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TITLE On The Conversion of Spectral Energy Curves to a Relative Energy Basis

ABSTRACT A method is described for converting spectral energy distribution curves to a relative energy basis which depends only upon the basic assumptions of the ICI system of color representation and a single experimental measurement of tube brightness. The method is useful for graphical comparison of phosphor efficiencies, and, in a modified form, for prediction of the color of phosphor blends from

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CONCLUSIONS

color data on the components alone. It is expected that with certain refinements of experimental technique it can be used to calculate the phosphor compositions needed to hold production color to very close tolerances, thereby eliminating the presently used, costly "cut-and-try" procedures for adjusting color.

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ON THE CONVERSION OF SPECTRAL ENERGY CURVES
TO A RELATIVE ENERGY BASIS

It has been found desirable to express spectral energy data on the various P4 phosphors on a relative energy basis in order to compare efficiencies and to predict the color that would result from mixing the various components in different proportions. The spectroradiometer data, as taken here, do not yield curves on a relative energy basis because it has been necessary to change the detection sensitivity of the equipment in order to account for the wide differences in phosphor efficiencies as well as the wavelength response character-istics of the photomultiplier detection device. The detection sensitivity has been changed by varying the dynode voltage on the 1P22 photomultiplier tube, keeping the tube-to-spectroradiometer spacing and the spectroradiometer slit widths constant.

Two methods will be considered here for converting the raw data, so taken at different levels of detection sensitivity, to a relative energy basis.

Method 1 consists of compensating for the changes in sensitivity by means of a calibration of galvanometer deflection, G_λ, as a function of dynode voltage, V. The function was found to be

$$G_\lambda \sim V^{7.45} \qquad\qquad 600 < V < 800 \text{ V.} \qquad \text{(ref. 1, 2)}$$

for the photomultiplier used. Several attempts were made to convert a series of curves to a relative energy basis using the above relation in the form

$$f = \left(\frac{V_1}{V_2}\right)^{7.45}$$

where f is the conversion factor to be applied to readings $G_{\lambda 2}$ to convert to the basis of curve 1. It was found, however, that the accuracy obtained was

poor because small errors in reading V gave rise to very large errors in f. The method was also unsatisfactory because the phototube response characteristics as a function of V can be expected to change with time and among different tubes.

Method 2 for the conversion of curves to a relative energy basis, although a more abstract concept, is much more reliable, since it depends only upon the basic assumptions of the ICI system of color representation [3] and upon a single experimental measurement of tube brightness.

The Y tristimulus value, calculated here for every set of spectroradiometer data to obtain the ICI color coordinates, x and y, is defined strictly as

$$Y = \int_{400\ m\mu}^{700} K I_\lambda\ \bar{y}_\lambda\ d\lambda$$

where I_λ is the intensity at a given λ and K is a measure of the detection sensitivity used for a given measurement,

$$K = \frac{G_\lambda\ k_\lambda}{I_\lambda},$$

$\bar{y}_\lambda$ is the $\bar{y}$ tristimulus function, proportional to the eye sensitivity curve and k_λ is a calibration function of the equipment.

It is defined experimentally as the approximating sum

$$Y = \sum_{\lambda = 400}^{700} G_\lambda\ k_\lambda \bar{y}_\lambda \quad \text{at } 10 m\mu \text{ intervals of } \lambda.$$

Since brightness is defined and measured as the average ordinate of the product of I_λ and the eye sensitivity curve

$$B = C \int_{400}^{700} I_\lambda \bar{y}_\lambda\ d\lambda$$

where C is a constant for the determination of the appropriate units,

it is evident that

$$B = \frac{CY}{K}.$$

For two curves to be on a relative energy basis, the value of K, the level of detection sensitivity, for the two curves must be made to be the same.

Therefore, to convert any curve, 2, to an energy basis relative to curve 1 it is merely necessary to apply a conversion factor, f, to the values of $G_{\lambda 2}$ (or $G_{\lambda 2}k_{\lambda}$) defined as

$$f = \frac{K_1}{K_2} = \frac{B_2\, Y_1}{Y_2\, B_1}.$$

Such a conversion factor is subject primarily to errors in the measured brightness, B, so that readings of brightness attendant with spectroradiometer readings should be taken with extreme care. In the normal range of brightnesses used for color readings here, the error in measurement of B is about one or two percent at most. This could introduce an error of up to four percent in f. The errors introduced by approximating the Y-integral with the summation and those arising from the wavelength sensitivity calibration of the brightness meter can be shown to be negligible.

