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Title Color Specification in Cathode Ray Tubes I

By

Electronic Tube Engineering Div.

Information prepared for

Tests made by

Information prepared by E. B. Fehr and A. Petraitis

Countersigned by K. C. DeWalt

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COLOR SPECIFICATION IN CATHODE RAY TUBES I

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I. Introduction

The only way to <u>specify</u> color of cathode ray tube screens used at present is in the form of spectrophotometric curves. This is a strictly physical method and such curves have no direct relation to an observer's eye. Another method, used in <u>production control</u>, is comparison of screen color with a sample, which may be either a standard screen tube or a light source with appropriate filter. This is a purely phychological method depending on an individual visual response; results cannot be expressed adequately in numerical terms.

A third method, "Tristimulus Colorimetry" is proposed in this data folder. This method expresses color in terms of the response of the normal observer as defined by the International Commission on Illumination (I. C. I.) in 1931. It permits expression of physically measured data in phychologically significant numerical terms.

The Committee on Colorimetry of the American Optical Society is at present issuing a "Report on Colorimetry". Chapter VII (see Jl. Opt. Soc. Am. 34, 633, 1944) contains numerous definitions, tables graphs, and references relating to quantitative colorimetry by the I. C. I. system.

The method and its application to surface colors and color filters is also described in "Handbook of Colorimetry" (Massachusetts Institute of Technology Press, 1936) and in "Photoelectric Tristimulus Colorimetry with Three Filters" (R. S. Hunter, National Bureau of Standards Circular C429, 1942). The latter contains a complete bibliography of the subject.

The system is used for measurement of color and specification of tolerances in fluorescent lamps (see for instance B. T. Barnes, Jl. Opt. Soc. Am. 29, 448, 1939, Rev. Scient. Instr. 16, 337, 1945

The I. C. I. system is based on the fact that light of any given color can be produced by mixing red, green and blue light of suitable character in the correct proportions. The relative amounts of these three colors required to match visually radiant energy of the various wavelengths are called the $\bar{x}$, $\bar{y}$ and $\bar{z}$ stimuli. The $\bar{y}$ coefficients are the I. C. I. standard visibility factors (eye response function).

Integration of the spectral radiant flux of a source (E_λ), multiplied by these respective distribution coefficients give

$$(1) \quad X = \int \bar{x} E_\lambda d_\lambda$$

$$(2) \quad Y = \int \bar{y} E_\lambda d_\lambda$$

$$(3) \quad Z = \int \bar{z} E_\lambda d_\lambda$$

X, Y, and Z are known as the tristimulus values of the source in question, where Y serves as a brightness characteristic.

The characteristics of color apart from its brightness are known as its chromaticity and can be represented by a point in a two-coordinate system (chromaticity diagram). Its coordinates, known as trichromatic coefficients can be obtained from this tristimulus values by a simple transformation.

Tolerances of color are specified by marking a region of the chromaticity diagram within which a sample point must lie.

There are two methods for determining tristimulus values.

a. From the spectrophotometric curves by mathematical integration according to equations (1), (2) and (3).

b. This integration can be performed automatically and without knowledge of the spectrophotometric curves by measuring the response of a phototube or photocell through a red, green and blue filter of suitable spectral transmission. The three readings correspond approximately to the tristimulus values.

This data folder discusses the theoretical basis of the I. C. I. system in some detail and describes the calculation of factors for a three filter system.

We are at present collecting data on color of cathode ray tubes, using both methods, with the aim of determining the necessary degree of accuracy of measurements and of setting tolerances in a chromaticity diagram, especially for white television tubes.

II. General Discussion of Methods of Color Specification.

There are three methods of specifying color:

(1) In terms of spectrophotometric curves. The relative energy distribution over the spectrum gives a complete picture of color in a physical sense, but has no connection with an observer since the eye perceives only the integral of the energy over the wavelength range. Familiarity with spectrophotometric curves makes it possible to predict color approximately from the shape of the curves, but they do not represent a useable system of specification of tolerances (see page 5).

(2) In terms of comparison with an accepted collection of samples such as the Munsell or Ostwald System. These systems consist in a logical arrangement and numbering of color samples according to brightness, hue, and saturation.

> Brightness is that attribute of color which serves to classify it as equivalent in visual stimulus to some member of a series of grays ranging from black to white. Hue is that attribute which permits it to be classed as red, green, etc. Saturation (or strength, purity) is that attribute which determines its difference from a gray of the same brightness.

(3) In terms of tristimulus values. A normal observer can duplicate the effect of any color stimulus by mixing light from three suitable color sources (primary stimuli), for instance a red, a blue and a green. A tristimulus designation for an unknown color consists of the amounts of three primary stimuli required to produce a color match for it. Since there are differences between individual observers, a group of selected observers was chosen to determine certain basic color mixture data. In 1931 the International Commission of Illumination (I. C. I.) used these data to define a Standard Observer by determining the relative amounts of three primary stimuli required by such an observer to color match a unit quantity of radiant energy at any part of the spectrum. These stimuli as functions of wavelengths are given in abridged form in Table I and in Fig. I. They are used in conjunction with spectrophotometric data to compute for any test sample the average tristimulus values that would have been observed by the selected observers. (See page 6).

III. Color Specification in Cathode Ray Tubes

(1) Spectrophotometric curves are used widely to designate color of C. R. T. screens. These give a complete specification for a screen; that is, two screens with the same spectral distribution curve have, of course, the same color. However, two screens with widely different curves do not necessarily have different colors as perceived by the eye. This is specially important in white television tubes. At present all white emitting phosphors are mixtures of two or more complementary colors (see Page 10) like blue and yellow or greenish blue and orange. Spectral distribution curves of two screens of this type are given in Fig. II. In spite of the difference between the two curves, these two tubes have very similar color to an average observer.

(2) This difficulty can be overcome by specifying the tristimulus values of the screen color. These are obtained by multiplying the spectral distribution function, in turn, with the three I. C. I. functions $\bar{X}$, $\bar{Y}$ and $\bar{Z}$ and taking the integral over the three products. This operation can be performed by any of the well known integration methods, such as selected ordinate method, equal ordinate method, or by mechanical integration. (A mechanical integrator developed especially for transforming spectrophotometric curves into tristimulus values is available in the General Engineering Laboratory).

A sample calculation, using fifteen equally spaced ordinates can be found on Table II.

Definitions & Symbols.- The symbols of the "Handbook of Colorimetry" are used here, although they are not very logical and the use of the same letters of the alphabet to denote functions, individual ordinates and integrated values introduces the possibility of errors.

$\bar{X}, \bar{Y}, \bar{Z}$ are tristimulus values of spectrum colors as functions of wavelengths.

$\bar{x}, \bar{y}, \bar{z}$ are the ordinates of these functions at various wavelengths.

