Designation: E 308 – 99

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

This standard is issued under the fixed designation E 308; 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 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 E 308 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.

The 1994 revision was made in order to introduce to the user a method of reducing the dependence of the computed tristimulus values on the bandpass of the measuring instrument, using methods that are detailed in this practice. These changes, however, lead to tables (Tables 6 in this practice) that are substantially different from the Tables 5 that have been in use since 1985. There is accordingly a danger, if the new tables are introduced but not universally adopted, that there may again be, perhaps for several decades, a significant disparity among the tables of tristimulus weighting factors commonly used. It is highly desirable that this should be avoided.

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.

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 according to Practice E 1164 with 1-, 5-, 10-, or 20-nm measurement interval.

1.5 Procedures are included for cases in which the spectral data are, and those in which they are not, corrected for bandpass dependence. For the uncorrected cases, it is assumed that the spectral bandpass of the instrument used to obtain the data was approximately equal to the measurement interval and was triangular in shape. These choices are believed to correspond to the most widely used industrial practice.

1.6 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

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[1] This practice is under the jurisdiction of ASTM Committee E-12 on Color and Appearanceand 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.

differences in these and other systems are given in Test Method D 2244.

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
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:

$\Sigma\bar{x}(\lambda) = 21.3714$
$\Sigma\bar{y}(\lambda) = 21.3711$
$\Sigma\bar{z}(\lambda) = 21.3715$

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

TABLE 2 *Continued*

λ(nm)	$\bar{x}_{10}(\lambda)$	$\bar{y}_{10}(\lambda)$	$\bar{z}_{10}(\lambda)$
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
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:

$\Sigma\bar{x}_{10}(\lambda) = 23.3294$
$\Sigma\bar{y}_{10}(\lambda) = 23.3324$
$\Sigma\bar{z}_{10}(\lambda) = 23.3343$

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

TABLE 3 *Continued*

λ (nm)	*A* $S(\lambda)$	*C* $S(\lambda)$	D_{50} $S(\lambda)$	D_{55} $S(\lambda)$	D_{65} $S(\lambda)$	D_{75} $S(\lambda)$
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
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

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

TABLE 4 *Continued*

λ(nm)	*F2*	*F7*	*F11*
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
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

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

2. Referenced Documents

2.1 *ASTM Standards:*

D 2244 Test Method for Calculation of Color Differences from Instrumentally Measured Color Coordinates[3]

E 284 Terminology of Appearance[3]

E 313 Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Color Coordinates[3]

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

2.2 *ANSI Standard:*

PH2.23 Lighting Conditions for Viewing Photographic Color Prints and Transparencies[4]

2.3 *CIE/ISO Standards:*

CIE Standard S 001/ISO IS 10526, Colorimetric Illuminants[4,45]

CIE Standard S 002/ISO IS 10527, Colorimetric Observers[4], [45]

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

2.4 ASTM Adjuncts:

Computer disk containing Tables 5 and 6[6]

3. Terminology

3.1 Definitions of terms in Terminology E 284 are applicable to this practice (see also Ref **(4)**).

3.2 *Definitions:*

3.2.1 *bandpass, n—of a passband*, the wavelength range over which the radiant power through the passband is at least half of its maximum value within the passband (syn: *bandwidth*) (see *passband*).

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

3.2.3 *chromaticity coordinates*, *n*—the ratio of each of the tristimulus values of a psychophysical color (see section 3.2.7.11) to the sum of the tristimulus values.

3.2.3.1 *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 supplementary colorimetric system, the same equations apply with all symbols having the subscript 10 (see 3.2.6.).

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

3.2.5 *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.

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

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

[4] Available from American National Standards Institute, 13th Floor, 11 W. 42nd St., New York, NY 10036.

[5] Available from USNC-CIE Publications Office, c/o Mr. Thomas M. Lemons, TLA-Lighting Consultants, 7 Pond Street, Salem, MA 01970-4819.

[6] Computer disk of 72 tables is available from ASTM Headquarters. Request Adjunct No. 12-ADJE0308.

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

3.2.7 *CIE 1976 (u′, v′) or (*u'_{10}, v'_{10}*)* chromaticity diagram, *n*—chromaticity diagram in which the CIE 1976 L^* u^* v^* (CIELUV) chromaticity coordinates are plotted, with u' (or u'_{10}) as abscissa and v' (or v'_{10}) as ordinate.

