Conversion of Visual to Instrumental Measurement of Yellowness

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ABSTRACT

Yellowness is the result of a tendency of many materials (especially organic) to absorb more light in the blue end than in the rest of the visible spectrum. For approximately 100 years, yellowness of materials has been rated by visual comparisons with either standardized glasses or standardized solutions of reagent grade chemicals. Since 1942, paints, textiles, plastics and many other materials have been rated for yellowness by photoelectric measurements based on the spectral response characteristics of the normal human eye. Four of the long-established and widely used visual scales for yellowness are related herein to four of the newer and more precise photoelectric tristimulus scales. The four visual scales are Lovibond, Hazen, Gardner and FAC. The tristimulus scales are ASTM D1925, ASTM E313, Hunter b and CIELAB b*. These interrelations between scales were actually developed more than 20 years ago by Ron Stillman of the AOCS, but his data were so voluminous that no opportunity for their publication was ever found.

INTRODUCTION

Yellowness is characteristic of many oils and liquids. It is the result of a more-or-less natural tendency of many materials (especially organic) to absorb more light at the blue end of the spectrum than in the rest of the spectrum. In this paper are some conversions of four of the long-established and widely used visual scales for yellowness to four of the newer and more precise photoelectric tristimulus scales.

VISUAL SCALES FOR MEASUREMENT OF YELLOWNESS

There exist as many as 25 different color scales for rating the yellowness of oils, resins, chemicals, solvents, plastics, fibers, fabrics, and so on, by visual comparisons with color standards (1). Only four are considered here: Lovibond (2), Hazen or APHA (3), Gardner (4) and FAC (2).

In the Lovibond Tintometer, unknown colors are matched visually with combinations of calibrated red, yellow and blue transparent glasses. The edible-oil industry in the U.S. uses only the yellow and red glasses in somewhat fixed ratios of 10Y to 1R to define an essentially one-dimensional scale of yellowness (2).

Two visual yellowness scales (Hazen or APHA, and Gardner) were initially identified by visually matching reagent grade "standard" chemical solutions of defined concentrations. Potassium chloroplatinate (K_2PtCl_6) was used for the Hazen or APHA Scale first proposed in 1892 (3). Ferric chloride ($FeCl_3$) was used for the darker part of the Gardner Scale (4); and Hazen's K_2PtCl_6 was used for the lighter part. Details of these visual color-measurement scales are shown in Table I.

All of the visual methods of measuring yellowness involve the simultaneous observation of two colored areas (sample and control) side by side in a field of view. The scale reading most closely matching that of the unknown

TABLE I

Visual Comparison Scales Most Frequently Used for Measuring Yellowness of Light-Transmitting Oils, Resins and Liquids

Scales and products measured	Method of measurement (including thickness of specimen)	References to descriptions of method and source of tristimulus data
Gardner Color Scale for paint- and chemical-industry drying oils, varnishes, fatty acids and resin solutions.	Sample in test tube 10.65 mm id is compared visually to find which of series of glass discs has closest chromaticity.	ASTM D1544, Color of Transparent Transparent Liquids (Gardner Color Scale), Parts 27 and 29, Annual Book of ASTM Standards. Table 1 gives Y,x,y values of "arbitrarily numbered glass standards."
Hazen, APHA, or Platinum-Cobalt Scale for nearly colorless organic solvents, liquid chemicals, waste water.	Find, visually, the closest of series of platinum-cobalt solutions, each of defined concentration. Use same thickness of solution and test specimen.	(3); ASTM D1209 (parts 27 and 29) and ASTM D2108 (part 30), Annual Book of ASTM Standards. (1) gives Y,x,y of 50-mm optical path.
Fat Analysis Committee of Amer. Oil Chemists Soc. series of glass color standards for inedible fats.	Fat, liquified and filtered, is poured into 10.5-mm id test tube and examined in visual comparator to find which of series of 29 glasses is closest in color.	(2), Color, FAC Standard Colors, (revised 1964). Section D gives Y,x,y of "Glass FAC Standards."
Lovibond (or Tintometer) Color Scale for edible oils (e.g., cottonseed, corn, soybean, palm), tallows, greases (color scales vary with product tested).	Visual comparisons of oil in 5 1/4-in. column (or sometimes 1-in. column with dark oils) with mixtures of yellow and red Lovibond glasses.	(2), Color, Wesson Method. NBS Technical Note 716, "The Ideal Lovibond Color System for CIE . . . Illuminants A and C . . ." (1972) gives Y,x,y for hundreds of mixtures of ideal Lovibond glasses.

