



Designation: D 2244 – 02

Standard Practice for Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates¹

This standard is issued under the fixed designation D 2244; 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

This practice originally resulted from the consolidation of a number of separately published methods for the instrumental evaluation of color differences. As revised in 1979, it included four color spaces in which color-scale values could be measured by instruments, many of which were obsolete, and the color differences calculated by ten equations for different color scales. The sections on apparatus, calibration standards and methods, and measurement procedures served little purpose in the light of modern color-measurement technology. The revision published in 1993 omitted these sections, and limited the color spaces and color-difference equations considered, to the three most widely used in the paint and related coatings industry. This revision adds two new color tolerance equations and puts two of the color difference equations from the 1993 version in an informative annex for historical purposes. The Hunter L_H , a_H , b_H and FMC-2 color difference equations are no longer recommended. This revision also changes the status of the standard from test method to practice.

1. Scope

1.1 This practice covers the calculation, from instrumentally measured color coordinates based on daylight illumination, of color tolerances and small color differences between opaque specimens such as painted panels, plastic plaques, or textile swatches. Where it is suspected that the specimens may be metameric, that is, possess different spectral curves though visually alike in color, Practice D 4086 should be used to verify instrumental results. The tolerances and differences determined by these procedures are expressed in terms of approximately uniform visual color perception in CIE 1976 CIELAB opponent-color space (1)², CMC tolerance units (2), CIE94 tolerance units (3), the DIN99 color difference formula given in DIN 6176 (4), or the new CIEDE2000 color difference units (5). The color differences based on Hunter L_H , a_H , b_H opponent-color space (6), or the Friele-MacAdam-Chickering (FMC-2) color space (7), are no longer recommended for industrial practice.

1.2 For product specification, the purchaser and the seller shall agree upon the permissible color tolerance between test specimen and reference and the procedure for calculating the

color tolerance. Each material and condition of use may require specific color tolerances because other appearance factors, (for example, specimen proximity, gloss, and texture), may affect the correlation between the magnitude of a measured color difference and its commercial acceptability.

1.3 *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 requirements prior to use.*

2. Referenced Documents

2.1 ASTM Standards:

- D 1729 Practice for Visual Appraisal of Colors and Color Differences of Diffusely-Illuminated Opaque Materials³
- D 4086 Practice for Visual Evaluation of Metamerism³
- E 284 Terminology of Appearance³
- E 308 Practice for Computing the Colors of Objects by Using the CIE System³
- E 805 Practice for Identification of Instrumental Methods of Color or Color-Difference Measurement of Materials³
- E 1164 Practice for Obtaining Spectrophotometric Data for Object-Color Evaluation³

2.2 Other Standards:

- DIN 6176 Farbmetrische, Bestimmung von Farbabständen

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 standard.

³ Annual Book of ASTM Standards, Vol 06.01.



bei Körperfarben nach der DIN99-Formel⁴

3. Terminology

3.1 Terms and definitions in Terminology E 284 are applicable to this practice.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *colorimetric spectrometer, n*—spectrometer, one component of which is a dispersive element (such as a prism, grating or interference filter or wedge or tunable or discrete series of monochromatic sources), that is normally capable of producing as output colorimetric data (such as tristimulus values and derived color coordinates or indices of appearance attributes). Additionally, the colorimetric spectrometer may also be able to report the underlying spectral data from which the colorimetric data were derived.

3.2.1.1 *Discussion*—At one time, UV-VIS analytical spectrophotometers were used for colorimetric measurements. Today, while instruments intended for use in color measurements share many common components, UV-VIS analytical spectrophotometers are designed to optimize their use in chemometric quantitative analysis, which requires very precise spectral position and very narrow bandpass and moderate baseline stability. Colorimetric spectrometers are designed to optimize their use as digital simulations of the visual colorimeter or as the source of spectral and colorimetric information for computer-assisted color matching systems. Digital colorimetry allows more tolerance on the spectral scale and spectral bandwidth but demand much more stability in the radiometric scale.

3.2.2 *color tolerance equation, n*—a mathematical expression, derived from acceptability judgments, which distorts the metric of color space based on the coordinates in that color space, of a reference color, for the purpose of single number shade passing.

3.2.2.1 *Discussion*—The color tolerance equation computes a pass/fail value based on which of the pair of specimens is assigned the designation “standard.” Thus, inter-changing the reference and test specimens will result in a change in the predicted level of acceptance between the specimens while the perceived difference is unchanged. A color difference equation quantifies distance in a color space using the metric of that space. Inter-changing the reference and test specimens does not change either the perceived or predicted color differences.