3.2.8 *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 $\bar{x}$ (λ), $\bar{y}$ (λ), $\bar{z}$ (λ) adopted by the CIE in 1931.

3.2.9 *CIE 1964 supplementary 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).

NOTE 1—Users should be aware that the CIE 1964 (10°) supplementary 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.

3.2.10 *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.

3.2.11 *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.

3.2.12 *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.

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

3.2.14 *CIE recommended fluorescent illuminants*, *n*—a set of spectral power distributions of 12 types of fluorescent lamps, the most important of which are *F2*, representing a cool white fluorescent lamp with correlated color temperature 4200 K, *F7*, a broad-band (continuous-spectrum) daylight lamp (6500 K), and *F11*, a narrow-band (line-spectrum) white fluorescent lamp (4000 K).

3.2.15 *luminous*, *adj*—weighted according to the spectral luminous efficiency function *V* (λ) of the CIE.

3.2.16 *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.

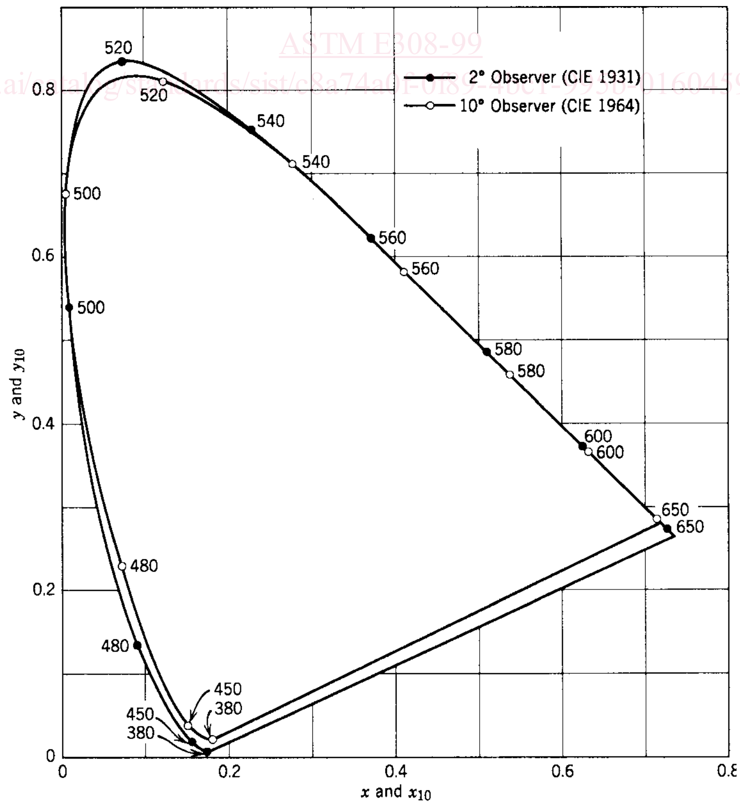


FIG. 1 The CIE 1931 *x* , *y* and 1964 x_{10}, y_{10} Chromaticity Diagrams (5) (see Note 2)

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 *passband*, *n*—a narrow portion of a dispersed spectrum, selected by the exit slit of a monochromator or the equivalent, for the purpose of defining an emitted spectral power function.

3.2.19.1 *Discussion*—The shape of the spectral transmittance function of the passband may be triangular, trapezoidal, or rectangular, among others, but is usually symmetrical.

3.2.20 *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.

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

3.2.22 *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.

3.2.23 *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.

3.2.24 *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.

3.2.24.1 *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).

3.2.25 *standard observer*, *n*—an ideal observer having visual response described by the CIE color-matching functions (see CIE S002 and Ref **(3)**).

3.2.26 *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.”

3.2.27 *CIE 1964 supplementary 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).

3.2.28 *tristimulus values*, *n*—see 3.2.8 and 3.2.9.

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 or 20 nm, used to compute tristimulus values by multiplication by the spectral reflectance, transmittance, or radiance (or the corresponding factors) and summation.

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

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 002 or D 001, or Ref **(3)** (see 3.2.25 and Note 1).

4.1.2 *Illuminant*—Select one of the CIE standard or recommended illuminants tabulated in this practice, CIE Standard S 001 or D 001, or Ref **(3)** (see 3.2.21).