TABLE II

Tristimulus Scales Most Frequently Used for Yellowness Measuring with Photoelectric Instruments

Scale and products to be measured	Relation to tristimulus values of 1931 CIE Standard Observer with Illuminant C (9)	Reference
YI (ASTM D1925) for nearly colorless transparent, or nearly white translucent or opaque plastics.	YI (ASTM D1925) = $\frac{[100(1.28X - 1.06Z)]}{Y}$	(8) Part 35.
YI (ASTM E313) for white textiles, paints, plastics and other materials.	YI (ASTM E313) = $(100(1-0.847Z/Y)$	(8) Part 46.
b_L (Hunter b) for yellowness when plus, and blueness when minus, of all diffusely reflecting materials.	b_L (Hunter b) = $7.0\ (Y-0.847Z)/\sqrt{Y}$	(6)
b* (CIELAB b) for yellowness when plus, and blueness when minus, of diffusely reflecting materials.	b* (CIELAB) = $43.1(Y^{1/3}-0.946Z^{1/3})$	(7)

sample is identified as the color of the sample and is so recorded.

PHYSICAL SCALES FOR MEASUREMENT OF YELLOWNESS

Within the past 40 years, not only transparent oils, resins and liquids, but also diffusely reflecting paints, plastics, textiles and the like have been rated for yellowness and yellowing. Yellowness indexes have been used recently to rate discoloration of materials from exposure, product impurity, oxidation, overheating and other sources of degradation. These applications of yellowness indexes have generally used the precise photoelectric tristimulus instruments that have become available recently.

Since the 1950s, a number of tristimulus yellowness scales have appeared as components of the so-called Opponent-Colors Scales for surface colors in which: L measures lightness—zero for black to 100 for perfect white; a measures redness when plus, gray when zero, greeness when minus; and b measures yellowness when plus, gray when zero, blueness when minus.

The b dimensions of the Hunter L,a,b Scale (5,6) and the b* dimension of the CIE 1976 L*a*b* (or CIELAB) Scale (7) have been used to describe yellowness. However, for the darker yellows, these b scales are not recommended. Table II shows equations relating these two b scales and two ASTM yellowness scales (8) (D1925 and E313) to CIE Illuminant C tristimulus values (9). Hunter b is sometimes called b_L to distinguish it from other b values.

In any measurements of yellowness (or any other aspect of color), specimen form and dimensions—whether obtained by instrument or visual comparison and whether observed by reflection or transmission—are important to results.

CONVERSIONS BETWEEN VISUAL AND PHYSICAL BASES

More than 20 years ago, the Inter-Society Color Council established a subcommittee, "Problem 14 on Transparent (Color) Standards Using Single-Number Specifications," which was chaired for many years by Ron Stillman of the Procter and Gamble Company. In a detailed interim report in 1962 (1), the committee attempted to relate the visual scales to the CIE tristimulus scales. The efforts of the subcommittee led to much of the color conversion data used in this report. A summary of the subcommittee findings was published by Johnston in 1971 (10).

Of the four tristimulus scales studied in this project, the YI scale defined in ASTM D1925 is the best for the overall single-number color identification of the various colorless-to-yellow-to-amber materials. This is because the D1925 scale provides a continuous scale from the colorless (or white) region toward yellow and from yellow toward reddish amber. The other scales are satisfactory only for the white-to-yellow portion of the color gamut because, as