X, Y, Z are the tristimulus values of any "unknown" color sample, where

$$X = \int \bar{x} E_\lambda \, d_\lambda$$

$$Y = \int \bar{y} E_\lambda \, d_\lambda$$

$$Z = \int \bar{z} E_\lambda \, d_\lambda$$

E is used to designate spectrum radiant flux of a light source. The symbol is used both for individual ordinates and for values integrated over the spectrum.

λ is wavelength

x, y, z are the trichromatic coefficients both of spectrum colors and of "unknown" color samples. For spectrum colors these coefficients are defined by

$$x = \frac{\bar{x}}{\bar{x} + \bar{y} + \bar{z}}$$

$$y = \frac{\bar{y}}{\bar{x} + \bar{y} + \bar{z}}$$

$$z = \frac{\bar{z}}{\bar{x} + \bar{y} + \bar{z}}$$

and for "unknown" color stimuli by

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

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

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

Since $x + y + z = 1$, usually only x and y are given as a specification.

There are two advantages of trichromatic coefficients over tristimulus values:

(1) The tristimulus values X, Y, Z are, of course, relative depending on the scale and number of the ordinates used, whereas the trichromatic coefficients give a complete specification of color.

(2) To represent the tristimulus values graphically would require a three-dimensional system, whereas the trichromatic coefficients can be plotted on a two-dimensional diagram (chromaticity diagram, see below).

One of the functions ($\bar{Y}$) of the I. C. I. Standard Observer was chosen to correspond exactly with the so called visibility function of the normal eye. This function indicates the relative brightness of equal amounts (energy basis) of spectrum colors of the various wavelengths. Thus, the value of Y will give a relative measure of the brightness of the sample to the eye.

(3) Graphical Representation of Chromaticity

In Fig. III the trichromatic coefficients of the spectrum colors (from Table III) are plotted. Point C represents the trichromatic coefficients ($x = .3101$ and $y = .3163$) of Illuminant C (average white daylight).

In order to facilitate photometric and colorimetry measurements the I. C. I. has designated three standard light sources, Illuminants A, B, and C. Illuminant A is a tungsten lamp operating at a temperature of 2848°K. Illuminants B and C use the same lamp plus certain liquid filters which raise the color temperature. Illuminant C is the accepted representative of average white daylight. Spectral distribution of energy from these illuminants is given on pages 19-22 of Handbook of Colorimetry.

The choice of Illuminant C as "white" point of comparison for light sources is arbitrary. It would be more logical to select an "ideal" white light emitting equal energy throughout the spectrum. Such a source is represented on the chromaticity diagram by a point with the coordinates $x = .3333$ and $y = .3333$.

All real colors lying within the solid line but above the dotted line of Fig. III can be considered as mixtures of Illuminant C and spectrum light of a certain wavelength. For instance the color of a television tube indicated by point T (Fig. III) whose trichromatic coefficients are $x = .289$ and $y = .321$ is shown to be a mixture of Illuminant C and spectrum light having a wavelength of 493 mu. This wavelength is known as dominant wavelength. Evidentally this tube is not so pure a blue as the corresponding spectrum color. A numerical specification for its purity can be achieved by determining on the chromaticity diagram the relative distances of T and the corresponding spectral point from the illuminant point C. The distance of T from the illuminant point is 9.5% of the distance of the spectrum locus from the illuminant point. The tube is therefore said to have a dominant wavelength of 493 mu and a purity or saturation of 9.5%.

The portions of the diagram lying within the solid line but below the dotted line in Fig. III represent the purples. For a discussion of the use of the concepts of dominant wavelength and purity to purples see Handbook of Colorimetry p.11.

In order to facilitate the determination of dominant wavelength and purity from trichromatic coefficient it is convenient to draw lines of constant dominant wavelength radiating from the illuminant point C. (Fig. IV)

This chart contains also contour lines of constant purity. Dominant wavelength and purity of an unknown sample may now be interpolated directly from the chart. Large scale drawings of the I. C. I. chromaticity diagram are found in Handbook of Colorimetry.

Tolerances for cathode ray tube colors can be given by specifying a certain area on the chart, within which all acceptable tubes must fall. This method is used for instance in the Lamp Development Laboratory at Nela Park for fluorescent lamps.

The two television tubes, whose spectral distribution curves are given in Fig. II have the trichromatic coefficients.

$$x_1 = .289 \qquad \text{and} \qquad x_2 = .289$$
$$y_1 = .321 \qquad\qquad\qquad y_2 = .300$$

From the chromaticity diagrams in Handbook of Colorimetry the dominant wavelengths are found to be

λ_1 = 493 mm and λ_2 = 481 mm

and the saturation

S_1 = 9.5% and S_2 = 9%

Thus the I. C. I. color specifications adequately express the fact that the two tubes have nearly ~~the~~ same color for the normal eye.

A chromaticity diagram is of great value in connection with <u>additive</u> mixtures of two or more colors. (For determination of <u>subtractive</u> mixtures however, spectrophotometric curves must be used). In Fig. V, suppose that a certain blue is located at B (x_1 = .18 and y_1 = .21) and a certain orange at O (x_2 = .42 and y_2 = .45). Regardless of the proportions in which these colors are additively mixed, the resultant color will always lie on the line joining B and O.

Obviously white light can be obtained by suitable mixtures of any two colors which are joined by a line passing through point C. The dominant wavelengths of such colors are said to be complementary. A list of complementary wavelengths is given in Handbook of Colorimetry P. 31.

If a and b are the relative proportion of the two colors indicated by points B and O and Y_1 and Y_2 are the relative brightnesses, then the resulting mixture will have trichromatic coefficients

$$x = \frac{a x_1 \frac{Y_1}{y_1} + b x_2 \frac{Y_2}{y_2}}{a \frac{Y_1}{y_1} + b \frac{Y_2}{y_2}}$$

$$y = \frac{a y_1 \frac{Y_1}{y_1} + b \frac{Y_2}{y_2}}{a \frac{Y_1}{y_1} + b \frac{Y_2}{y_2}}$$

(4) <u>Photoelectric Tristimulus Colorimetry with Three Filters</u>

The preceding method of computing trichromatic coefficients from spectral distribution curves furnished accurate and universally reproducible specifications for color in cathode ray tubes. However the method is tedious and not applicable to production control. Photoelectric tristimulus colorimetry is a much more direct and rapid method. The light emitted by the sample is measured with filter-photocell or filter phototube combinations which spectrally duplicate as nearly as possible the three distribution functions $\bar{X}$, $\bar{Y}$ and $\bar{Z}$ characterizing the standard observer. The result of integration with respect to wavelength is thus found automatically. The limitation of the method is due to the fact that the best available filter-cell combinations are not exactly spectrally equivalent to the I. C. I. standard observer.

