NATIONAL BUREAU OF STANDARDS REPORT

9845

JUST APPRECIABLE FADING OF THE AATCC L-4 WOOL STANDARD AND THE NBS STANDARD FADING HOUR (SFH)

For

American Association of Textile Chemists and Colorists

Committee RA-50 On

Colorfastness to Light

NBS

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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JUST APPRECIABLE FADING OF THE AATCC L-4 WOOL STANDARD AND THE NBS STANDARD FADING HOUR ((SFH)

by

Lawrence A. Wood, Paul J. Shouse, and Elio Passaglia

to

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L-4 WOOL STANDARD AND THE NBS STANDARD

FADING HOUR (SFH)

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SUMMARY OF CONCLUSIONS

The color difference resulting from just appreciable fading of the wool standards (as judged by the panel) can be expressed as about 3 NBS units. Equivalent values in other systems are about 1.5 for either the Scofield-Hunter relation or the Glasser-McKinney-Reilly - Schnelle cube-root relation, as compared with about 4.5 MacAdam units when use is made of the Friele-MacAdam - Chickering-Billmeyer treatment.

Just appreciable fading of the wool standards was produced by an exposure of slightly less than 14 clock hours in the NBS Master carbon-arc lamp.

The exposure resulting in just appreciable fading of the wool standards is equivalent to about 11 NBS Standard Fading Hours.

The first two conclusions are independent of each other and are not dependent in any way on the use of the NBS Light Sensitive Paper for calibration of the arc. The third conclusion is based on the use of the paper; this showed that the lamp was operating normally with a severity factor F near 0.9, as recommended.

1. Wool Standards

Carbon arc lamps are widely used in the textile and other industries for testing colorfastness and stability of materials to visible and ultraviolet radiation. The variability of the output of a given lamp and the differences between lamps have led to the extensive use of standard reference materials undergoing measurable changes when exposed to this radiation. [1]

The first set of textile standards recommended by the American Association of Textile Chemists and Colorists was described in their 1931 yearbook. [1, 2] Other standards were recommended in later years until 1942, when there were 8 blue standards designated LD 1 through LD 8. [3]

"LD 4 after 10 hours exposure should show barely perceptible fading--after 20 hours, marked fading. However, the terms perceptible and marked are loose and it has been proved that every operator has his own different conception of these terms". [3]

These early standards, like the blue wool standards sponsored by the International Organization for Standardization [I.S.O./TC38/SC1 USA Section 93, 310, page 55 February 1965] and still currently in use in Europe, used a different dye for each of the 8 standards.

The current set of 8 blue wool AATCC standards was developed by Christison in 1944 [4] and issued in 1945 [5]. Unlike the previous standards these are prepared by blending wool fibers. As described in the AATCC Technical Manual [6]: "These standards are specially prepared by blending varying proportions of wool dyed with a very fugitive dyestuff, Erio Chrome Azurole B (C. I. 43830), and wool dyed with a fast dyestuff, Indigosol Blue AGG (C. I. 73801), so that each higher numbered standard is approximately twice as fast as the preceding standard".

Seibert in 1947 [2] makes the following statement:

"Standards 2 to 8 serve to grade colors that fade to an appreciable degree on exposure in the Fadeometer for between 2.5 and 5 hours; 5 and 10 hours; 10 and 20 hours; 20 and 40 hours; 40 and 80 hours; 80 and 160 hours; and No. 8, the fastest, between 160 and 320 hours".

Thus Standard L-4 is intended for use in the range between 10 and 20 hours.

The term "just appreciable fading" is now defined by the AATCC [6] as follows:

"3.1 'Just appreciable fading' in the following methods means a change in color of any kind (whether a change in hue or saturation, or becoming lighter or darker) which is immediately noticeable in comparing the exposed area of the specimen with an unexposed area, when viewed in north sky light or equivalent source with illumination of 50 foot-candles or more on the surface. If closer inspection or a change of angle is required to make certain that there is a change in color, the fading is not considered to be 'appreciable'.

"3.2 "Just appreciable fading' is also the degree of contrast between the pair of pieces of paper illustrating step 4 of the International Geometric Gray Scale for Evaluating Change in Color."

No agreement has been reached on proposals to define just appreciable fading of the wool standards in terms of any quantity that can be measured directly with an instrument.

The unit of time in 1944 was called a "Fade-Ometer Hour", but the conditions of operation and the characteristics of the arc were not sufficiently well-defined to make this a very satisfactory unit. Surveys [3,7] of the arcs in use at about this time showed variations by a factor of two or three in the time required by different arcs to produce the same degree of fading.

2. Light-Sensitive Paper

Research work at the National Bureau of Standards over a period of years beginning about 1940 led to the development of light-sensitive paper strips as reference materials for the control of the dosage of radiation from carbon arcs. [8] Successive lots of these papers have been issued since 1945. [9] The luminous reflectance R_d (equal to the tristimulus value Y) as measured with a Hunter Color and Color Difference Meter (Gardner type) [10] is the quantity now used in the calibration of the light-sensitive paper.

3. Standard Fading Hours (SFH)

Over the years, the conditions of operation of the master arc lamp used with the papers have been controlled and specified with progressively increasing detail.

The records available to the present authors do not make it entirely clear just how the unit standard fading hour used at the National Bureau of Standards was established. There is some evidence that in 1947 a change in the controls was made reducing the intensity of the radiation by 10%. [11]

Three quotations are pertinent:

1. "As a temporary working basis 20 Standard Arc Hours has been defined as corresponding to 'appreciable fading' of AATCC No. 4 Blue Wool Standard." (NBS Directions for use of Light-Sensitive Paper July 1, 1947).

2. "The setting adopted was based on the 'Fade-Ometer Hour' used for some years in industry for rating colorfastness of textiles and dyes." (NBS General Letter dated July 3, 1947; NBS Letter Circular LC 906, May 21, 1948).

3. "The Standard Fading Hour scale now under trial was selected with the advice and cooperation of the committees on color fastness of light of the American Association of Textile Chemists and Colorists and of the American Society for Testing Materials. Samples of the paper were exposed simultaneously with samples of the AATCC dyed wool lightfastness standards. When the latter had faded to an extent the committees considered representative of 20 Fade-Ometer hours of exposure the paper was considered to have faded to an extent representative of 20 Standard Fading Hours of exposure."(NBS Circular LC 934 January 13,1949)

4. "Twenty standard fading hours of exposure in the master lamp is equivalent in fading action to 20 clock hours of exposure in the well known Atlas Electric Device Company's FDA-R Fade-Ometer, based upon the average results of tests in 130 of these lamps." (NBS Letter Circular LC 1004 August 30, 1951).