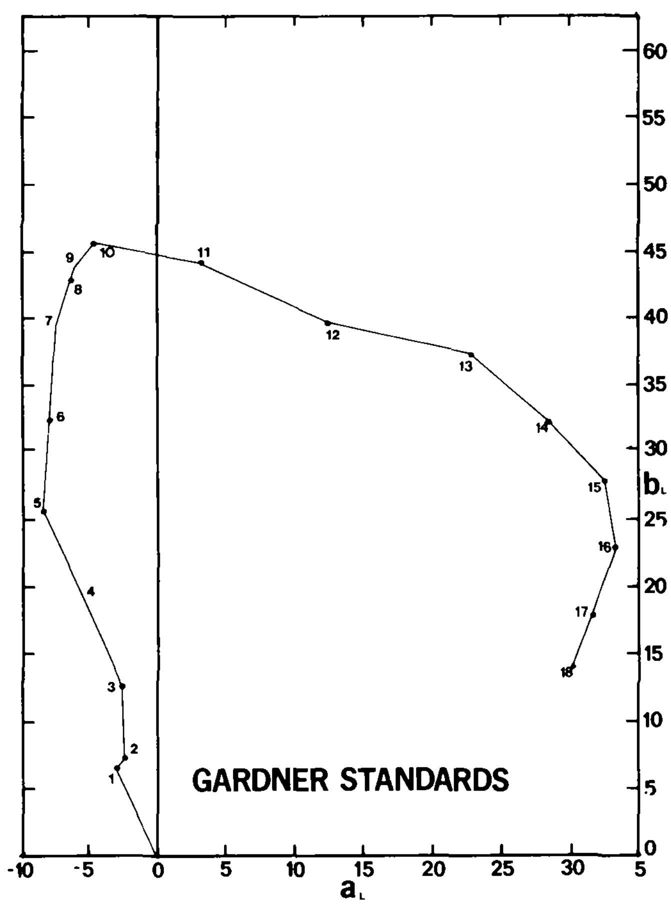

FIG. 1. Gardner colors, as specified in ASTM D1544, converted to Hunter a,b.

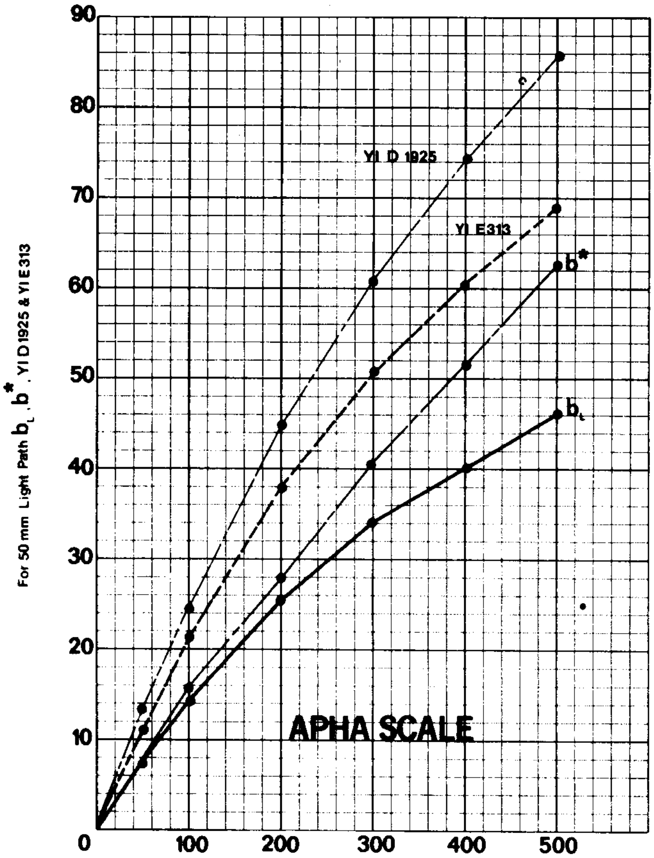

FIG. 2. Two values of b and two ASTM yellowness indexes plotted against APHA (Hazen) color for 50-mm light path.