4. Summary of Practice

4.1 The differences in color between a reference and a test specimen are determined from measurements made by use of a spectral based or filter based colorimeter. Reflectance readings from spectral instruments are converted by computations to color-scale values according to Practice E 308, or these color-scale values may be read directly from instruments that automatically make the computations. Color-difference units are computed, from these color-scale values, and approximate the perceived color differences between the reference and the test specimen.

5. Significance and Use

5.1 The original CIE color scales based on tristimulus

values X , Y , Z and chromaticity coordinates x , y are not uniform visually. Each subsequent color scale based on CIE values has had weighting factors applied to provide some degree of uniformity so that color differences in various regions of color space will be more nearly comparable. On the other hand, color differences obtained for the same specimens evaluated in different color-scale systems are not likely to be identical. To avoid confusion, color differences among specimens or the associated tolerances should be compared only when they are obtained for the same color-scale system. There is no simple factor that can be used to convert accurately color differences or color tolerances in one system to difference or tolerance units in another system for all colors of specimens.

5.2 For uniformity of practice, the CIE recommended in 1976 the use of two color metrics. The CIELAB metric, with its associated color-difference equation, has found wide acceptance in the coatings, plastics, textiles and related industries. While, it has not completely displaced the use of the Hunter L_H , a_H , b_H and the FMC-2 scales, their performance versus experienced visual color judgements is so poor, compared to the newer optimized tolerance equations based on the CIELAB coordinates, that they can no longer be recommended. Therefore, the two older scales are included in an Annex in this practice only for historical purposes. It is anticipated that in a future revision of this practice, the Annex may be deleted as well. The CIELAB metric, by itself, is also not recommended in this practice for use in describing small and moderate color differences (differences with magnitude less than $5.0 \Delta E^*_{ab}$ units). The four more recently defined equations, documented here, are highly recommended for use with color-differences in the range of 0.0 to $5.0 \Delta E^*_{ab}$ units.

5.3 Users of color tolerance equations have found that, in each system, summation of three, vector color-difference components into a single scalar value is very useful for determining whether a specimen color is within a specified tolerance from a standard. However, for control of color in production, it may be necessary to know not only the magnitude of the departure from standard but also the direction of this departure. It is possible to include information on the direction of a small color difference by listing the three instrumentally determined components of the color difference.

5.4 Selection of color tolerances based on instrumental values should be carefully correlated with a visual appraisal of the acceptability of differences in hue, lightness, and saturation obtained by using Practice D 1729. The three tolerance equations given here have been tested extensively against such data for textiles and plastics and have been shown to agree with the visual evaluations to within the experimental uncertainty of the visual judgments. That implies that the equations themselves misclassify a color difference with a frequency no greater than that of the most experienced visual color matcher.

5.5 While color difference equations and color tolerance equations are routinely applied to a wide range of illuminants, they have been derived or optimized, or both, for use under daylight illumination. Good correlation with the visual judgments may not be obtained when the calculations are made with other illuminants. Use of a tolerance equation for other than daylight conditions will require visual confirmation.

⁴ Available from Beuth Verlag GmbH, 10772 Berlin, Germany.



level of metamerism as per Practice D 4086.

6. Description of Color-Difference and Color-Tolerance Equations

6.1 CIE 1931 and 1964 Color Spaces—The daylight colors of opaque specimens are represented by points in a space formed by three rectangular axes representing the lightness scale Y and chromaticity scales x and y , where:

$$x = \frac{X}{X + Y + Z} \quad (1)$$

$$y = \frac{Y}{X + Y + Z} \quad (2)$$

where X , Y , and Z are tristimulus values for either the 1931 CIE standard observer (2° observer) or the 1964 CIE standard observer (10° observer) and standard illuminant D_{65} , or other phase of daylight. These scales do not provide a perceptually uniform color space. Consequently, color differences are seldom if ever computed directly from differences in x , y , and Y .

6.2 CIE 1976 L^* a^* b^* Uniform Color Space and Color-Difference Equation (1, 8)—This is an approximately uniform color space based on nonlinear expansion of the tristimulus values and taking differences to produce three opponent axes that approximate the percepts of lightness-darkness, redness-greenness and yellowness-blueness. It is produced by plotting in rectangular coordinates the quantities L^* , a^* , b^* , calculated as follows:

$$L^* = 116 \cdot \left(\frac{Y}{Y_n} \right)^{\frac{1}{3}} - 16 \quad (3)$$

$$a^* = 500 \cdot \left[\left(\frac{X}{X_n} \right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n} \right)^{\frac{1}{3}} \right] \quad (4)$$

$$b^* = 200 \cdot \left[\left(\frac{Y}{Y_n} \right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n} \right)^{\frac{1}{3}} \right] \quad (5)$$

$$\frac{X}{X_n}, \frac{Y}{Y_n}, \frac{Z}{Z_n} \geq 0.008856 \quad (6)$$

The tristimulus values X_n , Y_n , Z_n define the color of the nominally 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 phase of daylight, 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.