Absolete

We used a three color system, consisting of a No. 931 phototube (S4 surface) which was available in the Light Measuring Equipment (see G. E. I. - 18258) and three glass filters (described by Hunter and obtained from Photovolt Company, New York). Table IV gives the spectral distribution data of this system and shows the calculation of factors to obtain approximate agreement with the I. C. I. primaries $\bar{X}$, $\bar{Y}$ and $\bar{Z}$. Column II gives the relative sensitivity S_T of the phototube, Columns III, IV and V give the relative transmissions T_R, T_G and T_B of the red, green, and blue filters, Columns VI, VII and VIII give the products of Column II and Columns III, IV and V respectively. Summation of Columns VI, VII and VIII results in

$$(1) \qquad \sum S_T T_R = 1155$$

$$(2) \qquad \sum S_T T_G = 5743$$

$$(3) \qquad \sum S_T T_B = 11133$$

That is, for an ideal white light source (having equal energy throughout the spectrum) the response of the phototube through the three filters would be in the proportion 1155 : 5743 : 11133.

Adjusting for equal areas

$$(4) \qquad \sum 8.65\, S_T T_R = \sum 1.745\, S_T T_G = \sum .899\, S_T T_B = 10,000$$

A An approximation of the I. C. I. primaries (Fig. I) can be obtained by using 1/5 of the blue value .899 $S_T T_B$ for the short wavelengths part of the $\bar{X}$ function and 4/5 of the red value 8.65 $S_T T_R$ for the long wavelengths part of the $\bar{X}$ function and using the green values for the $\bar{Y}$ function and the blue values for the $\bar{Z}$ function. Thus we obtain the three primaries of our filter-tube system.

obsolete

(5) $\bar{r} = .179\ S_T\ T_B + 6.93\ S_T\ T_R$

(6) $\bar{g} = 1.745\ S_T\ T_G$

(7) $\bar{b} = .899\ S_T\ T_B$

These values are listed in Columns IX, X and XI of Table IV and plotted in Fig. VI.

Comparison of these tristimulus values for our system with the I. C. I. primaries (Fig. I) shows, that the agreement is not very good, due mainly to the low response of the 931 phototube in the red. Better agreement could be obtained by using a photocell instead of the 931 phototube and by using a fourth filter for the short wavelength portion of the $\bar{X}$ function as described by Barnes (l.c.).

Within these limitations of accuracy the tristimulus values of a cathode ray tube can be obtained by taking the relative light output R, G and B through the three filters and by transformation according to equations 5, 6 and 7 or, since only the relative values enter into the trichromatic coefficients, the approximate tristimulus values are obtained by

$$X = 3.97\ R + .103\ B$$

$$Y = G$$

$$Z = .515\ B$$

E. B. Fehr
12-13-44
E. B. Fehr
December 13, 1944

A. Petraitis
12-13-44
A. Petraitis
December 13, 1944

Countersigned
K. C. DeWalt
12-13-44
KCDeWalt
Dec 16, 1944

Table I

I.C.I. Tristimulus Values for Spectrum Colors (Equal Energy) (From Handbook of Colorimetry)

Wavelength	$\bar{x}$	$\bar{y}$	$\bar{z}$
400	.014	-	.068
10	.043	.001	.206
20	.134	.004	.646
30	.284	.012	1.386
40	.347	.023	1.740
50	.336	.038	1.773
60	.291	.060	1.669
70	.195	.091	1.288
80	.096	.139	.813
90	.032	.208	.465
500	.005	.323	.272
10	.009	.503	.158
20	.063	.710	.078
30	.165	.862	.042
40	.290	.954	.020
50	.433	.995	.009
60	.594	.995	.004
70	.762	.952	.002
80	.916	.870	.002
90	1.027	.757	.001
600	1.062	.631	.001
10	1.003	.503	-
20	.854	.381	
30	.642	.265	
40	.448	.175	
50	.284	.107	
60	.165	.061	
70	.087	.032	
80	.047	.017	
90	.023	.008	
700	.011	.004	

Table II

Calculation of Trichromatic Coefficients of the Two Television Tube Screens Represented by the Spectrophotometric Curves in Fig. II.

Wavelength	Curve 1				Curve 2			
	Relative Energy E_1	$E_1\bar{X}$	$E_1\bar{Y}$	$E_1\bar{Z}$	Relative Energy E_2	$E_2\bar{X}$	$E_3\bar{Y}$	$E_2\bar{Z}$
400	4	.06	-	.26	15	2.01	.06	9.7
20	15	2.01	.06	8.66	39	13.6	.9	68.2
40	26.5	9.3	.61	46.4	39.5	11.5	2.4	65.8
60	38	10.9	2.1	66.6	21	1.96	2.85	16.6
80	26	2.5	3.6	21.2	11	.05	3.55	3.0
500	16	.08	5.18	4.35	22	1.39	15.7	1.7
20	21	1.32	14.9	1.64	32	9.3	30.5	.6
40	27.5	7.96	26.2	4.54	28	16.6	27.8	.3
60	30	17.72	29.85	.01	22.5	20.6	19.6	
80	25	22.4	21.75		19	20.5	11.9	
600	19.5	20.8	12.35		15	12.8	4.9	
20	14	11.95	5.34		11	4.9	1.92	
40	8.5	3.81	1.49		7.5	1.2	.45	
60	4	.65	.24		4	.2	.06	
80	1	.09	.03		1	-	-	
700								

$X_1 = 112 \quad Y_1 = 124 \quad Z_1 = 150$

$X_2 = 117 \quad Y_2 = 122.5 \quad Z_2 = 166$

$$x_1 = \frac{X_1}{X_1 + Y_1 + Z} = .289$$

$$x_2 = \frac{X_2}{X_2 + Y_2 + Z_2} = .289$$

$$y_1 = \frac{Y_1}{X_1 + Y_1 + Z_1} = .321$$

$$y_2 = \frac{Y_2}{X_2 + Y_2 + Z_2} = .300$$

Table III

Trichromatic Coefficients
of Spectrum Colors
(From Handbook of Colorimetry)

Wavelength	x	y	z
400	.1736	.0048	.8219
10	.1726	.0048	.8226
20	.1714	.0051	.8235
30	.1689	.0069	.8242
40	.1644	.0109	.8247
50	.1566	.0177	.8257
60	.1440	.0297	.8263
70	.1241	.0578	.8181
80	.0913	.1327	.7760
90	.0454	.2950	.6596
500	.0082	.5384	.4534
10	.0139	.7502	.2359
20	.0743	.8338	.0919
30	.1547	.8059	.0394
40	.2296	.7543	.0161
50	.3016	.6923	.0061
60	.3731	.6244	.0024
70	.4441	.5547	.0012
80	.5125	.4866	.0008
90	.5752	.4241	.0006
600	.6270	.3725	.0004
10	.6658	.3339	.0002
20	.6915	.3083	.0001
30	.7079	.2920	.0001
40	.7190	.2809	-
50	.7260	.2739	-
60	.7300	.2700	
70	.7320	.2680	
80	.7334	.2666	
90	.7344	.2656	
700	.7346	.2653	