It is presumed that the tests referred to were those reported by Seibert in 1945.[7]

These four descriptive definitions, which were repeated in later publications, may or may not have been consistent with each other. We know of no numerical values which would serve as a basis for present-day comparisons. Consequently we consider it impossible to determine at the present time whether these four definitions were consistent with each other and, if not, which of them was actually given the greatest weight in controlling the arc. Indeed the answer to this question is not considered of very great importance at present, since we have no information concerning the early control of several factors now known to be of importance. Among the most significant of these are temperature, humidity, and air flow.

In any event, since February 25, 1949 (see NBS Letter Circular LC 1004 August 30, 1951) every effort has been to keep constant the dosage of radiation represented by 1 Standard Fading Hour (SFH) at the National Bureau of Standards.

With this purpose, over the years repeated observations have been made of the color changes found in a given lot of paper for a given number of hours of operation of the lamp. No significant differences have been found in measurements made in our own laboratories. Each new lot of paper has been compared carefully with one or more of the preceding lots at the time it has been introduced. The exposures of the new lot have then been expressed in terms of the SFH defined by the previous lots.

When a major change in the lamp was made in 1954 by the installation of an enclosed arc in place of an open arc, the output was carefully compared with that of the earlier lamp by the use of the light-sensitive paper, and ratings with the new lamp were continued in terms of the SFH already in use.

The present NBS Master Lamp is an Atlas Electric Devices SMC-R Fade-Ometer with a drum diameter of 20 inches (50.8 cm) rotating at 3 revolutions per min., using No. 70 Solid Carbons and No. 20 Cored Carbons. The black-panel temperature is held at 150±5°F (65.6 ± 2°C) by the use of dampers which automatically control the ratio of exit air to recirculated air. The control element for the dampers is in the stream of humidified inlet air and is manually so adjusted as to maintain the black panel temperature at 150°F. The variation during a single run seldom exceeds ± 4°F. The ambient temperature (77°F, 25°C) and humidity (45%.Dew Point 54.5F, 12.5°C), and size of our present laboratory are such that under these conditions the temperature of the exit air is usually 117 ± 2°F (47.2 ± 1°C).

Moisture is added to the circulating air by water sprayed from a rotating disk so as to raise the relative humidity of the exit air to 30% at the dry bulb temperature of 117°F. A bimetallic thermostat responding to wet-bulb temperature starts and stops the rotating disk. In this manner the humidity is controlled by automatically maintaining the wet bulb temperature at the desired value of 87°F (30.6°C) in the present instance.

The dew-point under these conditions is 80°F (26.7°C). It would not be at all convenient to maintain a higher humidity than this, since a dew-point higher than room temperature gives rise to condensation difficulties when the air is allowed to cool from 117°F to room temperature.

Under these conditions, with an arc voltage of 120-145 v. A. C. and an arc current of 15-17 amp (ranges specified by the manufacturer), 20 hours of operation of the lamp are found to fade the light-sensitive paper to an extent equivalent to about 18 SFH.

Defining a severity factor F for a given run as the ratio of standard fading hours (SFH) to clock hours (CH), one finds that F is thus about 0.9, as recommended [12, 13].

The severity F is obviously lower than that employed some years ago (when F=1.0). This reduction is probably due chiefly to the lowering of the effective black panel temperature from about 165°F (73.9°C) to 150°F. The present authors have been unable to discover from a study of the available publications any logical reason for the difference between the black-panel temperature of 150° ± 5°F maintained in the NBS Master Lamp ever since the time that the black panel was first introduced, and the corresponding figure of 145° ± 5°F recommended in the AATCC Method 16A - 1964. It is hoped that this annoying discrepancy can be eliminated in the future.

It is possible to vary the severity factor somewhat by varying the arc voltage by using a different transformer tap. Only a limited range of adjustment is possible by this means. The severity factor is altered markedly by deviations from the standard conditions of temperature and humidity.

The objectives of the work described here were: (1) to make a study of the visual ratings of samples of the 1957 L-4 Wool Standard which had received known dosages of radiation in the present NBS Master Lamp, and (2) to determine the relation between spectrophotometric color difference and dosage for these specimens.

4. Exposure of Wool Specimens

Sixty specimens of the 1957 lot of AATCC L-4 Standard Wool [2,6] 2 3/4 x 4 3/4 in. (6.98 x 12.1 cm) were cut from pieces 18 x 28 in. (45.7 x 71.1 cm) furnished by the Technical Director of the AATCC [14]. An area about 5.0 x 4.0 cm. at one end of the specimen was exposed (without backing) in October 1966 in the NBS Master carbon arc lamp.

Ten specimens were faded at a time simultaneously with 9 specimens of the NBS Light-Sensitive Paper Lot 700a. [15] Six different exposures, namely 10.1, 12.0, 14.0, 16.0, 18.0, and 20.0 hours were made. The luminous reflectance R_d of the faded paper strips was measured with the Hunter Color and Color Difference Meter [10] as described in NBS Letter Circular LC 1036. [15] The numbers of SFH corresponding to each value of reflectance read from the graph given in LC 1036 were as follows: 7.2, 9.1, 11.6, 13.6, 15.0, and 17.7 SFH. Therefore the values of the severity factor F, the ratio of SFH to clock hours, were found to be 0.71, 0.76, 0.83, 0.85, and 0.89 respectively, in approximate agreement with the recommendation [12,13] that the arc be adjusted to give an F ratio near 0.9.

5. Visual Rating of Wool Specimens

The judgment of "just appreciable fading" was conducted independently by a panel of 6 trained observers selected by Mr. F. A. Sievenpiper of Allied Chemical Co. at the request of the AATCC Committee RA50 (Committee on Colorfastness to Light). They were:

1. Leander Ricard, Chairman, Committee RA50
   I. C. I. Organics Inc. Providence R. I.
2. Otto A. Ofjord, Secretary, Committee RA50
   E. I. DuPont de Nemours and Co., Wilmington, Delaware
3. Edward W. Boland
   American Aniline Products, Lock Haven, Pennsylvania
4. Louis J. Provenza
   Geigy Chemical Co., Yonkers, N. Y.
5. Lewis Oechslin
   American Viscose Co. Marcus Hook, Pennsylvania
6. George Keilman
   Allied Chemical Co., Bala Cynwyd, Pennsylvania

The panel assembled at the National Bureau of Standards, on February 14, 1967. Each panel member was given a set of 10 specimens randomly picked from the 6 different exposures and asked to make an independent judgment without consultation by placing each of them in one of 3 categories:

(1) Less than just appreciably faded (Score, -1)

(2) Just appreciably faded (Score, 0)

(3) More than just appreciably faded (Score, +1)

In making his selections each observer held the specimens in a Macbeth Illuminator set to furnish an illumination equivalent to north sky light of 200-225 foot-candles. Comparisons could be made as often as desired with Step 4 of the AATCC International Gray Scale for Evaluating Change in Color. [6] In the second round each observer had a different set of 10 specimens. This was continued until all 6 observers had independently and individually rated all 60 specimens, giving 360 ratings in all.