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*—The user should ascertain whether or not the spectral data have been corrected for bandpass dependence. The accuracy of tristimulus values is significantly improved by incorporating a correction for bandpass dependence into either the spectral data or the tables of tristimulus weighting factors (see 7.2). The procedures used depend on this and on the measurement interval.

4.2.1 For data obtained at 1- or 5-nm measurement interval, the procedures of 7.2 should be followed.

4.2.2 For data obtained at 10- or 20-nm measurement interval, the tables of tristimulus weighting factors contained in Tables 5 should be used with spectral data that have been corrected for bandpass dependence. The tables contained in Tables 6 should be used with spectral data that have not been so corrected; these tables include a provision that minimizes the error introduced by bandpass dependence when employing a triangular passband equal in half width to the measurement interval.

4.2.3 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.

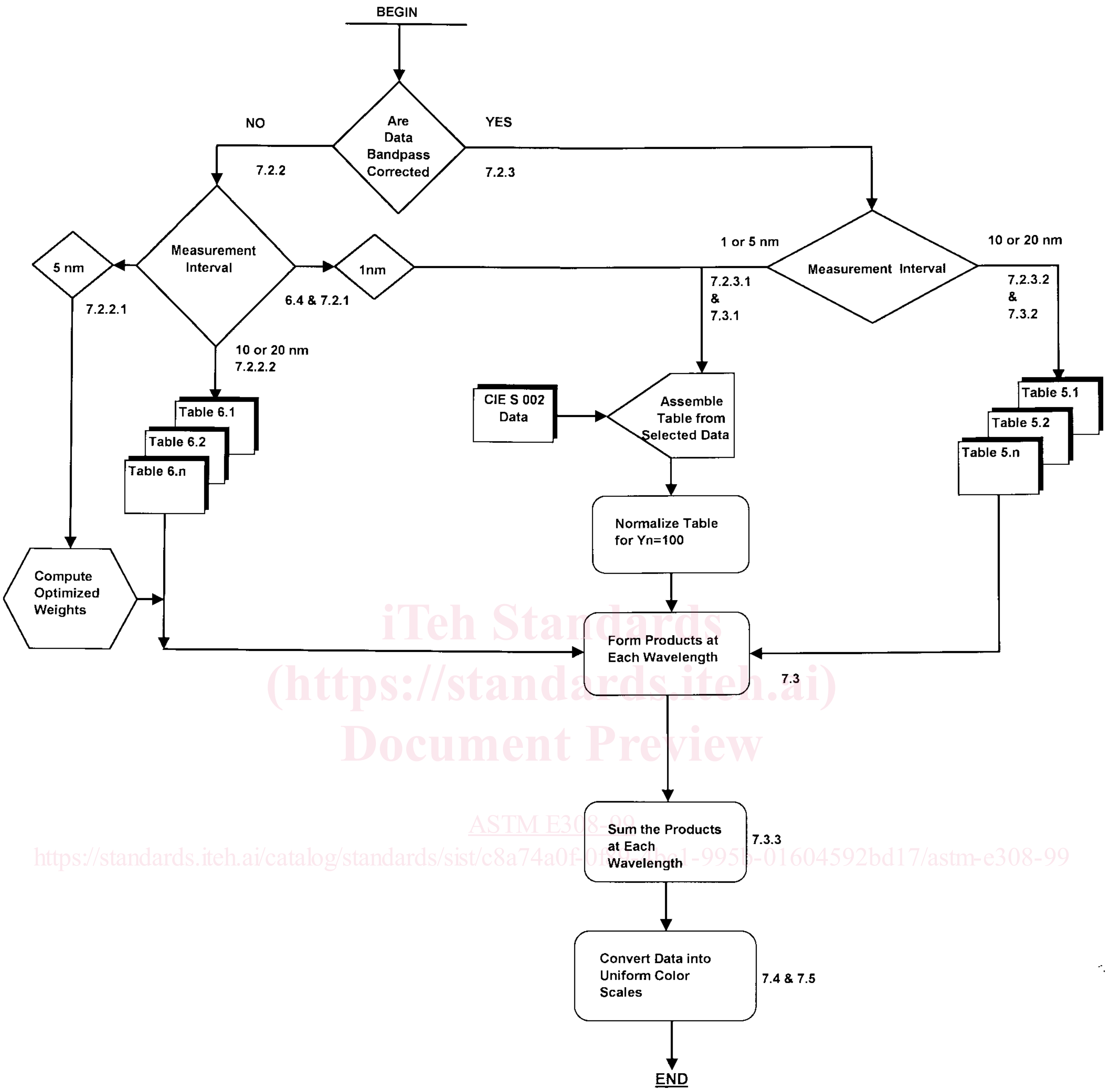
4.3 *Calculations*—CIE tristimulus values *X*, *Y*, *Z* or X_{10}, Y_{10}, Z_{10} are calculated by numerical summation of the products of tristimulus weighting factors for selected illuminants and observers with the reflectance factors (or transmittance or radiance factors) making up the spectral data.