Table IV

Calculation of Factors for 3-Filter System

I Wavelength	II Sensitivity of 931 Phototube S_T	III Transmission of Red Filter T_R	IV Transmission of Green Filter T_G	V Transmission of Blue Filter T_B	VI $S_T T_R$	VII $S_T T_G$	VIII $S_T T_B$	IX $10^{-3}x(.179 S_T T_B - 6.93 S_T T_R)$	X $10^{-3}x1.745 S_T T_G$	XI $10^{-3}x0.899 S_T T_B$
400	30.5									
10	33.2			4.6			153	.027		.137
20	35.4		.2	24.5		7.1	869	.156	.012	.780
30	37.4		.4	37.4		14.0	1398	.251	.025	1.255
40	40.2		.6	42.2		24.7	1740	.312	.043	1.565
50	42.2		.9	43.4		38.0	1830	.328	.066	1.643
60	43.6		1.5	41.2		65.4	1796	.321	.114	1.611
70	44.7		2.5	32.8		111.8	1465	.262	.195	1.318
80	45.3		4.0	21.2		181.2	961	.172	.316	.865
90	45.5	.1	6.1	11.3	4.6	277.5	507	.123	.484	.456
500	45.3	.3	8.7	5.7	13.6	394	258	.141	.687	.230
10	44.4	.6	11.7	2.4	26.6	519	106.5	.203	.906	.096
20	42.8	1.1	14.9	.9	47.1	638	38.6	.334	1.113	.035
30	39.7	2.1	17.4	.3	83.4	691	11.9	.580	1.217	.011
40	34.8	3.4	19.3		118.2	672		.820	1.182	
50	29.4	5.1	20.3		150	598		1.040	1.042	
60	24.3	6.8	20.3		165.3	493		1.142	.816	
70	19.5	8.2	19.2		159.8	374		1.096	.653	
80	15.0	9.0	17.5		134.8	263		.930	.458	
90	11.0	9.2	15.2		101.2	168		.703	.293	
600	7.6	9.2	13.1		70.0	995		.485	.174	
10	5.0	8.4	10.9		43.2	54.5		.299	.095	
20	3.2	7.2	8.8		23.6	28.2		.163	.049	
30	2.2	6.1	7.2		13.4	15.8		.093	.022	
40	1.6	5.0	5.9		8.0	9.5		.055	.017	
50	1.2	4.0	4.6		4.8	5.5		.033	.010	
60	.9	3.2	3.8		2.8	3.4		.019	.006	
70	.6	2.4	3.0		1.4	1.8		.009	.003	
80	.5	1.9	2.4		.9	1.2		.006	.001	

FIGURE I

TRISTIMULUS VALUES
FOR SPECTRUM COLORS

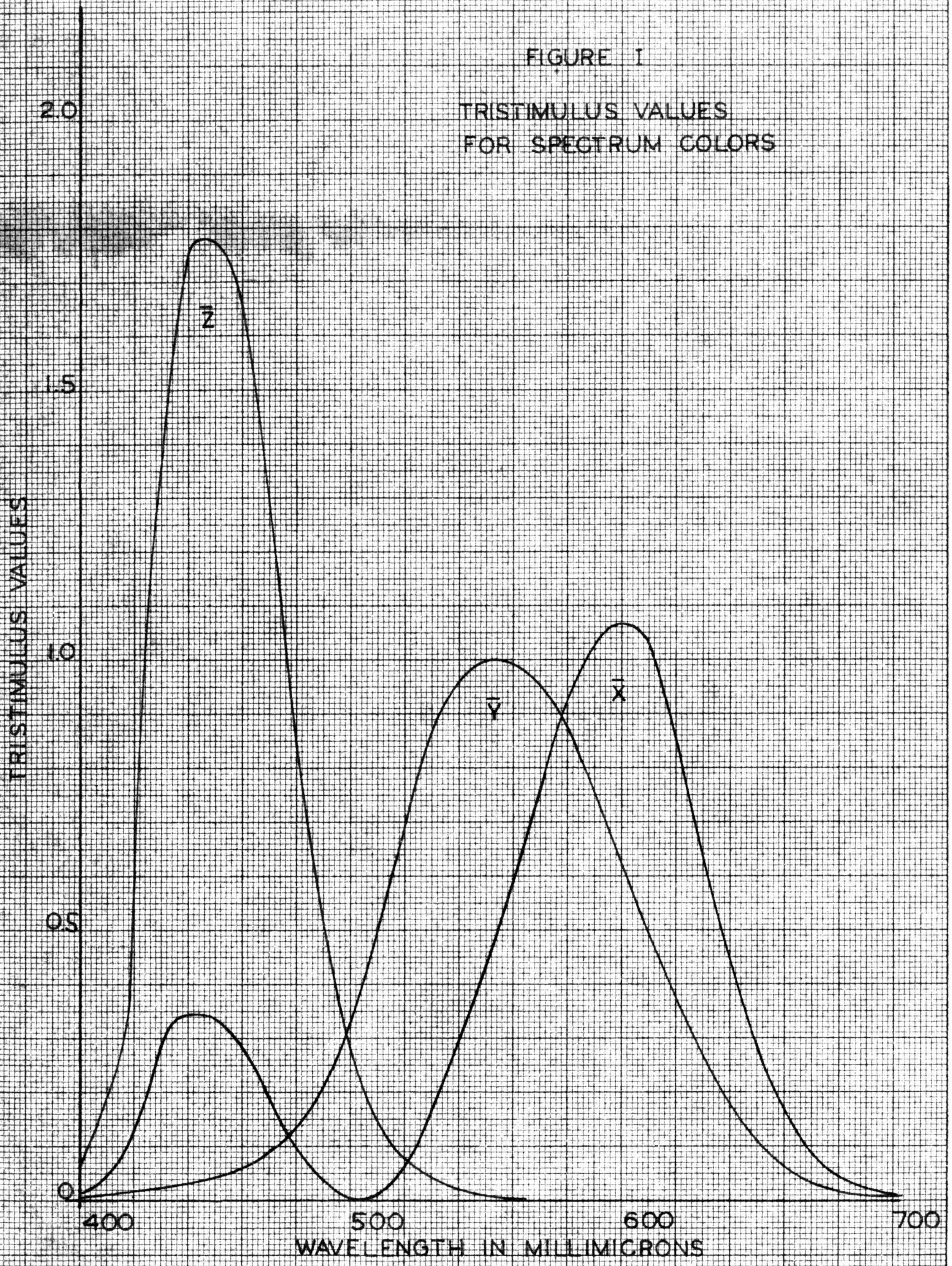
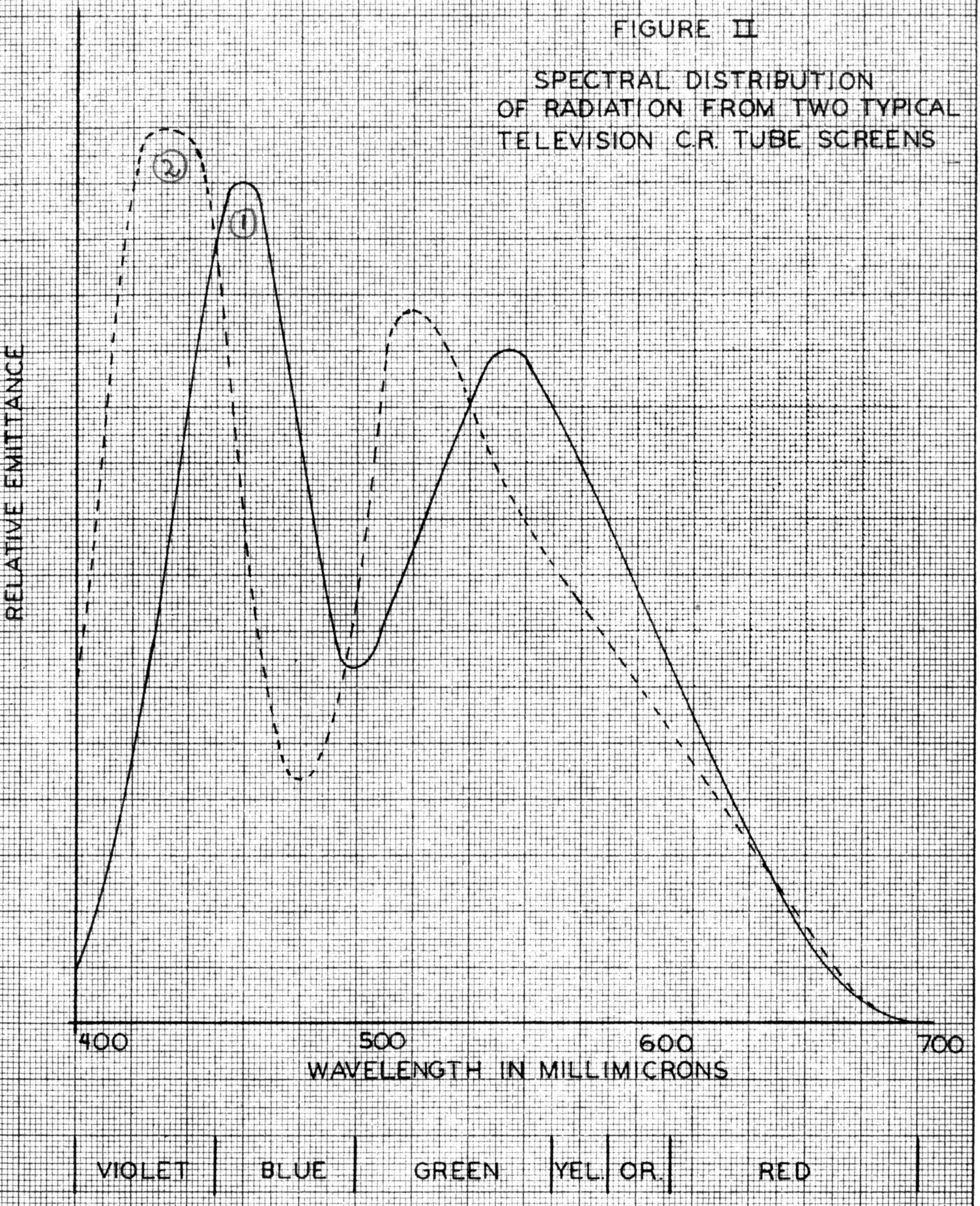