The effect of variation from specimen to specimen is considered first. The sum of the scores assigned by the 6 observers to a given specimen was taken as the score of that specimen. For example, if all 6 observers rated a specimen more than just appreciably faded it would receive a score of +6. The total of the 10 individual specimen scores was divided by 10 to give an average specimen score for each exposure. In Fig. 1 the circles represent the average specimen score as a function of the exposure in SFH.

The crosses in Fig. 1 represent the frequency distribution of the individual specimen scores. The specimen numbers (indicated at the right of each cross) represent position around the drum during the exposure. The frequency of each score (i. e. the number of specimens having a given individual specimen score) is plotted along the axis previously used for SFH, with values increasing to the right and measured from a zero axis placed on the vertical line through the circle in each case. The vertical axis itself is scaled to represent the average or individual specimen score, as the case may be.

No significant pattern showing the effect of specimen position during exposure is discerned here. The spread of scores is quite wide in the 4 intermediate exposures but becomes appreciably narrower at the two extremes, where judgment would be expected to be easier. Only one specimen (No. 19) of the 10 in the lowest exposure group was judged to be less than just appreciably faded by all observers (score -6.0); and only one specimen (No. 14) of the highest exposure group was judged to be more than just appreciably faded by all observers (score, +6.0). There were 2 such specimens at each of the adjacent exposures. Of all the 60 specimens investigated there was no single specimen which was rated as just appreciably faded by all 6 observers. In the three instances where the individual specimen score was 0, positive scores were balanced by negative.

The graph drawn through the circles representing the mean specimen score at each exposure would be expected to be asymptotic to the value -6 at the lowest values of exposure and to +6 at the highest, since there were 6 observers. This appears to be approximately true, the actual scores attained at the lowest exposure being about -4, and at the highest, about +4. This means that only about two-thirds of the specimens given the lowest dosage were rated as under-exposed by the average observer and that only about two-thirds of the specimens given the highest dosage were rated as over-exposed. The remaining one-third in each case (with a single exception) were rated as just appreciably faded.

The graph drawn through the circles representing mean scores passes through 0 at about 11 SFH. Under the present conditions then, 11 SFH is seen to give rise to just appreciable fading of the L-4 Wool Standard, as judged visually by the 6 observers.

The effect of variation from observer to observer is shown in Fig. 2. The sum of the scores assigned by a given observer to the 10 specimens of a given exposure was taken as the individual observer score. Thus for example if an observer rated all 10 specimens more than just appreciably faded he would receive a score of +10 for that exposure. The total of all the individual observer scores was divided by 6 to give an average observer score for each exposure. In Fig. 2 the circles represent the average observer score as a function of the exposure in SFH.

As would be expected this quantity is found to be somewhat larger in absolute value than the average specimen score plotted in Fig. 1. This should show an asymptotic approach to the value -10 at low exposures and +10 at high. The graph drawn through these points, like that of Fig. 1, passes through 0 at about 11 SFH.

Here the frequency curves are analogous to these in Fig. 1, and show the number of observers reporting a given individual observer score. The identifying number arbitrarily assigned to each observer is shown near each respective point. It is not related to the order in which the observers are listed at the beginning of this section. It is immediately apparent that there is a very significant pattern showing differences among observers. Observers Numbers 3 and 4 assigned consistently high scores, while Observers 5 and 6 were consistently low.

6. Spectrophotometric Measurements of L-4 Wool Specimens

The spectral directional reflectance of the 60 specimens was measured by personnel of the NBS Colorimetry and Spectrophotometry Section. The instrument used was a General Electric recording spectrophotometer [16] equipped with slits of approximately 10 nm of spectral width over the visible spectral region for the condition of included specular component. Corrections were made for zero-curve errors and for the NBS Vitrolite standard. Observations were made on the exposed and unexposed portions of each specimen and repeated after a 90° rotation of the specimen. The spectral reflectance was measured at each of 36 wave lengths from 400 to 750 nm, for a total of 8,640 observations. CIE source C was used for illumination.

Each observation was recorded automatically on punched paper tape by digital readout equipment. The values were transferred from the tape to punched cards for processing by a high speed digital computer. Computer programs were written to yield chromaticity coordinates x and y and daylight reflectance Y. Additional computer programs were then written to obtain color differences between the exposed and unexposed portions of each of the 60 specimens.

Definitions and descriptive references [A1-A15] for various color difference units have been treated in the Appendix.

Typical observations of spectral reflectance for a single specimen are plotted as a function of wave length in Fig. 3. For comparison the corresponding reflectances for light-sensitive paper 700a are shown. The change in spectral reflectance of the paper during exposure is from 10 to 20 times that noted for the wool.

7. Color Differences

The computer program furnished the color difference in NBS units between the exposed and unexposed portions of each of the 60 wool specimens. The relations used are given in Part I of the Appendix [A2-A5]. Table 1 lists $\overline{\Delta E_1}$ the arithmetic mean of the 10 color differences calculated for the 10 specimens for each exposure, together with $\Delta(\text{Sp Ref.})_{670}$, the average change in spectral reflectance at 670 nm (in the region of greatest change of spectral reflectance) and $\overline{\Delta Y}$ the average change in tri-stimulus value. The numbers in parentheses indicate the coefficient of variation (ratio of standard deviation to mean value) of a single observation from the arithmetic mean of the 10 observations at each exposure. The table also lists the standard deviation and coefficient of variation of a single ratio from the mean of the 6 ratios reported.

Four different relations described in the Appendix were used to obtain the color differences shown in Table 2. The computer program furnished the 10 individual values for ΔE_1 at each of the 6 exposures. The value $\overline{\Delta E_1}$ shown in the table is the arithmetic mean of these 10 values. On the other hand, the labor involved in making 60 computations of $\overline{\Delta E_2}$ $\overline{\Delta E_3}$, and $\overline{\Delta E_4}$ in this way was not considered to be justified. Consequently the average values of X, Y, and Z for each exposure were taken and a single computation was made from these average values to obtain the results shown in the table. This method, of course, yielded no information about the standard deviation of a single observation.