4.4 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,



NOTE 1—References to Section 7. Calculations are Included.

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

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 supplementary 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 (*F*2) unless results are desired for 6500 K broad-band daylight (*F*7) or 4000 K narrow-band white (*F*11) fluorescent illumination.

6.3 *Selecting the Measurement Interval*— For greater accuracy select the 5-nm measurement interval over the 10-nm 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 ensure themselves that the resulting accuracy is sufficient for the purpose for which the results are intended. For many industrial applications use of the 20-nm interval may be satisfactory.

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

6.3.2 The measurement interval should never be greater than the bandpass (half width of the passband). The use of a measurement interval less than the bandpass does not improve the *accuracy* of the computation, but may improve the *repeatability* by providing redundant spectral data.

6.4 *Other Miscellaneous Conditions*— While the above selections cover the majority of industrial practices, the possibility exists that other conditions could be encountered. Further, the deconvolution routine used to produce Tables 6 is not unique and uses approximating techniques that, while providing overall a good approximation to the true value, may not in a specific instance provide the best approximation. 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 to 9). The fundamental definition is in terms of integrals,

$$X = k \int_{\lambda} R(\lambda)\, S(\lambda)\, \bar{x}(\lambda)\, d\lambda \qquad (1)$$

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

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

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

$$k = 100 / \int_{\lambda} S(\lambda)\, \bar{y}(\lambda)\, d\lambda \qquad (2)$$

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

$$X = k \sum_{\lambda} R(\lambda)\, S(\lambda)\, \bar{x}(\lambda)\, \Delta\lambda \qquad (3)$$

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

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

with:

$$k = 100 / \sum_{\lambda} S(\lambda)\, \bar{y}(\lambda)\, \Delta\lambda. \qquad (4)$$

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

$$W_x(\lambda) = k\, S(\lambda)\, \bar{x}(\lambda) \Delta\lambda \qquad (5)$$

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

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

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

$$k = 100/\sum_{360}^{780} S(\lambda)\, \bar{y}(\lambda)\, \Delta\lambda \qquad (6)$$

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* (λ) 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* (λ) in the following equations:

$$X = \sum_{360}^{780} W_x(\lambda)\, R(\lambda) \Delta\lambda \qquad (7)$$

$$Y = \sum_{360}^{780} W_y(\lambda)\, R(\lambda) \Delta\lambda$$

$$Z = \sum_{360}^{780} W_z(\lambda)\, R(\lambda)\, \Delta\lambda$$

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.

7.2 *Summary of Calculations* (see Note 2)—A general outline of the procedure is given in Fig. 2 in the form of a flow chart. Begin by determining whether or not the spectral data have been corrected for bandpass dependence.

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 S001 and S002 (or on CIE D001 Disk) and (Eq 3) and (Eq 4).

7.2.2 *Procedures for Spectral Data With Bandpass Correction:*

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 5) and (Eq 6). 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 7.2.3.2 and 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.

7.2.3 *Procedures for Spectral Data Without Bandpass Correction*:

7.2.3.1 *Procedure for Data Obtained at 5-nm Measurement Intervals*—Prepare optimized tables of tristimulus weighting factors for desired illuminant-observer combinations, using the spectral data in Tables 1-4 (see Note 2), and procedures described in the literature **(10, 11)**. Use the tables so prepared as described in 7.3.

7.2.3.2 *Procedures for Data Obtained at 10- or 20-nm Measurement Intervals*—Select the appropriate tables of tristimulus weighting factors from Tables 6 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 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 3) and (Eq 4).