FIGURE II

SPECTRAL DISTRIBUTION OF RADIATION FROM TWO TYPICAL TELEVISION C.R. TUBE SCREENS



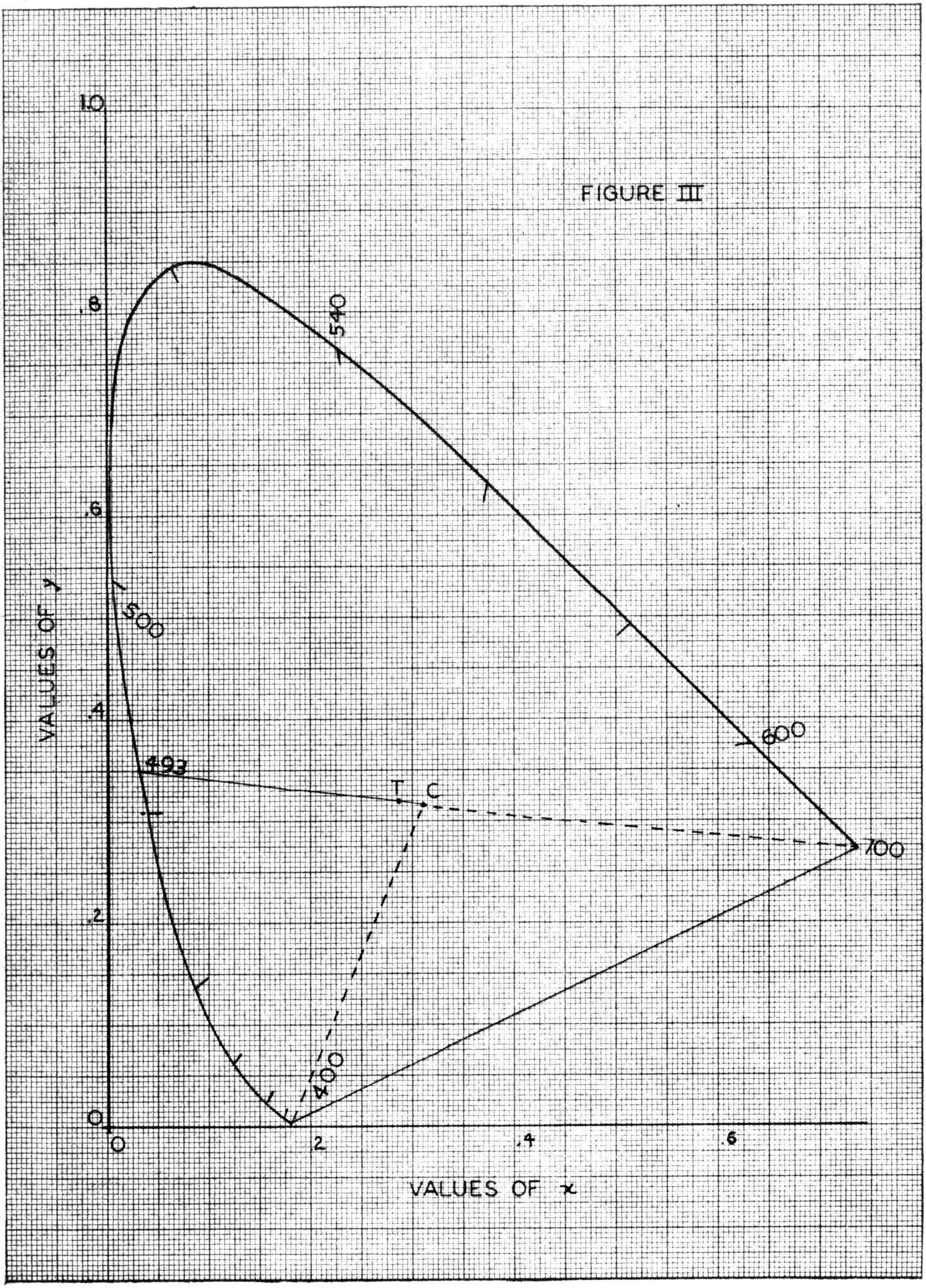