As an example of the application of this method the spectral energy curves of the four basic DuPont ZnS and Zn-CdS components are presented in Figure I on a relative energy scale of ordinates. Similarly, the five silicized counterparts of these basic components are shown in Figure II, plotted on the same ordinate scale as Figure I. All the data were taken at the same conditions of input energy to the tubes carrying the components, so that the efficiencies are directly comparable.

As a check on the accuracy of the method, calculations have been made to determine the color of various two-component blends by addition of the spectral energy curves of the components, first put on a relative energy basis, and then scaled down in proportion to the percentages of each component in the blends. A typical comparison between a calculated and actually measured

spectral energy curve is shown in Figure III.

Figure IV shows the comparison between the measured and calculated color for a carefully mixed series of two-component blends. The values of calculated color were determined by the analytical method described below rather than by actual addition of curves.

It is not necessary to make the calculations graphically, or even by operations on each individual $G_\lambda k_\lambda$ value. A simple, analytical method can be used which has the advantage that it gives rise to no compounded errors. It is illustrated by the following example.

If we have experimental data, G_λ and B, for the two components, 1 and 2, and from the values of G_λ have calculated X, Y and Z by the standard method [3] corrected for the spectroradiometer calibration, the procedure will be as follows:

1. To get the data for the second component on a basis relative to the first we make

$$Y_2 \text{ corrected} = Y_2 f = \frac{B_2 Y_1}{B_1}.$$

This operation implies also that

$$X_2 \text{ corrected} = X_2 \frac{B_2 Y_1}{Y_2 B_1}$$

$$\text{and } Z_2 \text{ corrected} = Z_2 \frac{B_2 Y_1}{Y_2 B_1}.$$

2. To weight the contributions of component 1, weight percentage α in the blend, and component 2, percentage $(100 - \alpha)$

$$X_1 \text{ effective} = \alpha X_1$$
$$Y_1 \text{ effective} = \alpha Y_1$$
$$Z_1 \text{ effective} = \alpha Z_1$$

and $\quad X_2$ effective $= (100-\alpha) X_2$ corrected

$\qquad Y_2$ effective $= (100-\alpha) Y_2$ corrected

$\qquad Z_2$ effective $= (100-\alpha) Z_2$ corrected.

3. Adding the effective outputs of the two components gives

$$X = X_1 \text{ effective} + X_2 \text{ effective}$$
$$Y = Y_1 \text{ effective} + Y_2 \text{ effective}$$
$$Z = Z_1 \text{ effective} + Z_2 \text{ effective}$$

from which the predicted color of the blend becomes

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

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

The entire procedure can be condensed to the symbolic form

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

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

where $\qquad X = \alpha X_1 + (100-\alpha) \frac{B_2 Y_1}{Y_2 B_1} X_2$

$\qquad Y = \alpha Y_1 + (100-\alpha) \frac{B_2 Y_1}{B_1}$

$\qquad Z = \alpha Z_1 + (100-\alpha) \frac{B_2 Y_1}{Y_2 B_1} Z_2$

The extension of this procedure to three or more components is straightforward.

It can be seen from Figure IV that the method can be used to predict the color of two-component blends to within about ± 0.020 in both x and y. The error in three component blends will be somewhat larger. This accuracy is not as great as is desired to hold production color within the close tolerances of the GE color acceptance box. However, it will be shown that the amount of error can be considerably reduced by changing the experimental procedure.

