such cases, the terminal voltage at the lamp shall be adjusted to provide the specified color temperature.

NOTE 10: The maximum diameter of the projector exit aperture and the angle at the test sample thus subtended should not exceed that specified in paragraph 4.1.

5.5 Goniometer sample holder and other supports. Suitable supports shall be provided for the source, telecolorim and test samples as required so that the geometric arrangement required for calibration and measurements can be ach d and maintained. The goniometer shall support the test sample so that the complement of the specified entrance angle does not change more than ± 0.5 percent. The vertical angle of the goniometer shall be set perpendicular to the axis of incident light. The horizontal angle movement shall permit colorimetric measurements which require plus or minus angle settings.

5.6 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.

NOTE 11: The observation distance D' must be large enough so that the lateral displacement of the retroreflected light within the optical elements of the retroreflective material is small relative to the lateral distance d of the measurement. For most spherical lens materials with optical elements less than 0.005 inches in diameter, this displacement is negligible. For large cube corner constructions, it may be significant. Thirty meters is generally a sufficient observation distance for typical cube corner constructions. Shorter observation distances may be used for spherical lens retroreflectors.

NOTE 12: The lateral distance (d) is an important parameter. It can easily be measured by mounting a riflescope on the goniometer at the reference center of the sample. The cross hairs of the scope can then be centered and focused on the exit aperture of the light projector. By sighting through the riflescope, a pointer can be located on the axis of incident light at the point where the lateral distance line intercepts the axis of incident light. The lateral distance can then be precisely measured. Table IV gives the lateral distance d for various values of the observation distance D' and the observation angle.

TABLE IV. Lateral distance as a function of observation angle and observation distance

Observation angle (α) (degrees)	Observation distance (D') (feet)	Lateral distance (d) (inches)
0.2	50	2.09
0.33	50	3.46
0.5	50	5.24
1.33	50	13.93
2.0	50	20.95
8.0	50	84.32
0.2	100	4.19
0.33	100	6.91
0.5	100	10.47
1.33	100	27.86
2.0	100	41.90
8.0	100	168.65

5.7 Calibration standards. Calibration filters (calibrated on a spectrophotometer), having relative spectral transmittance curves similar in shape to those of the spectral reflectance of the test sample, shall be used. (By similar shapes is meant that the ratio of the spectral reflectance of the sample to the spectral transmittance of the filter is approximately constant.)

6. TEST PROCEDURES

6.1 General. The geometry used to determine the performance of retroreflective materials shall be in accordance with figures 1 and 2.

6.2 Goniometer calibration. The goniometer shall be calibrated at the 0° entrance angle position in the vertical and horizontal planes of the test sample. All measurements shall be made relative to this point and shall be checked 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 that the goniometer be calibrated at the 90° entrance angle position for greatest accuracy.

> NOTE 13: This can be accomplished by locating a 300-mm (12-inch) 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.

6.3 Procedure I.

6.3.1 Calibration of the telecolorimeter. Place a spectrally flat white diffusing surface that does not alter the color temperature of the reflected light in the sample position as shown in figure 5. Focus the telecolorimeter, equipped with the field aperture to be used during the color measurements, on the white surface. Obtain a reading with the telecolorimeter for each of the "instrument" filters. First obtain a reading for Y' (usually a reading of 100 is obtained). Then read X'_{red}, X'_{blue}, and Z'. The following values must be obtained:

$X'_{blue} = 0.0538\ Y'$

$X'_{red} = 1.0445\ Y'$

$Z' = 0.3555\ Y'$

Then insert a reference filter, calibrated to a standard color with a spectrophotometer and assigned X_{true}, Y_{true}, Z_{true}, values, into the instrument's auxiliary filter holder. With each of the instrument's filters positioned in turn before the photoreceptor, read X''_{red}, X''_{blue}, Y'', and Z''. Calculate the color correction factors CF_X, CF_Y, and CF_Z as follows:

$$CF_X = \frac{X_{true}}{X''_{red} + X''_{blue}}$$

$$CF_Y = \frac{Y_{true}}{Y''}$$

$$CF_Z = \frac{Z_{true}}{Z''}$$

where: CF_X, CF_Y, CF_Z = correction factors

X_{true}, Y_{true}, Z_{true} = the X, Y, and Z values assigned to the reference filters. These values are determined with a spectrophotometer for Illuminant A and the 1931 Standard Observer.