FIGURE III

FIGURE IV

CHROMATICITY DIAGRAM

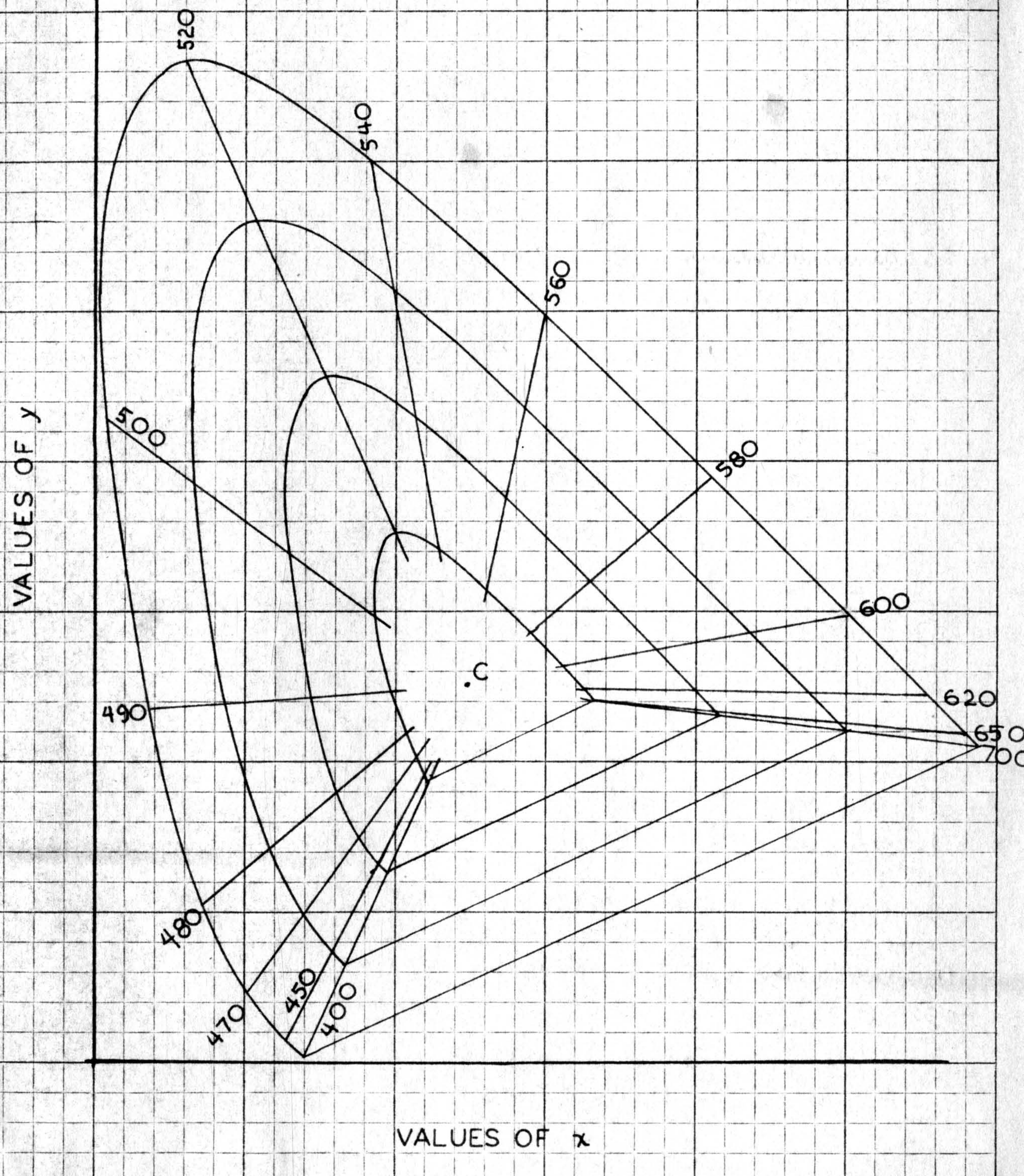
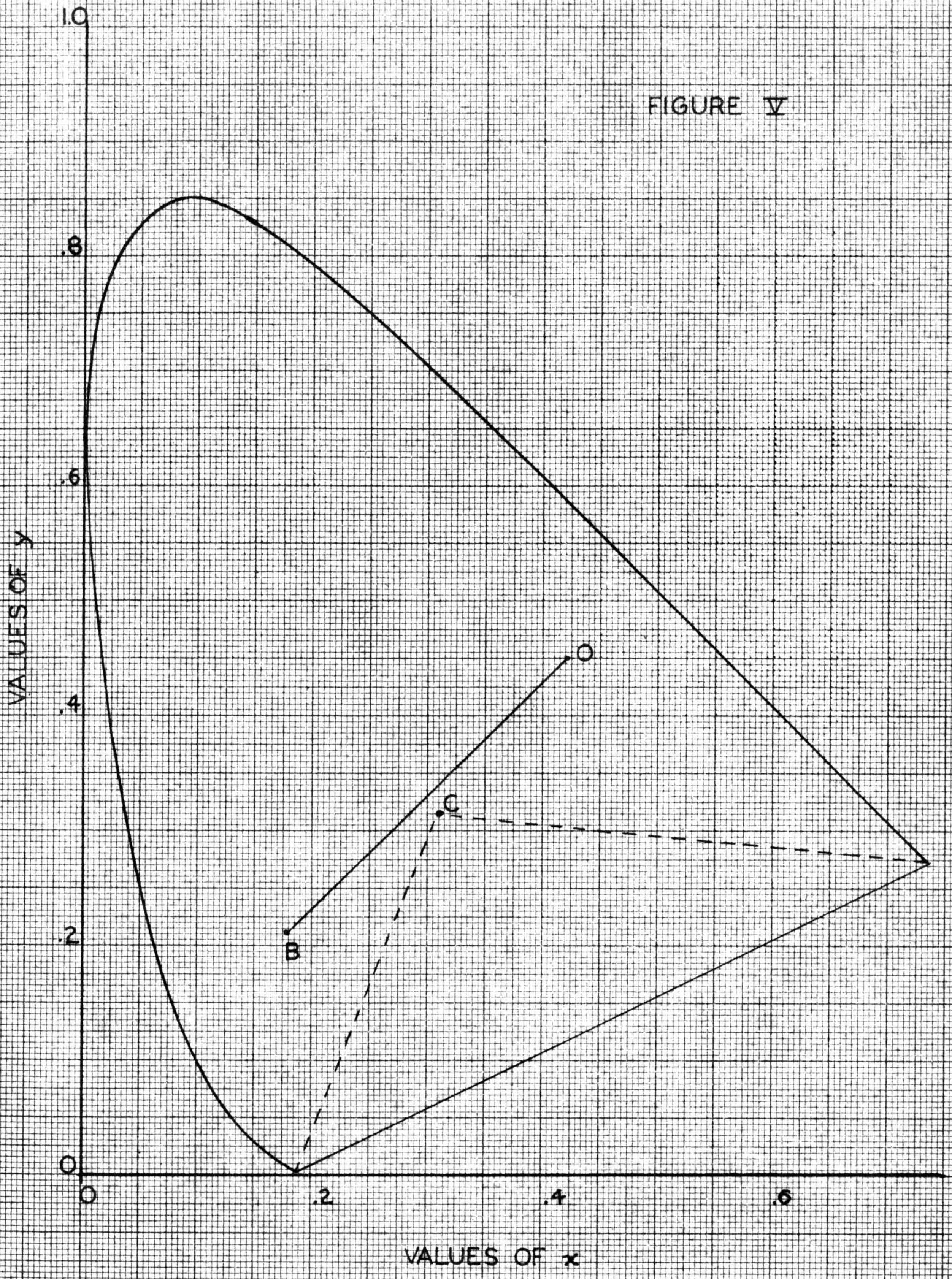