8. Conclusions

8.1 Visual Ratings

The observers were asked to place the specimens in three categories, but were given no instruction regarding the range which might be covered by the middle category ("just appreciably faded"). Of the 360 ratings, there were 99 in Category 1, 127 in Category 2, and 134 in Category 3. Thus it appears that there was a tendency for the observer to assign about the same number of specimens to each category and to make the range of just appreciable fading about as wide as those of the underexposed and overexposed specimens furnished in the present study.

Of the specimens exposed for the shortest time (7.2 SFH) only about two-thirds were rated as less than just appreciably faded by the average observer. Of the specimens exposed for the longest time (17.7SFH) only about two-thirds were rated as more than just appreciably faded by the average observer. The remaining one-third in each case (with a single exception) were rated as just appreciably faded.

The graph representing mean specimen scores (Fig. 1) and the graph representing mean observer scores (Fig. 2) both pass through zero at about 11 SFH. This means that 11 SFH as measured under the presently-specified conditions of operation of the Master Arc Lamp at the National Bureau of Standards gives rise to just appreciable fading of the L-4 Wool Standard, as judged visually by the 6 panel members. The position of the specimen around the drum during exposure was found to have no significant effect. None was to be expected since the drum was rotated constantly about an axis intended to pass through the arc.

Two of the panel members were found to have given consistently high scores, while two gave consistently low scores, as compared with the average scores or with those of the other two. From the ratings of the first pair alone one would have concluded that just appreciable fading occurred at about 10 SFH; from the ratings of the second pair alone, the value would have been 13-14 SFH.

Of all 60 specimens investigated, there was no single specimen which was rated as just appreciably faded by all 6 panel members. Conclusions drawn from visual observations on single specimens are thus of doubtful significance.

8.2 Spectrophotometric Measurements

Measurements of spectral reflectance over the visible range of wavelengths by the General Electric Recording Spectrophotometer showed wide variations from specimen to specimen. Color differences computed for the fading of each specimen also showed large variations. The standard deviation of a single value of color difference from the mean was found to lie in the range 0.35 to 0.50 NBS unit of color difference. This corresponds to a coefficient of variation of about 20% at the shortest exposure. This coefficient is about 15% at the intermediate exposures and about 10% at the longest. The values calculated are shown in Table 1. With only one exception the coefficient of variation of the color difference values is less than that of either the change in spectral reflectance at 670 nm or that of the change in tri-stimulus value Y.

It can be seen from the columns of ratios that the change in spectral reflectance and the change in tri-stimulus value are each approximately a fixed multiple of $\overline{\Delta E_1}$, the color difference in NBS units.

It will be noted from the columns of ratios in Table 2 that the values in two instances are about 0.5, and in the other about 1.5 times the values expressed in NBS units. These ratios are seen to show no systematic trend with varying times of exposure. Thus, apart from considerations of precision, there appears to be no particular advantage in using one relation rather than another as a quantitative measure of the limited type of color differences produced by the fading of the L-4 Wool Standards. The coefficient of variation of the ratios for ΔE_4 appear to be somewhat smaller than that for the ΔE_2 and ΔE_3 ratios. This would indicate that ΔE_4 shows a better correlation with ΔE_1 than the others.

It was noted that the average color difference $\overline{\Delta E}_1$ was roughly proportional to the square root of the time of exposure, t. The method of least squares was applied to the 7 observations including a value of $\Delta E_1 = 0$ for $t = 0$ as well as the 6 different exposures. When the color difference was in NBS units and the time in SFH the empirical relation found was:

$$\overline{\Delta E}_1 = 0.909 \ t^{1/2}$$

where the coefficient 0.909 had a standard deviation of 0.030 or 3.3%.

Table 3 shows the color difference $\overline{\Delta E}_1$ as calculated from the equation at several different times of exposure. It also shows the other quantities used in Tables 1 and 2, as calculated from $\overline{\Delta E}_1$ by the use of the respective ratios. The exposure marked with an asterisk (11 SFH) is that rated by the panel as producing Just Appreciable Fading.

The observed values of $\overline{\Delta E}_1$ are plotted in Fig. 4 against the exposure time and also against the square root of the exposure time. The curve and the straight line are those representing the empirical equation from the least squares analysis.

Three points shown as triangles in Fig. 4 represent observations on 4 specimens at each of 3 exposures of L-4 Wool Standards measured in our laboratories in 1966 as a preliminary to the present investigation. The agreement with the present results is quite satisfactory.

From the equation it may be calculated that the standard deviation of a single value of color difference, which has been given as ranging between 0.35 and 0.50 NBS unit, corresponds to a standard deviation of exposure time of 2.6 to 3.4 SFH. Nearly the same values of standard deviation were obtained for the 4 specimens at each of the 3 exposures studied in 1966.

The conclusion is that the precision of measurement is such that only two-thirds of a group of single measurements of color difference of the L-4 Wool Standards would be expected to fall within a range of ± 3 SFH around the mean value.

9. Summary

Finally we recapitulate the three major conclusions which may be drawn from the present investigation:

1. The color difference resulting from just appreciable fading of the wool standards (as judged by the panel) can be expressed as about 3 NBS units [A2-A5]. Equivalent values in other systems are about 1.5 for either the Scofield-Hunter relation [A2-A9] or the Glasser-McKinney-Reilly Schnelle cube-root relation [A4,A10] as compared with about 4.5 MacAdam units when use is made of the Friele-MacAdam - Chickering- Billmeyer treatment [A11-A15].

2. Just appreciable fading of the wool standards was produced by an exposure of slightly less than 14 clock hours in the NBS Master carbon-arc lamp.

3. The exposure resulting in just appreciable fading of the wool standards is equivalent to about 11 NBS Standard Fading Hours.

The first two conclusions are independent of each other and are not dependent in any way on the use of the NBS Light Sensitive Paper for calibration of the arc. The third conclusion is based on the use of the paper; this showed that the lamp was operating normally with a severity factor F near 0.9, as recommended.