As has been previously discussed, the f -factor is subject to as much as four percent error due to errors in reading brightness. The method neglects both absorption effects of the phosphors for their own radiation and any effects caused by a cascade luminescence action between the components. Both of the latter two effects are known to come into play to some extent; it is expected that absorption effects are quite considerable, but that cascade luminescence effects are small [4]. Measurements are being made to give absorption data on the DuPont components.
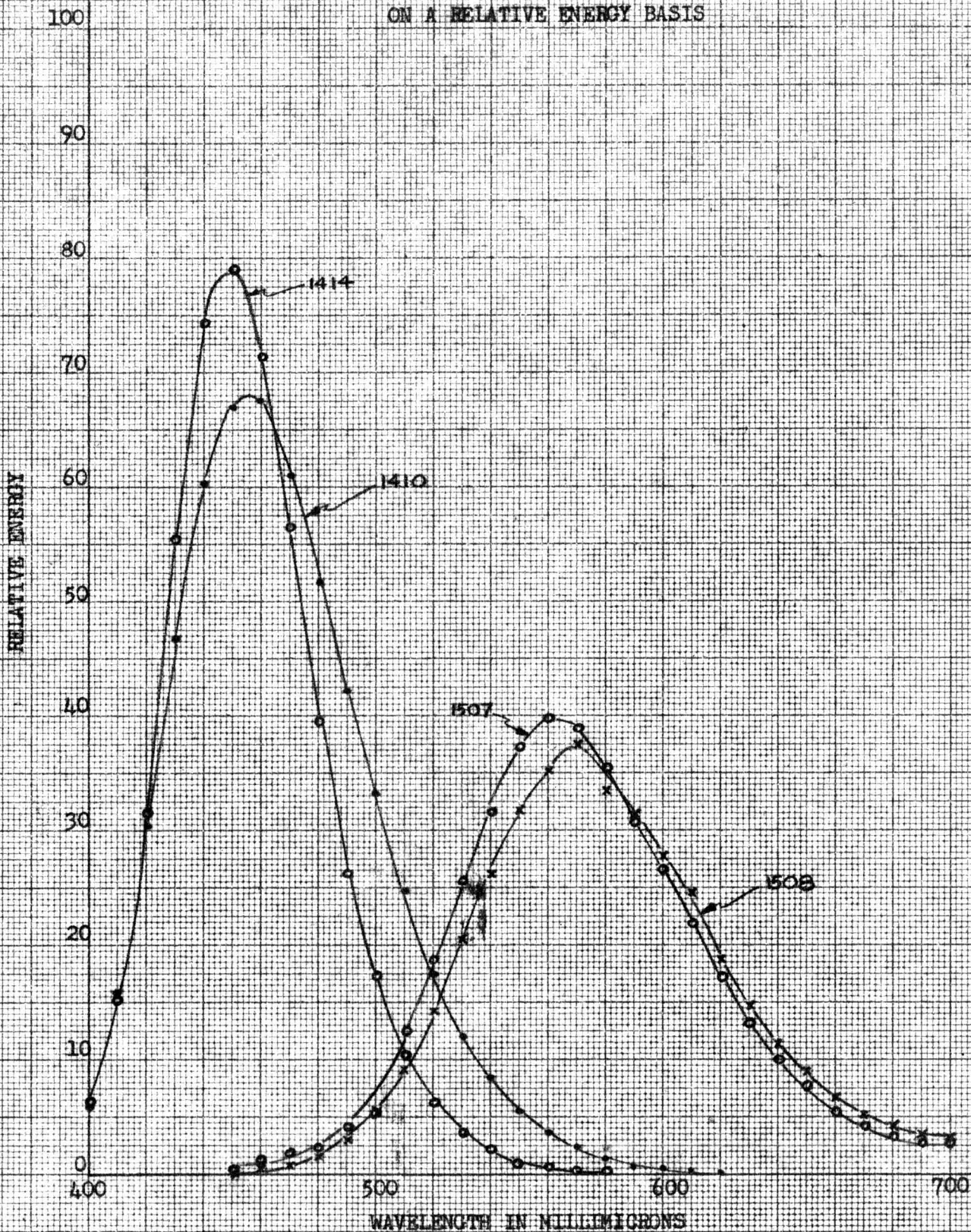
A much more serious error is introduced in the data presented in Figures I and II (which are used as the basis for all color prediction) which arises from the fact that the data on the components were taken on finished tubes. Unfortunately, the measured brightness of a tube depends not only upon the efficiency of the phosphor, but also upon the overall efficiency of the tube, including that of the cathode and gun. Overall efficiency, for tubes built with the same phosphor, can vary by more than ten percent. There- fore, although the Y/B values used to convert the curves shown in Figure I and II were in all cases the average on two or more tubes, the relative ordinates of the curves can be expected to be in doubt by as much as ten percent. It would therefore be very desirable to make measurements for the relative spectral energy curves for the components on slides in a demountable tube, where the variation in gun efficiency could be eliminated.

With this refinement in experimental procedure, and with appropriate corrections for the absorption characteristics of the various components, it is expected that the method will allow for the calculation of the color of two-and three-component blends to within $\neq 0.005$ in x and y. With this accuracy it can be used to determine blend compositions to hold production color tolerances to within as close tolerances as the tubes can be built, thereby eliminating the present unsatisfactory "cut-and-try" methods used for adjusting color.