X''_{red}, X''_{blue}, Y'', Z'' = telecolorimeter readings of X_{red}, X_{blue}, Y, and Z for Source A equipped with the respective filter.

NOTE 14: The color correction factors are attempts to bring the telecolorimeter's responses into agreement with the true tristimulus values of the spectrum colors for the 1931 Standard Observer as shown in figure 3.

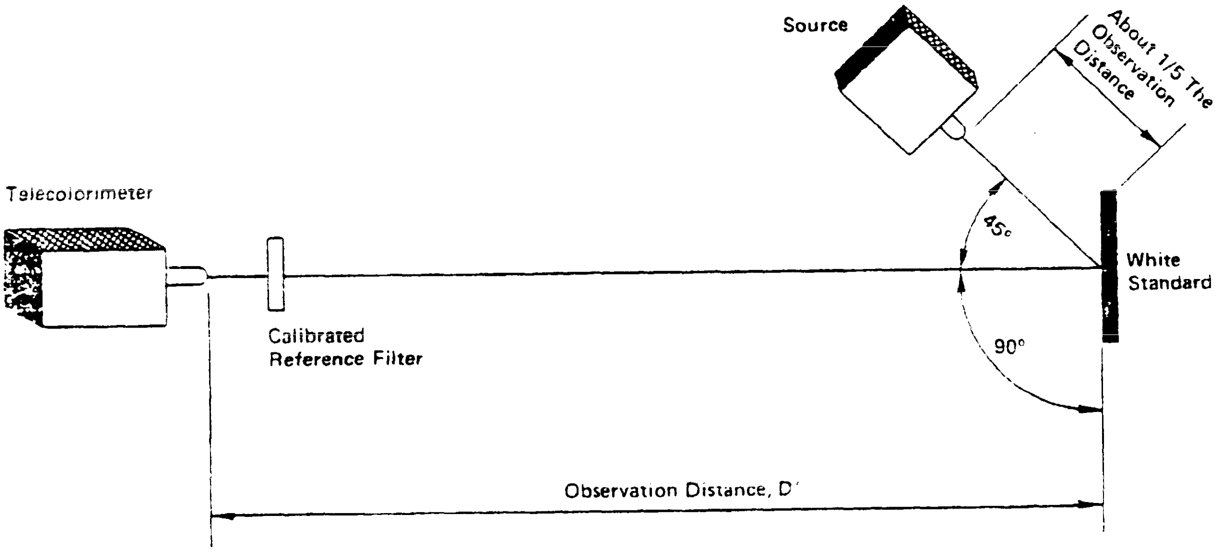

FIGURE 5

Arrangement for calibration of the telecolorimeter

6.3.2 Color measurement. Reposition the telecolorimeter to achieve the arrangement specified in figures 1 and 2 and in the specification 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. To minimize errors in the color temperature of the light source, the same light source shall be used for both calibration and color measurement. The collection optics of the telecolorimeter must be adjusted so that, when placed in the receptor position, either the entire retroreflective sample is contained within its field of view or the entire field of view is contained within the uniform sample surface. In the case of retroreflecting devices, the first of these conditions is recommended. Focus the telecolorimeter on the test surface, and ensure that the field stop aperture of the telecolorimeter is completely filled with light. Read the X_{red}, X_{blue}, Y, and Z values of the sample by positioning each of the tristimulus filters in turn before the telecolorimeter. Then correct these values by the following equations:

$$X_{test} = (X_{red} + X_{blue})\ (CF_X)$$

$$Y_{test} = Y\ (CF_Y)$$

$$Z_{test} = Z\ (CF_Z)$$

Compute the chromaticity coordinates x and y of the test sample by the following equations:

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

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

The computed CIE chromaticity coordinates, x_{test}, and y_{test}, locate a point on the CIE diagram. The test sample meets specification requirements when this point falls within the color block established in the specification for the material (see 4.1a).