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APPENDIX

COLOR DIFFERENCE EQUATIONS

I. Color Difference in NBS Units   References A2, A3, A4 and A5

1. Chromaticity co-ordinates

$$x = \frac{X}{X+Y+Z} \quad \text{and} \quad y = \frac{Y}{X+Y+Z}$$

2. Hunter chromaticity co-ordinates

$$\alpha = \frac{2.4266\,x - 1.3631y - 0.3214}{x + 2.2633y + 1.1054}$$

$$\beta = \frac{0.5710\,x - 1.2447y - 0.5708}{x + 2.2633y + 1.1054}$$

3.
$$\overline{\Delta\alpha}^{2} = (\alpha_2 - \alpha_1)^2$$

$$\overline{\Delta\beta}^{2} = (\beta_2 - \beta_1)^2$$

$$\overline{Y}^{1/4} = \left(\frac{Y_1 + Y_2}{2}\right)^{1/4}$$

$$\Delta(Y^{1/2}) = Y_2^{\,1/2} - Y_1^{\,1/2}$$

4a. Color difference when Y_1 and Y_2 are expressed as decimals

$$\Delta E_1 = \{[700\,\overline{Y}^{1/4}\,(\overline{\Delta\alpha}^{2} + \overline{\Delta\beta}^{2})^{1/2}]^2 + [120\,\Delta(Y^{1/2})]^2\}^{1/2}$$

4b. Color difference when Y_1 and Y_2 are expressed in percent

$$\Delta E_1 = \{[221\,\overline{Y}^{1/4}\,(\overline{\Delta\alpha}^{2} + \overline{\Delta\beta}^{2})^{1/2}]^2 + [12\,\Delta(Y^{1/2})]^2\}^{1/2}$$

II. Color Difference in Scofield-Hunter Units   References A2-A9

1a. When X, Y, and Z are expressed as decimals

$$L = 100\ Y^{1/2}$$

$$a_L = 175\ (1.02\ X - Y)\ Y^{-1/2}$$

$$b_L = 70\ (Y - 0.847\ Z)\ Y^{-1/2}$$

1b. When X, Y, and Z are expressed in percent

$$L = 10\ Y^{1/2}$$

$$a_L = 17.5\ (1.02\ X-Y)\ Y^{-1/2}$$

$$b_L = 7.0\ (Y - 0.847\ Z)\ Y^{-1/2}$$

2. $$\Delta L = L_2 - L_1$$

$$\Delta a_L = a_{L2} - a_{L1}$$

$$\Delta b_L = b_{L2} - b_{L1}$$

3. $$\Delta E_2 = [(\Delta L)^2 + (\Delta a_L)^2 + (\Delta b_L)^2]^{1/2}$$

III. Color Difference Calculated by the Cube-Root Relation of Glasser, McKinney, Reilly, and Schnelle References A4, A10

1. $R = 1.02\,X$

   $G = Y$

   $B = 0.847Z$

2. $\Delta(R^{1/3}) = R_2^{1/3} - R_1^{1/3}$

   $\Delta(G^{1/3}) = G_2^{1/3} - G_1^{1/3}$

   $\Delta(B^{1/3}) = B_2^{1/3} - B_1^{1/3}$

3a. When X, Y, and Z are expressed as decimals

$$\Delta L = 174\,\Delta(G^{1/3})$$

$$\Delta a = 492\,[\Delta(R^{1/3}) - \Delta(G^{1/3})]$$

$$\Delta b = 196.5\,[\Delta(G^{1/3}) - \Delta(B^{1/3})]$$

3b. When X, Y, and Z are expressed in percent

$$\Delta L = 25.29\,\Delta(G^{1/3})$$

$$\Delta a = 106.0\,[\Delta(R^{1/3}) - \Delta(G^{1/3})]$$

$$\Delta b = 42.34\,[\Delta(G^{1/3}) - \Delta(B^{1/3})]$$

4. $\Delta E_3 = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{1/2}$

IV. Color Difference in MacAdam units Calculated by the Modified Formula of Friele, MacAdam, and Chickering as presented by Billmeyer References A11 - A15

X, Y, and Z are to be expressed in percent

1. $$P = 0.724\,X + 0.382Y - 0.098Z$$

$$Q = -0.48\,X + 1.37\,Y + 0.1276Z$$

$$S = 0.686\,Z$$

2. $$\Delta P = P_2 - P_1$$

$$\Delta Q = Q_2 - Q_1$$

$$\Delta S = S_2 - S_1$$

3. $$a^2 = 17.3 \times 10^{-6} (P_1^2 + Q_1^2) [1 + 2.73\, P_1^2 Q_1^2 (P_1^4 + Q_1^4)^{-1}]^{-1}$$

$$b^2 = 3.098 \times 10^{-4} (S_1^2 + 0.2015\, Y_1^2)$$

4. $$K_1 = 0.55669 + 0.04934\, Y_1 - 0.82575 \times 10^{-3}\, Y_1^2 + 0.79172 \times 10^{-5}\, Y_1^3 - 0.30087 \times 10^{-7}\, Y_1^4$$

$$K_2 = 0.17548 + 0.027556\, Y_1 - 0.57262 \times 10^{-3}\, Y_1^2 + 0.63893 \times 10^{-5}\, Y_1^3 - 0.26731 \times 10^{-7}\, Y_1^4$$

5. $\Delta L_1 = (P_1 \Delta P + Q_1 \Delta Q)\ (P_1^2 + Q_1^2)^{-1/2}$

$\Delta L_2 = 0.279\ \Delta L_1 / a$

6. $\Delta C_{rg} = (Q_1 \Delta P - P_1 \Delta Q)\ (P_1^2 + Q_1^2)^{-1/2}$

$\Delta C_{yb} = S_1\ \Delta L_1\ (P_1^2 + Q_1^2)^{-1/2} - \Delta S$

7. $\Delta C_1 = [(\Delta C_{rg}/a)^2 + (\Delta C_{yb}/b)^2]^{1/2}$

$\Delta C = K_1\ \Delta C_1$

$\Delta L = K_2\ \Delta L_2$

8. $\Delta E_4 = [(\Delta C)^2 + (\Delta L)^2]^{1/2}$

COLOR DIFFERENCE REFERENCES

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Table 1. Color Difference, Change in Spectral Reflectance at 670 nm, and Change in Tri-Stimulus Value Y at Different Exposures

Exposure CH	Exposure SFH	ΔE_1 NBS	Δ(Sp Ref) 670 %	Ratio $\overline{\Delta(\text{Sp Ref})670}/\overline{\Delta E_1}$	$\overline{\Delta Y}$ Tri-Stimulus %	Ratio $\overline{\Delta Y}/\overline{\Delta E_1}$
10.1	7.2	2.411 (20.8%)	0.618 (24.8%)	0.256	0.3201 (32.1%)	0.1328
12.0	9.1	2.931 (14.1%)	.657 (16.3%)	.224	.4073 (22.3%)	.1390
14.0	11.6	3.060 (15.0%)	.738 (9.4%)	.241	.3879 (17.7%)	.1268
16.0	13.6	3.253 (9.9%)	.777 (15.8%)	.239	.4444 (11.2%)	.1366
18.0	15.0	3.600 (10.8%)	.788 (15.2%)	.219	.4858 (14.1%)	.1349
20.0	17.7	3.815 (9.3%)	.918 (14.0%)	.241	.5360 (14.6%)	.1405
Mean Ratio				.237		.1351
Std. Dev.				.013		.0049
Coeff. of Var.				5.6%		3.6%

Notes

1. For calculation of ratios, the values are given to one more significant digit than the number justified by the precision of the measurements.