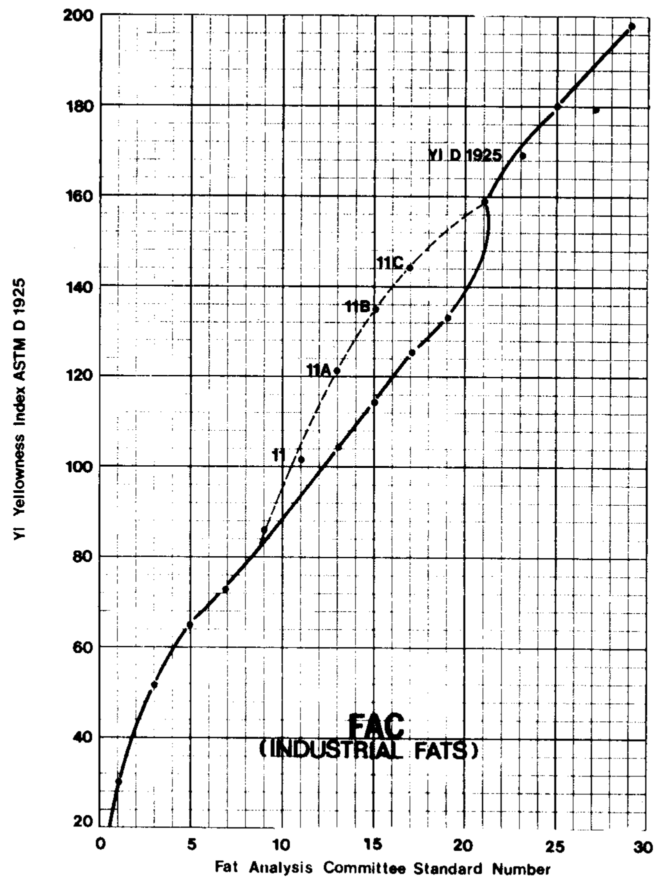

FIG. 4. ASTM D1925 yellowness index plotted against AOCS fat analysis Committee Color Standard numbers (10.5-mm id test tubes used).

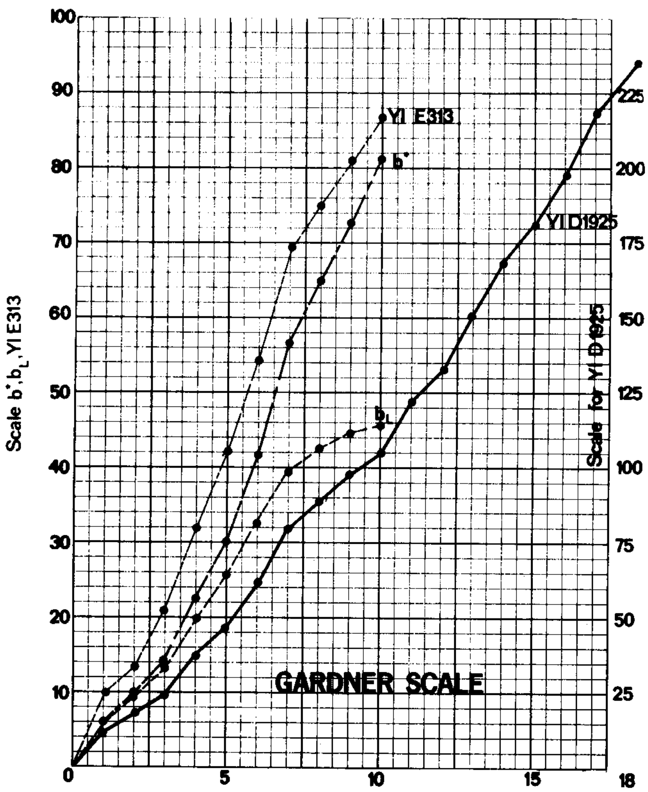

FIG. 3. Two values of b and two ASTM yellowness indexes plotted against Gardner color for 10.65-mm light path.

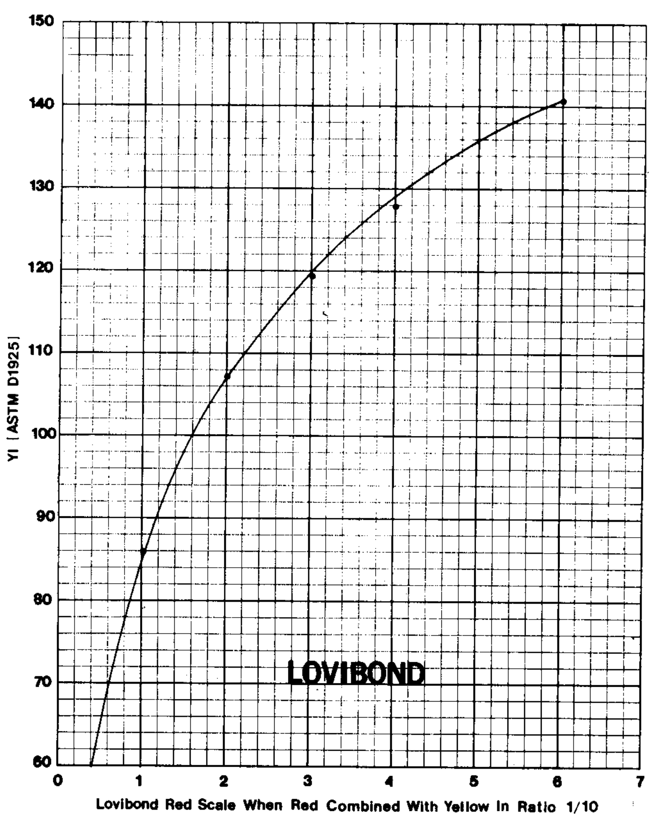

FIG. 5. Lovibond red scale combined with yellow in ratio 1:10, plotted against ASTM D1925 yellowness index.