FIGURE V



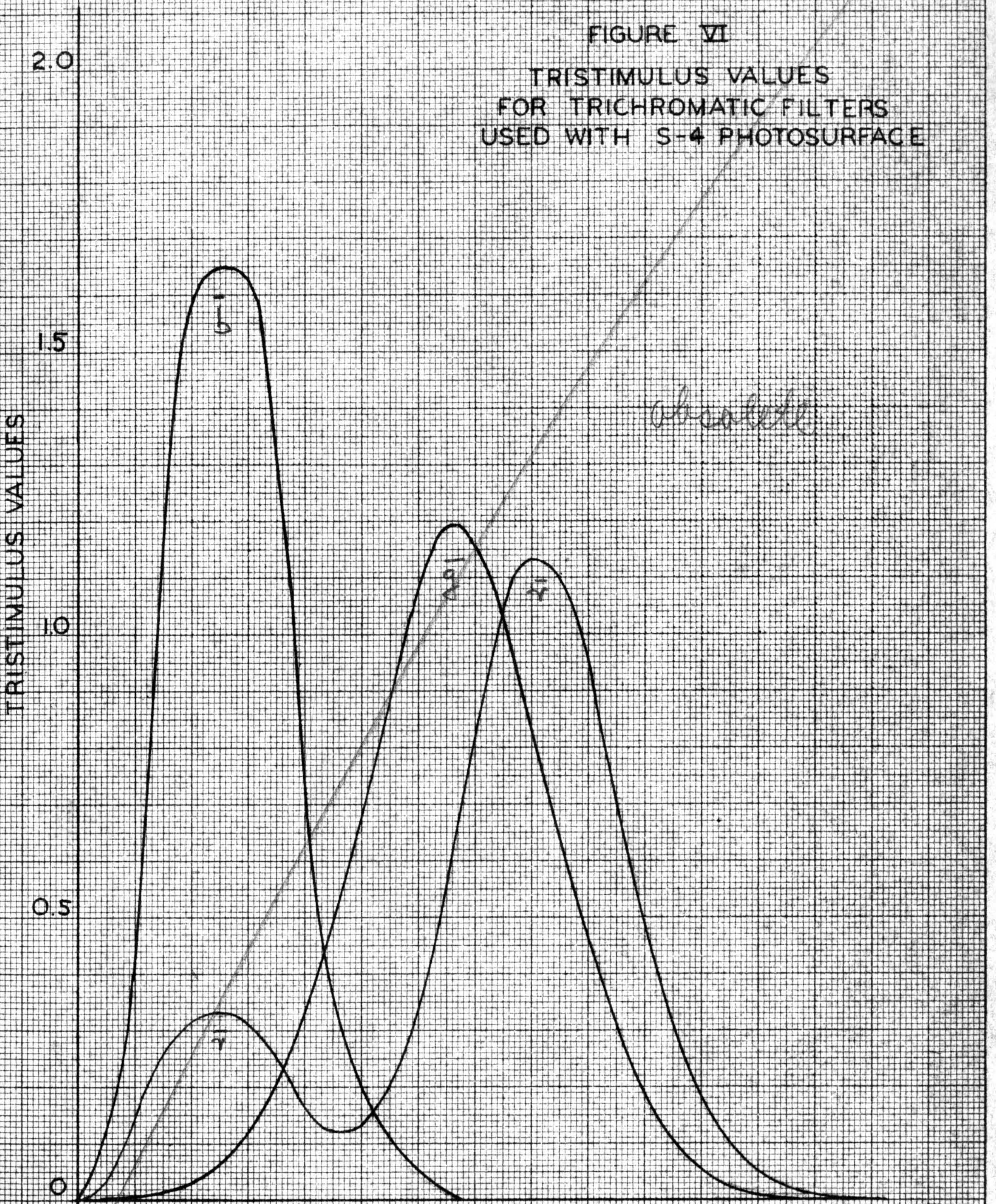
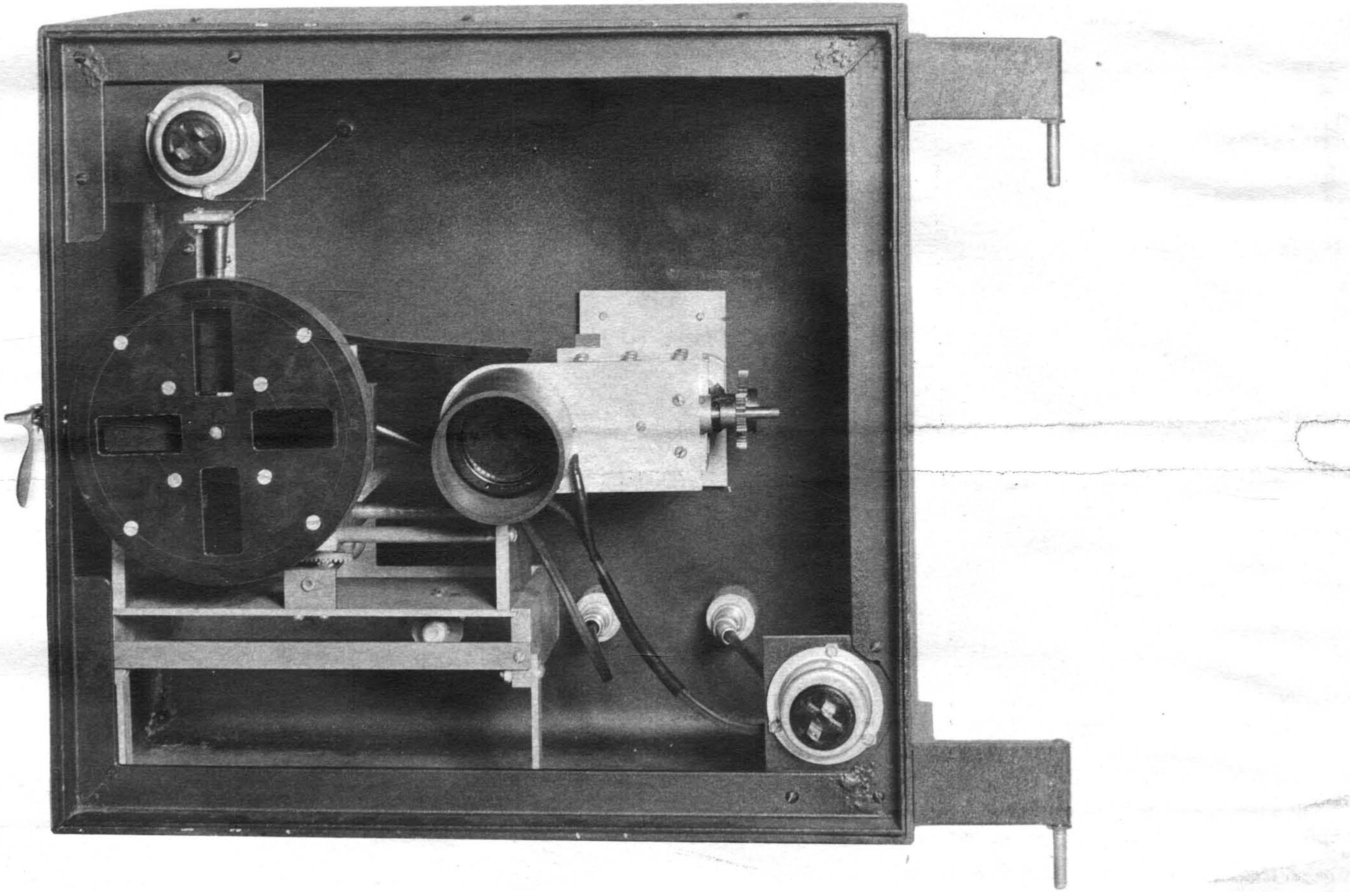