6.2.1 The total color-difference ΔE^*_{ab} between two colors each given in terms of L^* , a^* , b^* is calculated as follows:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (7)$$

NOTE 1—The color space defined above is called the CIE 1976 L^* a^* b^* space and the color-difference equation the CIE 1976 L^* a^* b^* color-difference formula. The abbreviation CIELAB (with all letters capitalized) is recommended.

6.2.2 The CIE 1976 (L^* a^* b^*) metric fails to converge to zero appropriately when one or more of the ratios X/X_n , Y/Y_n , and Z/Z_n is less than 0.008856. In calculating L^* , values of Y/Y_n less than 0.008856 may still be utilized 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.

$$L^* = 903.3 \left(\frac{Y}{Y_n} \right), \quad \frac{Y}{Y_n} < 0.008856 \quad (8)$$

6.2.3 In calculating a^* and b^* , values of X/X_n , Y/Y_n , Z/Z_n less than 0.008856, may still be included if the normal equations are replaced by the following modified equations for calculations of a^* and b^* :

$$a^* = 500 \cdot \left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right) \right] \quad (9)$$

$$b^* = 200 \cdot \left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right) \right] \quad (10)$$

where:

$$f\left(\frac{X}{X_n}\right) = \left(\frac{X}{X_n}\right)^{\frac{1}{3}} \quad \text{if} \quad \frac{X}{X_n} \geq 0.008856 \quad (11)$$

$$f\left(\frac{X}{X_n}\right) = 7.787 \cdot \left(\frac{X}{X_n}\right) + \frac{16}{116} \quad \text{if} \quad \frac{X}{X_n} < 0.008856 \quad (12)$$

$$f\left(\frac{Y}{Y_n}\right) = \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} \quad \text{if} \quad \frac{Y}{Y_n} \geq 0.008856 \quad (13)$$

$$f\left(\frac{Y}{Y_n}\right) = 7.787 \cdot \left(\frac{Y}{Y_n}\right) + \frac{16}{116} \quad \text{if} \quad \frac{Y}{Y_n} < 0.008856 \quad (14)$$

$$f\left(\frac{Z}{Z_n}\right) = \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}} \quad \text{if} \quad \frac{Z}{Z_n} \geq 0.008856 \quad (15)$$

$$f\left(\frac{Z}{Z_n}\right) = 7.787 \cdot \left(\frac{Z}{Z_n}\right) + \frac{16}{116} \quad \text{if} \quad \frac{Z}{Z_n} < 0.008856 \quad (16)$$

6.2.4 The magnitude, ΔE^*_{ab} , gives no indication of the character of the difference since it does not indicate the relative quantity and direction of hue, chroma, and lightness differences.

6.2.5 The direction of the color difference is described by the magnitude and algebraic signs of the components ΔL^* , Δa^* , and Δb^* :

$$\Delta L^* = L^*_B - L^*_S \quad (17)$$

$$\Delta a^* = a^*_B - a^*_S \quad (18)$$

$$\Delta b^* = b^*_B - b^*_S \quad (19)$$

where L^*_S , a^*_S , and b^*_S refer to the reference or standard, and L^*_B , a^*_B , and b^*_B refer to the test specimen or batch. The signs of the components ΔL^* , Δa^* , and Δb^* have the following approximate meanings **(9)**:

$$+ \Delta L^* = \text{lighter} \quad (20)$$

$$- \Delta L^* = \text{darker} \quad (21)$$

$$+ \Delta a^* = \text{redder (less green)} \quad (22)$$

$$- \Delta a^* = \text{greener (less red)} \quad (23)$$

$$+ \Delta b^* = \text{yellow (less blue)} \quad (24)$$

$$- \Delta b^* = \text{bluer (less yellow)} \quad (25)$$

6.2.6 For judging the direction of the color difference between two colors, it is useful to calculate their CIE 1976 metric hue angles h_{ab} and CIE 1976 metric chroma C^*_{ab} as follows:

$$h_{ab} = \tan^{-1} \left(\frac{b^*}{a^*} \right) \quad (26)$$