6.4 Procedure II.

6.4.1 Use of the spectroradiometer. This method employs a spectroradiometer to measure the spectral distribution of the irradiance on the sample 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 sample is contained within its field of view or the entire field of view is contained within the uniform sample surface. In the case of retroreflecting devices, the first of these conditions is recommended. When the entire sample is included in the field of view, the field of view should be sufficiently larger than the sample to avoid problems in alignment, but not so large as to cause difficulty by collecting stray radiation. When the entire field of view is contained within the retroreflecting area, the field of view should be sufficiently smaller than the retroreflecting area in order to avoid problems with misalignment, but should not be so small as to cause difficulty with sample nonuniformity.

6.4.2 Color measurement. Place the spectroradiometer in the receptor position, and take readings $R_1(\lambda)$ of the light reflected from the retroreflector being measured at each wavelength from 400 to 700 nm at 10-nm intervals. Then place the spectroradiometer in the sample position, ensure that the entire source exit aperture is contained in the field of view of the spectroradiometer, and take readings $R_2(\lambda)$ at each wavelength from 400 to 700 nm at 10-nm intervals.

NOTE 15: An alternate set of $R_2(\lambda)$ readings can be obtained by viewing the radiation reflected from a $BaSO_4$ plaque as shown in figure 5. This method has the advantage that $R_1(\lambda)$ and $R_2(\lambda)$ 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 $R_2(\lambda)$, and its collection optics must not be changed from that used when $R_1(\lambda)$ is measured. A large observation angle (such as 45°) must be used, for $BaSO_4$ surfaces retroreflect in a manner which is difficult to predict and therefore calibrating at small observation angles can result in large errors.

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

$$X = k \sum_{380}^{760} R_1(\lambda)/R_2(\lambda)\, S_A(\lambda)\, \bar{x}(\lambda)$$

$$Y = k \sum_{380}^{760} R_1(\lambda)/R_2(\lambda)\, S_A(\lambda)\, \bar{y}(\lambda)$$

$$Z = k \sum_{380}^{760} R_1(\lambda)/R_2(\lambda) S_A(\lambda) \bar{z}(\lambda)$$

where: R_1 = reading of the sample

R_2 = reading of the incident radiation, either directly or reflected from a $BaSO_4$ plaque.

The chromaticity coordinates x and y are given by:

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

7. PRECISION

7.1 Precision. The standard deviation of measurement of the chromaticity coordinates for samples of various colors is given in table V. This precision statement is based on repeat measurements (see 8.5) of the same samples and does not include variations introduced by sampling. Participating laboratories were allowed to select values for all parameters in section 4 based on individual preference and availability of equipment. It is anticipated that measurements using a uniform set of test parameters will be more accurate than the measurements summarized in table V.

TABLE V. Standard deviations of single nighttime chromaticity measurements

Color	Number of specimens	Degrees of freedom		Standard deviations			
		Within one laboratory	Between laboratories	Within one laboratory		Between laboratories	
				x	y	x	y
White	6	12	48	.005	.002	.011	.005
Yellow	6	12	48	.002	.002	.007	.006
Red	8	16	64	.004	.002	.007	.007
Blue	7	14	56	.008	.011	.010	.032
Green	8	16	64	.005	.009	.008	.021
Orange	9	18	72	.003	.006	.006	.005

7.2 Repeatability. The repeatability statement in table VI is based on repeat measurements using a tristimulus filter colorimeter over a period of several months in one laboratory.

7.3 Reproducibility. The reproducibility statement in table VI is based on an international interchange of samples between nine laboratories (see 8.5). One set of samples was measured both by tristrimulus colorimeters and by spectrophotometers.

TABLE VI. Maximum allowable differences for two determinations (95% C.I. for a range of two)

Color	Repeatability* (within one laboratory)		Reproducibility** (between laboratories)	
	x	y	x	y
White	.015	.006	.031	.014
Yellow	.006	.006	.021	.017
Red	.012	.006	.021	.020
Blue	.024	.033	.028	.091
Green	.015	.027	.023	.059
Orange	.009	.018	.017	.014

* The limits for repeatability are stated such that one would expect the difference between a pair of individual determinations to exceed this value one time in twenty.

** The limits for reproducibility are stated such that one would expect the difference between a single determination in one laboratory and a single determination in a second laboratory to exceed this value one time in twenty.

8. REFERENCES

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