FIGURE VI

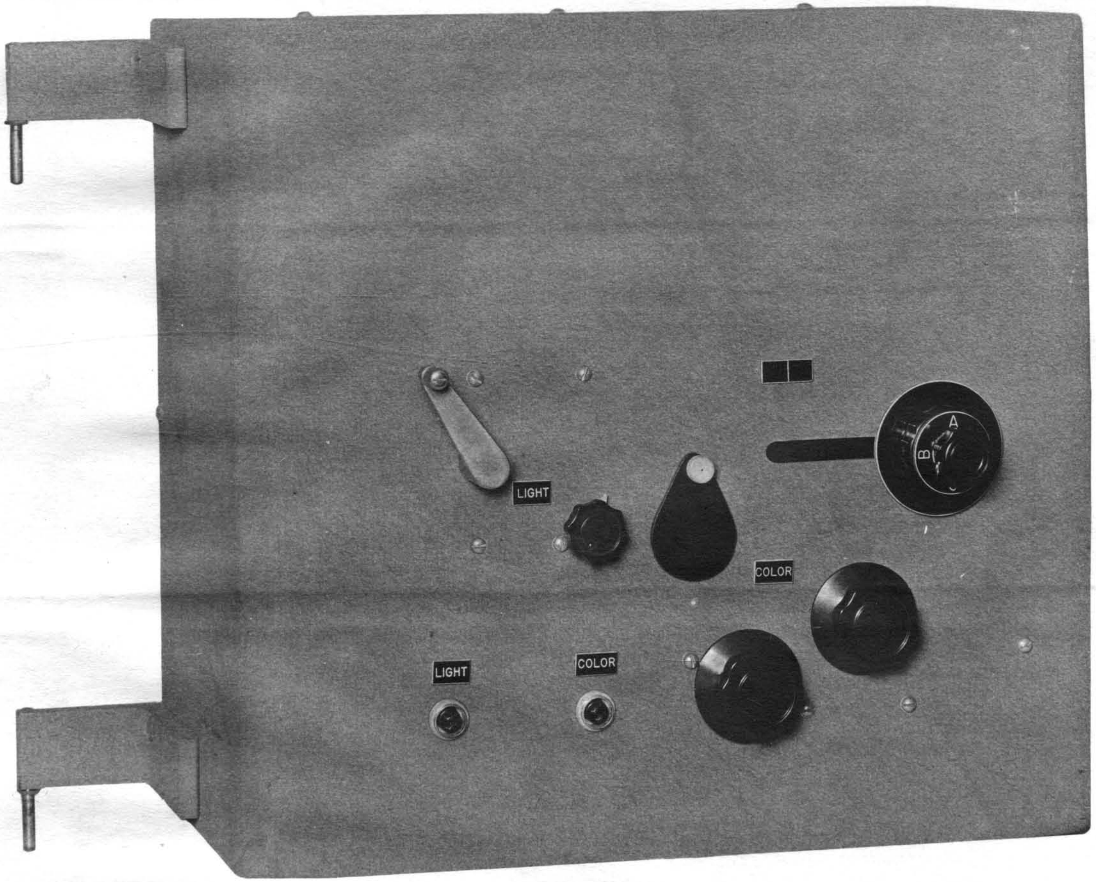
TRISTIMULUS VALUES
FOR TRICHROMATIC FILTERS
USED WITH S-4 PHOTOSURFACE

obsolete



1022 342 G-E LIGHT AND COLOR MEASUREMENT EQUIPMENT FOR CATHODE-RAY TUBE. REAR VIEW.

FILING NO.6920, 8851 E369.9 3-27-46



1022 343 G-E LIGHT AND COLOR MEASUREMENT EQUIPMENT FOR CATHODE-RAY TUBE. FRONT VIEW.

FILING NO.6920, 8851 E369.9 3-27-46

ASSIGNED BY JUNE 3.46 RJL
JUNE 3, 1946
JK-8551

K-69087-1A54

SECTION OF I.C.I. COLOR DIAGRAM