TABLE III

Yellowness-Scale Interconversions of a Pale Yellow and an Amber Liquid

	Pale yellow liquid	Amber liquid
	Gardner no. 4	Gardner no. 12
10-mm thickness: from Fig. 3, YI ASTM D1925 (8)	35.8	133.6
Using YI D1925 values for conversion: from Fig. 4, FAC (Fat Analysis Committee)	1.5	15 or 11B
	At 50 mm, color becomes Gardner no. 8	At 50 mm, color becomes Gardner no. 16
A 50-mm thickness should be similar in color to 4 steps up the Gardner scale ($1.4^4 = 5.06$); from Fig. 3, YI ASTM D1925 (8)	89.2	196.5
Using YI D1925 values for conversion: APHA (Hazen) scale (Fig. 2)	530	Off scale
Lovibond (50-mm cell) (Fig. 5)	1.2R 12Y	Off scale
5 1/4 in Cell Lovibond Rating using Fig. 6	3.2R 32Y	Off scale

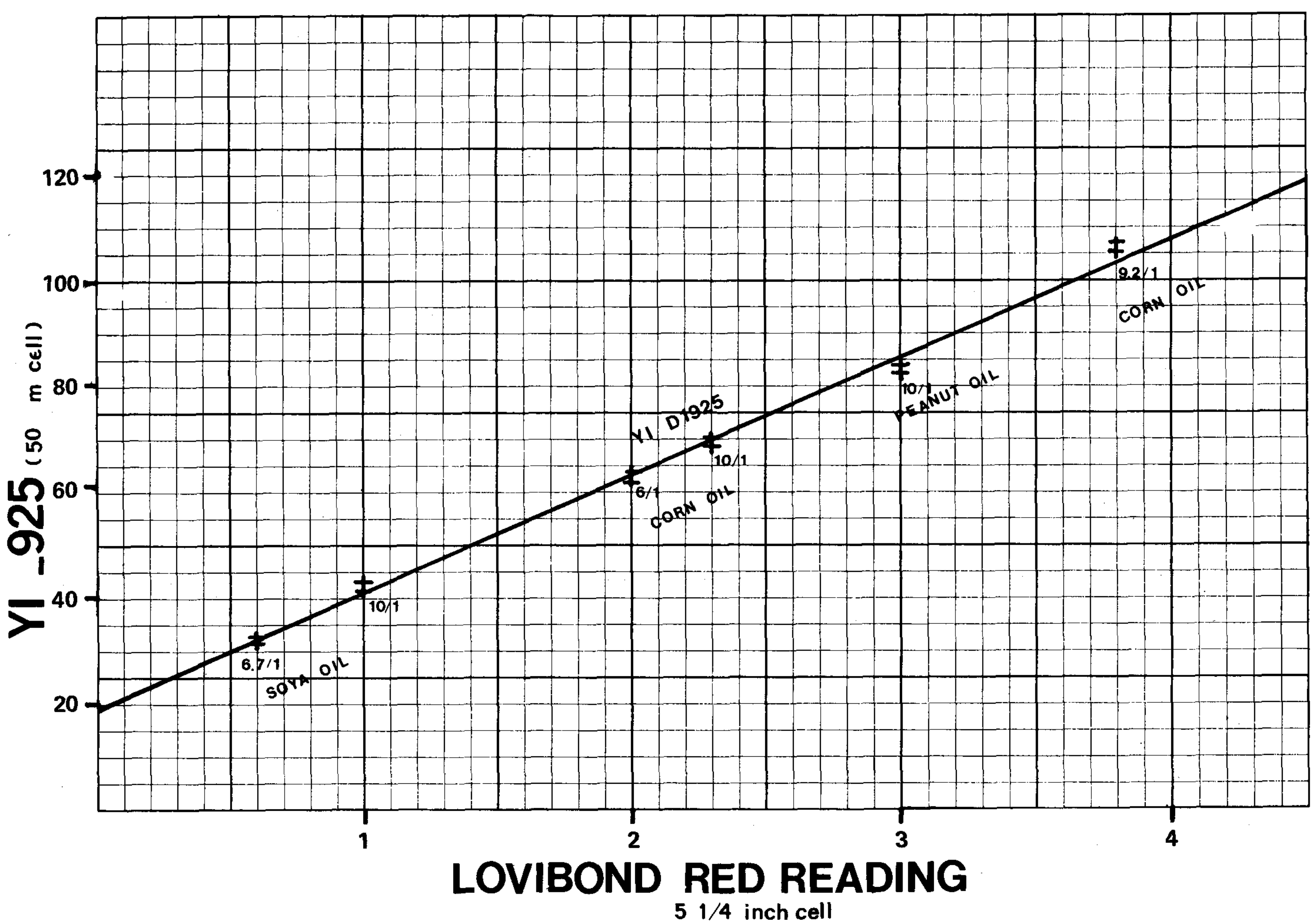

FIG. 6. Lovibond red (5 1/4") reading of vegetable oils plotted against YI D1925 (50 mm).

shown in Table II, the numerator of the equation for YI (D1925) features the difference between X and Z. The other indexes, however, feature differences between Y and Z.

The importance of this distinction is shown in Fig. 1, which plots the locus of Gardner colors on a Hunter a,b diagram. The colors vary when pale (Gardner 1 to 10), from colorless toward the yellow (+b) direction. All the Y-Z equations, such as YI of ASTM E313, follow this trend from colorless toward yellow very well. However, as Z approaches zero for the strongly yellow colors, the trend (as the materials continue to darken from Gardner 10 to 18) is from yellow toward reddish-amber in the (+a) direction. The curve of Gardner colors turns sharply at the top of Fig. 1. Meanwhile, b_L, which measures yellowness, actually decreases from Gardner 10 to 18 because of darkening. For separating the whole gamut of yellow-to-amber materials, the X-Z scale of D1925 is superior to any of the Y-Z scales.

The Hazen or APHA scale is limited in use to pale colorless-to-yellow liquids. The Gardner scale covers both the pale-to-yellow and yellow-to-amber ranges. The remaining two scales apply mainly to the yellow-to-reddish-amber ranges of color, where only the D1925 YI equation should be used.

EXAMPLES OF THE USE OF THE GRAPHS