2. The numbers in parentheses indicate the coefficient of variation (ratio of standard deviation to mean value) of a single observation from the arithmetic mean of the 10 observations at each exposure.

Table 2 Color Difference In Various Units at Different Exposures

Exposure SFH	$\overline{\Delta E}_1$ NBS	$\overline{\Delta E}_2$ Scofield-Hunter	Ratio $\overline{\Delta E}_2 / \overline{\Delta E}_1$	$\overline{\Delta E}_3$ Glasser McKinney, Reilly Schnelle	Ratio $\overline{\Delta E}_3 / \overline{\Delta E}_1$	$\overline{\Delta E}_4$ Friele MacAdam Chickering Billmeyer	Ratio $\overline{\Delta E}_4 / \overline{\Delta E}_1$
7.2	2.411	1.203	0.499	1.349	0.560	3.578	1.484
9.1	2.931	1.509	.515	1.566	.534	4.358	1.487
11.6	3.060	1.324	.433	1.431	.468	4.231	1.383
13.6	3.253	1.567	.482	1.693	.520	5.132	1.578
15.0	3.600	1.804	.501	1.910	.531	5.514	1.532
17.7	3.815	2.130	.558	2.232	.585	5.917	1.551
Mean Ratio			.498		.533		1.502
Std. Dev.			.041		.040		0.069
Coeff. of Var.			8.2%		7.4%		4.6%

Table 3 Calculated Color Differences and Related Quantities

Exposure SFH	$\overline{\Delta E}_1$ $0.909\ t^{1/2}$	$\overline{\Delta E}_2$ Ratio - 0.498	$\overline{\Delta E}_3$ Ratio-0.533	$\overline{\Delta E}_4$ Ratio-1.502	$\Delta(\text{Sp Ref})_{670}$ Ratio-0.237	ΔY Ratio-0.135
10	2.87	1.43	1.53	4.31	0.680	0.388
*11	3.02	1.50	1.61	4.54	.716	.408
15	3.52	1.75	1.88	5.29	.834	.476
16	3.64	1.81	1.94	5.47	.863	.492
18	3.86	1.92	2.06	5.80	.915	.521
20	4.07	2.03	2.17	6.11	.965	.550
22	4.26	2.12	2.27	6.40	1.010	.576

* Exposure rated as producing Just Appreciable Fading by 6-member panel on February 14, 1967.

LEGENDS FOR FIGURES

Figure 1. Average specimen score (circles) as a function of exposure time

Vertical coordinate: average specimen score
Horizontal coordinate: exposure time

Frequency distribution (crosses) of individual specimen scores

Vertical coordinate: individual specimen score
Horizontal coordinate: number of specimens having the given individual specimen score (measured in each case from a vertical zero axis through the average specimen score at each exposure time).

The individual specimen numbers near each cross represent position around the drum during exposure.

Figure 2. Average observer score (circles) as a function of exposure time

Vertical coordinate: average observer score
Horizontal coordinate: exposure time

Frequency distribution (crosses) of individual observer scores

Vertical coordinate: individual observer score
Horizontal coordinate: number of observers reporting the given individual observer score (measured in each case from a vertical zero axis through the average observer score at each exposure time).

The individual observer numbers are shown near each cross.

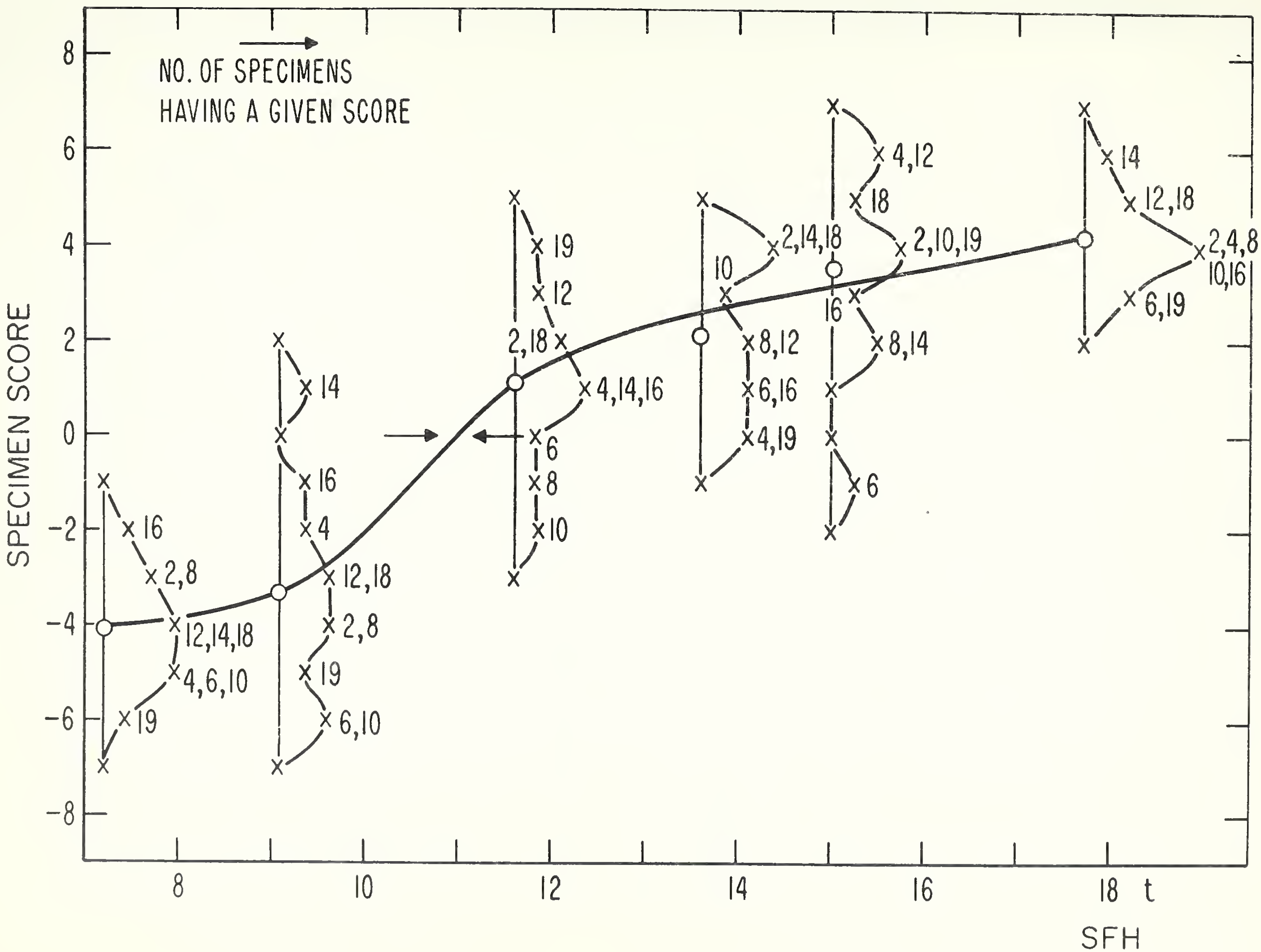
Figure 3. Spectral reflectance as a function of wave length

The number of SFH of exposure is shown near each curve.