7.3.2 *Use of Data Obtained at 10- or 20-nm Measurement Intervals*:

7.3.2.1 *Data Available over the Wavelength Range 360 to 780 nm*—Select the appropriate tables of tristimulus weighting factors, computed for triangular bandpass and 10- or 20-nm measurement intervals, for the desired observer and illuminant, from among the 36 sets included in Tables 5 **(12)** for bandpass-corrected data, and from among the 36 sets included in Tables 6 for data that have not been corrected for bandpass dependence. No normalization of any data from Tables 5 or 6 is required.

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 *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 supplementary 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:

$$L^* = 116(Y/Y_n)^{1/3} - 16 \tag{8}$$

$$a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$$

$$b^* = 200[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$$

where:

$$X/X_n;\ Y/Y_n;\ Z/Z_n > 0.01. \tag{9}$$

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).

7.5.1.1 The CIE 1976 ($L^*a^*b^*$) space fails to approximate uniform color spacing when one or more of the ratios X/X_n, Y/Y_n, and Z/Z_n is less than 0.01.

7.5.1.2 In calculating L^*, values of Y/Y_n less than 0.01 may be included if the normal formula is used for values of Y/Y_n greater than 0.008856, and the following modified formula is used for values of Y/Y_n equal to or less than 0.008856:

$$L^* = 903.3(Y/Y_n) \qquad Y/Y_n \leq 0.008856 \qquad (10)$$

7.5.1.3 In calculating a^* and b^* values of X/X_n, Y/Y_n, Z/Z_n less than 0.01 may be included if the normal equations are replaced by the following modified equations for *all* calculations of a^* and b^*:

$$a^* = 500[f(X/X_n) - f(Y/Y_n)] \qquad (11)$$

$$b^* = 200[f(Y/Y_n) - f(Z/Z_n)]$$

where:

$$f(X/X_n) = (X/X_n)^{1/3} \qquad \mathrm{X/X_n} > 0.008856 \qquad (12)$$

$$f(X/X_n) = 7.787(X/X_n) + 16/116 \qquad \mathrm{X/X_n} \leq 0.008856$$

$$f(Y/Y_n) = (Y/Y_n)^{1/3} \qquad \mathrm{Y/Y_n} > 0.008856$$

$$f(Y/Y_n) = 7.787(Y/Y_n) + 16/116 \qquad \mathrm{Y/Y_n} \leq 0.008856$$

$$f(Z/Z_n) = (Z/Z_n)^{1/3} \qquad \mathrm{Z/Z_n} > 0.008856$$

$$f(Z/Z_n) = 7.787(Z/Z_n) + 16/116 \qquad \mathrm{Z/Z_n} \leq 0.008856$$

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):

$$L^* = 116(Y/Y_n)^{1/3} - 16 \qquad \mathrm{Y/Y_n} > 0.01 \qquad (13)$$

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

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

with:

$$u' = \frac{4X}{X + 15Y + 3Z} \qquad (14)$$

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

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

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

7.5.2.1 In calculating L^* values for Y/Y_n less than 0.01, use the same equation given in 7.5.1.3.

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:

$$h_{\mathrm{ab}} = \tan^{-1}(b^*/a^*) \quad \text{or} \quad h_{\mathrm{uv}} = \tan^{-1}(v^*/u^*) \qquad (15)$$

CIE 1976 chromas:

$$C^*_{ab} = [(a^*)^2 + (b^*)^2]^{1/2} \quad \text{or} \quad C^*_{uv} = [(u^*)^2 + (v^*)^2]^{1/2} \qquad (16)$$

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 Test Method D 2244).

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 or 6 for measurement intervals of 10 or 20 nm, 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 E 313).

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 supplementary 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}, $F2$, $F7$, $F11$.

8.1.5 *Bandpass Correction*—Indicate whether or not the spectral data were corrected for bandpass, and which sets of tables of tristimulus weighting factors were used.

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 $L^*C^*_{\mathrm{ab}}h_{\mathrm{ab}}$, or CIELUV results as $L^*u^*v^*$ or $L^*C^*_{\mathrm{uv}}h_{\mathrm{uv}}$.

9. Precision and Bias

9.1 *Precision*—The precision of results calculated by use of Tables 1-5 is limited by the precision of the measured spectral data and round-off of the data used in the calculations. The precision of Tables 6, incorporating correction for bandpass dependence, is believed to be about 4.5 log units (digits). Thus the precision of the results is expected to be limited by the precision of the spectral data, not of the tables.

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.