Figures 2–6 show, for each of the four visual scales, the corresponding tristimulus yellowness values. These values should be useful for converting photoelectrically measured values of yellowness to ratings on the various visual scales, or vice versa.

Table III shows some specific examples of conversions. The two columns in the table refer to a pale yellow color and a dark amber color. Starting with a 10-mm thickness to represent the conditions of the Gardner Scale comparisons, we use the Gardner colors, nos. 4 and 12, as examples. Figure 3 demonstrates that the Gardner nos. 4 and 12 YI values for ASTMA D1925 are 35.8 and 133.6, respectively. The FAC colors (Fig. 4) corresponding to the same YI D1925 values are 1.5 FAC for the pale yellow color and either 15 or 11B FAC for the dark color, depending on which branch of the dual curve is read.

For the other two scales (Hazen and Lovibond), our charts (Figs. 2 and 5) apply to 50-mm light paths; therefore, a change in specimen thickness is required. The changes in color with this five-fold change in thickness can be estimated by referring to the Gardner scale. When the Gardner concentrations were initially chosen, each successive Gardner tube was half again as dense in color concentration as the adjacent tube.

It happens that 1.5, raised to the fourth power, is 5.06. Therefore, we can approximate a five-fold increase in the light path thickness by going up four steps on the Gardner scale: from no. 4 to no. 8 (in the case of the pale yellow) and from no. 12 to no. 16 (in the case of the dark amber). This will correspond to a thickness increase of 5.06.

From the graphs, we read YI (D1925) for Gardner no. 8 as 89.2. The corresponding APHA value for the same YI is 530, and the Lovibond value read from Fig. 6 is 1.2R12Y. These APHA and Lovibond values should correspond to a 50-mm thickness of the corresponding liquids. Both APHA and Lovibond are off scale for the YI value of 196.5, computed for the Gardner no. 16 tube.

Figure 6 shows the straight-line relationship between Lovibond readings of six oils from an industrial laboratory and YI D1925 readings of 50 mm thickness of the same oils made in the author's laboratory.

(Full-page copies of Figs. 2-6, suitable for making scale conversions, are available without charge from the author).

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