The paper is a specimen of Lot 700a.

The wool is a specimen of the 1957 Lot of L-4 Wool.

Figure 4. Color difference as a function of time of exposure (upper curve, upper abscissa) or of square root of time of exposure (lower curve, lower abscissa).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HAVING A GIVEN SCORE
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SFH
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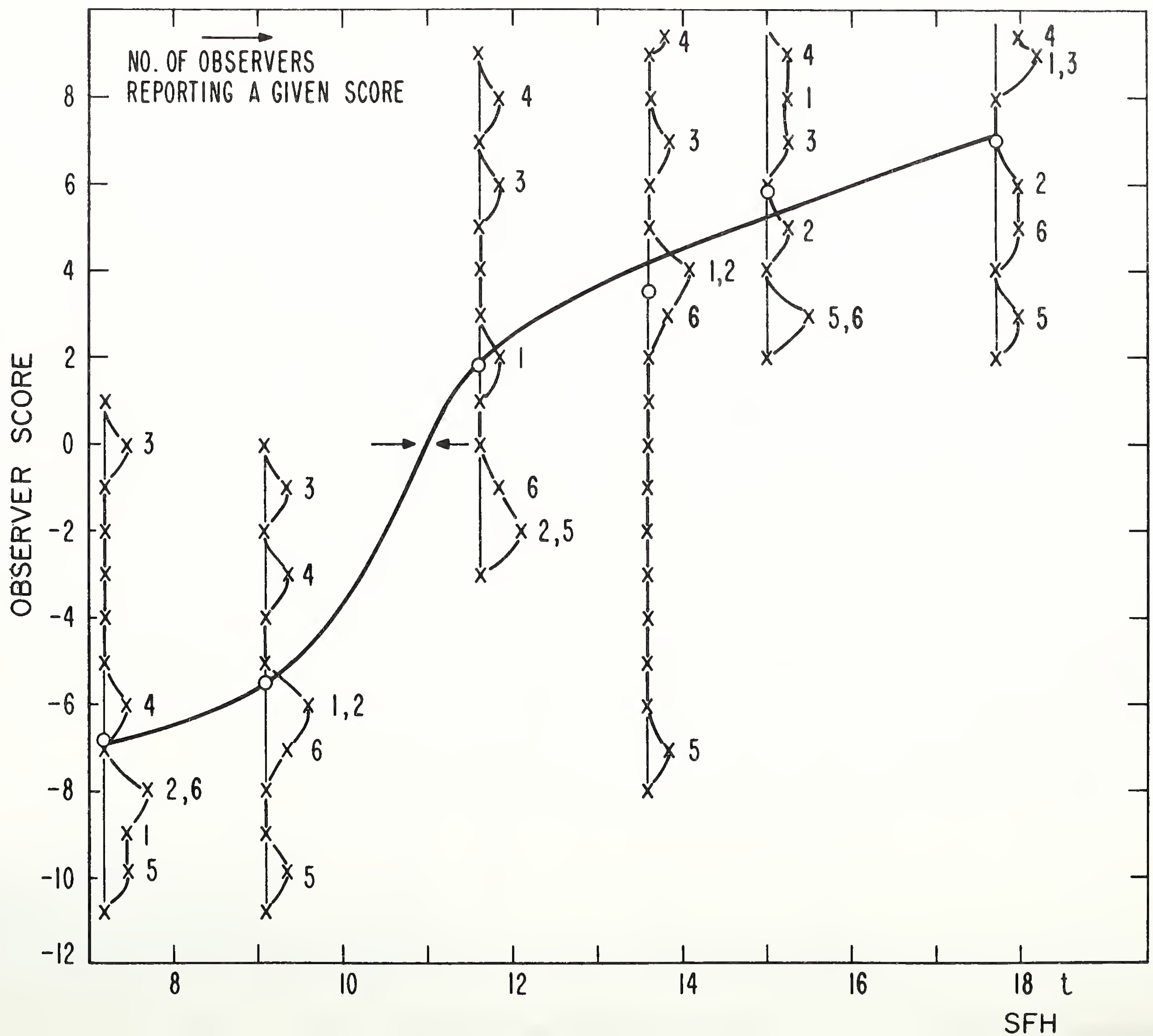