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FIGURE I
SPECTRAL ENERGY DISTRIBUTION
FOR THE BASIC DUPONT COMPONENTS
1414, 1410, 1507, 1508
ON A RELATIVE ENERGY BASIS

FIGURE II
SPECTRAL ENERGY DISTRIBUTION
FOR THE DUPONT SILICIZED COMPONENTS
ON A RELATIVE ENERGY BASIS

2546 – lightly silicized 1507
2387 – heavily silicized 1508
2545 – lightly silicized 1414
2388 – heavily silicized 1410
2605 – lightly silicized 1410

FIGURE III
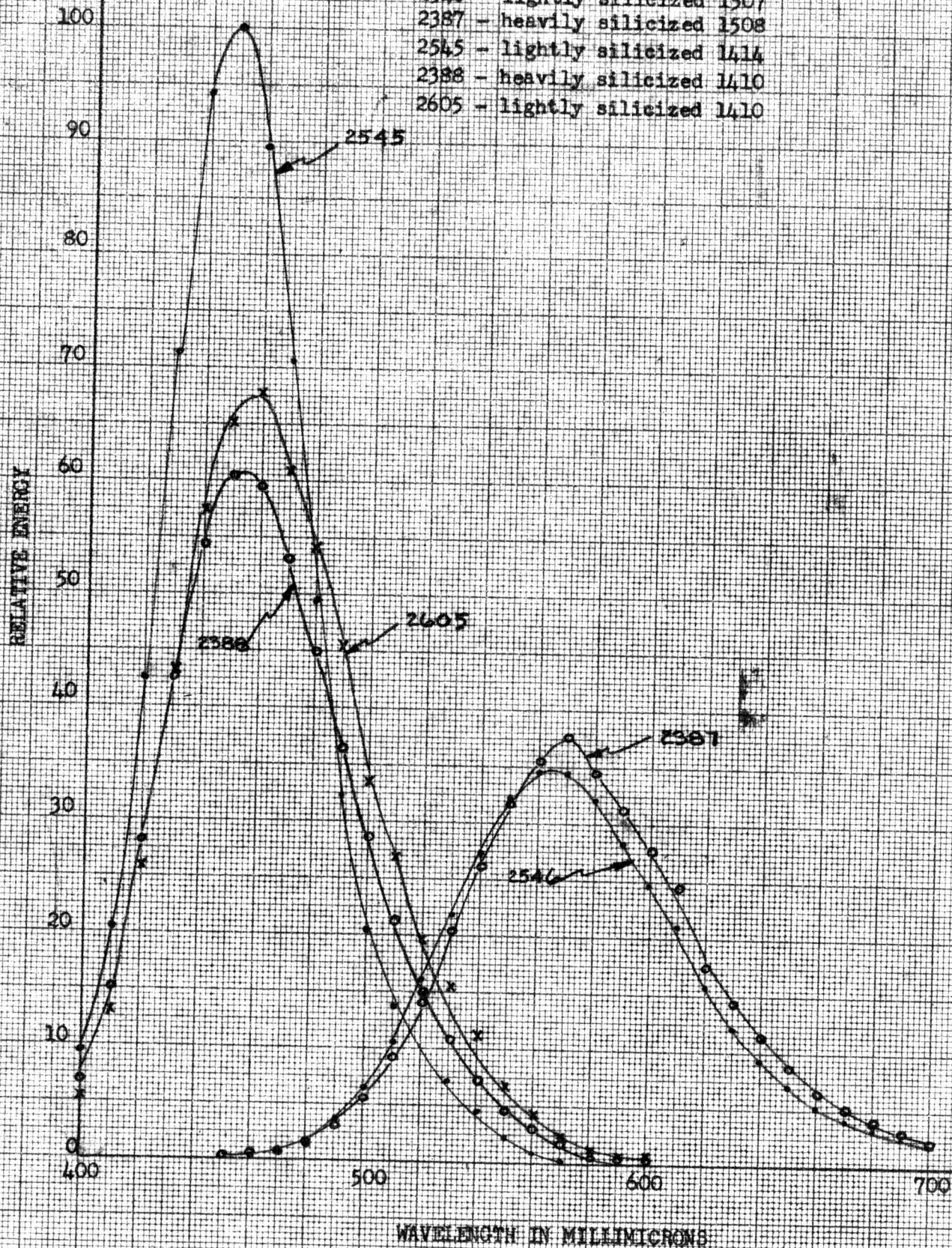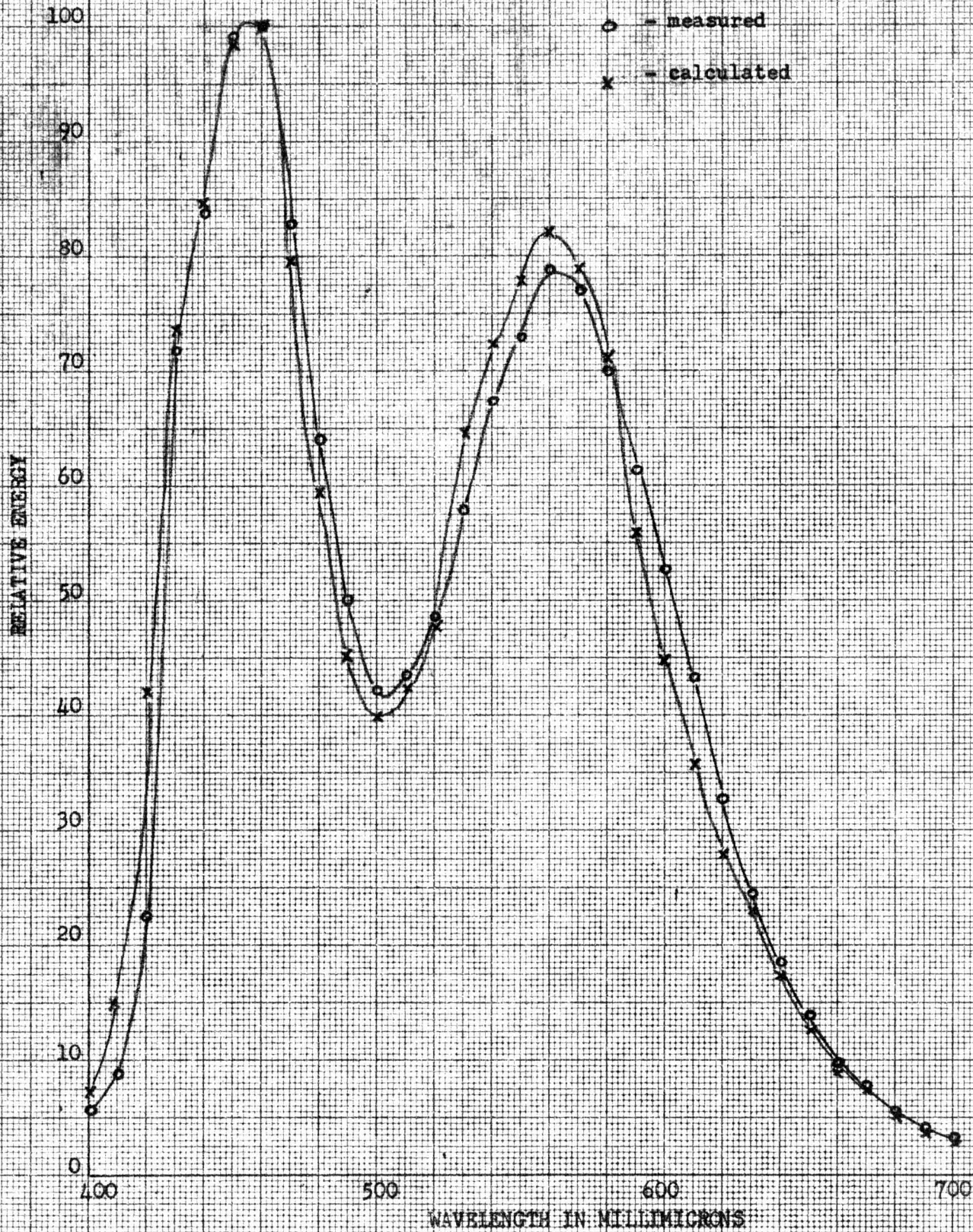COMPARISON OF MEASURED
AND CALCULATED SPECTRAL ENERGY CURVES
Blend 60% 1507
40% 1414

○ — measured

× — calculated

FIGURE IV

COMPARISON OF MEASURED AND CALCULATED COLOR
FOR A SERIES OF TWO-COMPONENT BLENDS

o — Measured
x — calculated