NO. OF OBSERVERS REPORTING A GIVEN SCORE
OBSERVER SCORE
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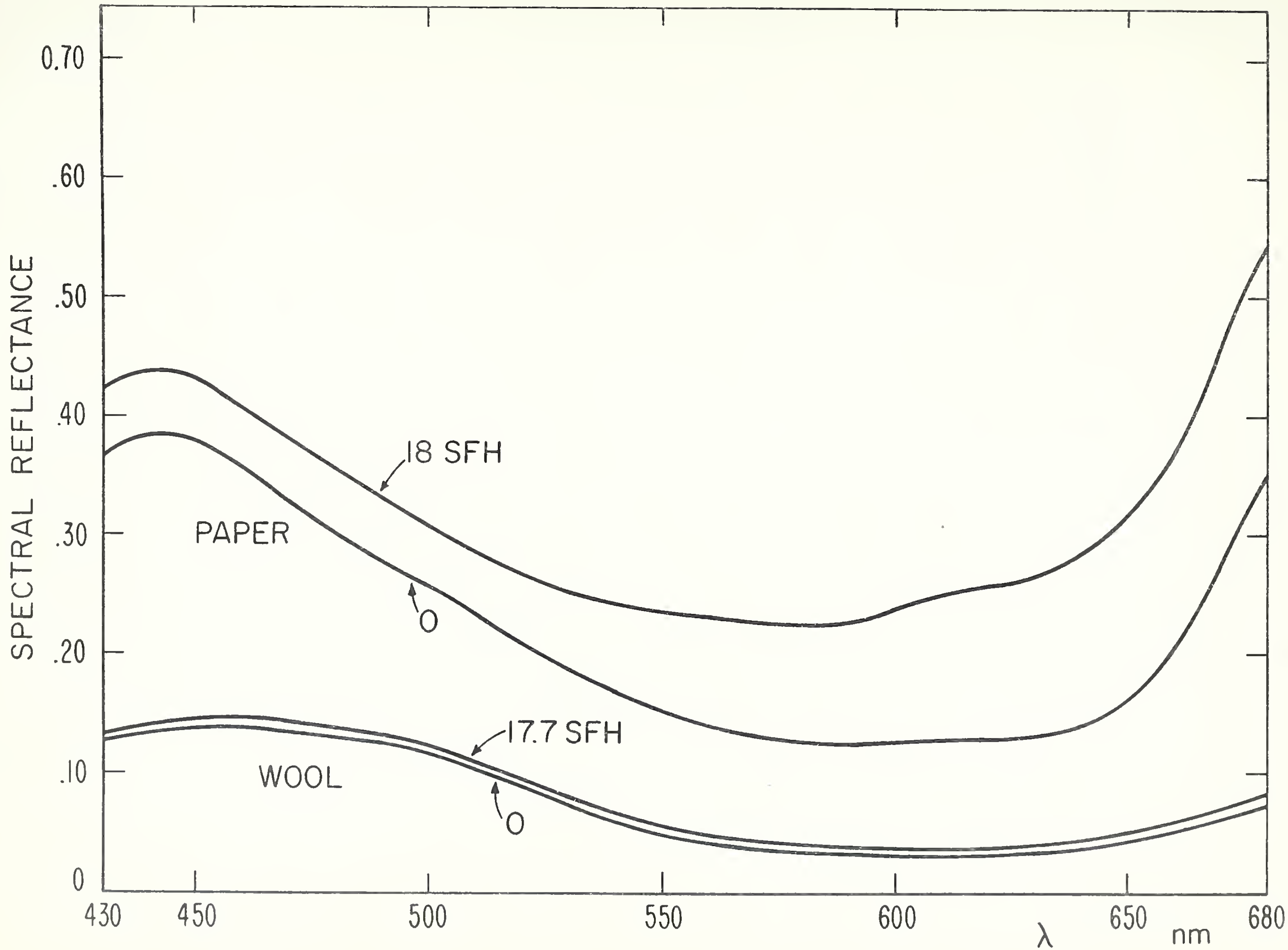
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SPECTRAL REFLECTANCE
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680
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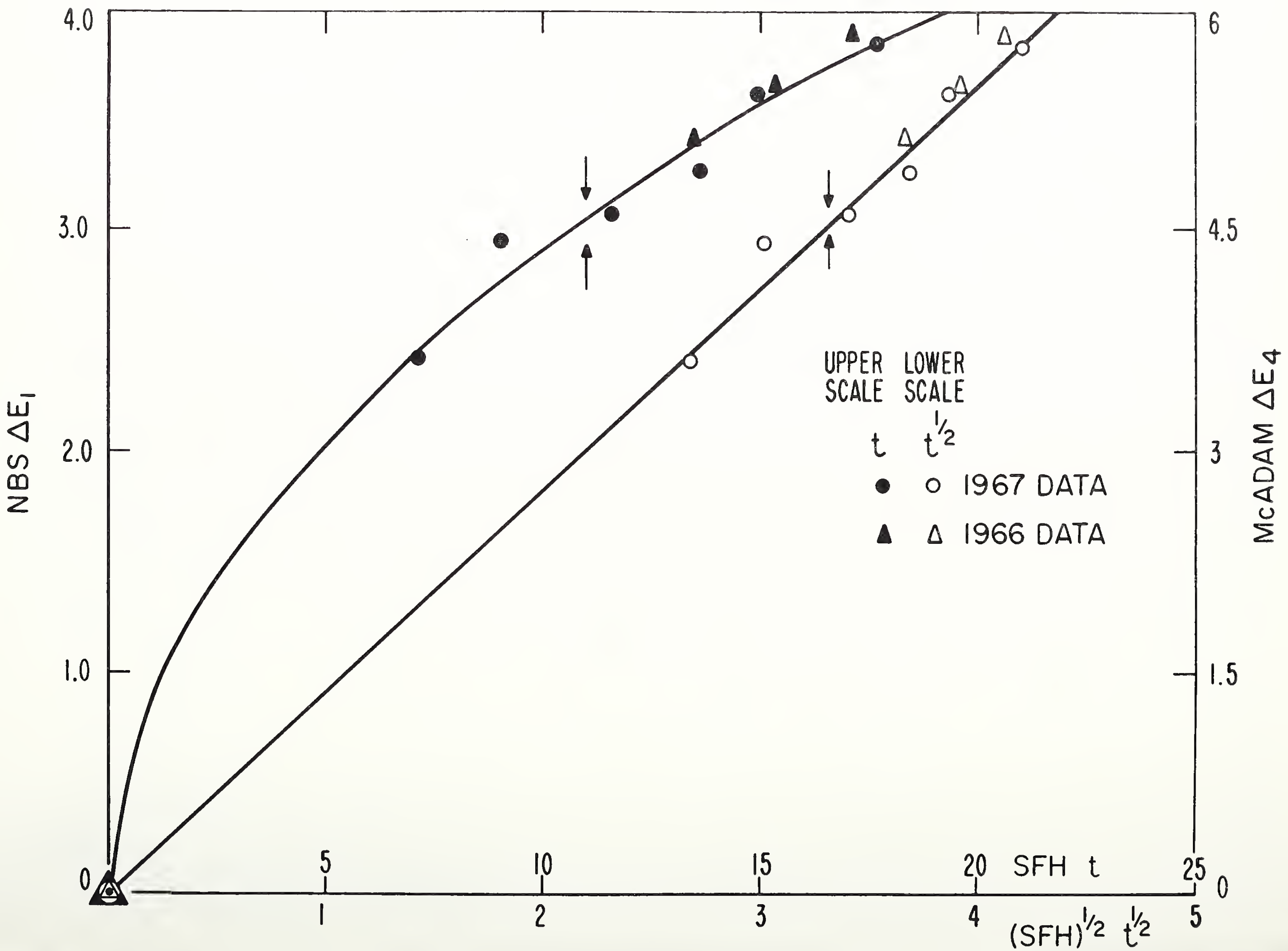
nm



NBS ΔE1
McADAM ΔE4
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3.0
2.0
1.0
0
6
4.5
3
1.5
0
5
10
15
20
25
SFH t
1
2
3
4
5
(SFH)^½ t^½
UPPER SCALE
LOWER SCALE
t
t^½
1967 DATA
1966 DATA

DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS